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Phonological contrast and feature inventories in sign language: a study on French Sign Language (LSF)

Justine Mertz

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Phonological contrast and feature inventories in sign language

A study on French Sign Language (LSF)

Thèse de Linguistique

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Abstract

In this dissertation, we aim at providing a comprehensive analysis of contrast and feature inventories in sign language (SL) from a theoretical, empirical, and experimental point of view. We use data from French Sign Language (LSF), a language still understudied and for which little is known about its phonology. First, we dig into feature-based theoretical models to better understand the nature of SL inventories. An investigation of one particular location on the hand, the webbing part of the fingers, provides us with a better sense of how to determine the content of feature inventories. We show that because of the difficulties in finding genuine minimal pairs, other forms of contrast must be used to compose phonological inventories, among which near-minimal pairs, productivity, as well as neutralization. Contrary to previous analyses based on American Sign Language (ASL), we provide evidence from LSF that the feature [web] must be included among the features that signers can use to create phonological contrast. Its status then led us to reanalyze (sub)location features as orientation features in some phonological models for SL. Our second study on features allows us to revisit the status of orientation in the composition of signs. In many phonological models, orientation is derived from a specification in handshape and a specification in location, while in others it is considered as an absolute property of the hand. Our analysis of two-handed signs produced on the signer's body in LSF provides evidence that both are necessary for the representation of this category of signs, and the implementation of secondary planes in a formal framework allows us to do so. In the third study we capitalize at a more global level on the notion of feature and feature geometry models to capture complexity in sign articulation. We evaluate the ability of a theoretical model to reflect the complexity of signs in LSF. We compare an error-driven measure based on a repetition task, in which hearing non-signers had to copy existing signs, to a model-driven measure derived from the phonological structure of signs in the framework of the Prosodic Model (Brentari, 1998). Our results show that phonological models manage to capture overall articulatory complexity, as well as the one in handshape and location, but not in movement, the only dynamic phonological class. Altogether, these results indicate that an accurate theoretical model

of sign phonology/phonetics reflects the degree of complexity as a result of the perceptual and articulatory properties of signs. In the last study, we focus on the psycholinguistic mechanisms behind the perception of contrast in SL. We explore the perception of contrast at the experimental level by conducting a study on categorical perception (CP) in LSF, in both handshape and location. We show that a CP effect is observed in handshape in Deaf signers, but not in hearing non-signers, a population never exposed to the phonological system of LSF. In location, no CP effect was observed which is in accordance with the literature. The unexpected significant effect observed in our allophonic pair in handshape puts into perspective the perception of (non-)contrastive units in SL and allows us to highlight the finesse of contrastiveness in the visual-gestural modality. From the various dimensions we have addressed in this thesis, we demonstrate that the study of LSF provide useful insights in the understanding of how distinctive features capture contrast in SL in general, as well as their role in determining sign complexity and perceiving contrast.

Keywords – French Sign Language, Sign language phonology, Contrast, Phonological inventories, Distinctive features, Feature geometry, Relative orientation, Articulatory complexity, Categorical perception.

Résumé

Dans cette thèse, notre objectif est de fournir une analyse complète du contraste et des inventaires de traits dans les langues des signes (LS) d'un point de vue théorique, empirique et expérimental. Nous utilisons les données de la Langue des Signes Française (LSF), une langue encore peu étudiée et dont on connaît peu la phonologie. Nous explorons les modèles théoriques basés sur les traits afin de cerner la nature des inventaires des LS. L'étude d'un emplacement particulier sur la main, la partie palmée des doigts (*webbing*), permet de mieux comprendre comment déterminer le contenu des inventaires des traits. Nous montrons qu'en raison des difficultés à trouver de véritables paires minimales, d'autres formes de contraste doivent être utilisées pour composer les inventaires phonologiques, telles que les paires minimales approximatives, la productivité, ainsi que la neutralisation. Contrairement aux études sur la Langue des Signes Américaine (ASL), nous apportons la preuve à partir de la LSF que le trait [web] doit être inclus parmi les traits que les signants peuvent utiliser pour créer un contraste phonologique. Son statut nous a alors conduit à revoir les traits de (sous-)emplacement comme traits d'orientation dans certains modèles phonologiques. Notre deuxième étude sur les traits nous permet de revoir le statut de l'orientation dans la composition des signes. Dans de nombreux modèles phonologiques, l'orientation est dérivée d'une spécification de la configuration manuelle et d'une spécification de l'emplacement, tandis que d'autres la considère comme une propriété absolue de la main. Notre analyse des signes à deux mains produits sur le corps du signant en LSF apporte la preuve que les deux sont nécessaires à leur représentation, et l'implémentation de plans secondaires dans un cadre formel nous permet de le faire. Dans la troisième étude, nous capitalisons à un niveau plus global sur la notion de traits et les modèles géométriques pour appréhender la complexité articulatoire des signes. Nous évaluons la capacité d'un modèle théorique à refléter la complexité des signes en LSF : nous comparons une mesure basée sur les erreurs de répétition de signes existants produites par des entendants non-signants à une mesure basée sur la structure phonologique des signes dérivée dans le cadre du *Prosodic Model* (Brentari, 1998). Nos résultats montrent que les modèles phonologiques saisissent la complexité articulatoire globale, ainsi que

celle de la configuration manuelle et de l'emplacement, mais pas celle du mouvement, la seule classe phonologique dynamique. En somme, ces résultats indiquent qu'un modèle théorique précis de la phonologie/phonétique des signes reflète le degré de complexité associé aux propriétés perceptives et articulatoires des signes. Dans la dernière étude, nous examinons les mécanismes psycholinguistiques qui sous-tendent la perception du contraste dans les LS. Nous explorons la perception du contraste à partir d'une étude sur la perception catégorielle (PC) de la configuration manuelle et de l'emplacement en LSF. Nous montrons qu'un effet de PC est observé dans la configuration manuelle chez les Sourds signants, mais pas chez les entendants non-signants, une population jamais exposée à la phonologie de la LSF. Dans l'emplacement, aucun effet de PC n'a été observé, conformément à la littérature. L'effet significatif inattendu observé dans notre paire allophonique de la configuration manuelle remet en perspective la perception des unités (non-)contrastives dans les LS, et nous permet de mettre en évidence la finesse de la contrastivité dans la modalité visuo-gestuelle. A partir des différentes dimensions abordées dans cette thèse, nous démontrons que l'étude de la LSF apporte des éléments nécessaires à la compréhension de la manière dont les traits distinctifs rendent compte du contraste des LS en général, ainsi que leur rôle dans la détermination de la complexité des signes et dans la perception du contraste.

Mots clés – Langue des Signes Française, Phonologie des langues des signes, Contraste, Inventaires phonologiques, Traits distinctifs, Géométrie des traits, Orientation relative, Complexité articulatoire, Perception catégorielle.

Abbreviations

Since this is an article-based thesis, the abbreviations vary from chapter to chapter. We have grouped them here.

A Articulator

ASL American Sign Language

BSL British Sign Language

CP Categorical Perception

H1 Dominant hand

H2 Non-dominant hand

HS Handshape

IF Inherent Features

LIS Italian Sign Language

LOC Location

LSF French Sign Language

PF Prosodic Features

POA Place Of Articulation

RTs Reaction Times

SL Sign Language

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Chapter 1

Introduction

1.1 General introduction

Sign language research has made great strides in the last forty years, and the interest they attract has only increased. The visual-gestural modality on which they depend puts much of the existing knowledge about languages into perspective and challenges our understanding of language perception and production. The difference with the oral modality of spoken languages suggests lots of variation, but as natural languages, they also share language properties independent of modality. Increasing our knowledge of sign language allows us to deepen the concepts and notions already defined and attested in linguistics, including phonology, our field of interest. In this article-based dissertation, we aim to study the notion of *contrast* in French Sign Language (LSF), the language used by the majority of Deaf signers in France. LSF is a minority language heavily under-studied, especially in phonology. In this dissertation, we try to fill this gap by investigating distinctive features and phonological contrast from a theoretical, empirical, and experimental point of view. Our objective is to understand the mechanisms underlying the phonology of LSF and the foundations of the notion of *contrast* through the analysis of the phonological structure of signs, the status of phonological classes, the link between theoretical representation and phonetic articulation in the complexity of perception and production of signs, and the mental representation of sign phonological classes.

The theoretical framework of this thesis is developed within the scope of feature-based phonology applied to sign language, with or without feature-geometry. It is the study of features and their interactions that allows us to conduct our research on LSF. We focus on features of four phonological classes that constitute signs: handshape, location,

movement, and orientation.¹ We conduct four studies that are all connected by a common overarching theme: distinctive features and their role in capturing phonological contrast in LSF. Each study constitutes a chapter which has been either published or submitted to a journal in the form of a scientific paper. Together they allowed us to pinpoint the major role that features play in the analysis of phonological processes in sign language, as well as, perhaps more importantly, revise the composition of sign sub-categories.

Before presenting an overview of the studies we have conducted, we offer a brief introduction to basic background information about the properties of sign languages that are necessary for the understanding of their phonology and the subsequent chapters. In the following sections, we first provide a brief description of the specific characteristics of the visual-gestural modality (1.2), then we offer a detailed overview of each chapter of this thesis (1.3). For convenience, all references and appendices are listed at the end of the manuscript.

1.2 Sign language properties

Sign languages use the visual-gestural modality. What makes sign and spoken languages intrinsically different is obviously the articulatory apparatus. Contrary to spoken languages, sign languages can use either one or two hands as articulators depending on whether the non-dominant hand is active or not, as well as body postures and facial expression as independent articulators (Brentari, 1998). Whatever the type of sign, the two hands are not equally independent: the dominant hand (usually the right hand for right-handed signers/the left hand for left-handed signers) is autonomous in her behavior, unlike the non-dominant hand which is subject to more phonological constraints and depends more on the other hand's properties (Battison, 1974). First of all, one-handed signs can only be produced by the dominant hand. In two-handed signs, properties of the dominant hand determine the behavior of the non-dominant hand: when both hands are active, the non-dominant hand copies the dominant hand (same handshape, location, orientation, and movement). When the non-dominant hand is static, there are two alternatives: either the two hands have the same handshape, or they are different. In the former case, the handshape of the non-dominant hand is an exact copy of the other hand configuration. In the latter, both hands have distinct handshapes, but the shape of the non-dominant is restricted to a limited set of configurations. These have been attested in many (if not all) sign languages (Battison, 1974), and have been identified as unmarked forms in terms of phonological structure.

¹Non-manual components (facial expressions, eyebrow-raising, *etc.*) also constitute a phonological class, but since our research questions do not focus on their study, we do not consider them in this thesis.

Contrary to speakers who use their vocal tract to produce and their ears to perceive language, signers use their upper body to produce and their visual system to perceive instead. Besides the intrinsic differences between the physical properties of the two modalities (see Brentari, 2002, for a detailed comparison of the visual *vs.* auditory systems), the visual-gestural modality has some properties of its own. To only name a few, most of the phonological units are produced simultaneously rather than sequentially (Section 1.2.1), and sign languages carry more iconicity than spoken languages (1.2.2). These two specificities thus influence the composition of sign language lexicons (1.2.3), and consequently on their phonology. Such properties raise fundamental questions about the perception and production of signs and their phonetic and phonological composition.

1.2.1 Simultaneity and sequentiality in signs

In spoken languages, the speech apparatus is physically constrained by the oral cavity, and the composition of the articulator (the tongue) does not accept the production of multiple segments at the same time, which forces the sequentiality in the production of sounds. Simultaneity is mostly observed at the supra-segmental level with prosodic units (e.g., accent, tones, *etc.*) being superimposed to segments.

Simultaneity is more pervasive in sign language than in spoken language because there are multiple and partially independent articulators: in addition to the two hands, the upper part of the body, the head, and the face can also carry phonological information. Moreover, as mentioned above (section 1.1), signs are composed of four (manual) phonological classes - handshape, location, orientation, and movement - of which the first three must co-occur. As we will see in Chapters 2 and 3, orientation depends on handshape and location, the simultaneous production of these components is therefore not negligible and must be taken into account in the analysis of the phonological structure of signs.

Movement also shows some peculiarities that require particular care. As the only dynamic component, movement is responsible for visual saliency (i.e. sonority) and constitutes the syllable nucleus of signs. As opposed to words that are frequently composed of several syllables, most signs are composed of only one movement or simultaneous movements (e.g., when a hand is moving in space and the fingers are also changing shape). The lexicon of sign language is thus mainly composed of monosyllabic signs. Disyllabic signs, i.e. signs composed of two sequential movements, also appear in the sign language lexicon but they are less represented (Brentari, 1998), which adds on the high propensity for simultaneity in sign language.² Hence, in addition to its dynamic character, the role of movement in

²At the morpho-phonological level however, sequentiality remains very present and its role has been

the simultaneous organization of syllables provides it with a suprasegmental function as it is also responsible for the prosodic structure of signs. This particular property is again a parameter we take into account in this thesis, especially in our study of categorical perception presented in Chapter 5 and introduced below (1.3).

1.2.2 Iconicity

The high proportion of iconic signs in the lexicon of sign languages is one of the main reasons why they have long been thought of as a collection of gestures (imitation, mimics, *etc.*) devoid of linguistic structure. By its very definition, iconicity is a direct mapping between a word's/sign's form and its meaning (see Taub, 2001, for a comprehensive study on iconicity in sign language), which puts it in direct opposition with the notion of *arbitrariness*. Since Stokoe's pioneering work (Stokoe 1960, republished in Stokoe 2005), we now know that sign languages are complex linguistic systems governed by rules and composed of hierarchical combinatorial structures. By addressing phonology in sign language, Stokoe put forward the existence of meaningless units that combine to form lexical entities and showed that the obvious iconicity component of signs does not negate the part of arbitrariness in sign language.

Iconicity is expressed in various forms such that it is not a binary (iconic *vs.* non-iconic) but rather a gradient property; while many signs are iconic, most of them are not *highly* iconic (see Caselli et al., 2017, for data in American Sign Language (ASL)). Below we provide a non-exhaustive example of LSF signs distributed along the continuum of iconicity in Figure 1; on one extreme one can find transparent signs, i.e. signs for which the meaning is directly identified from the referent, such as in DRINK, and on the other extreme one can find opaque signs, i.e. signs for which the meaning is not accessible at all, as in RESPECT. Between the two, the degree of iconicity of other signs varies, such as in DIABETES, PSYCHOLOGY, CLASS *etc.*, and signs are distributed along the continuum.

The iconic component of signs plays an important role in the processing of signs and must therefore be taken into account in the study of sign languages. Indeed, it interacts with phonological and morphological processes, such that it is more and more investigated in the sign language literature (Perniss et al., 2010; Emmorey, 2014; Taub, 2001; Thompson et al., 2010; Baus et al., 2013, among others). For instance, Eccarius and Brentari (2010) showed that iconicity has an impact on phonology and that while many signs have a high degree of iconicity, some of them lost their iconic motivation over time. An example in

very well-studied (Liddell, 1984; Liddell and Johnson, 1989; Sandler, 1986, 1989; Brentari, 1998, 2002, 1993, to name a few), but since we focus on the segmental level we do not go into details.

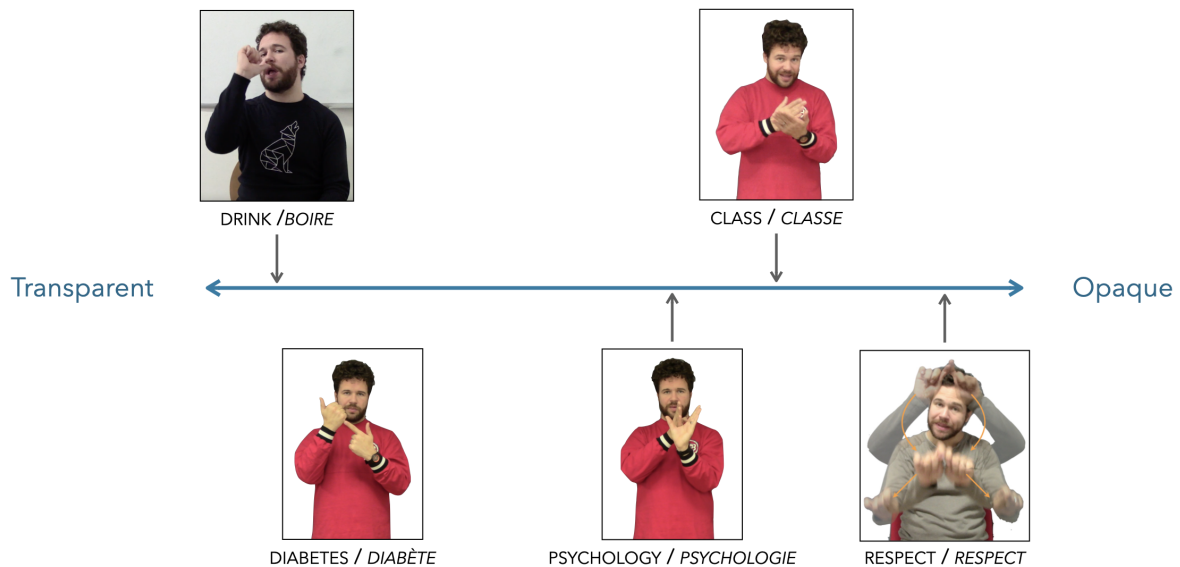


Figure 1: Example of signs in LSF distributed along the spectrum of iconicity.

LSF is the sign for WOMAN (Figure 2): the index finger near the cheek was referring to the ribbon of the hats that women used to wear (Delaporte, 2007), and this iconic component is no longer available.

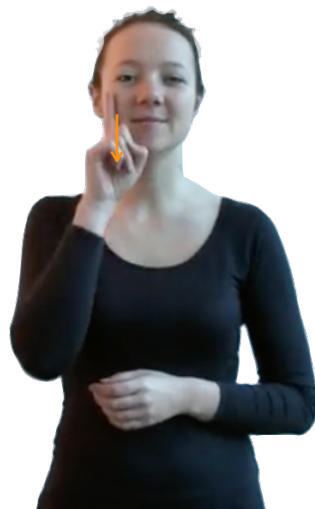


Figure 2: Sign WOMAN in LSF: its iconic component was lost over time.

Of course, iconicity is also observed in spoken languages (e.g., see Dingemanse et al., 2015, for a review), but the visual-gestural modality makes it largely more represented in sign language, in such a way that not only does it structure a large part of the lexicon, but above all, it generates a certain pressure on the composition of signs and the formation rules (Eccarius and Brentari, 2010). Importantly, iconicity does not behave similarly across the lexicon. Hence, it does not facilitate the task of linguists who need to identify the part that iconicity takes in the phonological processes, especially since tools and

methodologies are still few and far between. Iconicity intervenes at various levels, and its role in the phonological structure of signs remains to be identified. It is, therefore, safer and wiser to focus on signs that are not (highly) iconic to focus on pure phonological components that participate in the composition of signs, without worrying about the effect it may have, a position we have chosen to follow in this thesis.

1.2.3 Sign language lexicon(s)

The lexicon of sign language is composed of two main components: the native lexicon and the non-native (or foreign) lexicon (Brentari and Padden, 2001, see Figure 3).

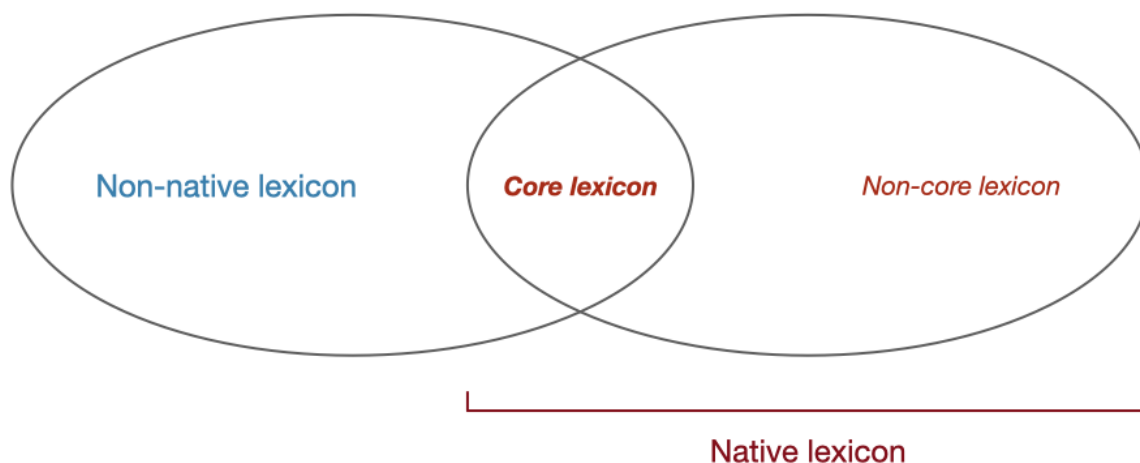


Figure 3: The sign language lexicon (adapted from Brentari and Padden, 2001).

The native lexicon is itself divided into two subcomponents, the core and the non-core lexicon, which are also referred to as core and spatial lexicons, respectively (Brentari and Padden, 2001). The core lexicon consists of signs that can be decomposed into meaningless sublexical units, in which a conventionalized form is associated with a meaning. In this respect, it is composed of signs whose articulatory status is only phonological, as the sign IRON in LSF (Figure 4).

The non-core or spatial lexicon, on the other hand, is composed of meaningful units, generally referred to as classifier constructions that correspond to partially lexicalized forms. Classifier predicates are composed of several morphemic and/or syntactic units in which the verbal root is associated with affixes (i.e. a movement associated with either the handshape or the location, see Supalla, 1982). In classifier constructions, the handshape is often responsible for iconic representation as it transmits information about the shape and/or the size of its referent. Indeed, they generally represent concrete entities, and



Figure 4: The sign IRON in LSF is part of the core (native) lexicon.

classifier handshapes are mostly used to show how objects are handled or to represent the shape of an entity (in part or as a whole). Therefore, contrary to the core lexicon, classifiers have gradient properties, which makes them less discrete (for an overview of the various types of classifiers, see Benedicto and Brentari 2004; for a general overview of classifier constructions, see Emmorey 2003).

Some classifier constructions get lexicalized when they lose their iconic component. This is the case of the LSF sign WOMAN presented above (Figure 2). In the beginning, the hand was referring to a subpart of the object (the ribbon of the hat), the handshape reflected its size and shape (the index finger suggesting a thin object), and location referred to its place on the head. In the past, WOMAN was part of the non-core lexicon, but now it is part of the core lexicon since the mapping between the form and the meaning is not relevant anymore and the sign does not refer to an existing object.

Finally, the non-native lexicon corresponds to borrowings and initializations, i.e. signs in which the configuration of the hand(s) corresponds to a configuration belonging to the manual alphabet (i.e. hand configurations allowing (finger) spelling). As shown in Figure 3, the core lexicon is an overlap between the native and non-native lexicons: some foreign lexical units get lexicalized, and the lexicalization process, as in spoken languages, can be accompanied with phonological adjustments (Brentari and Padden, 2001).

Large variation and asymmetries have been observed across the three components, as well as across languages (Brentari and Eccarius, 2010; Eccarius and Brentari, 2010). The three components show phonological and morphological differences in handshape, resulting in specific inventories for the native and non-native components, of which only a part is in common.

An important point to mention is that each study presented in this dissertation focuses on the core lexicon as it shows more stability compared to the other components. This means that the results and generalizations that we present are not necessarily true for the other components of the lexicon.

All of these properties that are specific to sign language participate in shaping the structure of their phonology, in a way that all contrast types (minimal pairs, allophonic variation *etc.*) are not represented uniformly across the lexicon. In the next section, we briefly introduce the theoretical background of sign language phonology to present the studies we conducted.

1.3 Sign language phonology

Stokoe (1960) paved the way for sign language phonology by demonstrating the presence of distinct minimal units in sign languages, i.e. phonemes, the first step towards the status of natural languages. Since then, many studies have been carried out, and various models have been developed to describe the phonology of one or more sign languages by representing the phonological structure of the signs. Together with phonemes, the well-established notions such as *contrast*, *markedness*, *distinctiveness*, as well as *economy* (as in Drescher, 2009; Clements, 2003, 2009, 1985, 1989, 2009; Sagey, 1986, among others) come along and are evidently an integral part of the research work. Thus, theoretical models allow the study and analysis of phonological processes and contrast in the visual-gestural modality.

Some models use features to describe the phonological structure of signs, and each phonological class contains its own set of features. Part of these models are built in the framework of feature geometry (for a fully developed version of feature geometry, see Clements and Hume 1995, and for a non-exhaustive list of models in sign language built within this framework, see Brentari 1998; Sandler 1986, 1987b,a, 1989, 1993b, 1996; Sandler and Lillo-Martin 2006; van der Hulst 1995; van der Hulst and Mills 1996; van der Hulst 1993; van der Hulst and van der Kooij 2021; van der Kooij 2002a). The other models are not (Liddell and Johnson, 1986; Liddell, 1984, 1993; Johnson and Liddell, 1984, 2010, 2011; van der Kooij and van der Hulst, 2012; Liddell and Johnson, 1989, among others). But whatever the model, as in spoken languages, distinctive features represent properties of phonemes and therefore structure phonological inventories of languages (Clements, 2006, 2009, 1985; Sagey, 1986; Beltzung, 2015; Hall, 2001; Clements and Hume, 1995; Drescher,

2009, to only cite a few)).³ A more thorough description of features and feature-based models is provided in Chapter 2.

Most theoretical models are built on internal linguistic data, such that generalizations are based on a large amount of data from one specific language, and data from other languages will only be used as complementary information. This suggests that in feature-based models, features that are implemented in the inventory are attested in the language under study but their presence is not guaranteed in others. In other words, they run the risk of misrepresenting the content of feature inventories of all sign languages. Additionally, the study of contrast in sign language is not as straightforward as in spoken language. Indeed, exact minimal pairs are difficult to find in sign languages (Eccarius and Brentari, 2010), such that methods of analysis to justify the presence or absence of features in their phonological inventories must be done more carefully for sign languages than for spoken languages. We have conducted two studies on the structure of signs in LSF and their composition in terms of distinctive features, and they have allowed us to revise these methods for identifying contrast in sign language, a necessary step in the composition of phonological inventories of sign languages, and in our case that of LSF.

In Chapter 2, we show that the feature [web], which refers to the webbing part of the fingers, has to be included in the inventory of location/orientation from which sign languages can create contrast. Analysis of near-minimal pairs, phonological processes such as productivity in simultaneous compounds and neutralization as well as the relevance of saliency show that [web] should indeed be (re)introduced into the list of active features. cursory inspection in the lexicon of Italian sign language and careful consideration of ASL data shows the need for more typological research to refine existing phonological models of sign language. From this study, we also highlight the important role that salience and the representation of orientation play in the composition of feature inventories. Thus, in addition to showing that a distinctive feature has been omitted or prematurely removed from the feature inventory of signed languages, our study is a major step in identifying the mechanisms necessary for contrast perception in sign language. It also shows the need to study data from several languages to refine existing theoretical models, usually established from the detailed study of one single language, and to revise the empirical generalization when needed. The theoretical contribution has a much larger cross-linguistic impact. We start by discussing how the distribution of [web] in the LSF lexicon reveals an unexpected asymmetry between dominant and non-dominant hands. The account we offer to explain this asymmetry requires an important restructuring of current models of

³Models without features also exist and describe the phonology of signs in other frameworks (Perlmutter, 1991, 1990, 1992; Uyechi, 1995, 1994), but since our work is conducted in the former context, we will not go further into details.

sign phonology allowing a more precise characterization of relative orientation in terms of feature dependency.

Our second study on features, presented in Chapter 3, is a revision of the status of orientation in the composition of signs, particularly two-handed signs produced on the signer’s body. In attempting to derive the phonological structure of two-handed signs within the framework of the *Prosodic Model* by Brentari (1998), we encountered new difficulties. Indeed, we have identified problematic cases of two-handed signs produced on the signer’s body: when both hands are in contact with a part of the body other than the non-dominant hand, it is sometimes impossible to avoid phonological misrepresentations in models that refer to orientation only in a relative way. In many phonological models orientation is derived from a specification in handshape and a specification in location (Brentari, 1998; Crasborn and van der Kooij, 1997; Liddell and Johnson, 1989; Uyechi, 1995, among others). Our data on [web] in LSF have supported this relationship between the two phonological classes. In contrast, other models consider orientation as an absolute property of the hand (Battison, 1978; van der Hulst, 1993; van der Kooij, 2002a; Sandler, 1989, among others), and we finally provide evidence that it is also necessary for the representation of two-handed signs produced on the signer’s body. In fact, we show that relative orientation does not allow an adequate description of these signs when the orientation of both hands must be specified, since it can capture either the orientation between the two hands or the orientation with respect to the body, but not both. To model the orientation of these signs in a formal framework, we propose the implementation of secondary planes. While this implementation requires minimal adjustments to current formal models, its impact on the general theory of segmental phonology of signs is considerable. Secondary planes impose geometric restrictions and force absolute orientation; the concept of orientation as a simple relational phonological class is therefore no longer sufficient for these signs. This work allows us to highlight the need for an absolute orientation in addition to a relative orientation for a subclass of signs to describe the segmental phonology of sign languages. The implementation of secondary planes then improves the current models and allows them to account for the phonology of problematic signs.

In Chapter 4, we question the ability of a theoretical model to reflect the complexity of signs in LSF. The study of articulatory complexity has been shown to provide useful insights into the phonological mechanisms of spoken languages since phonetic complexity and phonological structure have been shown to be intimately related. In sign languages, this type of knowledge is poorly documented. Therefore, we chose to conduct a study to compare an error-based complexity measure and a model-based complexity measure. The first measure is based on the error rates obtained during a sign repetition task in LSF

performed by non-signers. This measure includes errors produced on handshape, location, orientation, movement, and fluency of sign repetition. The second measure is obtained from the phonological structure of the same set of signs derived in the framework of the *Prosodic Model* (Brentari, 1998), a model built based on feature geometry (Clements, 1989). Our results indicate that handshape is the most difficult constituent to reproduce, followed closely by movement, then orientation, and location, which generate fewer errors from non-signers. By comparing the two measures, we obtain a significant correlation for overall complexity. When examining the effects of individual phonological classes on complexity, a significant correlation is found for handshape and location, confirming the results obtained in other studies on sign perception and production. However, this is not the case for movement for which the correlation is not significant. This may be related to the fact that movement, as a dynamic component of signs, cannot be directly compared to its static counterparts (i.e. handshape and location, as well as orientation). Still, these results indicate that an accurate theoretical model of sign phonology/phonetics reflects the degree of complexity as a result of the perceptual and articulatory properties of signs. By using the richness of phonetic representations to predict accuracy levels in a sign repetition task, our study marks an important step in advancing our knowledge of the role of a theoretical system in the assessment of sign complexity.

Finally, in Chapter 5 we present an experiment on categorical perception (CP henceforth), a study we conducted to widen the perspective on phonological contrast by investigating the psychological mechanisms underlying the perception of LSF signs. Most of the studies have been conducted on ASL and the results obtained are contradictory. On the one hand, some studies show a CP effect in handshape (Emmorey et al., 2003; Baker et al., 2005), while others do not (Newport, 1982; Morford et al., 2008; Best et al., 2010). For location, on the other hand, the two studies that included this phonological class in their research showed no CP effect (Newport, 1982; Emmorey et al., 2003). Only Boutora (2008) tested the CP of handshape in LSF and reported no effect in signers. Our study is thus the second in LSF, and especially the first to test location in this language. We created pseudo-signs with an avatar and generated two continua per phonological class, one created based on a contrastive pair of signs (phonemes), the other based on a non-contrastive pair (allophones). For the first time in the sign language literature, we presented our stimuli simultaneously in our discrimination task to exploit the visual-gestural modality of sign language and to avoid unwanted short-term memory effects related to the order of stimuli presentation. In addition, we were able to adapt to the constraints of the COVID-19 health crisis by conducting our experiment online. Deaf signers participated in our study and constituted our target group. Having been exposed to LSF from birth or early years of life, Deaf signers have access to the language and its phonological system during critical

periods of acquisition, so they are expected to be sensitive to the contrast (or lack thereof) in their language. Our control group is composed of hearing non-signers, a population never exposed to a sign language and therefore theoretically not sensitive to the phonology of LSF. According to our results, Deaf signers show a CP effect in handshape, contrary to non-signers. For location, our results confirm those of previous studies since no CP effect was identified, whatever the task and whatever the population tested. We then confirm the results obtained in the study of Emmorey et al. (2003) in ASL, with one exception. Contrary to our expectations, an effect for the allophonic pair in Deaf signers turned out to be significant in handshape. One possible explanation is that, by varying finger spreading in the ‘Y’-handshape in which the feature [spread] is not contrastive, we ended up targeting a phonological contrast since [spread] is distinctive in other contexts. Therefore, by testing pseudo-signs, we captured the context-independent nature of perception. In other words, when tested in an unfamiliar environment, perception does not take into account a specific context but calls upon the phonological system in its entirety. This does not contradict the results of Emmorey et al. (2003) who did not report an effect for their allophonic pair. Unlike us, the authors used lexical signs, which could have caused a lexical effect in signers who would then have recognized that the two extremes of the continuum are not meaningful. An additional innovation in our work lies in the recording of reaction times (RTs) as no CP study in sign language reported it. Spoken language CP studies showed that RTs are the reflection of accuracy, i.e. the more difficult the task, the longer the time required. Unexpectedly, we found that perceptual cues (e.g., the visibility of the nails in handshape) interfere with RTs and help answering faster, whether they are present at the category boundary or not. Taken together, the innovative implementations in our experimental design provide further knowledge about the perception of phonological contrast in sign language.

We close this dissertation with a brief concluding chapter in which we bring together the results of the different studies presented in Chapters 2 to 5. This allows us to emphasize their implication with respect to the general objectives of this thesis.

Chapter 2

What [web] reveals about contrast and feature inventory in (French) sign language

Mertz, J. and Geraci, C. (*under review*). What [web] reveals about contrast and feature inventory in (French) sign language.

Abstract

Feature-based models of sign languages use distinctive features to describe the phonological structure of signs. In this study, we show that the feature [web], which refers to the webbing part of the fingers, should be included in the inventory of location/orientation from which sign languages can create contrast. The analysis of near-minimal pairs and phonological processes like productivity or neutralization in LSF show that [web] should be (re)introduced into the list of active features. In addition, we reconsider the status of the sub-parts of the body/sub-locations (e.g., [web]) as orientation features. By doing so, we not only remove redundancy in feature specification, but more importantly, we provide concrete evidence that orientation is a relationship between handshape and location. By investigating the structure of LSF signs in terms of distinctive features, we revise the methods for identifying contrast in sign language, a necessary step in the composition of their phonological inventories.

2.1 Introduction

Distinctive features contribute to establishing the notions of *opposition*, *contrast*, *markedness* and *distinctiveness*, both when defined only on an acoustic basis (Jakobson et al., 1952; Trubetzkoy, 1969), and on an articulatory basis (Chomsky and Halle, 1968). As in spoken languages, these notions are also relevant in the feature system of sign language (SL) phonology. Spoken language models based on feature geometry (Clements, 1985) heavily influenced the organization of SL phonology in terms of hierarchically structured groups and sub-groups of features (Ahn, 1990; Brentari, 1998; Sandler, 1986, 1987a,b, 1989, 1993a,b,c, 1996; Sandler and Lillo-Martin, 2006; van der Hulst, 1993, 1995, 1996; van der Hulst and van der Kooij, 2021; van der Kooij, 2002b).¹

The various articulatory dimensions in SL are developed as independent categories, each containing their own set of features. Since Stokoe’s work (1960), these dimensions are handshape, location (or place of articulation) and movement, and are treated as phonological primitives. These three dimensions are thus the three major classes of phonemes, to which (hand-)orientation has been added as the fourth phonological class (Battison, 1978), together with non-manual markers (Brentari, 1998).²

In the current study, we discuss the content of phonological inventories in SLs, as well as the contribution of features in their composition. We will see how they come into play when defining the notion of *contrast* in SL, and how the latter is integrated in the phonological treatment of signs. More specifically, we exploit feature contrasts in French Sign Language (LSF) to argue for the phonological status of one particular hand-part, namely webbing. We do so by investigating the various ways in which contrast manifests itself in sign phonology from saliency to minimal pairs, passing through near-minimal pairs, changes of phonological contexts, and phonological processes such as productivity (i.e. the creation of new signs), and neutralization. Evidence from LSF will bring us to (re-)introduce a dedicated feature, [web], in the set of features from which language specific phonological inventories are created.³ In line with Johnson and Liddell (2011), we first

¹Other feature-based models are used in SL (with no geometry, Liddell and Johnson, 1986, 1989; Liddell, 1990, 1993; Johnson and Liddell, 1984, 2010, 2011, 2012; Liddell, 1984), as well as a model based on the moraic structure of signs (Perlmutter, 1990, 1991, 1992), and mathematical geometry (Uyechi, 1995, 1994).

²To the best of our knowledge a fully-developed proposal for non-manual markers in feature geometry has not been proposed yet. Wilbur (2000) showed that the upper part of the face is associated to prosodic properties, while the lower part of the head carries more lexical and grammatical properties. Even though much work remains to be done, this is the first step for a lexical-phonological description of the role of non-manual components.

³From this moment on, we distinguish *webbing* from [web]; the former refers to the physiological part of the hand, the latter to the feature (phonetic and/or phonological) associated with this part.

propose to add [web] as part of the location features that constitute the sub-specification of the non-dominant hand. On the dominant hand, webbing is also active to determine relative orientation. Although the impact of adding one more feature to an already rich feature inventory may look minimal, we will also see that [web] unveil unexpected asymmetries. In understanding them, we will refine the nature of web, arguing that it is an orientation feature.

The rest of the paper is organized as follows. Section 2.2 presents the webbing part of the fingers as a feature in previous theoretical frameworks, and how contrast is taken care of in SL. Section 2.3 is dedicated to present our methodology and describing the data. Section 2.4 puts forward an analysis of [web] as an active feature in LSF, and shows how it accounts for the data presented in section 2.3. In Section 2.5, we discuss how our findings impact the way in which contrast create phonological inventories in SL. Finally, Section 2.6 briefly concludes the paper.

2.2 Webbing as a feature

The articulation of signs may involve a variety of body parts, the most complex of which is probably the hand (Brentari, 1998). Various hand-parts have been identified as contrastive in SL, like the radial and the ulnar side of the fingers: the signs MAJOR and MINOR (Figure 5) share the same handshapes, path movement and hand orientation, but the location is different since in MAJOR the dominant hand is located on the ulnar side of the non-dominant hand (above the second hand) and it is on the ulnar side in MINOR (below the second hand).

Among these hand-parts, *webbing* received very little attention in the literature, we think partly because its contrastive nature is hard to identify, partly because very few signs make use of it. In Section 2.2.1, we will see that despite it is a part of the hand, webbing has been treated either as a location feature, or as a part of the movement component in American Sign Language (ASL), rather than a handshape feature. Either way, its phonological status remained unclear, whether it is just a phonetic component or it carries some sort of phonological contrast. We then discuss the various ways in which contrast can be generated in SL (Section 2.2.2). These sections will form the basis upon which the LSF data will be presented in the following sections.



Figure 5: Contrastive signs in ASL based on hand sub-parts: MAJOR is produced on the radial part of the selected fingers (left) and MINOR is produced on the ulnar side of the selected fingers (right).

2.2.1 Different views on webbing

Location is one of the major phonological classes in SL. It is partitioned in two major categories according to where signs are produced: the neutral space⁴, or the signer’s body. The latter is further divided into macro body-parts such as the head, the torso, the arm and the non-dominant hand. In fact, the two hands do not have the same role, and are not interchangeable. The dominant hand is the most used as it is the one that produces one-handed signs (generally the right hand for right-handed, and the left for left-handed signers). The non-dominant hand is only activated in two-handed signs. When both hands are active, either they behave in the same way, or the non-dominant hand serves as the location for the entire sign. In the former case, the non-dominant hand is also an articulator as in the examples shown in Figure 6.⁵

In the latter case, the non-dominant hand is a major body part, and signs can be produced on various (sub-)parts of the hand. For example, the LSF sign AGAIN is produced on the palm of the non-dominant hand, the sign MUSHROOM on the tip of the index finger, and the sign NAME on the radial side of the index finger (Figure 7). These (sub-)locations are

⁴The neutral space is the 3D space in front of the signer, limited on the top by the upper part of the head, at the bottom by the lower part of the torso, and cannot extend over an arm distance on the right, the left and in front of the signer.

⁵Two-handed signs are divided into three categories, from Type-1 to Type-3 based on Battison’s classification (1978). Even though a distinction between symmetrical and non-symmetrical Type-1 signs can be made, the two hands are active and behave identically. To avoid heavy terminology and confusion among non SL linguistic experts, we will refer to all these Type-1 signs as *symmetrical* signs. This also include symmetrical alternating signs in which the two hands produce the exact same movement but in alternation, as in Figure 6b. We refer to the other two-handed signs, i.e. those in which the non-dominant hand is not moving, as *asymmetrical* signs.

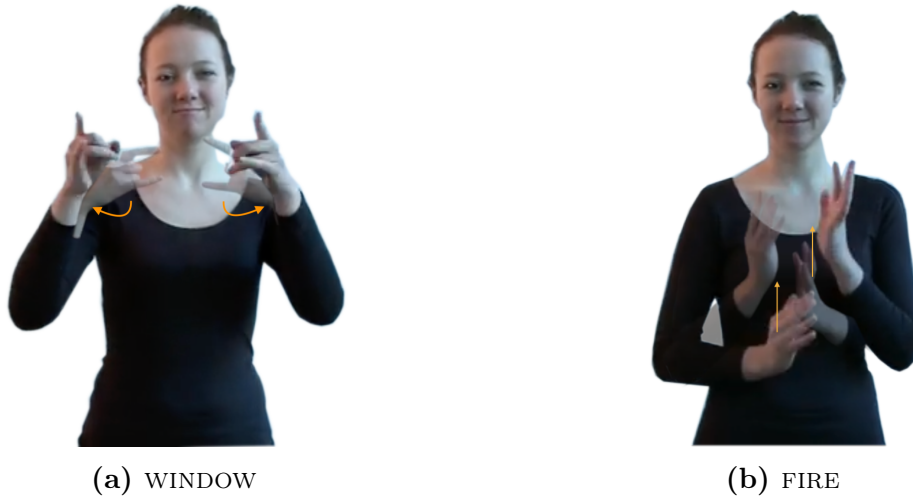


Figure 6: Examples of symmetrical signs in LSF.

contrastive in many SLs, so it is normal to assume they are part of the feature inventory of SLs. Phonological models of SL must include these features as part of the repertoire of features that can be used to create contrast.



Figure 7: Examples of signs in LSF located on various sub-parts of the non-dominant hand: on the palm (7a), on the tip of the finger (7b), or on the radial side of the finger (7c).

Another location where signs are produced is the webbing part of the fingers, as shown in the ASL examples in Figure 8.⁶ To our knowledge, the status of webbing has been debated in the literature of ASL only. The debate was about two aspects, the phonetic/phonological status of webbing (Sandler, 1986; Brentari, 1998; Liddell and Johnson, 1986, 1989) and its place within the macro phonological categories of signs (location or movement, as in Stokoe, 1960; Liddell and Johnson, 1989; Brentari, 1998).

⁶All ASL data presented in this paper are screenshots of videos of the Gallaudet Dictionary of ASL (Valli, 2006), pending authorization.



Figure 8: Examples of signs located on the webbing in ASL.

Depending on the theoretical perspective, the fact that some signs use the webbing part of the fingers was accounted differently. Stokoe (1960) treated it as a movement feature which he labeled *entrant*. According to him, this feature indicates when a part, generally finger(s), of the dominant hand intersects the space between two fingers as in the signs shown in Figure 8. For example, in FOOTBALL (Figure 8a) and WRESTLING (Figure 8b), all fingers of both hands are interlaced, twice after a long directional movement repeated, and once after a single directional movement, respectively. In PREGNANT (Figure 8c), fingers are interlaced during the entire sign, and both hands move together. In START (Figure 8d), the index finger of the dominant hand rotates between the index and middle fingers of the non-dominant hand, while in BREAK (Figure 8e), the hand is wedged between the middle and ring fingers of the non-dominant hand. Finally, in TICKET (Figure 8f), the non-dominant is inserted between the flexed index and middle fingers.

Liddell and Johnson (1989) analyzed webbing as a location feature as some signs were produced on this specific hand-part. In doing this, they did not provide evidence for phonological contrast, hence the feature was treated as phonetic but not phonological in ASL. Finally, Sandler (1986) and Brentari (1998) did not include it in the set of active features of ASL. Specifically, it is explicitly excluded in Brentari (1998): apparent contrasts

in ASL are then derived by selecting the [ulnar] feature of the non-dominant hand. At this point, [ulnar] and [web] are considered as phonologically similar in ASL, with /ulnar/ being the archiphoneme.⁷

According to Brentari (1998), the signs reported in Figure 8 would not require the use of the [web] feature in their phonological representation as the [ulnar] feature allows a correct phonological representation. Indeed, the contact point on the ulnar side of the fingers is well captured. Since Brentari (1998) treats [web] as a phonetic feature but not as a phonological one, [web] and [ulnar] are not in opposition. There seems to be no minimal pair based on webbing, nor specific phonological process targeting it. The lack of contrastive force brought Brentari to exclude this hand-part from the list of active features in ASL. However, even though this seems to be true for ASL, an extension to other SLs is not granted. Excluding this feature from the inventory of possible contrastive features in SL phonological models could be premature.

In this perspective, [web] could be viewed as a particularly marked feature available for SL and therefore infrequently used across SL and little seen within the vocabulary of a specific SL. It would be very similar to rare sounds in spoken languages which are for the most part allophonic in nature but could be also used contrastively in some languages, such as the glottal stop that is used contrastively in languages like Hawaiian (Elbert and Pukui, 2001) or Arabic (Watson, 1989) as opposed to other languages, in which glottal stops is used for accompanying or replacing voiceless word-final stops (like in most varieties of British English, cf. Ladefoged and Maddieson, 1996) or as a marker of phrase boundary (as in German, Kohler, 1994).

2.2.2 Contrast and features in sign languages

At the segmental level, minimal pairs are the stepping stone of constituting phonological inventories as their presence alone suffices to attribute the phonological *vs.* phonetic status of a feature (Pike, 1947; Trubetzkoy, 1969). In other words, they are a sufficient condition to identifying phonemes, and this might be the reason why they are so central to account for phonological contrast in spoken languages. This is less true in SL, mostly due to the fact that minimal pairs, as well as allophonic pairs, are more difficult to find at least at the feature level (Eccarius and Brentari, 2010). As a consequence, the task is harder for SL phonologists to properly distinguish phenomena that are phonologically motivated

⁷Two footnotes refer to this specific point in Brentari (1998): one mentions the ulnar part of the fingers (p.326) while the other mentions the radial part (p.329). In the text, we chose to keep *ulnar*, but whatever the chosen part, as long as the choice remains constant, the analysis does not change and the results obtained are identical.

from those that are simply articulatory. The difficulty in finding minimal pairs and in identifying phonological processes in SLs results in the fact that inventory composition and size remain poorly understood.

This does not mean that there is no phonology in SL; minimal pairs are not a necessary condition as other phonological processes can account for contrast in a language. In SLs, phonological processes such as assimilations, diachronic or synchronic changes, *etc.* (e.g., see Brentari, 1998, p.54), as well as near-minimal pairs are worth investigating to identify the appropriate phonological inventory of a language. Hence, these are the fields where SL phonologists should also look at when determining the inventories of SL.⁸

The risk of defining phonological contrast in this broader way is to create language-specific inventories that include more features than necessary. It is then a matter of overgenerating contrasts. Therefore turning to webbing, models which do not include it are considered as more economical since they exclude a feature with no phonological value (for more details on the notion of *economy* in phonology, see Clements, 2001; Sagey, 1986). However, in the next sections we will see that removing [web] from the list of potentially contrastive features in SL was a premature move. In fact, there is evidence that webbing has a phonological status in LSF because some contrasts cannot be accounted for by using other (geometries of) features.

2.3 The [web] feature

After a brief description of the methodology used in this work (Section 2.3.1), we present the core part of the LSF data in which webbing is selected, and provide evidence that the feature [web] should be included in the set of active features (Section 2.3.2). We then illustrate an interesting asymmetry that emerges from these data (Section 2.3.3). We conclude the section by offering a very quick look at how webbing is used in other SLs in particular, in Italian SL (Section 2.3.4).

As a preview of the argumentation line used in Section 2.3.2, we will first present some LSF near-minimal pairs where webbing generates contrast. Secondly, we show that faithfulness to webbing cannot be overridden by using other locations on the hand. In particular, the ulnar part of the hand cannot be a generic substitute for webbing. This evidence basically excludes for LSF the allophonic analysis of [web] proposed for ASL in Brentari

⁸For a detailed description of a typology of contrast types (distinctive, active and prominent) see Clements (2001), and for a comprehensive study of these contrasts in classifiers in SLs see Eccarius and Brentari (2010).

(1998). Then, we show that webbing is used as a target location for new lexical items like simultaneous compounds and that it can supply the output value under neutralization. All these facts will constitute our core evidence that [web] is phonologically active in LSF and therefore it must be granted a full phonological status and not just a phonetic one.

A note of caution before entering the details of LSF. In many SLs, some signs make clear use of webbing as an articulatory component, but its use has clear iconic motivations. One example is the sign FLIP-FLOP (Figure 9). This sign is found in many SLs, with very small articulatory variants.



Figure 9: Sign FLIP-FLOP in LSF (and other SLs).

Other signs that often use iconically motivated webbing are SKEWER and CHERRY. We do not dwell on examples of this sort as there is potentially no phonological evidence for the use of webbing because it is forced by faithfulness to some iconic representation of the concept. In the case of Figure 9, it is the corresponding webbing part on the foot which is translated on the hand. The role of iconicity is further developed in the discussion (cf. Section 2.5).


2.3.1 Methodology

The majority of the data was collected in a series of sessions with our Deaf consultant during which we elaborated this work, and online dictionaries were also consulted (“Spreadthesign”, Hilzensauer and Krammer 2015, and “Le Dico Elix”). Since the relevant signs are citation forms produced in isolation, the methodology of elicitation was quite simple. The first sessions consisted of discussions with our consultant. Physical constraints of the articulators (Battison, 1974) First, we explained the main goal: finding signs produced on webbing (no specification between dominant and non-dominant hand was given). As an example, we provided our consultant with frequently used signs in LSF, PICTURE (Figure 10b) and

MEAT (Figure 12a), two signs targeted in a previous study (Mertz et al., 2022). Then, all the signs found were video recorded in isolation. After these sessions, we checked in online dictionaries to see if the forms produced by our consultant were identical or if variation in production and/or homonyms could be found. The following sessions with our consultant were then devoted to elicitation work to compare the recorded to the newly found forms, and confirm the absence of context dependence of the target signs. As a final step, each sign was presented in isolation to our consultant and he was asked whether the location/point of contact could be displaced right next to webbing, or further away. All signs presented in the current study were validated and approved by our consultant (except for the incorrect forms presented in Figure 13).

Most of the data are from LSF, but we also expand a little to Italian Sign Language (LIS). LIS examples come from exchanges with Deaf colleagues who are native speakers of LIS (data were further assessed in available dictionaries)

2.3.2 LSF, webbing & [web]

Examples of near-minimal pairs involving webbing in LSF are given in Figures 10 and 11.⁹ Figure 10 represents the signs PSYCHOLOGY and PICTURE. Handshape and location are identical: both signs are composed of the  handshape and both are produced on the webbing part of the non-dominant hand. The two movements are quite similar too, with one straight movement towards the contact point repeated twice for PSYCHOLOGY and one straight movement towards the point of contact and one away from it for PICTURE. Orientation is however different since the ulnar side of the pinkie finger of the dominant hand faces the webbing of the non-dominant hand in PSYCHOLOGY, but the webbing part between the thumb and the index finger of the dominant hand is selected and faces the webbing of the non-dominant hand (i.e. this is a fully symmetric sign).

For sake of clarity, let us provide a detailed definition of orientation. While some theoretical models defined orientation in absolute terms and described it in an independent parameter/branch, as in Sandler (1989), a consensus has been reached towards relative orientation. In the current study, we use the following definition:

- (1) “ (...) orientation can be described by specifying how the hand relates to the place

⁹In spoken language, a near-minimal pair is defined as a pair of words that do not differ only by one sound, but can still constitute evidence of an opposition if the two sounds in question appear in an identical immediate context. Based on our knowledge, there is no formal definition in SL, so we tried to apply the same rationale. In addition, some minimal pairs are not minimally different from a formal perspective but still considered as such by native signers (Brentari, 2002); what we consider near-minimal pairs in the current study were approved by our consultant.



(a) PSYCHOLOGY




(b) PICTURE

Figure 10: Signs PSYCHOLOGY (10a) and PICTURE (10b) in LSF.

of articulation (Friedman, 1976; Mandel, 1981) (...) ” (Crasborn and van der Kooij, 1997, p.38)

Concretely, relative orientation is computed by considering where the most salient part of the dominant hand is facing to. In feature-based models, two features are required to capture this, one on the dominant hand, i.e. the handshape, and one on the location. Thus, in a sign like AGAIN (Figure 7a), the tip of the fingers is facing the palm; the feature [tip] is selected as a specification of the dominant hand (the handshape), and [palm] as a specification of the non-dominant hand (here the location).something very heavy and possibly ad hoc, especially when a simpler solution is available.

Figure 11 shows another case of near-minimal pair. The signs FRIES and HOSTEL have the same handshape , the hand orientation is identical and movement is almost identical (repetition of a short directional movement in FRIES compared to an aperture change, i.e. a flexion of the base knuckles, in HOSTEL). Since both are symmetrical signs, the macro location is the neutral space. Technically, it is the sagittal plane. A description along these lines leaves unaccounted for the fact that the fingers of the two hands display contact with the webbing only for FRIES, while they stop midway in HOSTEL. Again, what is crucially different in this pair is the location, more than the movement. Both hands face each other (and the sagittal plane), and contact is realized on the webbing in FRIES and at the level of the ulnar side of the fingers in HOSTEL.

Figures 10 and 11 show that webbing is systematically used to build near-minimal contrast in LSF. In both cases, the contrast is instantiated at the contact point. In the first pair, it involves a sign produced on the non-dominant hand (PSYCHOLOGY) and a symmetrical sign (IMAGE), while in the second pair the contrast is generated between two symmetrical



Figure 12: Examples of signs located on the webbing in LSF.

the thumb of the non-dominant hand, as it could be if one uses [ulnar], it results in a non-existing sign. This is also true for the sign CHEESE: the contact between the two hands cannot be displaced and has to be on the webbing part of the (selected) fingers of the non-dominant hand. This faithfulness to the webbing makes it more salient than the other parts of the hand(s) in such signs. In other words, no other hand-part can enter in allophonic alternation with webbing, as shown by the unacceptable forms in Figure 13. This constitutes a second argument to support the phonological status of [web] in LSF. Its relevance for accurate articulation makes it particularly salient to prevent allophonic alternations.




Figure 13: Incorrect productions of the signs MEAT and PSYCHOLOGY in LSF. Even though the meaning could be grasped in a specific context, these two productions are considered as incorrect with MEAT produced on the fingers and PSYCHOLOGY produced on the radial side of the index finger as opposed to the webbing.

Beside being active in the consolidated lexicon, webbing is also active as a target location for new signs. The sign PERVERT in Figure 14 is a simultaneous compound as both

hands produce a root/stem at the same time: the dominant hand represents *the child*, the non-dominant hand *the abuser* (for a detailed description of compounds in LSF, see Santoro, 2018). Here, the pinkie finger of the dominant hand is located behind the webbing part of the non-dominant hand. As in the examples presented in Figure 12, the location cannot be displaced and the pinkie finger has to be nowhere else than on the webbing part of the non-dominant hand, between the thumb and the index finger. Compounding is a morphological process that also targets phonological features, and the emergence of such signs is an indicator of productivity in a language. Compounds involving the webbing shows that [web] is a prominent feature in LSF.



Figure 14: Sign PERVERT in LSF (compound).

Finally, as the last point of contrast, we can show that [web] can enter in a neutralization process. This can be observed with the sign SHIT, and the two variants of EGG (Figure 15). In both SHIT and EGG-1, the two hands have a  handshape, and orientation between the two hands is identical (Figures 15a and 15b, respectively). The movement component is rather similar, slightly curved in EGG-1, while quite straight in SHIT. Location, on the other hand, is completely different. For EGG-1, the ulnar part of the fingers of the non-dominant hand is involved: the contact between the two hands is made on the ulnar part of the middle finger of the non-dominant hand. In SHIT, on the other hand, the webbing part of the two selected fingers is involved: the contact is made between the index and the middle finger of the non-dominant hand. Therefore, SHIT and EGG-1 count as a near-minimal pair. In EGG-2 (Figure 15c), handshape, orientation and movement are identical as in EGG-1 (Figure 15b), while the contact point is done on the webbing part of the fingers. The location is identical as in SHIT, but the two signs would not be homophonous because the movement is slightly different. Importantly, while both forms are accepted for EGG in LSF, producing SHIT on the ulnar side of the fingers is not acceptable. This means that the allophonic variation is unidirectional, namely it is

allowed for EGG but not for SHIT. This process of neutralization is an important asset in favor of the phonological status of webbing in LSF. To properly describe the neutralization illustrated with the signs in Figure 15, the feature [web] has to be active in the LSF phonological inventory. In fact, it represents a stronger argument than those introduced before because the output of neutralization is not the “unmarked” feature [ulnar] but the more marked one [web]. Specifically, in order to derive the form for EGG-2 from EGG-1, the near-minimal contrast with SHIT is lost in favor of the [web] feature. The direction of the alternation from [ulnar] to [web] found in LSF is the opposite than the one claimed for ASL where potential cases of [web] are reanalyzed as [ulnar].¹⁰

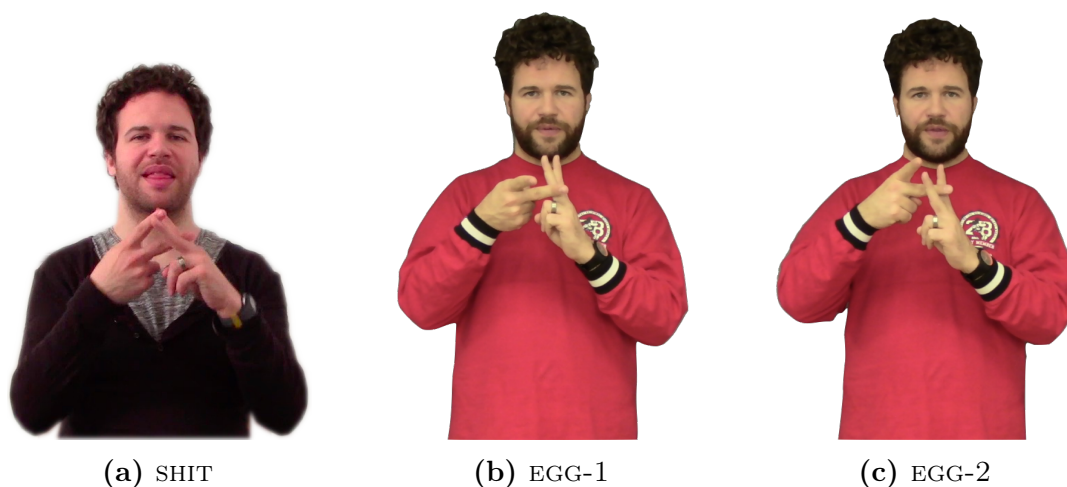


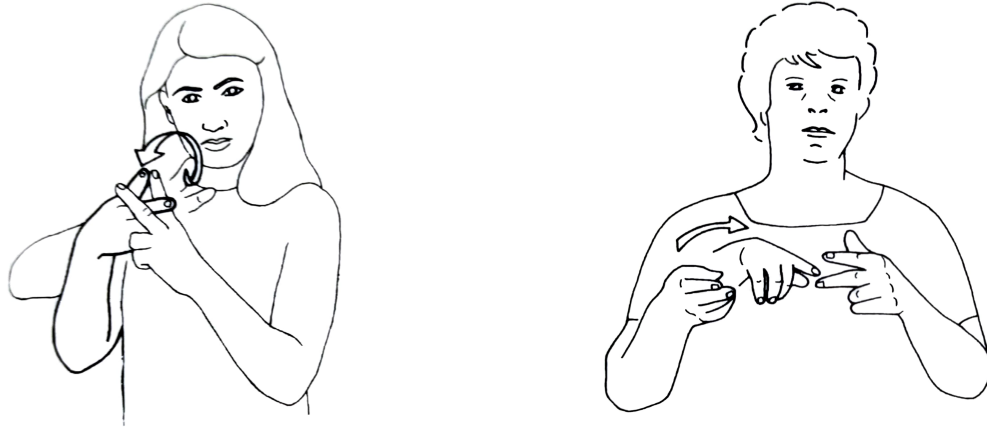
Figure 15: Sign SHIT (15a) and two variants of the sign EGG in LSF. EGG-1 (15b) is produced on the ulnar part of the middle finger, and EGG-2 (15c) is produced on the webbing part of the fingers between the index and middle finger.

One possible explanation for the fact that EGG-1 and EGG-2 seem to be in free alternation can be traced back to the historical origin of the sign EGG. In the etymological dictionary of LSF, Delaporte (2007) reports only the version with webbing (Figure 15c), while the old variant of SHIT, even if slightly different from the one shown in Figure 15a, was produced with the index finger of the dominant hand going between the index and middle fingers of the non-dominant hand, i.e. it reaches the webbing. Unfortunately, we have no records of how these forms evolved over time. Speculating a bit, one possibility is that the current variant of SHIT evolved from the old one, and that the variant of EGG-1 we report in this study (Figure 15b) is a new form that allows to distinguish EGG and SHIT. Neutralization of [ulnar] into [web] can then be motivated both historically and phonetically.¹¹

To conclude, in this section we have provided evidence that [web] is an active phonological

¹⁰See Section 2.4 for the specific rule to account for the alternation.

¹¹Notice that when asked, our informant was not aware of the fact that EGG-2 might be an older version of EGG-1. The same has been reported by other native signers that we informally consulted, hence confirming that the alternation is not lexical but phonological.



(a) Sign for EGG reported in Delaporte (2007). (b) Old sign for SHIT reported in Delaporte (2007).

Figure 16: Reproductions of the signs presented in Delaporte’s etymological dictionary of LSF: EGG (left) and SHIT (right).

feature of LSF. We showed that it is crucial to capture orientation in near-minimal pairs, that it cannot be generally modified in favor of “less” marked features like [ulnar/radial] as in MEAT, CHEESE, IMAGE, PSYCHOLOGY, *etc.*, although it is part of a neutralization process, as in EGG. Finally, it can be used productively to create new signs like the simultaneous compound PERVERT. All these pieces of evidence point towards an analysis of [web] as a location feature that determines relative orientation, rather than as a movement feature.

2.3.3 An interesting asymmetry

The empirical evidence used to build the arguments to support the phonological status of [web] as a location in LSF are based on two-handed signs. When the sign is not symmetrical, the feature is active only on the non-dominant hand, as in the signs PSYCHOLOGY, MEAT or PERVERT (Figures 10a, 12a and 14, respectively). Incidentally, this seems to be true also for ASL where the only documented case we are aware of webbing on the dominant hand is the sign TICKET. It is a well known generalization of SL that in two-handed asymmetrical signs, where the non-dominant hand serves as a location, only unmarked handshapes can appear on the non-dominant hand. This is known as the *Dominance condition* which stipulates that the configurations for the non-dominant hand are restricted to a subset of those attested on the dominant hand as stated in (2):

- (2) **Dominance condition (Battison, 1978, p.34)**

“ (...) if the hands do not have the same specification for handshape in a two-

handed sign, then one hand must be passive (i.e. not moving) while the other articulates the movement; also, H2 is restricted to a small set of handshapes ('B', 'A', 'S', 'C', 'O', '1', '5')." (Brentari, 1998, p.252).

The question then becomes whether it is possible in LSF to find cases of webbing in one-handed signs or asymmetrical two-handed signs where it is only the dominant hand that uses the webbing. We have been able to find only two of such cases, BEDROOM and BEGIN (Figure 17). The sign BEDROOM is located on the ipsi side of the head and contact is made with the front of the index finger and the thumb (Figure 17a). Crucially, the points of contact are not uniform because the index finger touches the forehead, while the thumb touches the chin. Capturing the appropriate specification of location features without [web] would require postulating a double location (forehead and chin) for this sign. On the other hand, the feature [web] specified as point of relative orientation on the dominant hand easily captures the appropriate location, which then would be the cheek.¹² However, the sign BEDROOM might not be an ideal candidate to represent a pure phonological use of webbing on the dominant hand because of its metaphoric iconicity, the whole sign would mimic the head resting on a pillow.

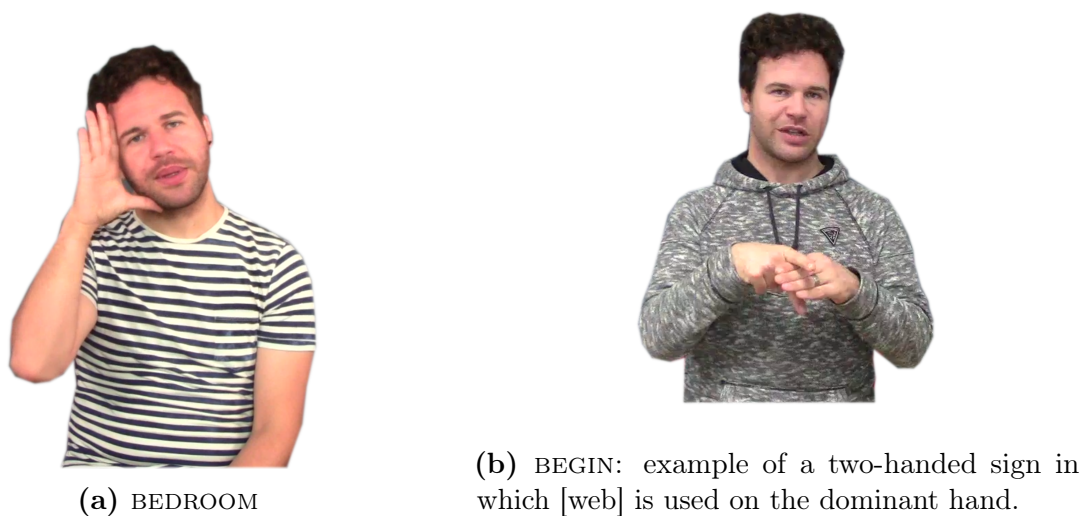




Figure 17: LSF signs using the webbing on the dominant hand.

In this respect, the sign BEGIN is more interesting, because no iconic component is apparent. The sign is an asymmetric two handed sign in which index and middle fingers are selected for a  handshape of the dominant hand while the  handshape is selected for the non-dominant hand. The location is the radial side of the non-dominant hand, while the movement is a short straight path movement towards the hand. The dominant hand intersects the non-dominant one as in the ASL sign TICKET (Figure 8f), until contact

¹²Contact of index and thumb with the rest of the face may come as a phonetic side effect.

with the webbing is reached, as shown in Figure 14. As in *BEDROOM*, if [web] is not available, a double selection of radial for the middle finger (facing the front of the fingers) and ulnar for the index finger (facing the back of the fingers) is required, but adding a secondary location is very costly and possibly ad hoc, especially because a simpler solution is available.¹³

All in all, beside the two cases discussed in this section, one of which could be spurious, it seems that webbing is much less active as a specification of the dominant hand than of the non-dominant hand. As briefly mentioned this could be due to the fact that it is mainly a location feature, a point to which we will come back in the discussion Section 2.5.2

2.3.4 [Web] in other languages

The LSF data illustrated in the previous sections clearly show that webbing can be systematically employed to create contrasts of various types in LSF and therefore qualify [web] as a phonological feature needed both to adequately capture location on the non-dominant hand and relative orientation on the dominant hand. Since it has been argued that if it is present in ASL its status should be considered at the phonetic level, one may wonder whether other SLs make use of webbing. In what follows we present a couple of signs from LIS. In the last part we go back to ASL with the sign *TICKET* and put the current account for ASL into perspective for ASL itself.

A short investigation of LIS revealed that webbing is actually used both as a location on the non-dominant hand and to determine relative orientation on the dominant hand, as shown with the signs *GORGONZOLA-CHEESE* (Figure 18a) and *JANUARY* (Figure 18b): both signs are produced on the webbing part of the fingers on the non-dominant hand. In the sign *GORGONZOLA-CHEESE*, the middle finger of the dominant hand contacts the webbing between the middle and ring fingers on the non-dominant hand. Not specifying [web] but [ulnar] instead does not capture the orientation between the two hands; for ease of articulation the non-dominant hand would be perpendicularly oriented. In the sign *JANUARY*, the back of the index finger of the dominant hand touches the entire webbing between the thumb and the index finger (the two selected fingers) of the non-dominant hand. Using [ulnar] would generate a contact either on the ulnar side of the thumb, or on the ulnar side of the index finger, thus creating a completely different sign.

The current account for ASL does not hold for these two signs as webbing seems to be phonologically active in LIS. Additionally, the one-handed sign *MOON* in LIS faces the

¹³Notice that tip of the fingers would not produce any relative orientation with respect to the non-dominant hand here.

same issue as *BEDROOM* in LSF (Figure 17a): both thumb and index finger are in contact with the head, on the forehead and the chin, respectively. Without [web] we find again the need for a double location which is not permitted in the existing phonological models as it produces an overly heavy and complex structure.

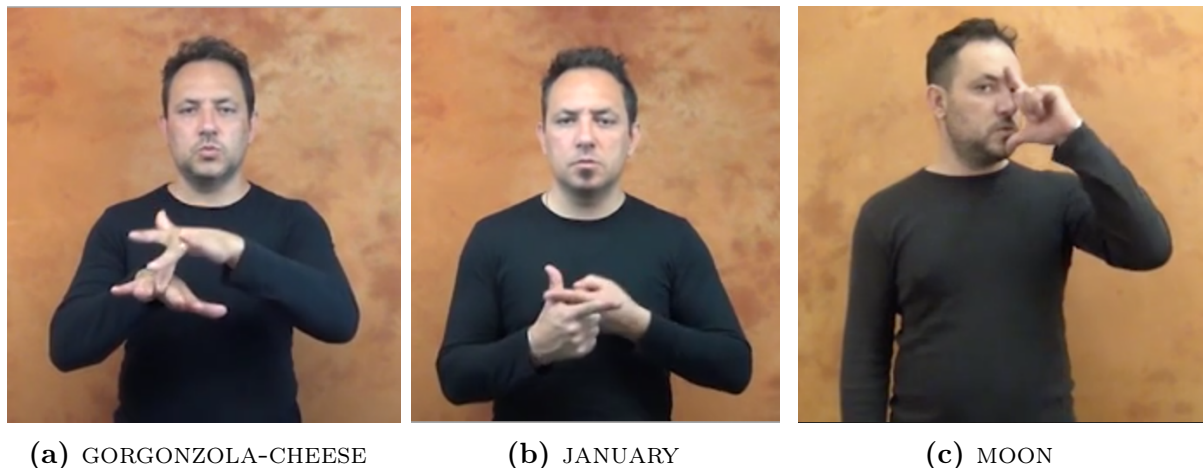


Figure 18: Examples of signs located on the webbing in Italian SL (LIS).

These cross-linguistic data are in line with the data presented above. Even if the examples are few and we do not have evidence about the phonological/phonetic status of webbing in LIS, they are enough to show a consistent presence of webbing in non-iconic signs in other languages, and that LSF might not be an isolated case.

Actually, a careful observation of the sign *TICKET* in ASL (Figure 8f) may suggest an interpretation along the same lines as the sign *BEGIN* in LSF (Figure 17b): the index and middle fingers are flexed at the non-base knuckles on the dominant hand, and the non-dominant hand is wedged between them. Without using the webbing as a reference point, one should either specify that the ulnar part of the index finger is facing the palm of the dominant hand and that the radial side is facing the back of the palm. This would then require a double specification of both orientation and location although this may not be enough to claim for a phonological status of webbing in ASL.

2.4 Analysis of [web] in LSF

The current account for the use of webbing in ASL suggests that [web] and [ulnar] are two allophones of the same (archi)phoneme /ulnar/. This led Brentari (1998) to propose an economical model for ASL, and possibly for other SLs, in which [web] is not part of those features that determine the phonological inventories of SLs. Data from Section 2.3 clearly show that this analysis does not extend to LSF and perhaps is not even adequate to

capture the orientation of some signs like the signs TICKET in ASL and MOON in LIS. The key-point is that [web] displays a variety of contrasts determined by near-minimal pairs, productivity and neutralization. These are the reasons motivating its inclusion in the pool of active features at least in LSF. Specifically, it can play a role in determining the appropriate location on the non-dominant hand and relative orientation on the dominant hand.

In this section, we offer an analysis of the LSF data in a feature-based model. At the end of this section we will tentatively extend the analysis to the LIS signs discussed in Section 2.3.4, while we leave the discussion of ASL to Section 2.5. The analysis is not framed in a specific model and can be easily implemented in any of the currently available models of SL phonology with some minimal assumptions.

The minimal assumptions needed in order for the analysis to work are two:

1. the non-dominant hand provides the primary location in asymmetric two-handed signs,
2. the phonological class of orientation must be considered in relative terms and not absolute, i.e. it is a specification of the dominant hand (cf. (1)).

Both assumptions are minimal in that they have been already part of most SL models and both are empirically well supported (Uyechi, 1995; Battison, 1978; Sandler, 1989; Brentari, 1998; Crasborn and van der Kooij, 1997; Liddell and Johnson, 1989).

Once these assumptions are in place, the account for the LSF data is straightforward. The minimal move is to include [web] among the features that determine both the location on the non-dominant hand, and the orientation of the dominant hand.¹⁴

To be more precise, the list of possible features once the non-dominant hand is selected as location is given in (3). The same pool is also active to determine orientation of the dominant hand.¹⁵

(3) **List of active feature on the non-dominant hand**

Palm of the hand, finger fronts, back of palm, back of fingers, radial side of selected fingers, ulnar side of selected fingers, tip of selected fingers/thumb, heel of hand,

¹⁴ The partial redundancy of having the same feature in two phonologically distinct classes can be removed if the sub-specification of locations within each major body part is treated as part of relative orientation. In this case, [web] would be treated as an orientation feature both when used on the dominant and non-dominant hand.

¹⁵This list is essentially the one proposed in Brentari (1998), to which [web] is added. However, nothing prevents from having more options in this pool, as long as they are empirically motivated. Other models may have slightly different labels for essentially the same hand-parts. What is relevant for us is that [web] is included in this pool.

web.

Near-minimal pairs like FRIES-HOSTEL (repeated in Figure 19) can be easily accounted for. Since these are symmetric two-handed signs, what is relevant is the orientation feature on the dominant hand. The non-dominant hand simply copies all the features from the dominant hand, which is facing the sagittal plane. Thus, FRIES specifies [web], while HOSTEL specifies [ulnar]. The same treatment holds for PICTURE in Figure 10b.

A slightly different treatment is needed for PSYCHOLOGY (see Figure 19 below). This is an asymmetric two-handed sign. Here the feature [web] is selected as location on the non-dominant hand, while the dominant hand selects [ulnar] as its orientation feature.



Figure 19: Signs FRIES (left), HOSTEL (middle) and PSYCHOLOGY (right) in LSF.

Once present in the pool of active features, [web] can then be used as the target for new signs. This is enough to account its use in the compound sign PERVERT.

The fact that [web] does not normally alternate with phonetically similar features like [ulnar] or [radial] in signs like MEAT, CHEESE, *etc.* can be due to its marked status¹⁶ and to the fact that webbing is the contact/endpoint of the sign movement, making it perceptually quite salient. These factors make [web] resistant to change, assimilation or location shift.¹⁷

¹⁶There are several ways in which [web] can be considered marked. Beside the fact that is not very much used as a location as witnessed by the very few signs documented, one can claim that its reduced surface makes it a more difficult region to target, hence more marked in production. The same reason would extend to perception, i.e. a small region is harder to see. We will come back to this point in Section 2.5.1.

¹⁷In a constraint-based framework, this resiliency can be captured by positing a feature-specific FAITHFULNESS constraint to be ranked above MARKEDNESS constraints that would favor the emergence of [ulnar] or [radial]. This account also extends to the sign SHIT, which does not show any alternation, unlike the one observed for the near-minimally different EGG-1/EGG-2.

Let’s now turn to the alternations between EGG-1 and EGG-2. Unfortunately, it is unclear whether there is any phonetic or phonological environment conditioning the alternation. Our main informant can use either form much freely. Here, we can tentatively postulate a neutralization rule that takes the sign EGG-1 as input and returns the sign EGG-2 as output. The process of course would be sensitive to the relevant feature only. Specifically, the input feature would be [ulnar], the location feature of the non-dominant hand, which is changed into [web]. What is interesting in the alternation is the fact that the process targets the relatively less marked [ulnar] feature and returns the more marked one, namely [web]. We speculate that this could be due to the pressure of an older variant of EGG where in fact [web] was used, as mentioned in Section 2.3.

Extending the analysis to other languages is relatively easy. If phonologically active in other languages, [web] can be used in a similar fashion to account for location and orientation. For instance, orientation in the LIS sign MOON can be captured by specifying [web] on the dominant hand and [nose] as location. The sign GORGONZOLA-CHEESE would specify [web] as a location feature on the non-dominant hand and [tip of the finger] as an orientation feature on the dominant hand.¹⁸

Given this picture, the question of how to reconcile the fact that ASL does not seem to need [web] as part of the phonologically active features remains. We will discuss this point in the next session where we will tie the behavior of [web] in ASL to its lack of saliency, i.e. phonetic cues.

2.5 Discussion

LSF data showed that [web] is active in a variety of contrasts, hence proving that it should be included in the phonological inventory of SL features. These facts provide interesting insights about the notion of phonological contrast and how this can be effectively used to generate mental representations of signs, i.e. word-level phonology. In this section, we discuss the implications of using multiple criteria for phonological contrast to determine SL inventories.

First, we discuss saliency as it addresses one weak property of contrast and could be used to explain the differences between LSF and ASL (Section 2.5.1) and maximizes contrast from a perceptual perspective. In Section 2.5.2, we examine why [web] seems

¹⁸In one-handed signs like BEDROOM in LSF and MOON in LIS, if it turns out that the contact between the fingers and the two sub-locations is not a phonetic side effect, the contact remains to be explained from a phonological perspective. We leave this question for future work.

to be required in environments that are not usually the targets of marked features (i.e. the non-dominant hand), producing the unexpected asymmetry introduced in Section 2.3.3. Finally, we emphasize the difficulties we face when trying to apply the same rules as for spoken languages to the visual-gestural modality of SL to determine phonological inventories (Section 2.5.3).

2.5.1 Saliency

In absence of quantitative measures that can determine a scale of articulatory and/or perceptual saliency of individual features for SL, we can take the fact that it is very difficult to find signs that use the webbing part as a first evidence of the particularly marked character of [web]. In Section 2.4 footnote 16, we also noticed that the portion of the hand that can be the target for this feature is small, when compared to other hand features like palm, finger fronts, but also radial and ulnar. This reduced space, we speculate, could be one reason that makes [web] articulatory and perceptually less salient, hence a disfavored locus to mark contrast.¹⁹

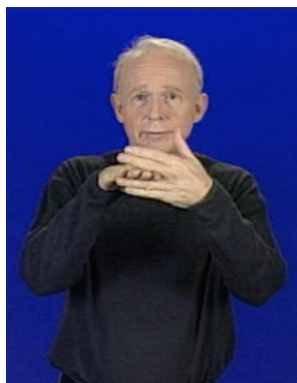
Saliency is also one of the first indicators of phonological contrast (Clements, 2009; Brentari, 1998). If we allow saliency to be a sufficient criterion to determine the status of phonological features, we may have one argument to explain why [web] can be treated as an allophonic (i.e. non-contrastive) feature in ASL but as a phonological (i.e. contrastive) one in LSF. Like spoken languages that may use different thresholds to discriminate the properties and the behavior of specific sounds, the same may happen in SLs. For instance, the degree of sonority determines whether a sound can be the nucleus of a syllable in spoken languages. Romance languages only allow for vocalic sounds to fill that position, while sonorant consonants can be nuclei in Slavic languages. Analogously, SLs may be sensitive to saliency in order to determine whether [web] can be manipulated by the phonological level of the grammar. In this respect, the grammar of ASL would be more restrictive and only allows [web] to act as an allophone, while the grammar of LSF would be less restrictive in including [web] among features that can generate phonological contrast.

Webbing is rarely used in both languages, although its distribution is remarkably different. For ASL, beside the sign TICKET, cases where webbing is clearly involved are only reported in symmetric two-handed signs with handshapes in which all fingers are selected. In signs

¹⁹Tip of the finger also uses a small portion of the hand, making it articulatorily less salient. However, its location at the distal boundary of the hand makes it perceptually very salient, hence overall less marked.



(a) START



(b) BREAK

Figure 20: Signs START and BREAK in ASL.

like START and BREAK (repeated in Figure 20), contact with the webbing is not obvious and perhaps the ulnar hand-part seems more salient than the webbing, or at least equally salient. The analyses offered in the literature then can dispense with the use of [web] as an active phonological feature.

The only problematic sign remains TICKET, as already observed in Section 2.4, which could be considered as a sort of exceptional sign in the ASL lexicon.

On the other hand, webbing is used in LSF in a variety of configurations, with multiple handshapes, possibly including one-handed signs. From the perspective of saliency, however, the most important evidence that webbing is targeted rather than other locations is given by signs like BEGIN, EGG-2, MEAT, PERVERT, PSYCHOLOGY and SHIT in which webbing is the contact/endpoint of the sign movement and its displacement generates non accepted signs. This interaction with movement makes [web] more salient in LSF than in ASL.

2.5.2 Orientation *vs.* location features

The investigation on the feature [web] has revealed two asymmetries, one empirical, the other theoretical. The empirical asymmetry, illustrated in Section 2.3.3, concerns the fact that [web] seems to be used more freely on the non-dominant hand than on the dominant one. The theoretical asymmetry, noted in Section 2.4 footnote 14, concerns the dual nature of [web], which is an orientation feature on the dominant hand, and a location specification on the non-dominant hand. In this section, we try to provide a unified account for them that goes beyond the specific facts of LSF, offering a wider perspective that can be used to study other SLs. Considering that this is the first study addressing these issues, the solutions we propose will be in part speculative. We try to

support them by making references to similar phenomena in sign and spoken languages; the fact remains, though, that the theoretical implementation needs to be tested with empirical facts from more languages.

If unexplained, the impact of the empirical asymmetry could be potentially big because it goes against one of the most robust generalizations of SL. As already mentioned, the contribution of the two hands in sign production is not identical. More specifically, the dominant hand is by large the most autonomous articulator. For instance it is the only articulator in one-handed signs and it is the one that moves in two-handed asymmetric signs. At the level of lexical phonology, the non-dominant hand is either a copy of the dominant hand, as in symmetric signs, or it serves as a location in asymmetric signs. However, the differences are not limited to the global level of sign articulation. Even at the feature level the dominant hand shows more autonomy. In fact, it can use all the phonologically active features in a language, while the non-dominant hand can only use a subset of them, unless they are copied from the dominant hand. This results in the *Dominance Condition* already reported in (2) in Section 2.3.3, in which it is stated that only a limited number of unmarked handshapes can serve as locations in two-handed asymmetrical signs (the ‘BASCO15’ handshapes).

Against this wide evidence, the behavior of [web] in LSF stems as an unexpected exception. The data presented in Section 2.3 go on the opposite direction. The webbing part of the non-dominant hand is targeted more often than the one of the dominant hand in two-handed signs; we found only one one-handed sign in which [web] is selected for orientation, namely BEDROOM.

The most natural explanation, which we already anticipated in Section 2.3.3 and developed in Section 2.4, is to attribute the asymmetry to the fact that [web] is a location feature. Since only the non-dominant hand can serve as location for signs, it comes natural that it shows an independent more autonomous behavior from that of the dominant hand in this particular domain. However, in its strictest form, this explanation makes the strong prediction that, actually, [web] cannot be an active feature at all on the dominant hand. If [web] is a location feature and the dominant hand cannot serve as location, [web] should never be selected by the dominant hand. The data seem to prove that the claim is too strong. In fact, there are signs (BEDROOM and BEGIN in LSF, MOON in LIS and TICKET in ASL) in which the webbing part saliently targets the dominant hand.

The solution we offered is to treat [web] on the dominant hand as an orientation feature as well. Although minimal, this move introduces an unwanted redundancy in the distribution of features, and another asymmetry at the theoretical level. The redundancy consists in

the fact that the same set of features (see the list in (3) above) serves both as location features on the non-dominant hand, and as orientation features on the dominant hand. This problem is more general and it is not induced by the presence of [web]. It depends on the very definition of relative orientation as derived by the interaction between a location feature and a hand-part, already noted in Crasborn and van der Kooij (1997); Brentari (1998); van der Hulst and van der Kooij (2021). Interactions between features of different types are well documented both in sign and spoken languages, like closed fists being less compatible with extended wrists (Mandel, 1979; Brentari, 1998); or nasal features spreading on vowels. What is theoretically problematic is that a whole set of features is shared between two distinct phonological classes, namely location and orientation. To bypass the problem, one could consider that sub-specification of locations are actually orientation features (as suggested in footnote 14), including hand-part specifications.

At the theoretical level the redundancy and the asymmetry disappear, because there would be one set of features for orientation which is specified on both hands in asymmetric two-handed signs. The price of this move, though, is that the explanation for the empirical asymmetry is completely lost. If [web] is a pure orientation feature available on both hands, we would expect it either to equally target both hands or the dominant hand in a more prominent way. This is not what we observed in LSF.

In order to accommodate the empirical asymmetry again, an additional move is required. We propose that there is only one set of hand-part features, which are orientation features that can be specified as a sub-component of both handshape and location. It is this different specification that can determine potential asymmetries in the distribution of [web] (and of the other orientation features that specify hand-parts). The idea is that orientation features may freely and independently interact with handshapes and locations. These interactions may determine different and separate degrees of saliency on the same features. Depending on language specific constraints, the typology in (4) is predicted.²⁰

(4) **Typology of interaction between orientation and handshape and/or location**

- a. Interaction with location produces high saliency
→ [web] becomes phonologically active on the non-dominant hand
- b. Interaction with handshape produces high saliency
→ [web] becomes phonologically active on the dominant hand
- c. Interaction with both handshape and location produce high saliency
→ [web] is equally active in both hands

²⁰The typology makes explicit reference to [web], but it can be easily restated in a more general way as to include any orientation feature.

d. No interaction

→ [web] is not active as a phonological feature




The typology stated in (4) determines whether the feature [web] becomes phonologically salient as a location and/or hand-part specification. If this is on the right track, LSF may instantiate the type described in (4a), while ASL the one in (4d). Concretely, the grammar of LSF is such that the interaction between orientation and location induces enough saliency to make [web] a phonological feature. However, it does not say anything about cases where [web] is selected as an orientation part of the dominant hand. What we can speculate here is that once the interaction between location and orientation has made [web] part of the phonological inventory of orientation features, hand-part can start using it for the dominant hand as well. The asymmetry we observed in LSF, then, simply reflects the fact that [web] has entered the pool of phonologically active features via the interaction with location. Thus, more signs are found in the lexicon that use [web] as part of relative orientation that depends on location, than signs that use [web] as hand-part of the dominant hand.

As a final step, let's consider how [web] is derived in symmetrical signs, i.e. signs in which both hands are active and behave identically. In this category of signs, the non-dominant hand is not a location anymore but an articulator just as the dominant hand, and the dominance relationship between the two disappears (Battison, 1978). We speculate that for LSF, [web] would not be selected as an orientation feature on the dominant hand but rather on the non-dominant hand. While the handshape features active on the dominant hand are copied to the non-dominant hand in symmetrical signs, the orientation features could be copied in the other direction. This can be determined by the simple fact that [web] appears more in the non-dominant hand in asymmetric signs compared to the dominant hand in LSF. In languages instantiating the type in (4b), i.e. [web] mostly appears on the dominant hand, [web] would be copied from the set of features of the dominant hand instead.

The broad implications for models of SL phonology are relatively clear. If our explanation is correct, relative orientation is not just a by-definition product of the interaction between a hand-part on the dominant hand and a location, specifically the non-dominant hand. We provided concrete evidence that this is phonetically and phonologically grounded in how the articulator/hand and location determine saliency on individual orientation features. Phonological models that already implement orientation in this way are superior than models in which orientation is captured as an independent parameter, because the latter have to introduce additional stipulations to explain the interactions of orientation with handshape and location. Furthermore depending on the specific model, we expect that

location features and handshape features enter in a geometrical relation with orientation features. We leave these as open issues for future research.

2.5.3 Consequences for SL phonological inventories

Feature-based models generate phonological inventories based on active features. Across languages, there is a pool of features that is more or less systematically active. Typically, these are unmarked features, like those determining the extended index finger , the fully closed  or open handshape . Other more marked features may be active or not depending on the specific language. Understanding which ones are phonologically active is probably one of the most complicated challenges that SL phonologists encounter when determining the inventory of active features for a specific language. Minimal pairs are probably the most powerful resource that researchers have to identify contrastive features. Unfortunately, as we explained in the previous sections, this tool is not of great help in the case of SL. Other types of contrasts must be used to determine the status of individual features. One of these is to relax the notion of minimal pair and consider near minimal pairs as a sufficient criterion to determine contrast.²¹ Another is to use saliency, although this would require special stipulations, especially in absence of phonetically measurable criteria. Finally, one can resort to (morpho-)phonological processes targeting specific features, like word-creation, deletion, replacement, metathesis, *etc.*

An immediate consequence of this move is that there is a concrete risk of overestimating the number of active features for a specific language. Parsimony and economy are often used as leading criteria in modeling inventories. This is what led Brentari (1998) to remove [web] from the pool of active features in ASL, because the various combinations attested in the lexicon can be described without making use of it. By extension, one should try to adopt similar explanations before (re-)introducing a new feature. This is what we first tried to do with LSF. It is only when faced with the impossibility of meeting even descriptive adequacy that we have been legitimated to introduce [web] as an active feature. The burden of the proof was on our shoulders. However, the introduction of the new feature was not without consequences. On the one hand, it solved the problems that we highlighted, on the other hand it introduced a certain amount of redundancy in phonological descriptions. Take for instance the LSF sign FRIES (repeated in Figure 21). In a system where [radial], [ulnar] and [web] are all active in the same phonological system, descriptive adequacy for orientation can be reached in at least three ways: by specifying

²¹Things are not so easy, though. The criteria to define what count as a near minimal pair are still to be consolidated in SL.

either [radial] or [ulnar], or [web] for the dominant hand (the non-dominant hand would copy the same value since it is a symmetric sign). The first two options would mimic the ASL analysis (and would require an additional neutralization of [web]), while the third one would simply target the relevant feature. This type of redundancy is known in SL phonology and has been discussed with respect to handshape in Brentari (1998, p.104). In a sense, it is not different to the one found, for instance, when [+sonorant] and [+syllabic] both target sounds that can fit the nucleus of a syllable in some languages. The challenge then is understanding whether there is a phonological need for all these features to be active within a language or not. This in turn requires to look for specific contrasts that might disentangle the issue. In our case, the LSF signs FRIES-HOSTEL illustrate the need of both [radial] or [ulnar] (for HOSTEL) and [web] (for FRIES).²² Contrasts of this type allows us to reach adequate explanation.



Figure 21: Signs FRIES and HOSTEL in LSF.

Phonological models for SLs should be taken as an overall indication of how features are organized within a system. Determining which ones are active in a specific language and at what level, only phonetic or both phonetic and phonological, is then an empirical task. Missing to distinguish the two levels and offering a restricted set of features, perhaps because it is well established in one specific language, may result in more parsimonious and elegant models, but it risks to miss adequate explanations for the facts. Here, we documented the case of [web], which appears to be quite a marked feature, still contrastively used in LSF.

A similar observation can be made for highly marked (at least for European SLs) handshapes like those involving the ring finger as the only selected finger. While these are

²²The need of both [radial] and [ulnar] is independently determined for instance by signs like NAME (Figure 7c) where the dominant hand requires an [ulnar] orientation while location on the non-dominant hand requires [radial].

virtually absent in European SLs and extremely rare in ASL (e.g., the number “eight”), these are not uncommon in Asian SLs. Phonological models build on Western World SLs may completely obliterate the existence of geometry of features that would allow a handshape to select the ring finger only. In doing this they are more economical, but completely excluding those combinations of features from those that can in principle become phonetically or phonologically active would be a gross mistake.

We want to conclude this section with a caveat concerning the interaction of iconicity and phonology in the make-up of active features. Loosening the criteria to identify contrast is a necessity given the peculiar phonology of SLs. However, this carries the risk of including more features than actually needed. This is particularly true for signs that are clearly iconically motivated. Limiting the discussion to locations, the sign SHORTS (Figure 22a) is produced on the thighs, and the sign EARRINGS (Figure 22b) is produced on the earlobes in LSF. If [web] is considered a legitimate location feature, why would not [thighs] and [earlobes] be so too? After all, both locations would probably meet the saliency criterion for being considered phonologically active.



Figure 22: Examples of signs produced on locations not listed as phonological features of location in current phonological models: [thigh] in SHORTS (22a) and [earlobes] in EARRINGS (22b).

There is at least one good reason not to consider iconically motivated features as fully relevant for “core SL phonology”. Iconic signs are processed differently (Perniss et al., 2010; Caselli et al., 2021) and often disobey constraints imposed by phonology (Brentari and Padden, 2001). The locations of SHORTS and EARRINGS are iconically motivated. There is no expected phonological alternation for these locations. Any modification in the location would carry modifications in the meaning of these signs: longer or shorter SHORTS, or NOSE-EARRING or BELLYBUTTON-EARRING. van der Kooij (2002a) highlighted that some,

mostly rare, features get regularized to better fit in and align with parts of the linguistic system that are more stable. However, Geraci (2009) documented cases where movements in classifier predicates violate the phonological constraints of LIS and cannot be reduced within the limit of LIS phonology (see also Liddell, 1995, 2003; Supalla, 1982, for similar examples in ASL). In all these cases, iconicity makes salient properties of objects or events which in turn determine specific articulatory patterns. These patterns are highly salient. However, they are so because of iconic reasons, not phonological ones. Location is no exception to this. It is a source of iconicity in its own right and what is allowed in the articulation and phonology of iconic signs should be considered with extreme care.

Thus, what type of saliency is instantiated in iconically motivated locations? What is the key property to exclude iconic saliency from SL phonology? Probably the fact that phonological saliency is arbitrary, it depends on specific visual-perceptual cues and it is completely untied from meaning. Iconic saliency depends on the meaning it transmits.

2.6 Conclusions

In this study we showed that the feature [web] should be included in the pool of features that contribute to determine the phonological inventories of LSF. Differently from ASL, where descriptive and explanatory adequacy of signs using the *webbing* part of the hand can be captured by the [ulnar] feature, the phonology of LSF uses [web] in a contrastive way. We motivated the phonological contrast in terms of saliency, near-minimal pairs, word-formation and neutralization.

For reasons of economy and elegance, we propose that [web] should be considered as an orientation feature, rather than a location or a movement feature, and that orientation features enter in a dependency relation either with handshape and/or location. This allowed us to explain the unexpected asymmetry found in the use of [web].

The analysis we offered opened an often ignored discussion in SL of how to determine contrast and what is the pool of features that a comprehensive phonological model should include. Our view is that SL models must specify the architecture and the possible geometries among groups of features, while the pool of active features must be determined by looking at the empirical facts of individual SLs. There is no economy in limiting the number of features that can create contrast. However, parsimony must be used in modeling individual SL phonology, and attributing phonological *vs.* phonetic status to features must be done taking into consideration the various ways in which contrast is determined in SL.

Chapter 3

Phonological representation of 2-handed signs in LSF: Reconsidering absolute orientation in the phonological models of sign language?

Mertz, J. (2020). Représentation phonologique des signes à deux mains en LSF: faut-il reconsidérer l'orientation absolue dans les modèles phonologiques des langues des signes? In *6e conférence conjointe Journées d'Études sur la Parole (JEP, 31e édition), Traitement Automatique des Langues Naturelles (TALN, 27e édition), Rencontre des Étudiants Chercheurs en Informatique pour le Traitement Automatique des Langues (RÉCITAL, 22e édition)*, pages 424–432. ATALA.

This chapter is an English translation of the original French publication.

Abstract

The goals of this paper are i) to provide evidence for the need of *absolute* orientation in addition to *relative* orientation in order to fully capture sign language segmental phonology, and ii) to enrich current models which are only based on *relative* orientation so that the phonology of otherwise problematic signs is also accounted for. We focus on one particular category of signs in French sign language: two-handed signs produced on the signer's body (contact with a body part other than the non-dominant hand). We show that *relative* orientation does not meet descriptive adequacy when the orientation between the two hands has to be specified, since it either captures the orientation between the hands or the orientation towards the body, but not both. We propose secondary planes as a formal step to model orientation for these signs.

While the implementation of this solution requires minimal changes in current formal models, the impact on the whole theory of segmental phonology for sign is quite big. The core conceptualization of orientation as a purely relational phonemic class does not hold anymore (at least not for these signs), as secondary planes impose geometrical restrictions that force absolute orientation.

3.1 Introduction

The segmental phonology of sign languages is shaped by feature geometry and dependency relations (Clements, 1985; Anderson and Ewen, 1987). Since the early work of Stokoe (1961), phonological models of sign languages have presupposed three phonemic classes as primitive: handshape (shape of the dominant hand (H1), and that of the non-dominant hand (H2) in two-handed signs), location (place where the sign is produced), and movement (size and shape of the movement of articulators). A fourth phonemic class, orientation, was later incorporated into the models (Battison, 1978). Orientation is also found in relation to movement as in orientation changes (see e.g., Blondel and Miller, 2001; Brentari, 1998); although this is very interesting, it is dealt with in the phonological representation of sign movement and is therefore not relevant to this study since we are only focusing on orientation as a phonemic class.

From a phonetic point of view, orientation can be defined in terms of the geometry of space: once an object of any kind is placed in (physical) space, it is automatically positioned in a plane of that space, and *oriented* relative to that plane. Thus, once placed in space, the hands are automatically oriented with respect to a plane in this same space. From a phonological point of view, in sign language linguistics, orientation is derived from the interaction between handshape and location; it is defined by a binary relation between a part of the hand (determined by a feature of the handshape) and the part of the location where the sign is produced (determined by a feature of the location). Orientation is thus treated as a derived phonemic class (Brentari, 1998, 2002; Crasborn and van der Kooij, 1997; Liddell and Johnson, 1989; Uyechi, 1994, 1995). In addition, we find minimal pairs as illustrated in Figure 23 with the signs FAX and METRO in LSF. In the sign FAX, the orientation is derived from the relationship between the handshape feature [palm] of the dominant hand and the location feature [palm] of the non-dominant hand. For the sign METRO, only the handshape feature is different since the [back of palm] of the dominant hand faces the same location, everything else is identical. The orientation is therefore the only parameter that differentiates these two signs.

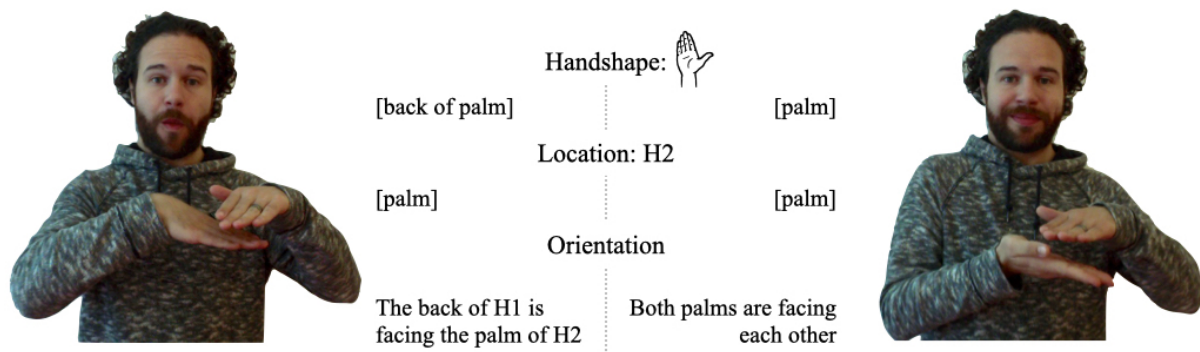


Figure 23: Minimal pair SUBWAY (left) ~ FAX (right) in LSF. The relevant features of handshape and location are shown for each sign, as well as the orientation obtained from these features.

Of these four phonemic classes of sign languages, the handshape has attracted the most interest from linguists and is therefore more finely described and represented in the literature (Sandler, 1986; van der Hulst, 1993; Uyechi, 1994, 1995). This can be explained by the fact that the features of handshape carry the most phonemic contrast in the phonology of sign languages (Brentari, 1998). Researchers' interest in describing the features and degree of contrast of other phonemic classes has not been as great as for handshape. For example, very few generalizations and constraints on location or movement have been proposed in the literature, and the number of cross-linguistic comparisons is correspondingly small. Let's consider location, for example. Signs can be produced either in the neutral space, which is the space in front of the signer, or on the signer's body. The neutral space is divided into three main planes, the horizontal plane y , the vertical plane x and the sagittal plane z ; if it is produced in the neutral space, the sign will be realized with respect to one of these planes. The body can also be the plane when it is necessary for the phonological representation of the sign. In this case, the body becomes a plane, divided into four main parts (the head, the torso, the arm, and the non-dominant hand), themselves divided into eight sub-parts, all of them phonologically motivated (cf. Brentari, 1998). As far as location is concerned, only two general constraints have been proposed (Brentari, 1998; Sandler and Lillo-Martin, 2006):

1. When a sign is produced at a particular location on the signer's body, the body *should be* the location;
2. For lexical signs, only one plane can be selected.

As we shall see below, these constraints generate a systematic conflict in the analysis of the phonemic content of signs, and have direct consequences on the analysis of another phonemic class, orientation. Some models define orientation in relative terms (Brentari, 1998; Crasborn and van der Kooij, 1997; Liddell and Johnson, 1989; Uyechi, 1994, 1995),

i.e., based on features of primitive phonemic classes. This *relative* way of deriving orientation replaces the concept of orientation defined in *absolute* terms present in other models (Battison, 1978; van der Hulst, 1993; van der Hulst and Mills, 1996). Technically, the absolute orientation was determined from the signer’s body used as a reference plane, and the palm or wrist of the dominant hand as a fixed landmark of the hand. Thus, by replacing absolute orientation with relative orientation, phonological models of sign languages became more economical (less structure), and more explanatory (the nature of one phonemic class is captured from the definition of others).

According to Crasborn and van der Kooij (1997), absolute orientation is still necessary for a limited number of signs: classifiers and “asymmetric two-handed signs”, that is, two-handed signs with different handshapes and with the non-dominant hand static (also known as “Type 3 two-handed signs”, Battison, 1978).

In this paper, we highlight the overly strict empirical and theoretical character of this conceptualization of orientation and show that absolute orientation can be extended to other sign categories. The rest of the paper is organized as follows: in Section 3.2, we use French Sign Language (LSF) data to show that i) the implementation of absolute orientation is necessary and is not limited to the two sign categories mentioned above ; and that ii) absolute orientation is not only motivated by iconicity in two-handed signs but also by phonological features. In Section 3.3 we propose a formal analysis capable of capturing absolute orientation without making a radical change to the initial intuition that orientation is primarily relational for signs. In order to concretize this analysis, we implement it in the framework of the *Prosodic Model* (Brentari, 1998, 2002) although a similar strategy can also be implemented in the other models mentioned above. Finally, in Section 3.4 we present possible empirical and theoretical extensions to this line of research.

3.2 The need for absolute orientation

The first goal of language modeling is to provide the tools necessary to describe cross-linguistic properties. In other words, if a particular theoretical model is built from the properties and mechanisms of a specific language, it must be robust enough to account for identical phenomena in other languages. The linguistics of sign languages, as opposed to that of spoken languages, is a relatively recent discipline since the first works date back to the 1960s (Stokoe, 1960; Stokoe et al., 1965). The construction of theoretical models therefore represents a challenge for the scientific community. Usually built from the information of a single sign language (very often American sign language), they are

then extended to other sign languages with very little adaptation. This applies to most phonetic and phonological patterns, and affects all phonemic classes, including orientation. As mentioned in the introduction, some current models define orientation in relative terms (Brentari, 1998; Crasborn and van der Kooij, 1997; Liddell and Johnson, 1989; Uyechi, 1994, 1995): it is the result of the interaction between a handshape feature and a location feature. An example is given in Figure 24 with the sign ANGER in LSF. Orientation is defined by specifying the feature [*tip of the selected fingers*] or [*tip*] oriented towards the feature [*clavicle*], an active feature as soon as the *body* is selected as location.

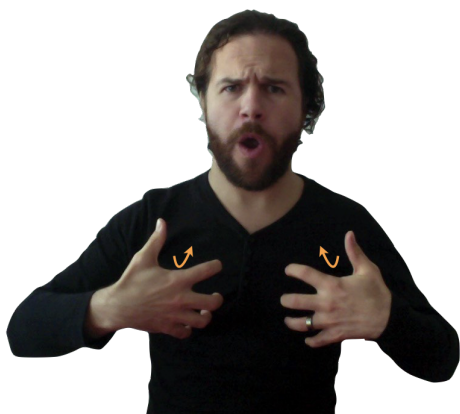


Figure 24: Sign ANGER in LSF.



Figure 25: Sign BELT in LSF.

We notice that the sign COLOR correctly answers the two constraints of the location indicated in Section 3.1 (Brentari, 1998; Sandler and Lillo-Martin, 2006). Indeed, the hands are in contact with the body, so the *body* is the location (see constraint 1), and no other plane is selected (see constraint 2).

However, these two constraints strongly restrict the shape of the signs. In particular, they predict that when the hands of two-handed signs are articulated on a body region (other than the non-dominant hand), they should never touch. The alternative would be a conflict in determining and specifying the location of the sign. However, this type of sign exists in LSF as we can see with the sign BELT illustrated in Figure 25.

On the one hand, both hands touch the waist and thus generate the selection of the body as a plane to establish the location. On the other hand, both hands touch each other and thus induce the production of the sign on the sagittal plane (which is a plane of neutral space). A similar case involving the torso and the horizontal plane is represented by the sign CODA in LSF (Figure 26). This phenomenon is also observed in other sign languages as we can see with the sign CANDIDATE in Italian Sign Language (LIS) presented in Figure 27.



Figure 26: Sign CODA in LSF.



Figure 27: Sign CANDIDATE in LIS.

To account for these signs, one could stipulate that location is unspecified (or underspecified) in the underlying forms, and that phonetics and phonotactics complement the articulatory material (Crasborn and van der Kooij, 1997). It is important to note that while the iconic component of the sign BELT is present, it is not for the signs CODA (LSF) and CANDIDATE (LIS)¹.

However, this analysis does not solve the problem of orientation. Indeed, the current models can only partially describe the orientation of these signs. In the case of BELT, if the feature [tip of selected fingers] (here the index finger and the thumb) and the feature [waist] are specified, the orientation with respect to the body is well defined, while the contact between the two hands is not. In this case, there is nothing to prevent the hands from crossing since the sagittal plane is not specified. In the situation where the feature [radial part of the selected fingers] and the sagittal plane are specified, the contact between the two hands is represented while the orientation in relation to the body is not. The sign should therefore necessarily be produced in the neutral space since the body is not selected (cf. constraint 1), which is not the case.

3.3 Analysis

In Section 3.2 we saw that underspecification does not solve the problem of identifying location and orientation in some two-handed signs produced on the body. In this section, we propose an alternative analysis based on the insertion of *secondary* planes generated by an additional relationship between the two hands. In the case of two-handed signs, the

¹The sign BELT was presented to twenty non-signers: none of them guessed its meaning. The link between signifier and signified is activated only with the knowledge of the signified, so its iconic value is not maximal since it is not a transparent sign.

latter corresponds to a specific orientation between the two hands that can be translated into an additional [contact] feature.

Secondary selection in sign languages has already been proposed in the literature to solve problematic cases related to finger selection (Eccarius, 2008). Here we simply propose to extend it to the field of location. Once the secondary planes are introduced into the structural representation of these signs, the handshape features can refer to them, thus solving both the problems of identifying the appropriate location and orientation. We illustrate this solution with the sign BELT in LSF.

Suppose that the body of the signer is the primary location according to the general constraint 1 introduced in Section 3.1. In this case, the feature [tip of the selected fingers] ([*tip*]) can be specified as the part of the hand facing the primary location. The secondary plane, in this case the sagittal plane, then prevents the two hands from crossing, and thus serves as a reference point for the “secondary orientation”, which is activated by a second handshape feature. In this case, this corresponds to the feature [radial part of the selected fingers] ([*radial*]) facing the sagittal plane; the specific contact point between the two hands is thus guaranteed.

A formalization of this development within the framework of the *Prosodic Model* is proposed in Figure 28. The node of location (POA for *Place Of Articulation*) dominates two branches, one for each plane: the body plane x with the relevant feature [waist], and the sagittal plane z . In the handshape branch (A for *Articulator*), the node H1 (dominant hand) directly dominates the relevant features needed for the orientation of the sign, i.e. the features [tip of the selected fingers] and [radial part of the selected fingers], each referring to a specific plane (respectively the body plane x and the sagittal plane z).

Implementing secondary planes to avoid hand crossing in signs such as BELT creates an interesting prediction about two-handed signs in which the hands are already crossed (i.e., signs in which the hands are in the contralateral position at the beginning of the sign). If these signs do not select a secondary location, the hands are free to “uncross” during a trajectory movement. This phenomenon is illustrated in Figure 29 with the sign UNEMPLOYMENT in LSF, where the body is the only selected plane.

However, when a secondary plane is selected, the hands are predicted to remain on the same contralateral side despite a trajectory movement; an example is given with the sign BONE in LSF (Figure 30) where the body is selected to represent the orientation between [clavicle] and [finger front], and the sagittal plane is inserted as a secondary plane to represent the orientation of the [radial part] of the two hands, and represents an imaginary line not to be crossed at the level of contact between the two hands.

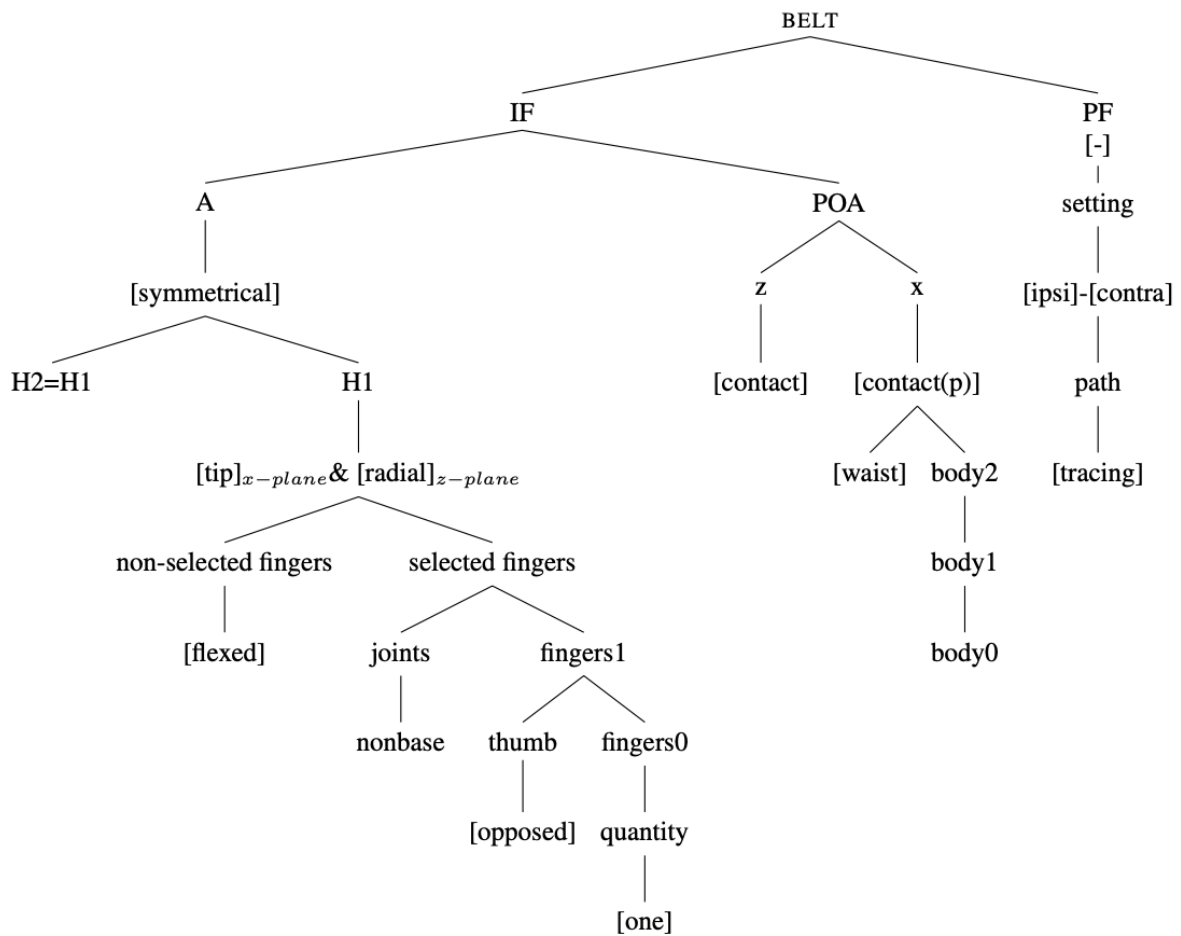


Figure 28: Structure of the sign BELT in the framework of the Prosodic Model.



Figure 29: Sign UNEMPLOYMENT in LSF.



Figure 30: Sign BONE in LSF.

3.4 Discussion

The analysis presented in the previous section allows us to represent the orientation of two-handed signs by introducing secondary planes into the formal description of the signs. Our implementation of this analysis in the framework of the *Prosodic Model* (Brentari, 1998) is however not without consequences. Here, we discuss two essential points. The first concerns overgeneration while the second deals with the status of orientation in signs that require secondary planes.

First, the analysis we offer does not restrict the use of secondary planes and thus predicts significant overgeneration, at least for two-handed signs including those for which the implementation of a secondary plane is not required. Limiting this overgeneration is possible by specifying the context in which secondary planes are introduced. One solution could be that a secondary plan is generated in all two-handed signs and then deleted in cases of redundancy.

Regarding the status of orientation, it is important to note that the impact of our analysis is stronger than suggested by the formalization shown in Figure 28. Indeed, while the implementation of secondary selected fingers (Eccarius, 2008) had no major consequences in the conceptualization of segmental phonology of signs, the extension of a secondary selection to location could (re)introduce a major and more radical change. In earlier models of sign language phonology, orientation was determined by the body as the plane of reference and the palm as the point of reference (Sandler, 1986; Uyechi, 1994, 1995). In our study we introduce *absolute* orientation in a more indirect way since the orientation depends on two planes (i.e. the body and the sagittal plane in the example discussed in this paper); our implementation thus allows to account for the orientation of the signs from a second spatial coordinate, it is the interaction of the orientation established between the primary and secondary planes that generates the *absolute* orientation.

3.5 Conclusions

Theoretical models are extremely important for defining and determining linguistic generalizations. However, extending them from one language to another without adaptation can lead to empirical inaccuracies. Since the *relative* orientation is apparently sufficient to represent the phonological form of signs, researchers have eliminated the *absolute* orientation from the description of sign languages. Data from two-handed signs in LSF and LIS, however, show that the *relative* orientation is not sufficient, and that the *absolute*

orientation is also necessary for the phonological description of some signs.

From a more general theoretical point of view, by reintroducing the *absolute* orientation, our solution represents a major innovation in the description of signs. The modification and adaptation of the current models remains however minimal, since to obtain the absolute orientation, the only condition is to have a “secondary” location. It should be noted that specifying a simple pair of features for absolute orientation leaves considerable room for phonetic adjustment, and thus retains the flexibility needed to study the cases discussed by Battison (1978).

It is also important to note that these changes are not simple phonetic adjustments since they are motivated by phonology (e.g., presence of minimal pairs). Iconicity is also not a sufficient motivation since the examples we have seen in LSF with the sign CODA or in LIS with the sign CANDIDATE (Figures 26 and 27) are not isolated cases.

Many questions about the extent of this need for absolute orientation remain, however. An in-depth study of LSF will be conducted in order to identify precisely the categories of signs affected by these modifications and thus determine the phonological rules underlying absolute orientation. We will also look at the theoretical studies conducted on the digital animation of signs in LSF ; this will also allow us to learn about the digital animation of signs in LSF. This will also allow us to know the limits of it and thus avoid the overgeneration currently present in our analysis.

Chapter 4

Measuring sign complexity: Comparing a model-driven and an error-driven approach

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Abstract

The study of articulatory complexity has proven to yield useful insights into the phonological mechanisms of spoken languages. In sign languages, this type of knowledge is scarcely documented. The current study compares an error-driven measure and a model-driven measure of complexity for signs in French Sign Language (LSF). The former measure is based on error rates of handshape, location, orientation, movement and sign fluidity in a repetition task administered to non-signers; the latter measure is derived by applying a feature-geometry model of sign description to the same set of signs. A significant correlation is found between the two measures for the overall complexity. When looking at the effects of individual phonological classes on complexity, a significant correlation is found for handshape and location but not for movement. We discuss how these results indicate that a fine-grained theoretical model of sign phonology/phonetics reflects the degree of complexity as resulting from the perceptual and articulatory properties of signs.

4.1 Introduction

Complexity in phonology refers to a set of elements that constitute a language system and how these elements are hierarchically organized within it (cf. Gierut, 2007, and references therein). It is thus an intrinsic property of the phonology of a language since every sound system is composed of several constituents dominated by higher level constituents. At the word-level phonology, these are features, segments, syllables, feet and prosodic words. This architecture was originally designed to account for the organization of spoken language phonology but it also largely reflects the organization of the sign language perceptual-articulatory system (e.g., Brentari, 2019), calling for an amodal spoken-sign language phonology, at least at the level of the foundation elements (e.g., binary features hierarchically organized, natural classes, weight units, syllables, etc.).

Complexity has been mostly investigated under two approaches in spoken phonology (cf. Chitoran and Cohn, 2009, for a review). On the one hand, a model-driven account of complexity uses the number of constituents of a (sound) system as a metric. Depending on the specific metric, these constituents are conceived in terms of distinctive features (Chomsky and Halle, 1968; Lehmann, 1974; Clements, 1985; Sagey, 1986; Anderson and Ewen, 1987), in other cases they are defined in terms of segments and syllables (see Maddieson 2005a,b, 2009; Maddieson et al. 2011; van der Hulst 2020; Easterday 2019 for a typological approach to complexity; Marsico et al. 2004 for a computational-based account). Under this view, complexity is related to the notion of markedness (Trubetzkoy, 1969): a form presenting a marked phonological specification is more complex than a form without it. On the other hand, there are approaches that make use of, for example, speech errors (e.g., Wells-Jensen, 2007; Meyer, 1992; Slis, 2018, for a review), or frequency (e.g., Romani et al., 2017), as diagnostics for phonological complexity. Under this other view, complexity is typically related to the notion of articulatory *effort* which crucially affects the rate of speech errors and shapes the patterns of acquisition (cf. Donegan and Stampe, 1979; Kirchner, 2001, for a formal approach). Under this kind of approach, complexity is intended in articulatory terms, hence the notion of effort is conceived as a sort of diagnostics for markedness: forms that are harder to articulate are more marked than forms that are easier to articulate. Ideally, these two views of complexity should converge, making a theoretical model of phonological systems a good predictor of the articulatory effort (but see Goldrick and Daland, 2009).

A similar scenario holds for sign language phonology, where model-driven approaches identify complexity in various ways, by counting the number of nodes required to accurately represent a form (e.g., the Prosodic Model by Brentari, 1998, p.214), by referring to more

global properties of signs (e.g., one-handed signs vs. two-handed signs, symmetry of form etc. as in Battison, 1978), or by using a physiological metric to compute effort as in the Ease of Articulation model by Ann (1996, 2006).

As for experimental approaches to sign phonology, several studies identified a variety of factors that may reveal the complexity of a sign, including accuracy in repetition tasks (Ortega and Morgan, 2015), error rates in production tasks (Thompson et al., 2005), frequency of a particular form (Ann, 1996) and lexical access (Orfanidou et al., 2009).

In particular, works on sign production focusing on articulatory effort (e.g., Emmorey et al., 2009a; Mann et al., 2010) have shown that articulation accuracy differs across the four phonological classes (i.e. handshape, location, orientation and movement). Ortega and Morgan (2015) showed that the overall structure of a sign contributes to its phonological complexity such that signs with multiple components are more complex than signs that do not have multiple components (e.g., two-handed signs are harder to produce than one-handed signs).¹

As we will shortly see, while these error-driven studies converge in identifying handshape as the most complex component of a sign, no study to our knowledge has tried to systematically investigate whether articulation errors derive from the intrinsic complexity of a particular phonological class and, if so, which one is responsible for the overall complexity of a sign. In other words, no study has tried to predict error-driven complexity of signs from a model-driven measure of complexity. The goal of this study is precisely to fill in this gap by comparing an error-driven measure of complexity based on error rates with a measure of complexity as derived from a specific phonological/phonetic model of word-level phonology for signs. In doing so, we will obtain a validated model-driven measure of articulatory complexity derived from the phonetic components of signs organised in a feature geometry.

Highly detailed feature-based models (e.g., the Prosodic Model (Brentari, 1998), the Dependency Model (van der Hulst, 1993), the Hand-Movement model (Sandler, 1986)) are designed to capture (the frequency of) patterns found in the phonotactics of sign language lexicon, as well as aiming to account for sign language phonological processes. We hypothesize that these models are also able to capture the kind of complexity as measured in terms of effort (error rates). If we are right, we expect to find a strong correlation between error rates and number of features required to describe a sign. This correlation will be interpreted as an indication that a given model is able to capture not

¹In Ortega and Morgan (2015) the authors use the term ‘component’ to refer to phonological classes (i.e. handshape, orientation, location and movement), as well as subnodes such as the H2 node in two-handed signs. We chose to report the same term to be in line with the authors’ terminology.

just the phonological system of a sign language but also the effort needed to produce signs even without any knowledge of the phonological system, hence proving additional phonetic ground to the model itself. We then investigate which phonological class among the four major ones (handshape, location, orientation and movement) has the strongest impact in determining complexity. We expect to find a significant contribution of handshape and possibly of other phonological classes. Although this study will not provide a feature-level scale of complexity, we will interpret its results in computational terms. Specifically, hand configuration has a higher degree of freedom than other phonological classes, requiring a higher number of features hence increasing the probability of error as a consequence of both perceptual complexity (simultaneous identification of the relevant nodes) and production complexity (control of a higher number of nodes).

In the next subsections, we will present studies on complexity and articulatory accuracy in sign repetition tasks (subsection 4.2). Particular attention will be given to those studies including production from hearing non-signers (with little-to-no prior exposure to sign language). Complexity as defined by sign language phonological models will be briefly introduced in subsection 4.3, followed by a presentation of the particular model used in this paper, namely the Prosodic Model by Brentari (1998), and arguments for the choice of this model over others in subsection 4.4. The error-driven measure from a sign repetition task with non-signers is presented in subsection 4.5, followed by the computation of the model-driven measure (subsection 4.6), and finally by the comparison of the two in subsection 4.7. Results are discussed in subsection 4.8, where we compare the error-driven measure from the sign repetition task and with the model-driven measure of complexity. subsection 4.9 concludes the paper.



Our study focuses on French Sign Language (LSF), a language for which phonological data is still scarce, although its impact can be easily extended to other sign languages.

4.2 Complexity and articulatory accuracy in sign repetition tasks

In this subsection we briefly report on previous studies on sign repetition tasks. These will frame the study on the error-driven measure of complexity to be presented in subsection 4.5, and motivate the use of non-signers as a valuable population.

Several factors may contribute to articulation errors in sign production, such as perceptual saliency of the sign components (Rosen, 2004; Bochner et al., 2011, for converging evidence),

size inventory (Hohenberger et al., 2002; Marshall et al., 2011), the complexity of mastering a novel motor task (Rosen, 2004; Mirus et al., 2001), age of exposure (e.g., Corina et al., 2020), frequency (Ann, 1996, 2006), and also factors related to the overall structure of a sign (e.g., one-handed signs vs. two-handed signs, Battison, 1978) and to the contribution of each phonological class (Ortega and Morgan, 2015).

As for articulation accuracy, Emmorey et al. (2009a), Mann et al. (2010) and Mirus et al. (2001) showed that articulation accuracy differs across the four phonological classes, the order of complexity varying according to the type of task, in line with findings on sign language acquisition (e.g., Conlin et al., 2000) and on the tip of the fingers effect (e.g., Thompson et al., 2005). For instance, in a repetition task in Russian Sign Language involving signers of American Sign Language (ASL) and non-signers, Emmorey et al. (2009a) showed that non-signing participants were least accurate in learning to reproduce handshape and most accurate in reproducing location. For movement, the performance of non-signers fell in-between that of handshape and location. They interpret the results of such error patterns (handshape as the most complex parameter) in terms of complexity in line with Brentari’s model. Mann et al. (2010) manipulated handshape and movement to control for complexity in a repetition task of British Sign Language (BSL) pseudo-signs administered to Deaf children (native² or early learners) and hearing non-signer children. Handshapes like  were treated as simple as opposed to more complex ones like  and others from the BSL handshape inventory, while path movements were treated as simple as compared to forms with two simultaneous movements (e.g., a path movement co-occurring with a handshape change). It was found that accuracy was lowest for signs that were more complex in both Deaf and hearing children (e.g., more complex signs were more likely to be replaced with simpler signs). This study highlighted the importance of articulatory grounding in processing the linguistic content in the visual-gestural modality. Even though the phonological knowledge of Deaf signers allows them to better perform the task, phonetic complexity affects their grasping of the phonological processing of signs.

Working on a holistic definition of complexity based on Battison’s (1978) classification system, Ortega and Morgan (2015) used a sign repetition task with hearing learners of BSL to study the effects of overall phonological complexity of signs and, separately, the influence of the four phonological classes on L2 sign acquisition. The different levels of complexity were based on the number of hands selected for the sign (one- vs. two-handed

²Native signers are congenitally deaf individuals born into deaf signing families. We use “Deaf” to refer to people who use sign language as their primary mean of communication and that, culturally, belong to the community that shares that language.

signs), the behavior of the non-dominant hand when selected (identical vs. different from the dominant hand), and the location of the sign (neutral space vs. signer’s body). Repetitions from hearing learners were coded based on a simple incorrect/correct grid so as to obtain a score for each stimulus with one point for each correct reproduction of each parameter. Participants’ scores were compared to the global complexity level of each sign. In addition, they reported accuracy scores for each of the four phonological classes. For the overall complexity of the sign, results showed that articulation accuracy gradually decreased as the number of phonological components of a sign increased, that is one-handed signs were less complex and hence more accurately reproduced than two-handed signs. For each class, it was found that location was the easiest (i.e. the most accurately reproduced), followed by orientation, movement and finally handshape.

To summarize, these studies show that handshape is the least accurate (i.e. more difficult to articulate) component of a sign, location is the most accurate, with movement and orientation falling in between (Ortega and Morgan, 2015); that complexity incrementally affects each subcomponent of a sign (Mann et al., 2010); and that adult signers are less prone to make phonological errors in repetition tasks than hearing non-signers and signing children (Emmorey et al., 2009a; Mann et al., 2010). While a phonological explanation of the complexity of handshape over the other sign components is easy to find in current phonological models (Emmorey et al., 2009a), it is less clear how to extend this explanation to cases where the effect is found in non-signers who are in principle unaware of the phonological properties of signs. We will interpret a similar finding in our work as evidence that at least part of the descriptive accuracy of phonological models is grounded in their phonetic basis.

4.3 Complexity through sign language models

Theoretical models account for phonological complexity based on phonetic/phonological markedness criteria. For instance, Battison (1978) formalizes sign complexity as a four-level scale ranging signs from Type-0 to Type-3 depending on the number of articulators involved and their overall behavior in the execution of the sign. Type-0 are one-handed signs, by default least marked both in terms of articulators involved and of features required to describe them (e.g., the LSF sign WOMAN in figure 31a). Two-handed signs are categorized based on the behavior of the non-dominant hand: Type-1 are two-handed signs with both hands acting in the exact same way, i.e. they share all four phonological classes (e.g., the LSF sign BED in figure 31b), Type-2 have the non-dominant hand static with the same handshape as the dominant one (e.g., the LSF sign SUBWAY

in figure 31c), and Type-3 have different handshapes between the two hands (e.g., the LSF sign AGAIN in figure 31d). While the behavior of the articulators is a key factor in determining sign complexity, this metric does not separate the individual contribution of more primitive components of signs such as handshape, location and movement and can thus only offer a preliminary and somehow rough categorization of the level of the complexity of signs. For instance, a one-handed sign with a fully closed handshape and a path movement would count as equally complex as a one-handed sign with two flexed selected fingers and a path movement with an orientation change and an aperture change.

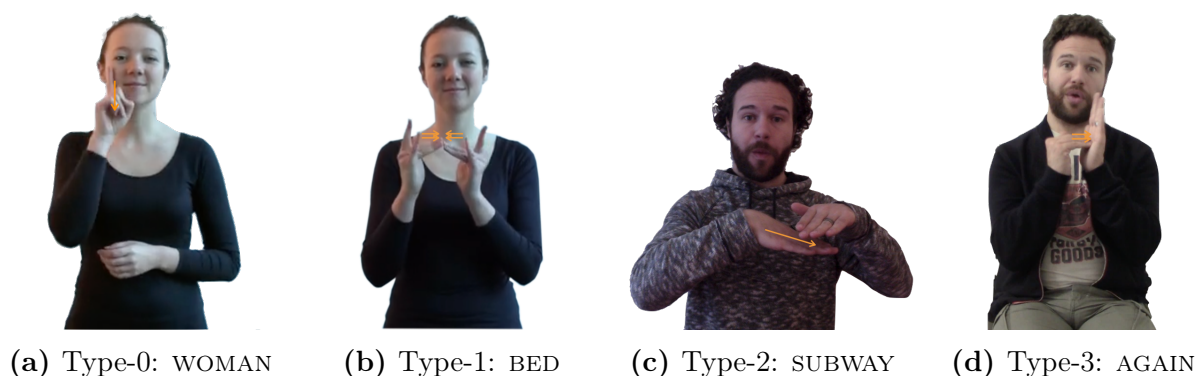



Figure 31: Examples of LSF signs based on Battison’s classification (1978).

Ann’s (1996) Ease of articulation model formalizes complexity based on the physiological properties of the hand. Complexity strictly depends on articulatory/motoric ease of production, which in turn depends on the group of muscles involved in the articulation. Under this framework, markedness depends on the number of muscles involved in the articulation of a handshape or on how difficult it is to control some contractions (e.g., those leading to a bent middle or ring finger). Unfortunately, this model remains limited to handshape, without extending a similar fine-grained complexity measure to the other phonological classes.

Turning to more comprehensive models of sign phonology, several of them have been proposed in the literature since the first pioneering work by William Stokoe later republished (Stokoe, 2005). All of them share a featural approach to sign description, while differing on the specific treatment of the phonological sublexical units or more subtly in the internal organization of groups of features. For instance, the Holds-and-Movement model treats signs as composed of sequences of handshapes interpolated by transitions between locations (Liddell and Johnson, 1989). Other models are more directly inspired by spoken language theories and organize features in a hierarchical/geometrical fashion (Clements, 1985). The Hand-Tier Model (Sandler, 1986, 1993c), the Dependency Phonology Model (van der Hulst, 1993; van der Hulst and van der Kooij, 2021) and the Prosodic Model (Brentari, 1998) all belong to this tradition. Amongst these only the

Prosodic Model explicitly defines a direct mapping between feature representation and degree of complexity: the richer the structure, in terms of positively specified features, the more complex the sign. Hence, markedness is determined by the number of branches contained in the structure (Brentari, 1998, pp.213-214), along the lines of Drescher and van der Hulst (1993).³

Aristodemo (2013) uses this definition of complexity to conduct a magnitude estimation study asking Italian Sign Language (LIS) Deaf signers and Italian hearing non-signers to rate a number of handshapes with respect to perceived complexity. Results showed that perceived complexity correlates with richness of the hierarchical representation and that the Prosodic Model better predicts perceived complexity than Battison’s four-level typology of signs. The study also reports some differences between the ratings of Deaf signers and hearing non-signers which are accounted for in terms of a pure phonological effect. For instance, handshapes that do not belong to the phonological inventory of LIS were rated as more complex by signers than by non-signers (e.g., ). Our study will apply the same rationale to evaluate whether error rates in a repetition task can be predicted by the Prosodic Model. Differently from Aristodemo (2013), we will address all phonological classes of a sign as captured by the Prosodic Model in a repetition task rather than a pure perception experimental design, and we shall only include non-signing hearing participants to avoid any phonological interference (which might have lead signers to be too accurate and reach a ceiling effect, Emmorey et al., 2009a). This will be done after a brief overview of how signs are represented in the Prosodic Model.

4.4 The Prosodic Model: An overview

The Prosodic Model (Brentari, 1998) decomposes each sign in a hierarchical structure of organized features divided into two main branches. One branch governs those features whose status does not change during the articulation of the sign, namely the Inherent Features; the other branch governs those features that introduce a change during the articulation of the sign, namely the Prosodic Features. The sublexical units of handshape and location are part of the Inherent Feature branch; orientation is derived as a relation between a specified handpart feature and location, while the Prosodic Feature branch captures the movement component in terms of location change, orientation change or handshape change. These are roughly corresponding to directional path movements (straight, arc or circular), wrist rotations and pronations, and hand opening/closing. In

³The aim of the current study is not to say how one particular model better predict complexity as opposed to others, but rather to evaluate its capacity to do so.

subsection 4.6 we use this feature approach to capture these dynamic components of signs as part of the movement category. Each branch dominates several nodes (and subbranches), while terminal nodes host contrastive features. An illustrative example is given in Figure 32, corresponding to the representation for the LSF sign TRAIN.

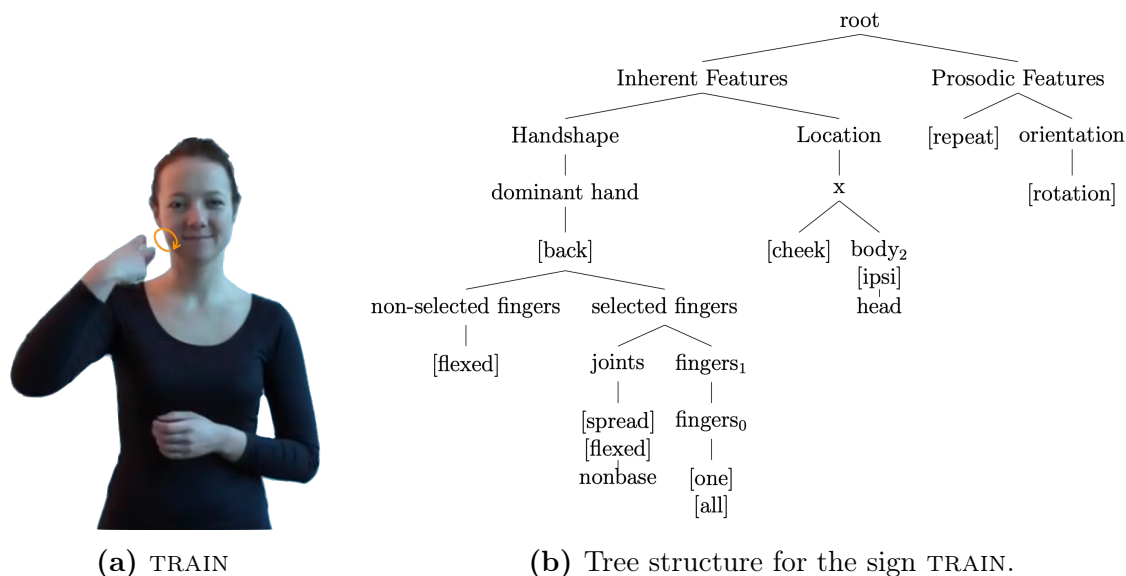






Figure 32: The sign TRAIN in LSF, and its phonological representation in the framework of the Prosodic Model (Brentari, 1998).

The tenets of feature dependency and feature geometry as in Clements (1985) and subsequent works are at the core of the Prosodic Model. This strong theoretical stand finds support in the relation between the phonetic facet and the phonological facet of a feature approach to sign description. On the one hand, each feature in the Prosodic Model has a descriptive value deeply grounded at the phonetic level. For instance, handshape features and their geometry partly subsume Ann’s Ease of Articulation model (1996; 2006), while movement features are organized in a sonority hierarchy. On the other hand, the contrastive force and the sensitivity to phonological processes provide concrete evidence of their phonological status. In its current development, the Prosodic Model counts 20 features and 28 nodes for handshape (including 12 features and 15 nodes for the dominant hand), 35 features and 12 nodes for location, and 23 features and 4 nodes for movement. From this figure, handshape and location clearly emerge as the richest phonetic/phonological classes; however, the number of possible combinations for handshape is considerably larger than for location thus explaining its higher contrastive power and higher level of complexity with respect to the other phonological classes (Emmorey et al., 2009a).

In the remaining part of this subsection we describe how each phonological class is incorporated into the Prosodic Model, providing examples of minimal pairs in LSF. This

will give the reader a concrete idea of how the model-driven measure of complexity for each sign has been computed in our study and guarantees replicability. Additionally, we provide a fully-expanded structure of the Prosodic Model, with all possible nodes and features, in Appendix 4.

Handshape. The handshape branch of structure has the largest inventory due to the amount of contrastive features (Hohenberger et al., 2002). These are necessary to appropriately capture the relevant fingers of a handshape (selected vs. non-selected fingers) and to identify the relation between the joints (e.g., [crossed]  vs. [spread] ), the behavior of the thumb (selected vs. non-selected, e.g.,  vs. ), etc. An example of the contrastive power of this system is illustrated by the LSF minimal pair WOMAN \sim WINE in Figure 33. The two signs differ in the number of selected fingers (one vs. two, respectively). Crucially, the model incorporates Battison’s intuition that two-handed signs increase complexity. Indeed, an H2 subbranch stemming from the Handshape node serves precisely the purpose of including the non-dominant hand, whether its shape and its behavior are similar to or different from the dominant hand. Even if not encoded as a primitive, also at the local level of the Handshape subbranch, the higher the number of features, the more complex the sign.

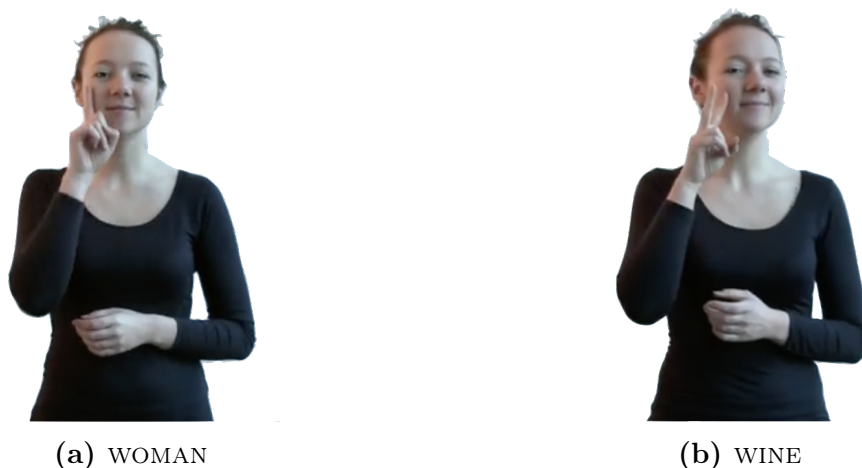


Figure 33: Example for a minimal pair on Handshape: WOMAN \sim WINE.

Location. A sign is produced either in the neutral space, i.e. the space in front of the signer, or on the signer’s body. In the phonological structure, if the sign is produced in the neutral space, only one node is selected between x, y and z, depending on the plane (respectively the vertical, horizontal or midsagittal plane). When it is produced on the body, the body itself *is* the plane. The x node is thus developed in many branches depending on the relevant major body part (head, torso, non-dominant arm, non-dominant hand), each dominating a set of features further specifying which subpart of the major

location is selected. For example, the LSF signs KNOW and AGAIN only differ on the location of the sign (head - forehead vs. non-dominant hand - palm, respectively), as shown in Figure 34. While neutral space is coarsely identified by one plane/node only, locations on the signer’s body receive a finer-grained specification, automatically resulting in a higher level of complexity.



Figure 34: Example for a minimal pair on Location: KNOW \sim AGAIN.

Orientation. Although contrastive, orientation is not treated as a primitive phonological class in the model. It is not represented by an independent (sub)branch in the Inherent Feature part of the structure. Rather, orientation is derived as a relation between a handpart feature and the plane of articulation (i.e. a feature referring to the hand part facing the location is specified in the Handshape branch of structure, and the developed Location branch of structure captures the location the specific handpart is facing). For example, in the LSF sign SUBWAY, the orientation is derived from the feature [back] of the dominant hand (Handshape branch of structure) facing the [palm] of the non-dominant hand (Location branch of structure), minimally contrasting with the orientation in the LSF sign FAX, where it is the [palm] of the dominant hand facing the location, as illustrated in Figure 35.

Movement. The movement component is captured by the Prosodic Feature branch of structure. This is done by identifying the proximal vs. distal joints governing the articulation of the movement, resulting in location change, orientation change or handshape change. Additional features describe the manner of path movements (circular, straight or arc) and whether repetitions occur. Simultaneous movements are captured by specifying features at each relevant node, thus increasing the complexity of the representation. In the LSF minimal pair TRAIN \sim EXPENSIVE, the circular vs. straight manner features contrastively distinguish the two signs as illustrated in Figure 36.



Figure 35: Example for a minimal pair on Orientation: SUBWAY \sim FAX.



Figure 36: Example for a minimal pair on Movement: TRAIN \sim EXPENSIVE.

4.5 An error-driven measure for defining complexity

The error-driven measure of complexity we developed is based on the error rates of a repetition task which was conducted as part of a larger project, SIGN-HUB, aiming among other things at creating a battery of assessment tests for a variety of sign languages including LSF. Specifically, the signs included in the study reported here have been selected to be part of a lexical test to be administered to signers (picture-naming task)⁴, while the repetition task discussed below was administered to non-signers in order to obtain an estimate of the articulatory complexity of the items to be included in the lexical test. A description of the lexical test can be found in Donati et al. (2020). All the analyses

⁴The relevant SIGN-HUB task is called PICTURE NAMING TASK IN LSF (LEXNAMLSF). For more information about the SIGN-HUB project: <https://www.sign-hub.eu/>.

for this study have been conducted using the software R (Team, 2018). For sake of clarity, the details of each statistical model are reported in the Appendix.

4.5.1 Material and methods

The materials for the repetition study come from a pool of 108 LSF signs originally chosen for the purpose of the SIGN-HUB assessment test. They were selected on the basis of lack of transparency with the help of a native Deaf consultant.⁵

Since a referent is more frequently retrieved when signed than when spoken due to its more direct link with the visual modality (Klima and Bellugi, 1979; Perniss et al., 2010), signs were chosen for being “non-transparent”, i.e. their level of iconicity was low enough to prevent non-signers from guessing their meaning without additional information (Bellugi and Klima, 1976). To validate the non-transparent status of the signs, we asked 20 hearing non-signers to guess the meaning of each sign. Note that these participants were not those who took part to the sign-repetition task. We excluded all signs whose meaning was correctly guessed by two or more participants. We also excluded signs produced by our consultant without movement, because this would make the assessment of this parameter impossible. Compounds (Santoro, 2018) and signs whose phonological structure is ambiguous have also been excluded. All in all, fourteen signs were eliminated from the set: PARTY (*gesture* referring to partying in the French culture), MOON (no movement), BELT, FACTORY, FAMILY, LION-2, SUBWAY, STAR-2, SAILING-BOAT (ambiguous in their phonological structure), and EURO, MOUSE, SLEEPERS, STAMP, TURTLE (compounds); thus leaving a total of 94 sign as stimuli for the repetition task.

We video-recorded our Deaf consultant signing each stimulus in isolation in front of a blue screen. A complete list of the signs is provided in Appendix 1.

Participants. Twenty hearing French adult non-signers acquainted with the visual culture of France were recruited (13 females, 7 males; age ranging from 21 to 72, mean = 40.26 y.o.). Participants were volunteers with no prior exposure to any sign language. Those with corrected vision were asked to keep their glasses/lenses.⁶

Procedure. The experiment took place either in the *Laboratoire de Linguistique Formelle* - Université de Paris/Paris Diderot (10 participants) or at the participants’ house (10 participants). Participants were sitting (except for two of them, who stood up for personal

⁵In this particular study, frequency and regional variation are not relevant since the participants do not have access to the language.

⁶We assume that the fact that hearing people are also gesturers is not affecting the study (Goldin-Meadow and Brentari, 2017).

convenience) in front of a screen placed on a table at arm distance (~ 1 to 1.5 meter from them). They were not aware of the purposes of the study. Each of them received the instructions of the task in French: he/she was asked to watch the video of a sign and to repeat it. They could watch the video of each sign only once and had to use the mouse and click to see the next sign. Their performance was video-recorded (2160 tokens). Though the sign stimuli were not randomized, no order effects were observed in the analyses (Appendix 3.1).

Data coding. Two interns with a basic competence in LSF coded each participant’s repetition. As in Ortega and Morgan (2015), we coded for the four phonological categories, (i) handshape, (ii) location, (iii) orientation, and (iv) movement. To these we added a fifth criterion, (v) sign fluidity, i.e. whether the repetition was done without hesitation. This last criterion allowed us to distinguish between a completely correct repetition produced with hesitation from a correct production without hesitation. As a matter of fact, the absence of error in a repetition task does not always account for ease of production. Lexical processing is still in progress during an hesitation, hence reflecting an additional complexity level to that of accuracy in the phonological component of a sign.

For all tokens, a binary value was assigned to each of these five criteria: the value “1” indicated a correct repetition, the value “0” an incorrect one. Therefore, for each sign, the overall accuracy was obtained by summing all the values of the five parameters. The values provided by the coders were assigned based on the following protocol, adapted from Ortega and Morgan (2015):

Handshape: handshapes can be described in terms of the number of selected fingers and their configuration (see Figure 36 for an example: the index and middle fingers are spread and flexed at the non-base joint). The repeated handshape had to correspond to the stimulus, otherwise it was considered as incorrect.

Location: in the neutral space, only the main plane was taken into account (i.e. no distinctions were made between the different 3D planes in space), the distinction between *ipsi* and *contra* was not. For body-anchored signs, the body was divided into six major regions (upper head/face, lower head/face, chest, neck/shoulder, arm, hand), and our coding was flexible as for more subtle divisions into subregions (Liddell and Johnson, 1989): when the repeated sign was produced in a region overlapping between two subregions (e.g., wrist for hand and arm; or jaw for lower head and neck), the production was coded as correct for both regions.

Orientation: the orientation of the hands is the phonological class the least described in the literature. As opposed to Ortega and Morgan (2015), we did not specify any

angle but rather considered as correct when both the hand part and the plane it was facing could be correctly identified.

Movement: in movement, the number of repetitions and the amplitude of movement were not taken into account in the evaluation. However, if a movement was considered as “almost” correct, it was coded as incorrect.

Sign fluidity: when the sign was not repeated fluently, i.e. when the participant hesitated, looked at his/her hands or produced a halting sign, the repetition was considered as non fluid.

The degree of accuracy was directly mapped onto a complexity scale, ranging from 0 to 5, with 0 being the least accurate (hence the most complex), and 5 the most accurate (hence the least complex). An example is given in Figure 37, where the model and the participant differ in the extension of the selected fingers.



Figure 37: Evaluation of the repetition of TRAIN produced by a non-signer. The participant’s production (Figure 37b) is fluid and accurate for location, orientation and movement, while the handshape is not with respect to the configuration prompted by the visual stimulus (Figure 37a) since the participant’s fingers are extended instead of flexed and spread. The total score for this particular production is thus 4/5 (Figure 37c).

Two coders (coders 3 and 4) with basic knowledge of LSF coded the entire data set (20 participants). In order to check reliability, two other coders (coders 1 and 2), also with basic knowledge of LSF, independently coded 25% of the data set (5 participants each), following the same instructions. A Gwet’s AC1 agreement coefficient (Gwet 2008), a measure of inter-rater reliability, was calculated across the four annotators. We report separate values of agreement for each phonological class and each combination of coders in Table 1.⁷

⁷A Kappa Coefficient of Agreement (Cohen, 1960), a common measure of inter-rater reliability, was

Table 1: Agreement coefficient estimate-AC1 (Gwet, 2008) and percentage of agreement for each phonological class between coders.

	Handshape	Location	Orientation	Movement
Coders 1 & 3 (Part. 19-20)	0.76 (86%)	0.96 (95%)	0.97 (96%)	0.80 (85%)
Coders 1 & 4 (Part. 16-17-18)	0.82 (89%)	0.93 (93%)	0.95 (96%)	0.72 (81%)
Coders 2 & 3 (Part. 3-5-14)	0.82 (88%)	0.96 (95%)	0.91 (93%)	0.74 (82%)
Coders 2 & 4 (Part. 11-12)	0.78 (85%)	0.98 (97%)	0.97 (98%)	0.82 (86%)

4.5.2 Results

The overall error-driven complexity mean was 4.304 (SD=0.43). The most accurately repeated sign was HAM with an average score of 5 (Figure 38a), and the least accurate sign (i.e. most complex) was HEDGEHOG with an average score of 3.15 (Figure 38b). Results for each item are reported in Appendix 2.



Figure 38: Illustration of signs with high and low complexity scores based on participants' repetition: (a) The sign HAM with the highest score (5/5), and (b) the sign HEDGEHOG with the lowest score (3.15/5).

From the distribution of errors across the four phonological classes (Figure 39), handshape emerged as the phonological class with the highest percentage of errors (40%), followed by movement (35%), sign fluidity (14%), orientation (6%) and location (5%).

As documented in a series of studies on various linguistic and non-linguistic topics (see Baayen, 2008, and references therein), and given the large age range of the participants

calculated across the four annotators. The resulting inter-rater reliability scores are indeed low, but this is explained by the low rate of errors made by the participants, i.e. one disagreement between the coders automatically appears to have a strong impact on the Kappa score. For this reason, we calculated the Gwet's AC1 agreement coefficient (Gwet, 2008) as it was shown to be more stable than Cohen's Kappa (e.g., see Wongpakaran et al., 2013).

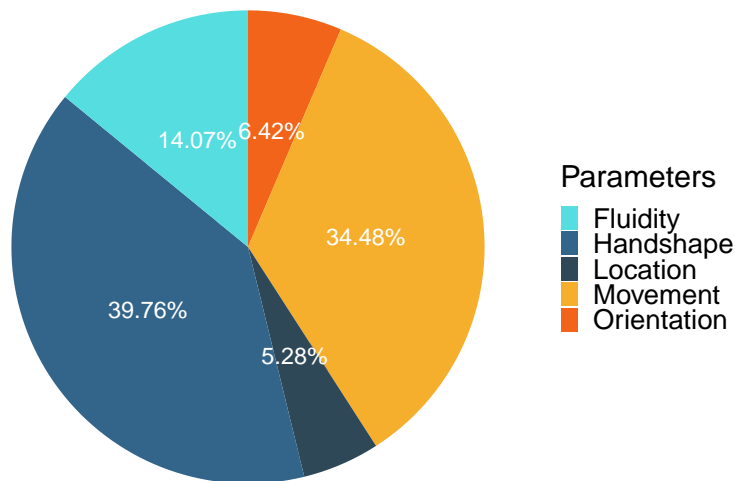


Figure 39: Errors produced in the sign-repetition task by 20 hearing non-signers: Distribution of errors across the five parameters (%).

(21-75, mean = 40 y.o.), we considered chronological age as a potential factor affecting accuracy. Specifically, we expect that accuracy declines with chronological age, i.e. younger participants being more accurate than older ones, as reported in other repetition studies (Corina et al., 2020). We performed a cumulative link mixed model (*ordinal* package, Christensen, 2019) using the overall complexity of the error-driven measure as dependent variable and the participants' age as predictor, with Participant and Item as random factors, and we found that accuracy decreased as age increased ($p < .05$, see Appendix 3.2 for details).

4.6 A model-driven measure of complexity

The Prosodic Model (Brentari, 1998) offers a concrete opportunity to evaluate how closely theoretical models of sign language phonology reflect actual articulatory effort in production, for the following reasons. First, it provides a detailed description of the articulatory properties of signs grounded on both articulatory and perceptual phonetic properties. Second, the specific way in which the groups of features are organized is based on their phonological properties (contrastiveness and sensitivity to phonological processes). Third, it offers an explicit rationale to measure complexity in terms of number of branching nodes. Furthermore, it subsumes most of the properties of other phonological models (see Chapter 1 of Brentari, 1998, for a detailed description of such properties as we have discussed in subsections 4.3 and 4.4 above.).

4.6.1 Material and methods

In order to conduct a direct comparison with the error-driven measure of complexity, we generated the Prosodic Model representation of each of the 94 signs considered in subsection 4.5 and then we computed their level of complexity by summing the number of nodes and positively specified features. We adopted the pool of features and branching nodes as described in Brentari (1998). This model was originally tailored for ASL phonology, although it easily extends to other sign languages. However, some features that are contrastive in ASL may not be contrastive in LSF and, vice versa, there could be other features that were not included in the original model because not contrastive in ASL which might be in LSF. The first point is not of particular concern as we are interested in the phonetic description and not in the phonological values of the features considered as we will compare this measure of complexity with error rates of non-signers, namely with the productions of individuals who are not sensitive to LSF phonology. Luckily, the second point was not relevant for our study in the sense that the pool of features included in the Prosodic Model allowed an adequate description of the 94 LSF signs in our data set (i.e. we did not have to introduce any new feature into the model⁸).

Coding procedure. A sign language linguist acquainted with the Prosodic Model (the first author) annotated the 94 signs used as stimuli in the repetition task on the basis of the hierarchical phonological representation of the features given by model.

The model-driven measure of complexity was obtained by summing the nodes and the features contained in the tree structure of each sign. For example, the phonological representation of the sign TRAIN (cf. Figure 37) and its corresponding total and partial scores are given in Figure 40 (for sake of replicability, a step-by-step description of the coding is provided in the Appendix 5). The Inherent Features branch of the structure is developed into two main branches for handshape and location. In the handshape branch, the shape of the (dominant) hand is described: the non-selected fingers are closed while the selected fingers (here the index and middle fingers) are spread and flexed on the non-base joints. In the Location branch of structure, the x node is developed since the sign is produced on the body. The right branch indicates the major body part, here the *ipsi* side of the head, and the location is specified in the left branch, the cheek⁹. Finally,

⁸Of course this does not mean that the same set of features that describes ASL phonology adequately describes the LSF phonology.

⁹Notice that in order to independently compute the number of nodes necessary to capture both handshape and location, the Inherent Feature node was counted twice. While this increases by one point the overall complexity of a sign, it does so uniformly across all signs. Since we did not compare the complexity of the Inherent and Prosodic branches this move does not affect any of the statistical analyses conducted in the study.

the Prosodic Feature branch of structure represents the rotational movement of the wrist which corresponds to an orientation change.¹⁰

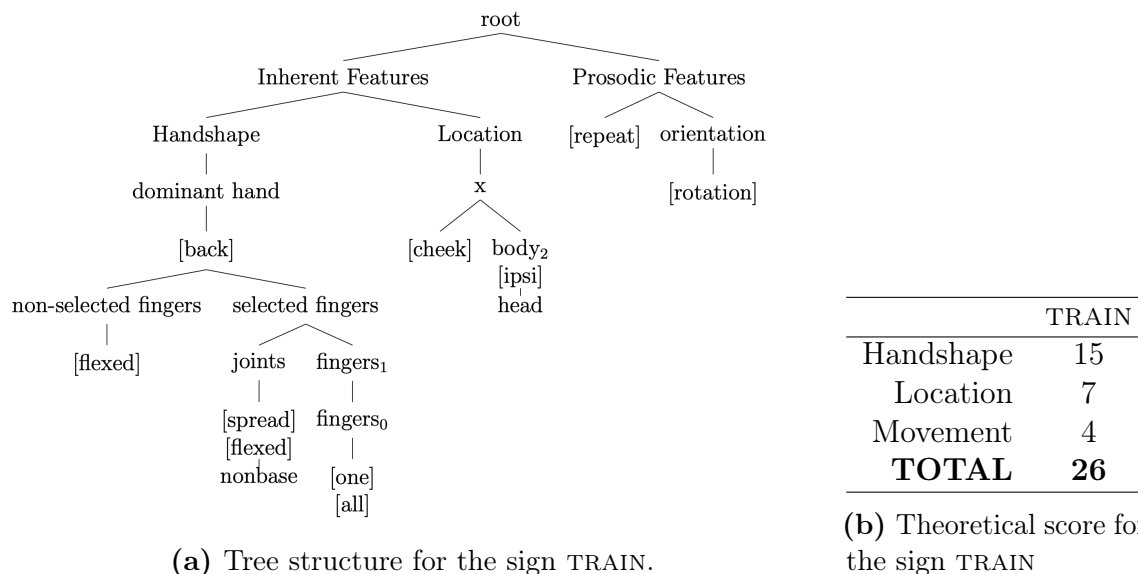








Figure 40: (a) Phonological representation of the sign TRAIN based on the Prosodic Model (Brentari, 1998), and (b) its theoretical complexity score.

In the current study, we made two additional choices. First, we developed the branch of the non-dominant hand even though its repertoire is a restricted set of handshape (e.g.,       handshapes in ASL).¹¹ Our second choice concerns the annotation of handshape changes in the movement branch of structure. A handshape change is a set of two handshapes which correspond to the open and closed versions of one single handshape (Brentari, 1998). In the phonological representation of our stimuli, we developed the handshape that was not the predictable open or closed version of the pair. For example, the specified handshape in PEN (see Figure 41b) is the initial handshape (here the [open] version) since the final one (i.e. the [closed] version) is predictable.

Partial and total scores of each sign are given in Figure 42 and a summary table is provided in the Appendix 2.

¹⁰Any movement is represented in the Prosodic Feature branch of structure, whether it is an aperture change, an orientation change or a location change (i.e. path movement or change in the 3D plane).

¹¹Despite their simple phonological structure, the number of positively specified features is not identical across these handshapes. Our choice allow us to obtain fine-grained distinction among this type of signs, something that is not possible if we were following Battison’s (1978) typology, for instance.

4.6.2 Results

Overall, we ended up with a set of 102 class nodes and terminal features: 46 for handshape (including 26 for the dominant hand), 29 for location and 27 for movement. Of the total number of features available in the Prosodic Model, we used 90% of handshape features, 50% of location features and 100% of movement features, indicating a considerable amount of variation in the quality of features in our sample.

Differently from the error-driven measure, where orientation and fluidity were part of the overall metric and received independent values, here the contribution of orientation is split between the handshape and the location branches because orientation is a derived phonological class in the Prosodic Model (see subsection 4.3), while fluidity is irrelevant as the signs were all fluidly produced by our actor model.

The 94 annotated stimuli had an index of complexity ranging from 15 to 39. The least complex sign was LION with a total score of 15 (Figure 41a), while the most complex sign was PEN with a total score of 39 (Figure 41b).



Figure 41: Illustration of signs with high and low complexity scores based on Brentari’s theoretical structure (1998): (a) The sign LION with the lowest score (15), and (b) the sign PEN with the highest score (39).

4.7 Predicting errors from the model: towards a theory of sign complexity

To evaluate whether the model-driven measure (independent variable) significantly predicts the error-driven measure (dependent variable), we conducted a series of analyses.

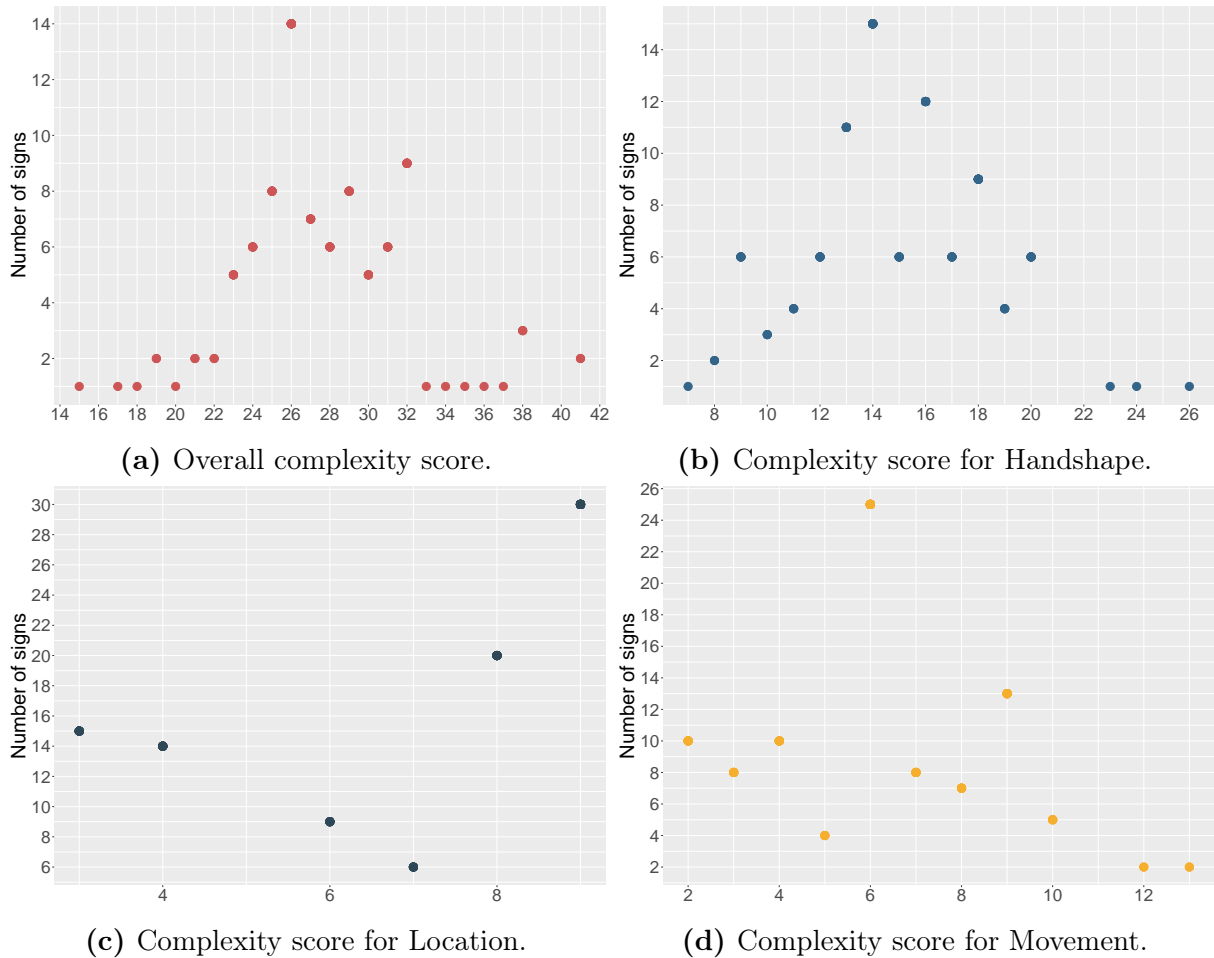


Figure 42: Distribution of complexity scores for (a) overall complexity, (b) handshape complexity, (c) location complexity, and (d) movement complexity from the annotation in the framework of the Prosodic Model (Brentari, 1998).

We hypothesized that the phonetic ground of the Prosodic Model and its complexity metrics could predict error rates in a sign repetition task performed by non-signers, hence establishing a strong relation between error-driven measures of complexity and model-driven metrics of complexity. In order to test this hypothesis we performed a cumulative link mixed model using the overall complexity of the error-driven measure as dependent variable and the overall model-driven measure of complexity as predictor, with Participant and Item as random factors. Results show a significant main effect of the model-driven factor ($p < .001$, see Appendix 3.3). The plot in Figure 43a shows the relationship between the two metrics of complexity: the lower the accuracy score of the error-driven measure, the higher the overall complexity measure of the stimulus. The overall computation of the model-driven measure of complexity is able to predict overall accuracy/error rates in the repetition task.

In order to verify whether each subbranch of the Prosodic Model adequately captures the partial accuracy of Handshape, Location and Movement of the error-driven measure

of complexity, we computed three separate generalized mixed model linear regressions (Figures 43b, 43c and 43d, respectively). Results show a significant effect for handshape ($p < .001$, see Appendix 3.4) and for location ($p < .05$, see Appendix 3.5), but not for movement ($p > .05$, see Appendix 3.6). In other words, while the Prosodic Model correctly captures complexity of handshape and location it does not seem to be able to capture the complexity of the movement component.

Table 2: Summary table of the values included in the linear regressions. The first column reports the mean value from the repetition task and the second column reports the ranging scale, for overall complexity and for each category.

	Error rate (mean (SD))	Theoretical complexity (scale)
Overall complexity	4.30/5 (0.43)	15-39
Handshape	0.72/1 (0.23)	7-24
Location	0.96/1 (0.07)	3-9
Movement	0.76/1 (0.23)	2-13

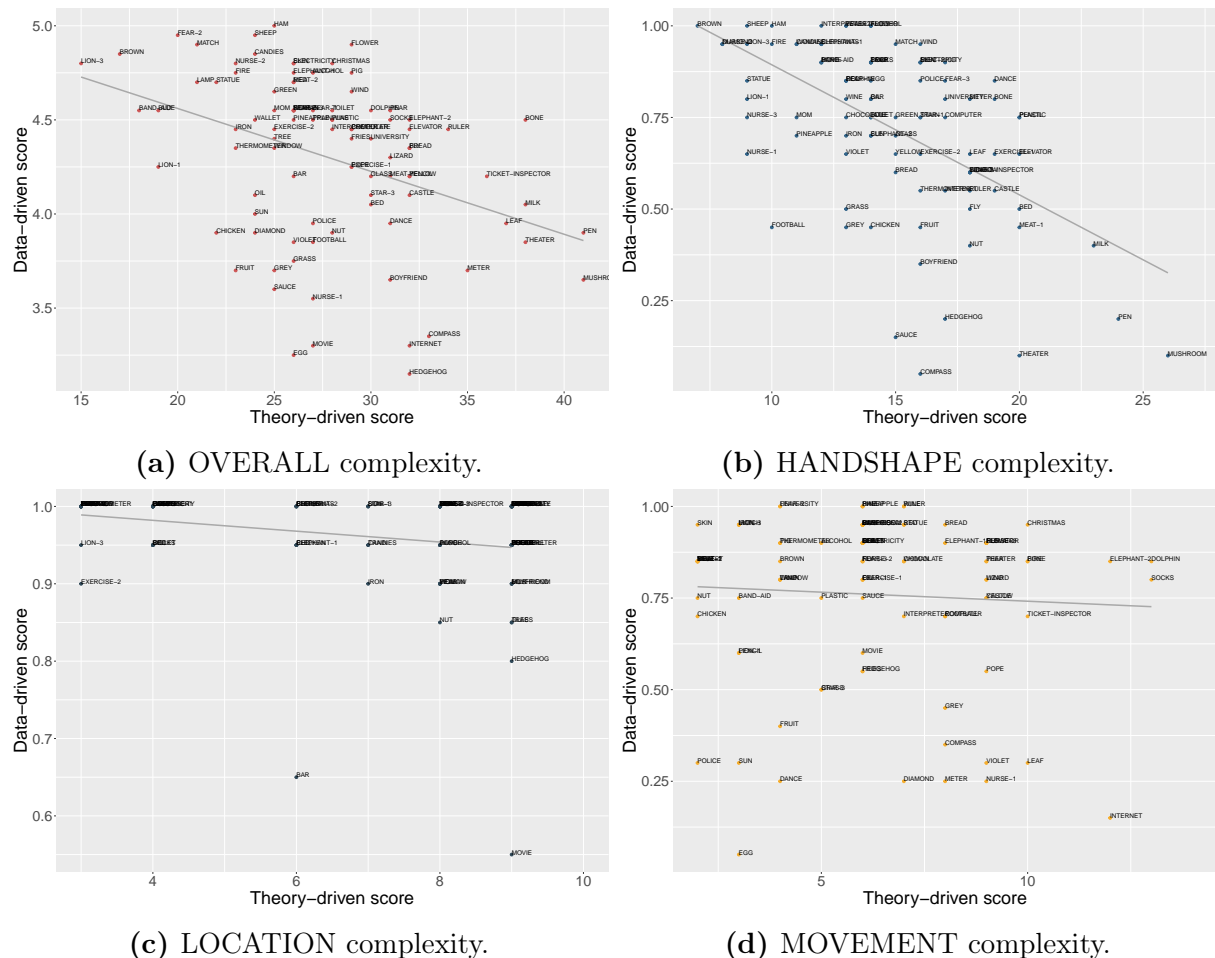


Figure 43: Correlations for (a) overall score, (b) handshape score, (c) location score, and (d) movement score between the error-driven and the model-driven complexity scales in LSF.

Finally, we performed a cumulative link mixed model analysis to establish whether the

complexity as predicted by each subcomponent of the Prosodic Model correlates with the error-driven complexity, and to what extent. We adopted a step-up procedure in which the dependent variable is the overall error-driven score, and the complexity of each model-driven phonological class is used as an independent predictor, with Participant and Item as random factors (Baayen, 2008; Baayen et al., 2008). Results show that handshape and location are significant main effects ($p < .001$ and $p < .05$, respectively) while movement is not ($p > .05$, see Appendix 3.7).

Specifically, the probability of having higher levels of accuracy decreases as complexity increases for either handshape or location, and the probability of lower levels of accuracy increases as complexity increases for either handshape and location.

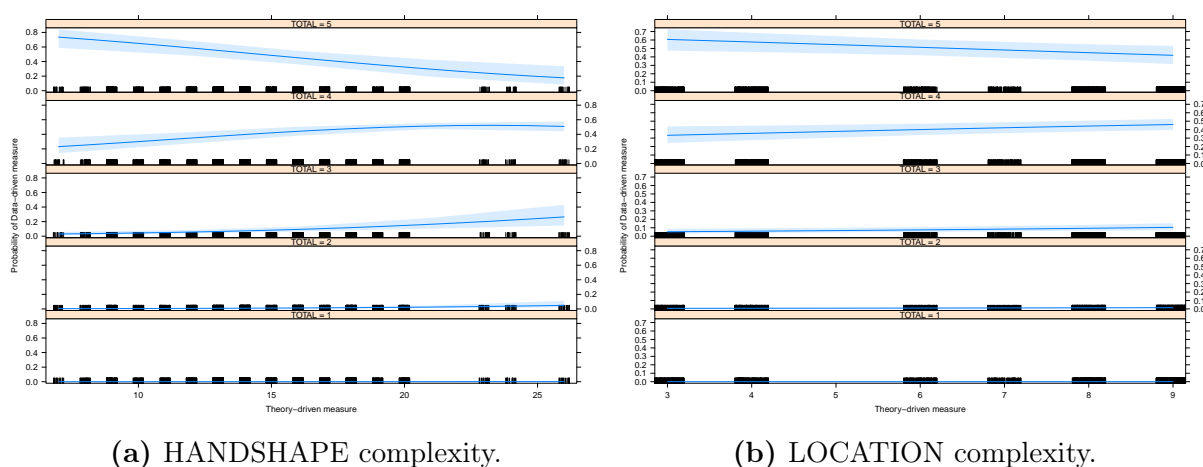


Figure 44: Probability of getting an overall error-driven score (from 1 to 5) based on model-driven measure for (a) Handshape and (b) Location.

These results confirm that while handshape and location as represented in the Prosodic Model adequately capture articulatory complexity, the movement component does not.

4.8 Discussion

Focusing on phonetic aspects, one way to measure complexity is by looking at accuracy in repetition tasks (Ortega and Morgan, 2015), but healthy adult signers may not be the ideal testers as they easily reach ceiling effect even with items coming from a sign language they do not know (Emmorey et al., 2009a; Mann et al., 2010). Furthermore, their performance might be influenced by language specific phonological constraints (Aristodemo, 2013). An alternative is to use non-signers as a population that is not affected by any sign language phonology, and experimentally measure the level of accuracy in purely phonetic repetition tasks and thus identify the degree of complexity for specific signs on the basis

of production errors. This is what has been done within the SIGN-HUB project as part of the validation procedure to select the items to be inserted in a lexical production task and this is the empirical source of the data considered in this study. While this procedure might seem as an inevitable step to develop standardized tests, it could be too expensive in terms of time and resources when it comes to create *ad hoc* psycho-linguistic tests where articulatory complexity is one among the many factors to be manipulated. Having another measure that strongly correlates with articulatory complexity and that can be used as a way to identify items with various degrees of complexity would be a viable alternative.

Current models of sign language phonology reach a sophisticated level of descriptive adequacy in two ways: by adopting a wide set of articulatory features and by organizing them in a hierarchical fashion. To what extent is this descriptive adequacy reflected in explanatory adequacy? There are two possible ways to address this question: one is to evaluate whether such models can account for phonological contrasts and for a reasonable range of phonological processes (e.g., deletion, epenthesis, assimilation, etc.). In other words, the evaluation concerns the phonological level more than the phonetic one. The other way to address their explanatory adequacy is to verify whether these models can be used to predict perceptual and articulatory complexity. This is what we did in this study. We used the richness of phonetic representations to predict the accuracy levels in a sign repetition task.¹²

In line with Ortega and Morgan (2015), the repetition task showed that handshape is the most difficult component to imitate, followed by movement, orientation and location. Similar results are observed in sign language aphasic patients with location being reported as the most stable and less impacted phonological class as opposed to handshape which is subject to a larger number of substitutions and other error types (Corina, 2000). These results are also consistent with studies on sign processing and lexical access with handshape and movement being the phonological classes less readily retrieved contrary to location and orientation which are less affected (e.g., in a misperception task with Deaf signers, Orfanidou et al., 2010). The same dichotomy has been observed in perception confusion studies with native Deaf signers, with contrasts in handshape and movement

¹²Since our data collection involves non-signing participants only, one may wonder whether our findings relate to the phonetics of signs as opposed to their phonology and whether the more gradient nature of non-signers in related tasks might affect our interpretation (Kita et al., 2014). We thank Shengyun Gu and Harry van der Hulst for pointing us these aspects. It is true that our study only targets phonetic aspects of sign representation. In fact, what we are offering is a way to compute pure phonetic complexity. As far as the more gradient behavior of non-signers as opposed to signers, a much more similar study to the one described here, namely Aristodemo (2013), showed that both signers and non-signers are gradient in their judgments about complexity. Notice further that the granularity found in our study does not depend on the behavior of the participants, but on the scale we used to compute complexity.

being the most difficult to discern in comparison with orientation and location (Tartter and Fischer, 1982). Even though location seems to be easier to repeat as opposed to the other phonological classes (e.g., Emmorey et al., 2009a), a reviewer made us notice that the error rate for location in our study is surprisingly low. This could be explained by the very rough distinction that was made among the different body regions when coding the repetition task (cf. subsection 4.5). The fact that signs produced on different body parts were not counted as incorrect when produced in the same large region might have led to an underestimation of the errors in location. Nonetheless, the model-driven metric of complexity used in this study is able to predict that signs that involve a higher number of place of articulation features and nodes are more prone to repetition errors than those requiring a less number of features and nodes.

Accuracy rate also tend to correlate with chronological age, with older participants being less accurate than younger participants. Several factors can account for the observed decline, such as age-related effects on working memory and/or on neuromuscular, i.e. physiological, abilities. While sign languages require a motor system that affects working memory and hence the storage for signs (e.g., Emmorey, 2001, pp.233-234), elderly individuals show a decrease of neuromuscular and motor skills with age (see Hunter et al., 2016, for a review). At the present time it is impossible to identify more precisely the exact origin of the chronological age effect, and additional studies must be carried out in order to test the impact of cognitive or motor-related causes. Such results remain nevertheless important for our understanding and interpretation of articulatory abilities.

Two reviewers pointed out that the source of error in the error-driven measure may not be fully attributable to articulatory complexity as the repetition task itself involves a first step in which the sign/gesture is seen on a video. It is possible then that perceptual complexity is an alternative source of error in addition to articulatory complexity. This is highly plausible and our study cannot disentangle this issue. However, what is relevant here is that the model-based metric, which capitalizes on articulatory features, is able to predict error rate independently from the fact that the source of that error is perceptual, articulatory or both. In fact, studies showed that there is a strict correlation between the two (e.g., Mann et al., 2010). Let us notice in passing that a perception version of this study, for example one in which participants are asked to rate the degree of complexity based on visual perception of handshape would not solve the problem either. This is what Aristodemo (2013) did, and she found a correlation between handshape complexity as computed with Brentari's model and complexity as emerging from a rating task. However, despite the fact that the task was clearly perceptual, it is not possible to exclude that participants were trying to reproduce the handshape itself in order to assess its degree of

complexity. A different experimental design is needed in order to separate the contribution of perception from that of articulation as potential source of error, something we leave for future works.

Statistical analyses successfully showed that theory-based models can be used as reliable measures to assess overall articulatory complexity. We also showed that among the major sub-lexical units of sign phonology/phonetics, handshape is the one where the correlation between the model-driven and the error-driven measure is stronger, followed by location, while no correlation is found with movement. The effect of handshape on sign complexity is in line with previous findings (Emmorey et al., 2009a) and can be accounted for in similar terms. Overall, the hand configuration has a higher number of joints, hence in principle a higher degree of freedom than the other components of a sign. This is probably the source of the higher error rates in the repetition task. The higher the number of joints that require overt control, the higher the probability to commit an error when trying to repeat. Crucially, the high degree of freedom of handshape is also reflected in theoretical models in terms of a higher number of handshape nodes and features required to meet descriptive adequacy when compared to the other sublexical components of a sign (53 handshape features vs. 16 for location and 28 for movement in the Prosodic Model). The high number of handshape features easily maps into a fine-grained complexity scale, which nicely matches the handshape error rate of our study and the perceived complexity in Aristodemo’s study (2013). Although to a minor extent, the articulatory features of the location subbranch are also able to predict location errors showing that even a complexity scale with a reduced number of nodes and features is able to capture some degrees of effort.¹³ What remains to explain, however, is why the feature geometry of the movement component does not capture the error rates of the repetition task, despite the fact that it contains a higher number of features than the location component. One possibility could be that the movement component of signs is somehow intrinsically different from handshape and location in a way that it is not captured by the feature geometry of the Prosodic Model. In line with categorical perception studies (e.g., Emmorey et al., 2003), location and movement are perceived as more ‘gestural’ as opposed to handshape which is perceived as being more ‘phonological’ (Goldin-Meadow and Brentari, 2017); both location and movement are considered to be more continuous. While our results on location are in line with the latter statement, results on movement are not, and this might be due to the fact that movement, as a dynamic component of signs, cannot be directly compared to its static counterpart (i.e. handshape and location, as well as orientation).

¹³As the Prosodic Model derives orientation from a relationship between handshape and location, we cannot measure its impact as an independent factor. Here we merged orientation with sign fluidity, and both can only be included in the overall complexity value in the sign repetition task.

Additionally, one aspect that is not taken into account in our study is the difference in movement types (path movements produced by a shoulder or elbow movement vs. orientation and aperture change produced by movement on the wrist or fingers, respectively). In the Prosodic Model, the movement branch of structure is built on a sonority scale, with larger movements being more sonorant than smaller movements. In other terms, the larger the movement, the easier it is to perceive (Brentari, 1998, pp.216-224). This is not reflected in the number of nodes and features, which means that we cannot account for the perceptual complexity of the different types of movement in the current state of our study.

An explanation along this line may find some support in the dual status of movement in sign phonology. In addition to playing a segmental role, thus capturing phonological contrasts, movement is also involved in higher-level functions. Specifically, its dynamic and temporal properties serve as prosodic units in the sign structure representing the syllable nucleus. This aspect is not encoded in the feature geometry of the Prosodic Features branch but it is included as an additional extension of the representation where the hierarchical structure is mapped into time slots. Currently there is no proposal on how to include this aspect as part of sign complexity. Of course, such a phonological explanation does not immediately extend to the phonetic nature of the mapping we are proposing in this study. Non-signers may be sensitive to their rhythmic correlates which could affect the perception and production of gestures. For example, while heavy syllables are represented with a similar number of features and nodes, they may surface with completely different trajectories and distribute over time in a different way. Similarly, repetitions of short and long movements may affect the sign repetition task in a way that is not captured by the Prosodic Model (or any other model as far as we know). If this is the case, then future work should better investigate how to measure the contribution of movement in the computation of sign complexity. For example, conducting a similar study while using the Dependency Model (van der Hulst and van der Kooij, 2021) might be interesting as the movement component is derived differently. A radically alternative explanation could be that the model-driven measure is sensitive to extreme values while it under-performs with intermediate values. In other words, the correlation with the error-driven measure could be stronger when very easy and very difficult items are considered. If we look at the distribution of the signs in our sample by the model-driven measure of complexity in Figure 42, we see that complexity increases more or less regularly for handshape and is probably slightly over-represented with location. Crucially, extreme values are under-represented in the movement plot, where most of the signs fall in the middle of the scale. It is possible, then, that the model-driven measure of complexity is not efficient for the movement branch because not enough items in our sample fall in

the extreme values of the complexity scale. In order to verify this possibility we ran an analysis where we only considered the five most complex and the five less complex signs for movement as resulting from the model-driven measure we used in this paper (Appendix 3.8). Results show that even when considering only extremes values, the model-driven measure for movement does not predict accuracy.

As familiarity ratings highly correlate with lexical frequency in corpus studies (Baayen, 2008), our study shows that a model-driven measure of complexity based on Brentari's Prosodic Model (1998) correlates with an error-driven measure of complexity based on repetition tasks by non-signers. At a very concrete level, the measure of complexity that we are proposing is easy to compute and provides a quick but robust test to control for the phonetic complexity of lexical items in experimental studies. However, our study addresses the issue of explanatory adequacy at a deeper level, providing independent support for a specific theoretical model of sign phonology, namely the Prosodic Model. We can easily speculate that other models, similarly based on feature-geometry principles, may yield comparable results, as long as their phonetic representation is accurate.

Finally, this study is the first to address articulatory complexity in LSF signs, thus increasing not only our knowledge of this language in particular, but also articulatory complexity of sign languages in general. The correlation between error rates in the repetition task performed by non-signers and the measure of complexity based on sign language models that we found indicates that a feature approach to complexity can be in principle extended to gestures in general. In fact, what we actually measure in our study is phonetic complexity. However, this does not mean that sign language models do not capture the phonological component of signs, but rather that this phonological component is well grounded on phonetic basis. Determining which feature is contrastive, hence susceptible to be included in a phonological inventory of a language, which node or group of features is subject to specific phonological processes (e.g., epenthesis) is a matter of phonology and these aspects are captured by constraining these models in a language specific way.

4.9 Conclusions

Research on phonological complexity has led and still leads to a better understanding of human language and its functioning. At present, phonetic complexity and phonological structure are proven to be intimately related in spoken languages, a relation that has been only marginally explored in sign languages. This study highlights the role of each

sublexical unit of signs in determining complexity. We elaborated a model-driven measure of complexity based on Brentari's (1998) Prosodic Model and we mapped the scale of complexity on an error-driven scale of complexity based on error rates in a repetition task performed by hearing non-signers. This is the first study of its kind, where the comparison is done both at the global level and at the individual level of each sublexical unit of a sign. As it stands, it acts as a stepping stone for future work on articulatory effort and phonological complexity. While here we focused the analysis on naïve hearing non-signers, thus contributing to the quantification of pure articulatory complexity, a more comprehensive study of how a phonological system impacts sign complexity is also needed to understand, for instance, how the categorical perception of phonological contrasts, the size and quality of phonemic inventories may reduce or amplify pure phonetic complexity.

Sign language communities are fragile for several reasons: they are language minorities and thus suffer of a number of issues related to language rights and language justice. Besides, language transmission to infants is not granted as only a small portion of deaf children is born into signing families. Moreover, local sign languages are not often recognized the status of fully-fledged legitimate languages, and consequently language access is seldom guaranteed in schools. The particular situation that characterizes sign languages urgently requires screening devices that reliably measure proficiency in all linguistic domains, including lexical phonology, and in a manner that adequately reflects the peculiarity and variety of Deaf signing populations, where natives are a minority, and go together with early and late learners. Within this frame, it is crucial that the items of both generalized screening tools and *ad hoc* tests are adequately controlled for a variety of factors like frequency, familiarity, transparency (Caselli and Pyers, 2017) and degree of complexity. Our study offers a quick and robust way to measure complexity and can be used as a basis to create experimental stimuli to assess this aspect of sign competence.

Chapter 5

Categorical Perception in French Sign Language (LSF)

Abstract

The current study investigates categorical perception (CP) of both handshape and location in French Sign Language (LSF) in an online experiment. In addition to use the simultaneous presentation of our stimuli in the discrimination task to precisely tap into language-specific mechanisms, we are the first to record reaction times (RTs) in a sign language CP study. First, we show that Deaf signers perceive handshape categorically as opposed to hearing non-signers. This confirms a sensitivity to phonological contrast in the population that has been exposed to the phonology of LSF. Second, variation across sign phonological categories in LSF occurs since no effect in location is observed. Interestingly, CP effects were also found in the allophonic pair in handshape in Deaf signers, which puts into perspective the notions of contrast and allophony in sign language. Results in RTs help understanding the role of visual cues in the discrimination of complex visual stimuli. We provide solid evidence that some sign sub-units are perceived categorically and that the visual-gestural modality is highly inclined to use perceptual cues.

5.1 Introduction

The visual-gestural modality of sign language raises important questions about the perception of human language in general. Numerous studies on categorical perception (henceforth CP) showed language-specific characteristics in the perception of speech sounds (see Repp, 1984, for a review), which drew attention of sign language phonologists due

to the difference in modality. Given that hearing people perceive some speech sounds in a categorical way, do signers perceive sign sub-units likewise? Is the perception of signs affected either by phonological knowledge (i.e. linguistics), or by the visual system (i.e. sensory modality), or both? At present, there is no clear answer as the few studies conducted almost exclusively on American Sign Language (ASL) show contradictory results. Our objective is to contribute to the study of CP in sign language and complement previous studies with another language, namely French Sign Language (LSF).

Sign languages are the means of communication for thousands of Deaf people around the world. As their spoken counterparts, they are complex linguistic systems with similar underlying mechanisms as well as language-dependent rules, at each linguistic level, i.e. syntax, semantics, morphology, as well as phonology (Quer et al., 2017; Sandler and Lillo-Martin, 2006). Each sign language is governed by its own rules and constraints responsible for the inventory of contrastive forms and features behind the permissible lexical and linguistic constructions. However, different from spoken languages, sign languages are more prone to simultaneity since their minimal phonological units are produced simultaneously (Vermeerbergen et al., 2007).

Humans perceive the world categorically, i.e. in a discontinuous fashion, even when the entities they observe are distributed continuously. In an experimental setting, this can be observed by participants grouping several items of a continuum into two categories with different labels, and a clear boundary arising between the two. Two items are less difficult to discriminate when they belong to two distinct categories than when they belong to the same, even though the physical difference between the items of each pair is identical. The observation of this distinction in the perception of items *within* and *across* categories is called a CP effect. In the auditory modality, CP effects have been observed in the perception of non-linguistic stimuli such as music (Cutting and Rosner, 1974), pure tones (Pisoni, 1977), lexical tones (Francis et al., 2003). As for speech sounds, various studies have shown that such an effect is observed, but CP is not equivalent across all speech contrasts. Indeed, while we perceive stop consonants categorically (e.g., Liberman et al., 1957), the perception of fricatives is less categorical (e.g., Fry et al., 1962), and vowels are, on the contrary, perceived as continuous (e.g., Pisoni, 1973). Hence, the difference of perception across the speech categories is based on the acoustic properties of sounds such that they are not treated similarly in the speakers' mind. From a psycholinguistic perspective, stop consonants (categorical) depend more on the phonological short-term memory, i.e. a language-dependent system, while vowels (continuous) rely on auditory memory, i.e. a sensory system (Pisoni, 1973). Additionally, speech sounds are more likely to be perceived categorically by participants who acquired a linguistic system in

which the sounds are actually phonologically contrastive (e.g., see Abramson and Lisker, 1970, for poor discriminability of non distinctive prevoicing in native English speakers), compared to control groups (typically, speakers of another language where the contrast is not present). Hence, the perception of speech sounds depends on underlying mechanisms of language. This is the difference between CP in a language-dependent system and CP in a general sensory, i.e. auditory, perceptual one.

Since sign languages rely on the visual-gestural modality, perception in the visual domain may come into play in the perception of signs. In the visual modality, some non-linguistic stimuli are also proven to be perceived categorically such as famous faces (e.g., Beale and Keil, 1995), emotional facial expressions (Calder et al., 1996, among others), species faces (Campbell et al., 1997), objects (Newell and Bühlhoff, 2002), as well as colors (Pilling et al., 2003, among others). Hence the question arises as to whether sign languages rely on a purely sensory system, i.e. vision, a language-dependent system, or both. And, to what extent the phonological structure of signs affects the perception of contrast in the visual-gestural modality. Because of the rarity of genuine minimal pairs in sign language, which constitute a direct proof of contrast in phonology, the study of categorical perception becomes an asset in establishing the definition of contrast and distinctiveness in the visual-gestural modality. Identifying what drives the perception of contrast from a psycholinguistic point of view will give us a better understanding of their phonological representation.

In the current study, we investigate the perception of sign sub-units in LSF, a language whose phonological system is poorly explored. To our knowledge, no description of the phonological inventory of LSF is available, and therefore no general overview of the contrastive strength of phonological features in LSF either. By conducting a CP experiment, we aim at improving our understanding of the perception of contrast in LSF in both handshape and location with phonologically contrastive and non-contrastive pairs. We introduce a major innovation in the literature of CP in sign language by presenting our stimuli simultaneously instead of sequentially. This choice allows to focus more on linguistic mechanisms and less reliance on short-term memory. Moreover, RTs have not been recorded so far; we will see that taking them into consideration provides new insights into the mechanisms involved in CP. In addition to testing CP in Deaf signers, we also include hearing non-signers as a control population. The role of the control group, which in our case is represented by hearing people without knowledge of sign language, is to disentangle what is contrastive at the linguistic level (i.e. phonology in signers only) and at the visual level (i.e. perceptual in both populations).

The rest of the paper is divided as follows: Section 5.2 is dedicated to the description of

the perception of signs; first, we provide a definition of phonology and contrastive units in sign language (5.2.1), then we give an overview of the results of the previous CP studies in sign language (5.2.2). The great variability in the results leads us to Section 5.3 in which we offer a comprehensive description of the methodological aspects that might be responsible for it. Next, we present the study we conducted; Section 5.4 is dedicated to the methodology and Section 5.5 to the description of the results. We then discuss what it stands for in light of the findings from previous studies in Section 5.6 with a particular emphasis on the perception of contrast in non-lexical items in sign language. Finally, Section 5.7 provides a general conclusion of the study.



5.2 Sign perception

If the perception of signs depends on the visual system only, as in the perception of objects, faces, colors, *etc.*, this means that whoever watches a sign should be able to categorize and discriminate it according to some sub-categories. In other words, there should be no difference between people exposed to a language and therefore to its phonology, and people never exposed to the linguistic system in question. By contrast, if sign perception depends on a language-dependent system, it means that only individuals with a native or native-like exposure and experience to that particular language will be able to perceive them categorically. If so, is it true for each sign sub-category? Signs are composed of four phonological classes: handshape, location, movement, and orientation.¹ In the next sections, we first define the notions of *phonemic pairs* (i.e. contrastive/minimal pairs) and *allophonic pairs* (i.e. non-contrastive pairs) in relation to these four phonological classes in sign language, then we present the results obtained in the sign language CP studies that have been conducted so far.




5.2.1 Contrast in sign language

At the manual level, contrast can emerge by manipulating one of the four macro phonological categories in sign language, namely handshape, location, orientation, and movement. We will focus on the first two because they are the two we test in this study, but also because they are the only ones that have been tested in previous experiments since CP in movement and orientation has not been addressed yet.

¹Non-manual components are also considered as a phonological class as they carry phonological and prosodic information (Brentari, 1998; Wilbur, 2000). However, since little is known about phonological contrast of non-manual components, in this study we will not take them into account.

Handshape refers to the configuration of the hand; a change in handshape can cause contrast as shown in Figure 45a with the signs SORRY and EMAIL in LSF. Both signs are produced on the non-dominant hand, both hands are facing each other, and the movement is circular. The distinction between the two signs is generated by the handshape: in SORRY it is  (referred to as ‘A-bar’) while in EMAIL it is  (referred to as ‘B-bar’). In a feature-based framework (Hall, 2001; Clements, 1985) applied to sign language phonology (Brentari, 1998; Sandler, 1989, to only cite a few), the contrast is generated by the flexion of the selected fingers represented by the feature [flexed], i.e. it would be selected in SORRY but not in EMAIL.

Location refers to the place where a sign is produced, either on the neutral space (i.e. the space in front of the signer) or on the signer’s body. An example of contrast is given in Figure 45b with the signs SMART and SMELL in LSF. Both handshape and movement are identical (extended index finger and circular movement, respectively). Only location differs between the two signs since in SMART the sign is produced on the forehead, while in SMELL it is on the nose.

Like in spoken languages, not every articulatory difference in sign language leads to a phonological contrast. In other words, allophonic alternations are documented. For example, the two variants of the same sign SMALL (see Figure 46a) are equally acceptable in LSF. Whether the extended fingers in  (referred to as ‘Y’) are spread or close to the flexed fingers, i.e. whether the feature [spread] is selected or not, is an allophonic alternation. The spreading of the fingers is however contrastive when combined with other finger selections, as in  vs.  (referred to as the ‘5’-handshape with spreading variation); in Section 5.6 we present and discuss these two configurations in more detail. Allophonic variation is also observed in location as in the sign WEEK in LSF that can be produced on any place on the forearm. Whether it is on the elbow or on the wrist (or in between), the change of location does not change the meaning of WEEK (Figure 46b). Allophones can either be complementary or in free alternation, and in our study our allophonic pairs corresponds to the latter case. Hence, in sign language phonology it is possible to distinguish phonemic and allophonic pairs (i.e. contrastive and non-contrastive pairs, respectively).

It is important to note, however, that genuine minimal pairs and allophonic pairs are difficult to find in sign languages. The high variability associated with the gestural modality makes the identification of contrast or the absence of contrast more difficult (Eccarius, 2008). Given these premises, if CP for signs is mediated by language and linguistic abilities, it is expected to emerge from the interaction of linguistic factors



(a) Phonemic pair based on *handshape* composed of the signs SORRY (left) and EMAIL (right).



(b) Phonemic pair based on *location* composed of the signs SMART ([forehead], left) and SMELL ([nose], right).

Figure 45: Examples of phonemic (contrastive) pairs in LSF for handshape (45a) and location (45b).

and the population to be tested. The linguistic factor corresponds to the phonemic *vs.* allophonic alternations, the population to be tested are Deaf (native/early) signers *vs.* hearing non-signers.

In the next section, we provide a summary of the results obtained in the sign language CP studies conducted so far on handshape and location. Remember that, even if signs are also composed of a movement and an orientation component, no study investigated these two parameters in a CP experiment.



(a) Allophonic pair based on *handshape* composed of the two variants of the sign PETIT ([–spread] vs. [+spread], respectively).



(b) Allophonic pair based on *location* composed of the two variants of the sign WEEK ([elbow] vs. [wrist], respectively).


Figure 46: Examples of allophonic (non-contrastive) pairs in LSF for handshape (46a) and location (46b).

5.2.2 CP studies in sign language

Six studies investigated CP in lexical signs, five in ASL, one in LSF.² Among these, only two of them tested CP in both handshape and location (Newport, 1982; Emmorey et al., 2003), while the others focused only on handshape (Baker et al., 2005; Morford et al., 2008; Boutora, 2008; Best et al., 2010).

Newport and Supalla were the first to investigate CP in ASL and tested signers' perception in both handshape and location without finding any CP effect in neither of the two categories. This pioneering study was more like a cursory exploration rather than a

²An additional study focused on classifiers in British sign language (Sehyr and Cormier, 2015), but since classifiers carry a heavy iconic component (Benedicto and Brentari, 2004), we will not address it here.

complete study because they tested only four Deaf participants. Their results must be considered with a certain caution as the statistical power is quite low. Nevertheless, from this point on, the way for CP studies in sign language was open and new studies were awaited to replicate and expand these first results. In 2003, Emmorey et al. ran a similar study, and they tested two populations, Deaf native signers and hearing non-signers, and compared phonemic *vs.* allophonic contrasts in both handshape and location. Interestingly, the CP effect was only found for Deaf signers when categorizing and discriminating the phonemic pair in the phonological class of handshape. Baker et al. (2005) also studied CP in ASL handshape. Contrary to previous work, they used pseudo-signs but they tested contrastive pairs only. They obtained the same results as in Emmorey et al. (2003): they found a CP effect in signers, but not in non-signers in two of the three pairs of pseudo-signs they tested. However, as the authors pointed out, the pair that did not show any effect actually contained an additional contrast that was not targeted beforehand, which interfered with the results, i.e. the space between a ‘5’-handshape and a fully-closed fist is a bent ‘5’-handshape that is contrastive in the language (). Follow up studies could not replicate the same effect for the handshape category in the Deaf population (Boutora, 2008; Morford et al., 2008; Best et al., 2010). Crucially, Morford et al. (2008) and Best et al. (2010) highlighted other interesting points, especially with respect to age of acquisition. This point is further developed in Section 5.3.5.

In sum, results that show a CP effect in handshape but not in location (Emmorey et al., 2003; Baker et al., 2005) are in line with studies showing a CP effect in spoken languages. More clearly, observing CP effects in one out of two categories in the population of interest (i.e. Deaf signers) shows a variation across sign sub-units, just as the ones observed in spoken languages (consonants *vs.* vowels). A parallel can be drawn between consonants and handshape being perceived categorically, but vowels and location continuously. Taken together, these results are the first indication that signs are perceived categorically but only in signers, suggesting that the perception of sign sub-units may rely on the linguistic system and not only on the visual modality. Nevertheless, the discrepancy observed among the different studies on handshape (e.g., Emmorey et al., 2003; Best et al., 2010) do not fully support this comparison. The question about CP in sign language thus remains unresolved.

Except for Boutora’s study (2008) which was conducted on LSF, all other studies have been conducted on ASL. Comparisons are therefore not sufficient to conclude of any cross-linguistic or language-specific effect.

One point that emerges by this overview is the lack of systematic replication, which may be due to the large variation in the experimental designs (Gerrits and Schouten, 2004)

adopted by the above-mentioned studies. In the next sections, we provide a detailed description of what we think are the strengths and weaknesses of each study and motivate the basis of our choices for our own experiment.

5.3 Methodological aspects of previous studies

From a psychophysical perspective, CP is the perception of finite categories instead of infinite entities distributed along a continuum (Liberman et al., 1957). In other words, while entities are distributed in a continuous way, they are stored in our mind under relatively distinct labels. CP emerges from a combination of two tasks: a categorization task and a discrimination task. First, results from a categorization task must show that participants partitioned a continuum into two separate categories, i.e. they assign each step of a continuum to either one or the other of its extremes. One or several items may not be perceived as strictly belonging to one or the other category, i.e. they are sometimes associated with one and sometimes with the other, they thus correspond to the boundary between the two categories. Second, the identification of the boundary is required for the discrimination task in which the distinction between items within and across categories is relevant. Therefore, whatever the design of the discrimination task (cf. Section 5.4.3 below), the accuracy between within and across category is compared. A CP effect is obtained when participants show a higher level of accuracy in distinguishing stimuli when they belong to two different categories, i.e. the boundary between the two categories is crossed, compared to when they belong to one of the two categories. For example, if a continuum is divided into 11 equal steps and the boundary is identified at step #6, participants are expected to show a higher accuracy in the pair 5-7 since the two items belong to two distinct categories, while their performance is expected to be lower in the pair 3-5 since the two items belong to the same category. To illustrate our statement, an example of idealized results is provided in Figure 47 (also reported in Appendix B1).

When testing linguistic units, such results suggest that the human mind creates categories and that contrast is built on this ability. When the accuracy within category and across categories in the discrimination task are not significantly different, the two categories are not perceived as contrastive in the phonological system of the tested population, and thus that the phonological class is not perceived as categorical but rather as continuous.

While the general paradigm is identical across all CP studies, i.e. the use of a categorization task and a discrimination task, the discrepancy observed in the results might be due to methodological differences and, more specifically, to the identification of the perceptual

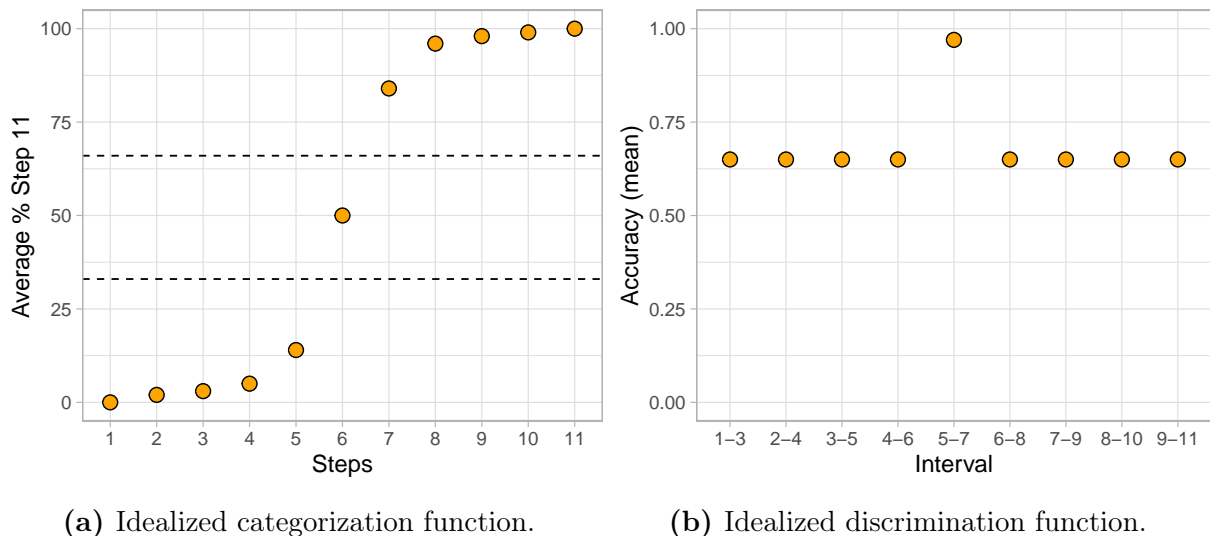


Figure 47: Idealized results in a CP experiment, adapted from (Morford et al., 2008, p.18). The categorization function (47a) indicates the expected percentage of answer “step 11” (x axis) for each step of the 11-step continuum (y axis). The discrimination function (47b) represents the mean of accuracy (x axis) in an XAB task for each stimulus pair composed of 2-steps apart stimuli (y axis). In this example, the boundary would be identified at step #6 as it falls within the 33-66% threshold (see Section 5.3.1), which means that the *target pair*, i.e. the one across categories, would be the pair 5-7.

boundary (5.3.1), the order of presentation of the tasks and stimuli (5.3.2), the types of stimuli (5.3.3), the timing of the experimental parameters (5.3.4), the population tested (5.3.5), and the integration of more types of measures (i.e. reaction times, 5.3.6). This allows us to emphasize the challenges faced by researchers in the elaboration of their experimental protocols, and thus to justify our own choices, which we summarize at the end of this section (5.3.7). Finally, we present our hypotheses in the Section (5.3.8).

5.3.1 Identification of the boundary

The main goal of a categorization task is to identify the number of times an item is classified in one or the other category. When the categorization task is performed as expected, the stimuli are unequivocally classified either in one or in the other category. The response rate for these items will therefore be high unlike for one item (sometimes two) for which the percentage will be lower because it will not be identified as clearly belonging to a single category. Best et al. (2010) and Boutora (2008) used the reference at 50% answer, Morford et al. (2008) used a 25-75% threshold, while Emmorey et al. (2003) identified the category boundary within a 33-66% threshold following Beale and Keil (1995). The identification of the boundary at a 50% rate restricts the boundary to one unique step and excludes the possibility of having a wider range of stimuli that could

be identified as the boundary, i.e. several items might not belong to one or the other category. The 25-75%, divides the response rate into three unequal parts, with chances for an item to be part of a category being lower than for the category boundary (25% for each category *vs.* 50% for the boundary). Finally, the 33-66% threshold divides the response rate into three equal parts, which increases the chances for an item to be part of a category.

There is no principled motivation to go in one direction over the other, the (arbitrary) decision is therefore left to the researcher.

5.3.2 Order of presentation of the tasks and stimuli

In speech, one factor that is known to affect CP is the order of presentation between the categorization task and the discrimination task. Depending on which task is conducted first, the results are not exactly identical. A categorization effect has been observed when the categorization task is conducted before the discrimination task (categorizing each token determines the category boundary), resulting in potentially biased results when discriminating the stimuli (Newell and Bülhoff, 2002). Although both orders of presentation have been used in the literature, presenting the discrimination task first seems to be the best option to avoid such a bias.

Another relevant factor is the type of discrimination task. For example, a proximity effect may appear when showing the stimuli in a sequential fashion: in an ABX task, in which A and B are two different steps of the same continuum and X is either equal to A or B, a bias is found towards B, while in an AXB task the bias is towards A (Gerrits and Schouten, 2004). Effects might be triggered by the short-term memory due to the fact that sequential presentation tap both perceptual and short-term memory functions (Calder et al., 1996).

Unfortunately, there is no way of removing this bias when studying speech sounds because given that they are produced and perceived sequentially, they can only be presented one after the other. Conversely, the visual modality is probably more attuned to simultaneous presentation. The simultaneous presentation of stimuli has been tested in the CP of object shapes (Newell and Bülhoff, 2002), while in sign language this option has not been exploited yet. There are enough arguments in favor of implementing this methodological choice in studies on CP in sign languages: in addition to the fact that sign languages use the visual modality, we know that some phonological units are produced simultaneously (e.g., Liddell, 1984; Brentari, 2002). Also, Deaf signers were found to have a shorter

phonological memory span in comparison with hearing speakers (Boutla et al., 2004; Wilson and Emmorey, 1998; Geraci et al., 2008). In other words, Deaf signers are less efficient in remembering temporal as opposed to spatial information.

5.3.3 Types of stimuli

When it comes to the presentation of sign stimuli, a choice has to be made on whether to use static or dynamic stimuli; avatar *vs.* recorded human; existing signs *vs.* pseudo-signs.

Half of the studies on sign perception use video clips (Newport, 1982; Morford et al., 2008; Best et al., 2010), the other half use images or pictures (Emmorey et al., 2003; Baker et al., 2005; Boutora, 2008). Each option has its own pros and cons. On the one hand, static presentation has the advantage of allowing simultaneous presentation. However, it makes the stimuli more artificial than dynamic presentation because signs must include at least one movement to be phonotactically permissible (Best et al., 2010). On the other hand, the presence of movement might affect CP on the other parameters. In other words, adding a movement might bias the results as it has a prosodic role and might trigger some lexical representations (e.g., see Brentari, 1998).

When testing language, experimenters usually try to reproduce natural situations. In sign language studies, a natural environment is typically achieved by using avatars or videos showing a Deaf signer. Pictures or videos of a human make the environment more naturalistic, but for CP studies it is harder to control for experimental parameters such as the regularity of finger bending or spacing. Those programs designed to create avatars have features that allow the manipulation of such parameters; the stimuli environment is therefore more controlled. Even though stimuli with an avatar are less realistic than with a human, the lightning progress of technology allows us to have more and more realistic avatars.

As far as the phonological status of the stimuli is concerned, Newport (1982), Emmorey et al. (2003), and Morford et al. (2008) used existing signs, Baker et al. (2005) and Best et al. (2010) pseudo-signs, and Boutora (2008) non-signs. One important aspect of the lexical status of the stimuli is that the perception of existing signs may generate a lexical bias in speakers/signers of a certain language while not in non-speakers/non-signers who have never been exposed to such a language before (see Ganong, 1980). This bias is avoided when using pseudo-signs that do not activate any lexical component.³

³Non-signs are productions that would violate phonotactic rules hence resulting in an ungrammatical sign. Since they can never be attested in a given language, they cannot reflect the linguistic/phonological properties under investigation in CP study.

Finally, previous studies have used several types of renders: (i) the entire upper part of the body (Newport, 1982; Baker et al., 2005; Morford et al., 2008), (ii) only the torso without the head (Best et al., 2010), (iii) either the head or the torso depending on the specific pair of items (Emmorey et al., 2003), or (iv) the hand alone (like in fingerspelling presentation) with no other body part (Boutora, 2008).

5.3.4 Timing of the experimental parameters

Varying and modifying some parameters such as the inter-stimulus interval (ISI), the inter-trial interval (ITI), visual masks, *etc.* in the experimental setting has been proven to affect the perception of some sound categories. For example, by manipulating the duration of the ISI in a CP experiment, Fujisaki and Kawashima (1970) showed that vowels are sensitive to short ISI, suggesting that vowels rely more on the general auditory memory, while consonants rely more on the verbal short-term memory. Increasing the ISI in a CP experiment may thus affect the perception of vowels, a conclusion reached through numerous studies conducted on spoken languages (e.g., Pisoni, 1973, 1975; Tartter, 1981).

Unfortunately, there are not enough studies on CP in sign language that allow us to know whether the manipulation of the ISI may have an impact on the CP of certain types of stimuli over others. We also have no insight on potential effects due to the manipulation of the ITI or the duration of stimulus presentation, nor to the use of visual masks (colors, texture, duration, *etc.*) which are generally used to wipe out visual carryover effects. The selection of the parameters (presentation of the stimuli, ISI, *etc.*) therefore remains an arbitrary choice in sign language studies. This particular point will be used in the discussion as a possible explanation of the results obtained in our study.

5.3.5 Population tested

In spoken language, a CP effect is only observed when the two tested sounds are contrastive in a language, i.e. they are phonemes. For example, Japanese speakers have difficulties in distinguishing the two liquids [l] and [r] because these two sounds are not contrastive, contrary to English speakers for whom /l/ and /r/ correspond to two distinct phonemes (Eimas, 1975). It is therefore necessary to test two populations for which the contrast is different in order to assert the phonological distinction in the target population. Comparing Japanese and English speakers allows to target a system that has acquired the contrast as opposed to one that has not (i.e. English and Japanese, respectively).

Studies on CP in sign language typically set the comparison with hearing non-signers, used as a control group (rather than comparing two sign languages with different phonological contrasts as in Emmorey et al., 2003; Baker et al., 2005; Boutora, 2008). By doing so, the authors set in opposition two groups of participants that do not share the same language modality (spoken *vs.* signing). Hence, in CP experiments of sign stimuli, not only hearing non-signers are unable to exploit their language-specific phonological knowledge, but are also tested on/confronted with a modality on which their daily communication barely relies on. More specifically, we know that in the hearing world gestures are part of the communication system (Goldin-Meadow and Brentari, 2017) and that the integration of visual information helps to recover speech especially in unintelligible listening situations (REF). However, phonological contrast in spoken languages remains primarily based on auditory cues (rather than visual). Therefore, not having been exposed to sign language makes hearing non-signers immune to sign language phonemes, but also rely on a purely perceptual/visual system devoid of any linguistic knowledge. Hence, based on results in spoken languages, Deaf signers are expected to be sensitive to phonological contrasts in signs, while hearing non-signers are not (e.g., Emmorey et al. 2003; Baker et al. 2005 but see Morford et al. 2008; Best et al. 2010). The difference of modality might be of particular interest since the study of CP can provide new evidence about the effects of the visual modality with no language input on sign perception, a point we develop in the discussion in more detail (Section 5.6).

In addition, age of exposure to a language plays an important role in the acquisition of phonological contrasts. Work on spoken language has shown that the perception of phonological contrasts is modulated by specific language experience, with a decrease in discriminability related to late exposure to a given language (e.g., see Hallé et al., 1999). In sign language, similar patterns are observed, but variation in the age of exposure is more prominent among Deaf populations with respect to hearing people. As a matter of fact, exposure to a sign language is not straightforward; it is more likely for a deaf child born in a deaf signing family to be exposed to a sign language from birth compared to a deaf child born in a hearing family. Moreover, various means of communication co-exist and many are used at the same time (e.g., oralism, cued speech, personal code, sign language . . . , see Colin et al., 2021). This means that for some Deaf people, sign language is either a first language acquired late or a second language, and that age of exposure affects the acquisition of the linguistic system (e.g., see Zorzi et al., 2022).⁴

⁴Note that the definition of *native* signer varies within the literature based on criteria such as (i) exposure from birth, (ii) with one or two deaf parents, and (iii) born in a deaf family are the most common, but while some researchers consider them all necessary, for others having one Deaf signing parent is unanimous.

For example, Morford et al. (2008) and Best et al. (2010) investigated the effect of age of exposure in the perception of handshape. Interestingly, while they did not observe a strict CP effect, i.e. no significant difference between across and within categories, they still found relative differences in CP processes across Deaf groups. Indeed, both studies indicate an effect of language experience related to age of exposure, with native signers being more homogeneous within categories, while early or late learners being more sensitive to the distance from the category boundary, i.e. the closer the boundary the less accurate. This raises the question of whether CP can emerge as attenuated because of the heterogeneity of the population, and how the visual modality drives the perception of signs. Since we do not know which cognitive mechanisms are responsible for these intra-categorical differences, within group analyses are not our primary concern.

Together with other experimental studies, this variation observed across Deaf groups shows that phonological knowledge plays an important role in sign perception and that testing them without taking sign exposure into account could lead to missing important linguistic information or biased results. To assess the role of the visual modality and test the amodal aspects of CP in language, it is therefore more relevant to avoid testing late learners if within group analyses are not foreseen.

5.3.6 Integration of more types of measures

Reaction times (RTs) are a direct measure of real-time language processing and indirectly reflect linguistic behaviors (Kaiser, 2014), which makes them a valuable tool in psycholinguistics. Combining both on-line and off-line methods (RTs and accuracy measurements, respectively) therefore allows us to better understand these two distinct but complementary measures and to identify the processes they capture. RTs are very rapid and not accessible to introspection, especially in tasks in which participants are asked to answer as fast as possible. Some researchers consider them as a simple reflection of the behavioral responses. In this case, they are expected to be aligned with the error rates (e.g., Pisoni and Tash, 1974). For others, this point of view is sometimes considered too simplistic (Santee and Egeth, 1982); RTs might not reflect the same behaviors but rather account for other processes.

On the one hand, CP studies in spoken language reported a sharp increase of RTs at the category boundary in the categorization task, reflecting a longer information processing to categorize stimuli that do not belong to either category (Pisoni and Tash, 1974; Studdert-Kennedy et al., 1963, among others). In the discrimination task, on the other hand, when the stimuli belong to two independent categories, RTs tend to be shorter as the stimuli

can be more easily distinguished. Several models have been built to capture the processes behind variation in RTs depending on the condition (Pisoni and Tash, 1974; Bornstein and Korda, 1984): RTs are faster when the perceptual information is sufficient to access the answer directly, and longer when the access to an additional categorical information is required to answer. In other words, when physical/perceptual cues are available, the answer is faster. When there are no cues, one must access the phonological categories to answer, which takes more time.

No study used RTs to assess CP in sign language, precluding direct comparisons with CP studies in spoken language.

5.3.7 Summary

To summarize, our study is the second to test CP in both handshape and location and the first to test CP in location in LSF. We tested phonemic and allophonic pairs in both Deaf signers and hearing non-signers. To do so, we created an avatar and generated pictures of pseudo-signs. We chose to use static stimuli instead of dynamic ones so as to avoid any unwanted effect of movement on CP. Furthermore, even though new technologies allow for highly controlled variation of distance in videos or pictures, using an avatar seemed to be more reliable to us because artificial stimuli are more easily manipulated. In addition, to be consistent across the continua and avoid participants, especially signers, to anticipate for any particular facial expression, the head and the torso were always visible.

To avoid the presence of spurious memory effects, stimuli are first presented in a simultaneous fashion. To avoid any categorization effect on the discrimination of the stimuli, the XAB discrimination task was performed before the categorization task. In the categorization task, a 33-66% threshold was used to identify the boundary between categories. As for the duration, we chose to follow Emmorey et al. (2003) and present the stimuli for 750ms and the ISI and ITI for 1000ms. Finally, for the first time, the experiment was conducted online (due to the COVID-19 pandemic) and RTs were recorded.

Our choices for each parameter as well as the studies that made these same choices are listed in Table 3.

5.3.8 Hypotheses

Our general hypothesis is that CP is mediated by linguistic properties only, and that variation across phonological classes exists as in spoken languages. Hence, we expect

	Our choices	Same choices in other CP studies
Categorization task	X	Emmorey et al. (2003) Baker et al. (2005)
Discrimination task	X(AB)	<i>None.</i>
Order of présentation	(1) discrimination task (2) categorization task	Emmorey et al. (2003) Baker et al. (2005) Best et al. (2010)
Stimuli: Human vs. avatar	Avatar	Emmorey et al. (2003) Morford et al. (2008) Boutora (2008)
Stimuli: Sign vs. pseudo-signs	Pseudo-signs	Baker et al. (2005) Best et al. (2010)
Stimuli: Static vs. dynamic	Static	Emmorey et al. (2003) Baker et al. (2005) Boutora (2008)
Duration stimuli	750ms	Newport & Supalla (1980) Emmorey et al. (2003)
Duration ISI/ITI	1000ms	Newport & Supalla (1980) Emmorey et al. (2003) Best et al. (2010)

Table 3: Summary of our choices for each experimental parameter and list of the CP studies in sign language in which they were also used.

to find a CP effect in the phonemic pair in handshape but not in the allophonic pair since the differences in the stimuli are not contrastive. We also expect the absence of CP effect in both stimulus pairs in location. We built our hypotheses based on Emmorey et al. (2003)’s results mostly because we largely followed their experimental design and procedure, but also because we implemented the simultaneous presentation of our stimuli to remove short-term memory effects that might have affected results in studies that did not observe any CP effect in handshape (Boutora, 2008; Best et al., 2010; Morford et al., 2008). In hearing non-signers (i.e. controls) we do not expect to find any CP effect, in neither phonemic nor allophonic pairs, since they should not be sensitive to contrast in a language they have never been exposed to, here LSF.

As for RTs, since no recordings have been done in sign language CP studies, we base our hypotheses on results from spoken language studies. We expect RTs to be aligned with accuracy, i.e. they should be longer when the task is harder, and shorter when it is easier. First, we expect RTs to be longer at the boundary in the categorization task in phonemic and allophonic pairs (in both handshape and location). Additionally, we expect RTs to be shorter across categories and longer within categories in the discrimination task, in both categories and in both phonemic and allophonic pairs.

5.4 Materials and methods

5.4.1 Participants

Thirty-three Deaf signers and twenty-five hearing non-signers participated in our study. Five participants were removed from the analyses: one Deaf signer and two hearing non-signers did not complete the task, and two Deaf signers were born outside in Morocco and Belgium (i.e. they might sign a dialect of LSF potentially very different from those signed in France). Among the twenty-four Deaf signers included in the analysis, thirteen were native, i.e. born deaf and exposed to LSF from birth, and eleven were early learners, i.e. exposed to LSF before the age of six. Six late learners also participated in the study but were not included in the current analyses. Their data will be used in a follow-up study. The twenty-three hearing non-signers were French monolinguals, and all of them attested to be never exposed to any sign language before.

The study was conducted over two sessions. Four Deaf early learners and one hearing non-signer only ran the first session, resulting in twenty Deaf signers and twenty-two hearing non-signers for the second session.

All participants were all of legal age and confirmed having normal or corrected-to-normal vision. Details about gender distribution and age are reported in Table 4.

	Deaf signers N = 24		Hearing non-signers N = 23
	Native N = 13	Early learners N = 11	
Age range	19 - 50	26 - 41	19 - 47
Mean (SD)	35.9 (8.6)	34.5 (5.1)	30.7 (7.9)
Gender	7 females 6 males	6 females 5 males	16 females 7 males
Age of exposure to LSF	0, born deaf	<6 y.o.	Never
# participants session 2	N = 13	N = 7 (-4)	N = 22 (-1)

Table 4: Distribution of age, gender, and age of exposure to LSF in Deaf signers and hearing non-signers.

5.4.2 Materials

We built 11-step continua to test for nine pairs of stimuli that were always two steps apart (e.g., steps 1-3, 2-4, ... 9-11). The avatar was created by using the 3D graphic software

Poser Pro (Bondware, 1995, v.11). The software contains a linear interpolation function that allows to generate equally distributed steps between the two extremes. We hence created a highly controlled continuum between two spatial positions, namely the extremes of the continua (details of the parameters used to create the avatar are listed in Appendix B2).

We chose the stimuli by following a two-step procedure: we first identified the features to test for handshape and location and found pairs of LSF signs targeting them; then, we created pseudo-signs. For the phonemic continua, extremes were based on minimal pairs, while for the allophonic continua, extremes were based on non-contrastive pairs. A Deaf consultant, a native signer of LSF, validated our materials.

For handshape, the phonemic continuum (henceforth HS-P) was built on the existing minimal pair SORRY \sim EMAIL in LSF (Figure 45a), to test for the distinction between the ‘A-bar’ and ‘B-bar’ configurations (also tested in Emmorey et al., 2003; Baker et al., 2005). To create pseudo-signs, we changed the location from the non-dominant hand to the arm. The allophonic pair (henceforth HS-A), on the other hand, was built on the spread feature in the the ‘Y’ handshape, as shown in the sign PETIT (Figure 46a, also see Section 5.2.1). This handshape is never contrastive in LSF. We changed the location and used the same as the phonemic pair, i.e. on the non-dominant arm. The two continua are given in Figure 48.



Figure 48: Steps in the continua to test CP in handshape based on the phonemic pair (HS-P, top) and the allophonic pair (HS-A, bottom).

For location, the phonemic continuum was built on the minimal pair SMART \sim SMELL in LSF (Figure 45b), where SMART is produced on the forehead while SMELL is produced on the nose. To transform the existing signs into pseudo-signs, we simply changed the ‘1’ handshape (extended index finger) into a ‘U’ handshape (index and major fingers

extended). The allophonic pair was built on the sign WEEK (Figure 46b) that can be produced either on the elbow or on the wrist (or in any location in between) without changing the meaning. The replacement of the original handshape by the ‘Y’ handshape generated a pseudo-sign. The two continua are given in Figure 49.

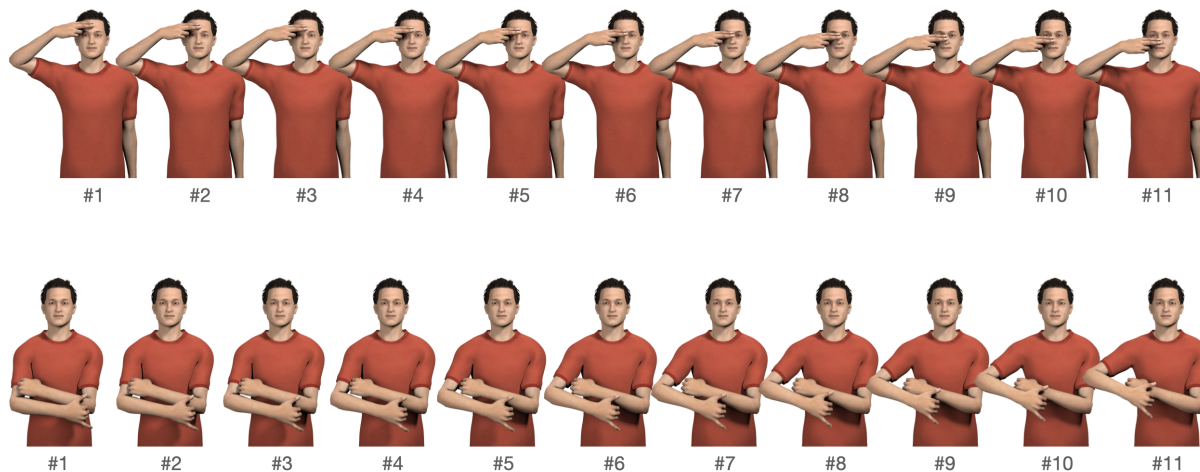


Figure 49: Steps in the continua to test CP in location based on the phonemic pair (LOC-P, top) and the allophonic pair (LOC-A, bottom).

The choice of the stimuli was particularly challenging, especially for the allophonic pairs (cf. Eccarius, 2008). Only one study compared contrastive and non-contrastive pairs of signs (Emmorey et al., 2003). The authors defined the allophonic variation in handshape based on the internal movement of the sign NO-NO in ASL. In other words, the sign is composed of two handshapes, and the various steps of the continuum are the different steps reached by the movement when going from one handshape to the other. This definition of allophony is specific and restricted. In the current study, we chose to rely more on a traditional notion allophony where the alternation of two handshapes or two locations does not generate contrast, i.e. it is not mediated by movement.

5.4.3 Design and procedure

Due to the COVID-19 pandemic, we ran our experiment online using the platform *Labvanced* (Finger et al., 2017). The background of the frames was light grey. The size of the experimental frames was fixed in pixels (800×450px). The avatar was 10cm high. Further details on the experimental parameters and design are provided in the Appendix B3.

The experiment was divided into two sessions conducted approximately one week apart; in the first session participants were tested on the handshape pairs, in the second session

the same participants were tested on the location pairs. In order to recreate a lab-like environment, the experimenter, a French native speaker and fluent LSF signer, met online with the participants at the beginning of each session. She provided the instructions to the participants and verified their installation. They were asked to be seated at a table and to be at arm’s distance from their keyboard; this allowed a minimum control of their environment and make it as close as possible between the participants.

Once settled, the experimenter sent them the link to launch the session. Participants started by validating the consent. The instructions were provided in written French for hearing non-signers, and signed in LSF for Deaf signers (videos were previously recorded with our native LSF consultant). Participants were instructed to use the keys F and J of their keyboard to indicate left or right, respectively (either to categorize or to discriminate the stimuli, depending on the task, see below). They were asked to answer as fast as possible (see Appendix B4 for details on the instructions of the experiment).

To get acquainted with the tasks without being tested on the target items, participants were exposed to a training phase containing a continuum that was not included in the main task. The handshape training continuum featured the ‘U’ to the ‘V’ handshapes; the location training continuum featured the space between the ear and the nose. Both continua were composed of only six steps (further details including the training items are provided in the Appendix B5).

First, participants completed the discrimination task, then the categorization task. The design of our discrimination task was an XAB task in which A and B were shown simultaneously rather than in sequence. The stimulus, X, was always equal to either A or B, which were randomly presented in the two positions (A on the left and B on the right, and *vice versa*), with A and B always two steps apart along the continuum. For each of the 9 pairs, the four possible combinations (AAB, ABA, BAB, BBA) were displayed two times, resulting in 72 trials per subject ($9 \times 4 \times 2$). First, X appeared for 750ms, then A and B were shown simultaneously. Participants were asked to tell which of the right or left image was identical to the image previously shown by pressing one of the two keys.

In the categorization task, the two extremes of the continuum, i.e. step #1 and step #11, were presented for 4 seconds (the position left-right was counterbalanced across participants). Then, participants were presented with single images of each step of the continuum (from #1 to #11) randomly. The whole sequence was shown 8 times per participant, resulting in 88 trials to be categorized. In this task, participants were asked to indicate whether the image they saw was more like the one presented on the left or the

one presented on the right. The design of the two experiments is presented in Figure 50.⁵

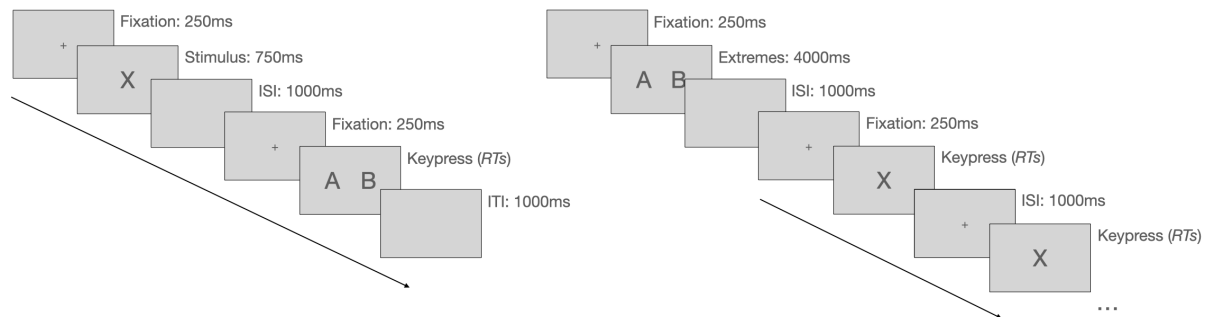


Figure 50: Visualization of the experimental design with information about the timing: discrimination task (left) and categorization task (right). In the discrimination task X is always equal to either A or B; in the categorization X corresponds to one random step among the eleven steps of the continuum, each step is shown one time before the extremes are shown again.

Reaction times (RTs) were recorded in both tasks. The recording started from the appearance of the target frame on the screen and lasted until the moment the participant pressed the key button.

5.5 Results

During the experiment, two measures were collected: Accuracy and RTs. RTs were analyzed on accurate responses only. RTs below 300ms and above 5000ms were removed to avoid too short and too long answers indicating automatic responses and drops, respectively. All the statistical analyses for the discrimination tasks were conducted by using the R software (Team, 2013) and the package *LmerTest* (Kuznetsova et al., 2017) in particular. We used mixed logistic regression models for accuracy and linear regressions and linear-mixed effects models for RTs. Within each phonological class (handshape, location), we ran four models fitting accuracy/RTs as function of target pair (taken as a fixed factor) for each group of participants (Deaf signers, hearing non-signers) and for each stimulus pair (phonemic, allophonic). This results in 16 models overall (8 for accuracy and 8 for RTs). Whenever possible, participants was treated as a random factor. A p -value of 0.5 was set as a threshold for significance.⁶ The coding and the outputs of the models, including the

⁵As described in Section 5.3.4, we did not include visual masks in our experiment because we do not know how they might affect CP in the visual-gestural modality. However, while masks are mostly used to get rid of any habituation effect, we think that an ITI of 1000 milliseconds should be long enough to erase such an effect, if any.

⁶In psychophysical studies, the analysis is often conducted on the d' instead of the raw mean values (e.g., Morford et al., 2008). Note that we also run a maximal model for accuracy and one for RTs (Barr et

bigger models whose results are not reported in the following sections, are provided in Appendix B6.

Even though the discrimination task was run before the categorization task (cf. Section 5.3.2), we will first present results from the categorization task as they are required for analyzing the data from the discrimination task, i.e. they are necessary to identify the category boundary in each participant group. Statistical analyses on the accuracy scores of the discrimination task will be provided before RT from the same task.

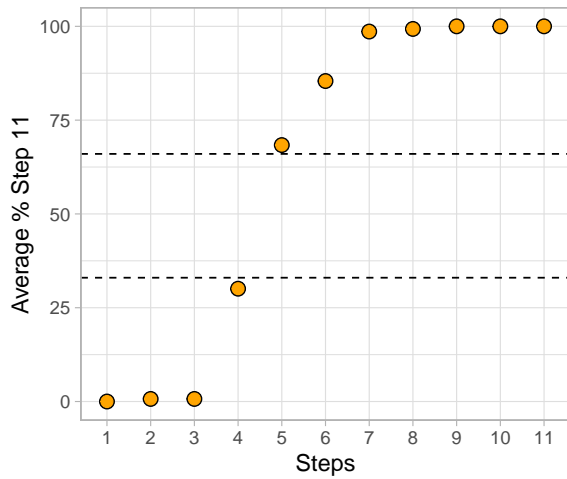
5.5.1 Direct measure: Accuracy

5.5.1.1 Categorization task

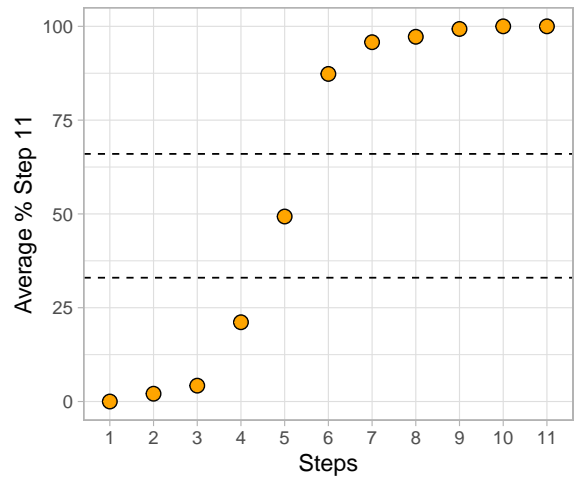
Figure 51 and 52 plot the mean percentage categorization for step 11 (y-axis) in relation to each step of the continua (x-axis). Figure 51 shows the results for handshape on both phonemic and allophonic pairs (HS-P and HS-A, respectively). The same holds for location as shown in Figure 52 (LOC-P and LOC-A, respectively). In both figures, results for Deaf signers are shown on the first line (top), hearing non-signers on the second (bottom). To identify the step at the category boundary, we used a 33-66% threshold (cf. Section 5.3.1) as indicated by the dotted lines in Figures 51a-51d and 52a-52d. The value that fell within that threshold, or the closest one, was then used to identify the *target* pair in the discrimination task.

Inspection of both Figures 51 and 52 reveals clear sigmoids in categorization functions with a steep slope between the two extremes of each continuum in both groups (first steps close to 0%, last steps close to 100%). Participants partitioned each of the stimulus continua into two distinct categories: values are very extreme on each side with slightly more homogeneity in Deaf signers. The boundary of both HS-P and HS-A continua was identified at step #5, in both Deaf signers (Figures 51a and 51b) and hearing non-signers (Figures 51c and 51d).

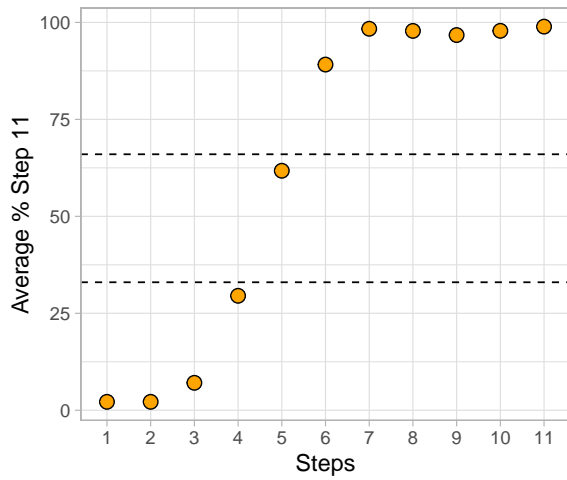
al., 2013) including all variables (target pair, participant group, phonological class, stimulus pair), their interactions and random intercepts. However, given the relatively small number of data points, models failed to converge. In our study, we could not use such a measure as the number of trials were not enough because of the limitations of the online experiment and its duration.



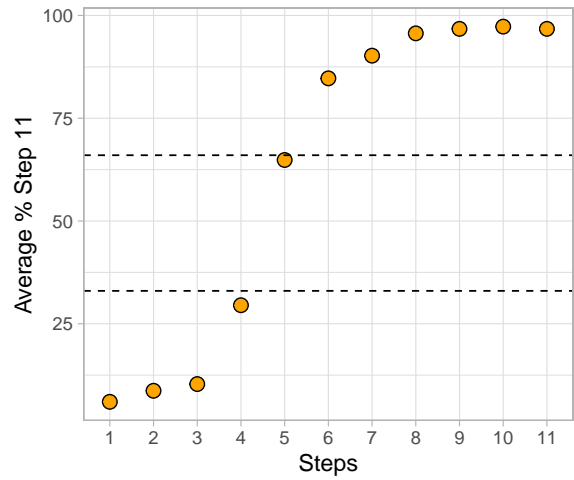
(a) HS-P in Deaf signers.



(b) HS-A in Deaf signers.



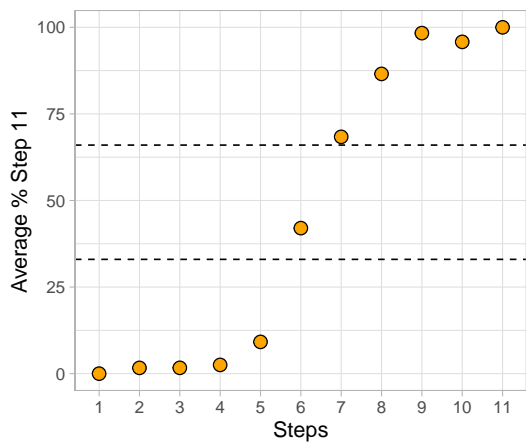
(c) HS-P hearing non-signers.



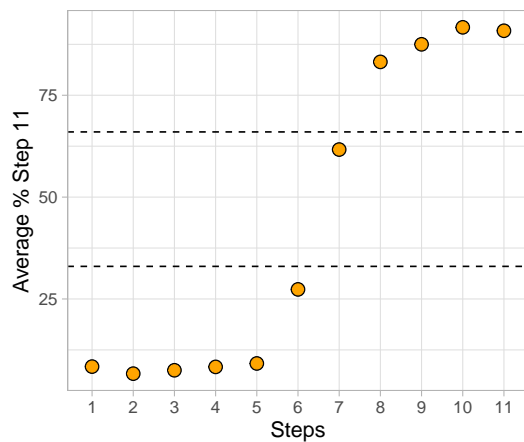
(d) HS-A in hearing non-signers.

Figure 51: Percentage of answer “step 11” for each step of the continua in handshape (HS) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

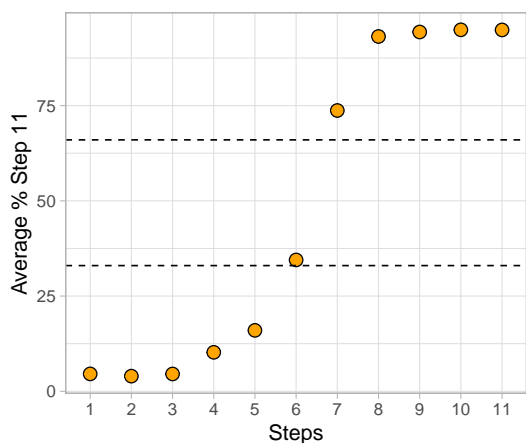
For LOC-P, the boundary was identified at step #6 in both groups (Figures 52a and 52c), and for LOC-A the boundary was at step #7, in both groups too (Figures 52b and 52d).



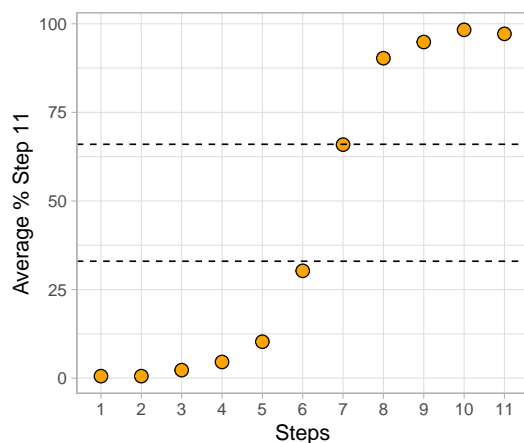
(a) LOC-P in Deaf signers.



(b) LOC-A in Deaf signers.



(c) LOC-P hearing non-signers.



(d) LOC-A in hearing non-signers.

Figure 52: Percentage of answer “step 11” for each step of the continua in location (LOC) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

5.5.1.2 XAB discrimination task

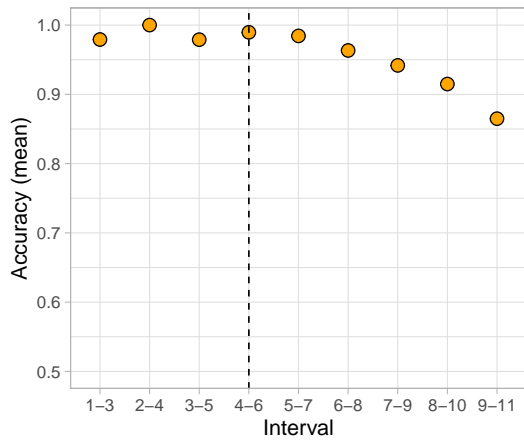
Figures 53 and 54 show the mean of accuracy (y-axis) for each interval (x-axis) in both stimulus pairs (phonemic *vs.* allophonic), phonological classes (handshape *vs.* location) and participant group (Deaf signers *vs.* hearing non-signers). In Figure 51 and 52 the target pair identified in the analysis of accuracy (cf. Section 5.5.1) is indicated by the dotted line in each condition which defines the target pair of stimuli that crosses such a boundary in the discrimination task.

A visual inspection of the plots indicates that discrimination functions are less clear when compared to ideal results (cf. Appendix B1); there is no clear “peak” showing a strong increase of performance across categories in comparison with within categories. In other words, there is no perceptible difference within and across categories visually. In HS-P, values tend to decrease closer to the end of the continua (‘B-bar’ handshape) in both signers and non-signers (Figures 51a and 51c), and the same pattern is observed in HS-A, but only in signers (Figure 51b). Additionally, in HS-A both groups were less successful as the means of accuracy are lower. In LOC-P and LOC-A results are quite homogeneous in both groups, with no inspectable distinction across the continua (Figure 54).

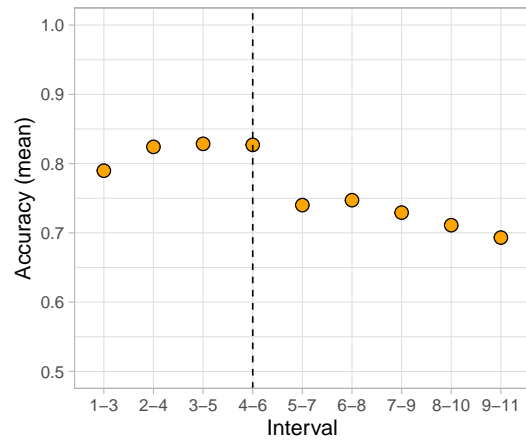
To test for significance, we ran eight mixed logistic regression models (4 for handshape and 4 for location, cf. beginning of this Section 5.5) fitting accuracy as function of target pair for each of the stimulus pair and participant group. As far as handshape is concerned, the model revealed a main effect of the target pair on the accuracy scores for Deaf signers. More specifically, Deaf signers were significantly more accurate across categories than within category in both HS-P ($\beta_{\text{within}}=-1.5317$, $\text{SE}=0.7124$, $z=-2.150$, $p=0.0316$) and HS-A ($\beta_{\text{within}}=-0.4487$, $\text{SE}=0.2079$, $z=-2.159$, $p=0.0309$). In hearing non-signers, no effect was found in none of the stimulus pairs (HS-P: $p=0.0561$, HS-A: $p=0.803516$), though a tendency is observed for HS-P.

In location, the models revealed no effect in both groups for both stimulus pairs (all $p>0.05$).

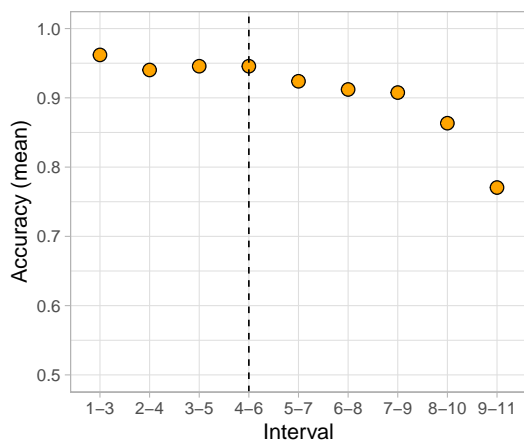
To summarize, in HS-P and HS-A, Deaf signers performed the task more accurately when stimuli A and B belonged to different categories than when they were part of the same category, even though physical differences are identical. These results were expected for HS-P but not for HS-A (cf. Section 5.3.8). The absence of a significant effect in location was expected too.



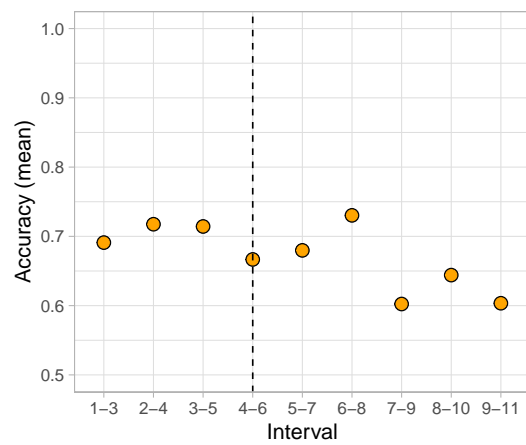
(a) HS-P in Deaf signers.



(b) HS-A in Deaf signers.

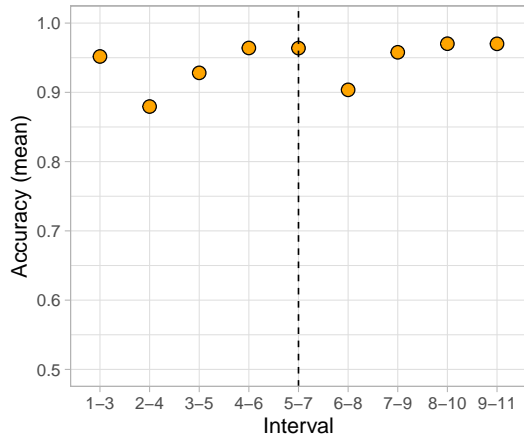


(c) HS-P hearing non-signers.

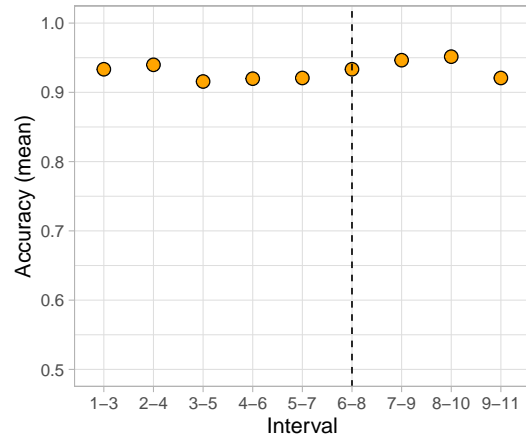


(d) HS-A in hearing non-signers.

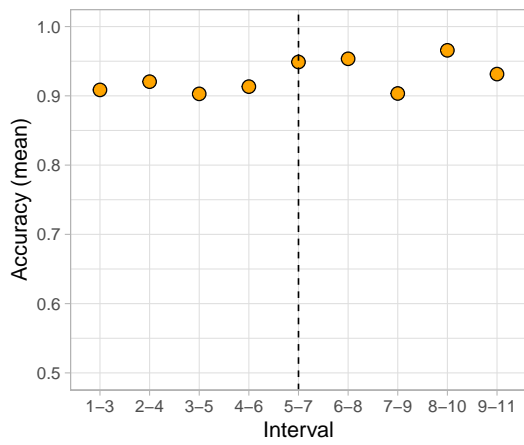
Figure 53: Accuracy for each pair of stimuli in handshape (HS) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.



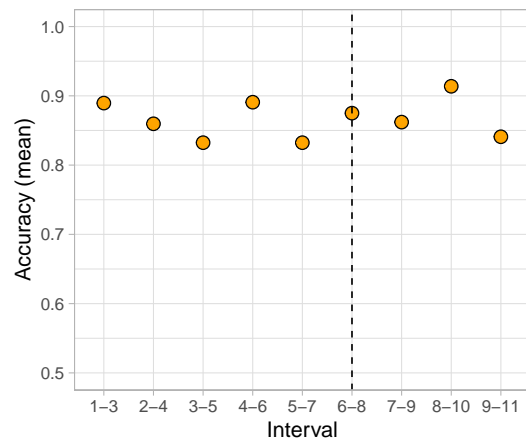
(a) LOC-P in Deaf signers.



(b) LOC-A in Deaf signers.



(c) LOC-P hearing non-signers.



(d) LOC-A in hearing non-signers.

Figure 54: Accuracy for each pair of stimuli in location (LOC) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

5.5.2 Indirect measure: Reaction times

5.5.2.1 Categorization task

Figures 55 and 56 show the time participants took to categorize each step to either the extreme presented on the left or the extreme presented on the right (y-axis) in both continua for handshape (HS-P and HS-A) and location (LOC-P and LOC-A). The target pair determined from the accuracy analyses is indicated by the dotted line. As expected, RTs increase when getting closer to the boundary and decrease when getting farther, suggesting longer processing when categorizing a stimulus as belonging to one or the other category. In handshape (Figure 57), Deaf signers show a sharper increase at the boundary compared to hearing non-signers. The same pattern is observed in location (Figure 58), even though the peak seems slightly less abrupt.

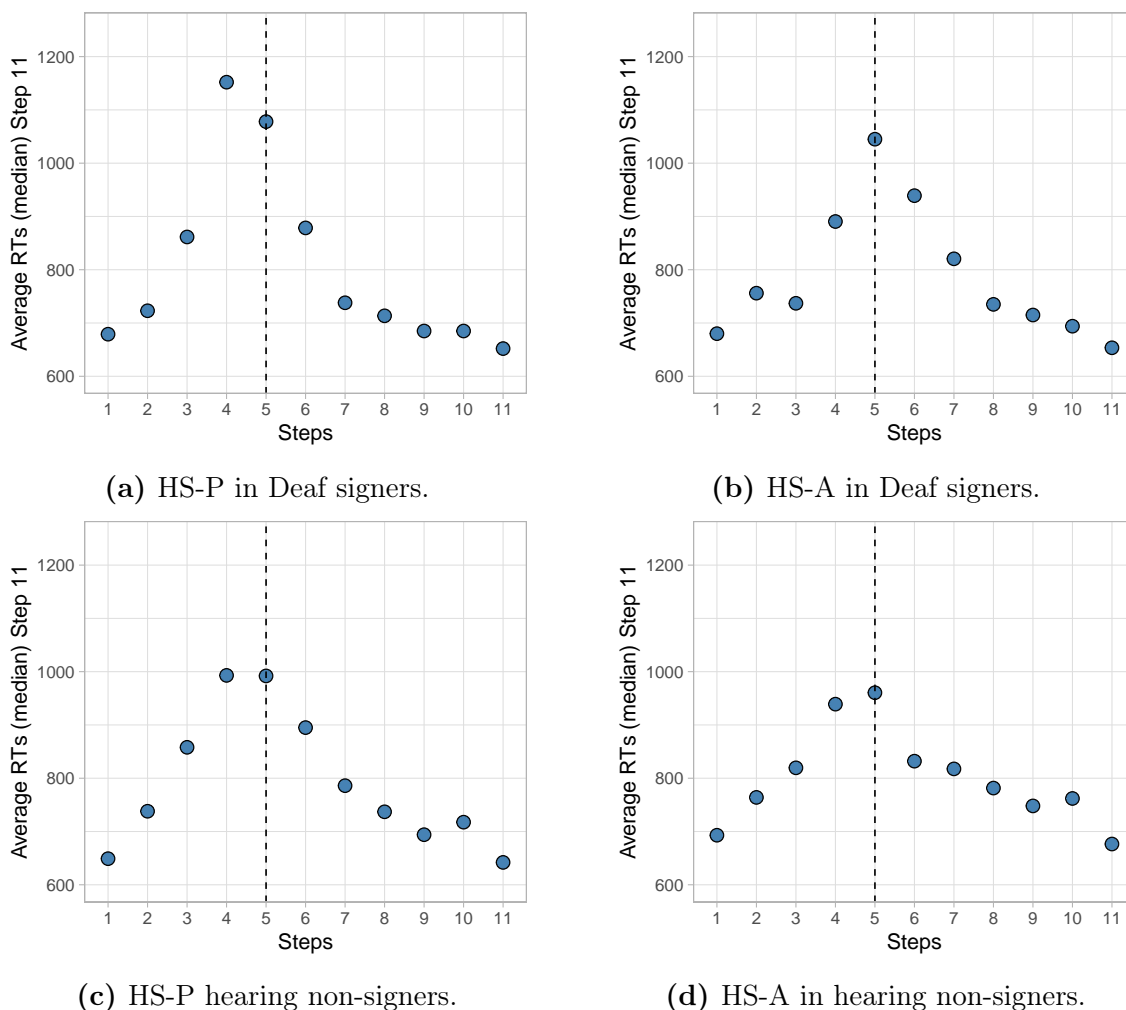
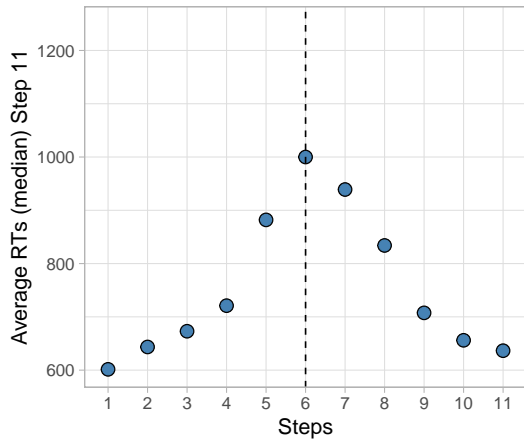
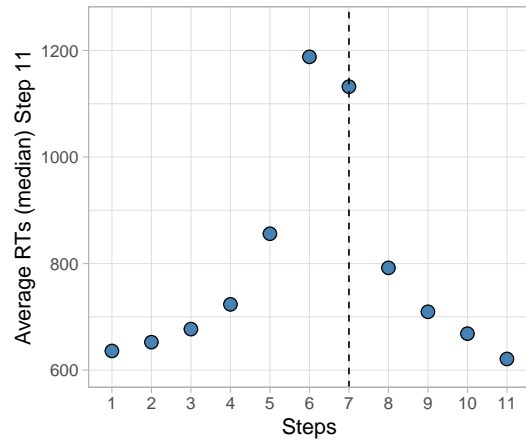


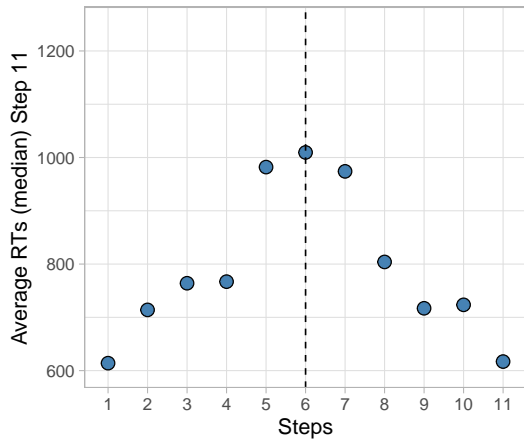
Figure 55: Categorization RTs for each step of the continua in handshape (HS) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.



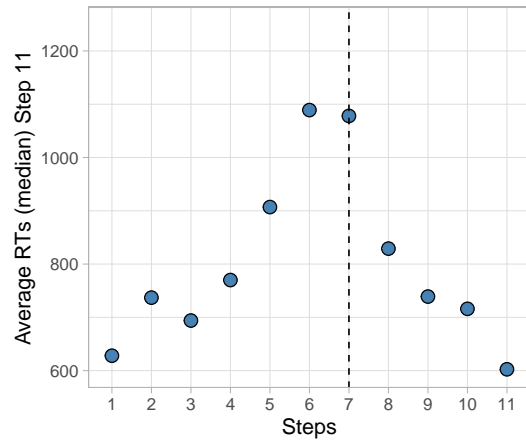
(a) LOC-P in Deaf signers.



(b) LOC-A in Deaf signers.



(c) LOC-P hearing non-signers.



(d) LOC-A in hearing non-signers.

Figure 56: Categorization RTs for each step of the continua in location (LOC) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

5.5.2.2 XAB discrimination task

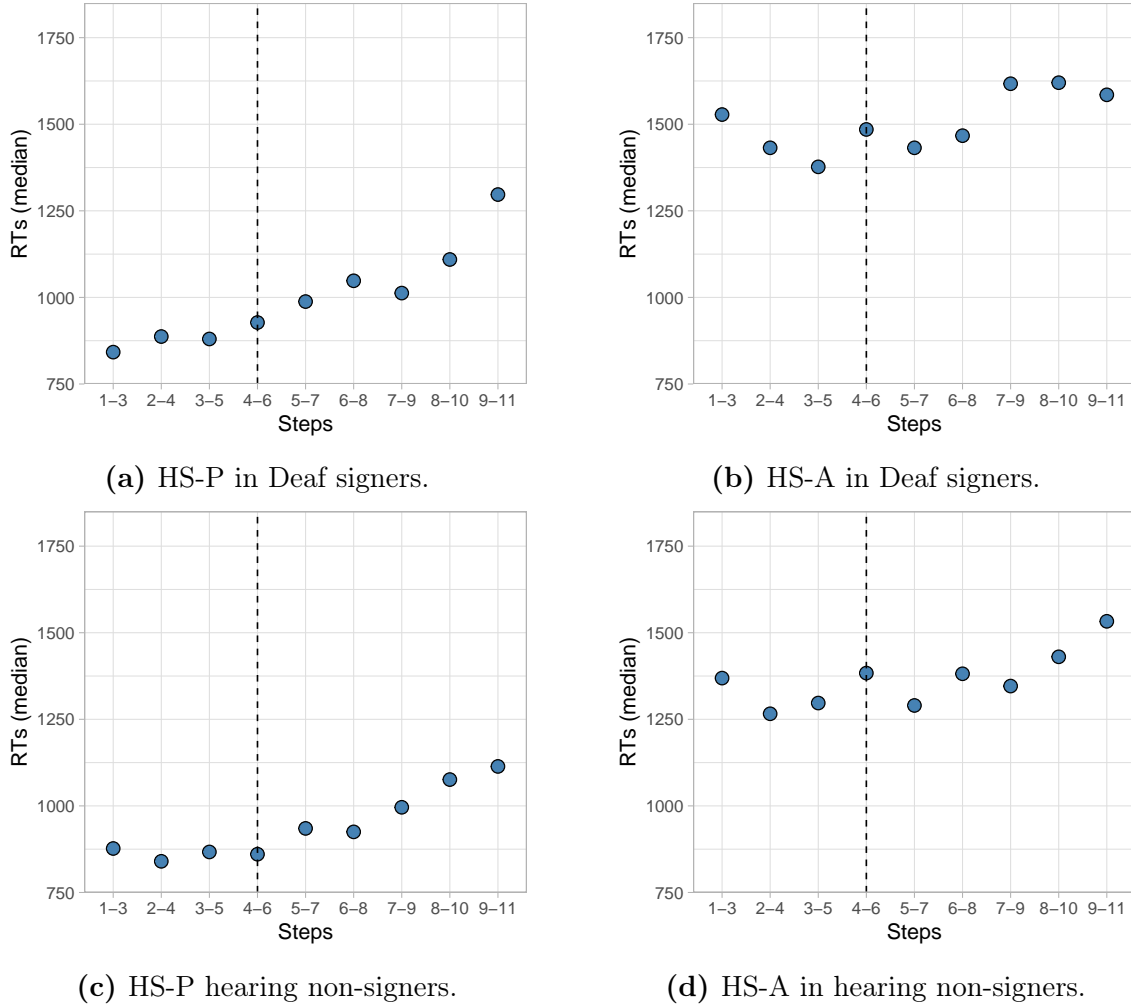
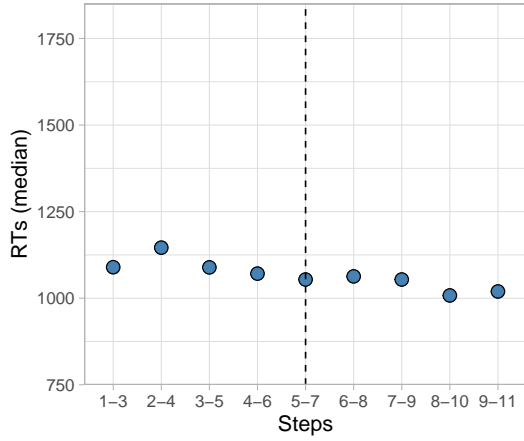


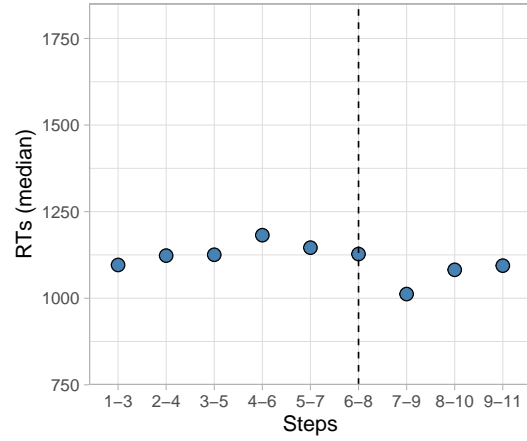
Figure 57: RTs in discrimination for each pair of stimuli in handshape (HS) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

By looking at the plots, one can see that in handshape there is no clear-cut at the boundary (cf. Section 5.3.1 and Appendix B1), i.e. RTs are not shorter at the boundary and homogeneously longer within categories in none of the stimulus pair and in none of the group. In HS-P, both groups show shorter RTs on the left side of the continuum (first steps) with an increase of RTs on the right side (last steps). In location, RTs are visually homogeneous, i.e. there is no clear pick at the category boundary, for each stimulus pair in both groups.

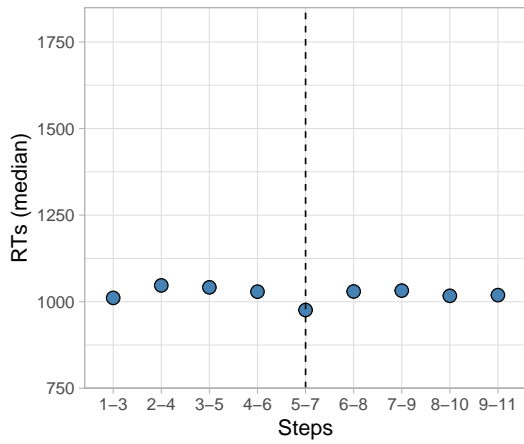
Due to the large overlap between standard errors across participants in each condition and the relatively small size of the datasets, some of the linear mixed-effects models were too complex to be computed resulting in singular fits (models for HS-A in Deaf signers, and HS-A and LOC-A in hearing non-signers). Following Barr et al. (2013), we simplified



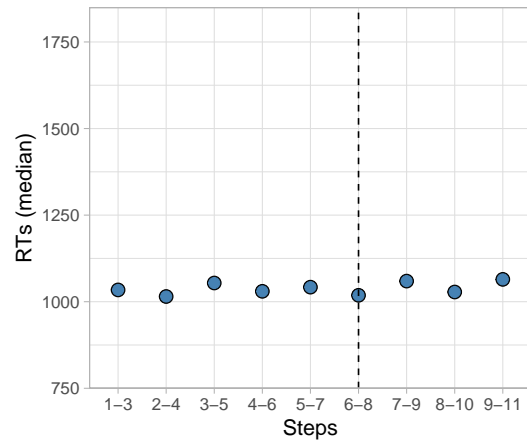
(a) LOC-P in Deaf signers.



(b) LOC-A in Deaf signers.



(c) LOC-P hearing non-signers.



(d) LOC-A in hearing non-signers.

Figure 58: RTs in discrimination for each pair of stimuli in location (LOC) for Deaf signers (top) and hearing non-signers (bottom) on both phonemic (P) and allophonic (A) pairs.

these models by removing the random factor (participant, see Appendix B6).

For handshape, Deaf participants were significantly faster at the category boundary than within categories in the phonemic pair (HS-P: $\beta_{\text{within}}=0.08003$, $\text{SE}=0.03114$, $t=2.57$, $p=0.0102$) but not in the allophonic pair (HS-A: $p=0.528$). The same pattern was observed in hearing non-signers, with a significant effect being observed in the phonemic pair (HS-P: $\beta_{\text{within}}=0.07616$, $\text{SE}=0.02677$, $t=2.845$, $p=0.00444$) but not in the allophonic pair (HS-A: $p=0.724$).

For location, Deaf participants were significantly faster at the category boundary than within categories in the phonemic pair (LOC-P: $\beta_{\text{within}}=0.10509$, $\text{SE}=0.03473$, $t=3.026$, $p=0.00248$). Conversely, they were significantly faster within categories than across categories in the allophonic pair (LOC-A: $\beta_{\text{within}}=-0.07132$, $\text{SE}=0.03259$, $t=-2.189$, $p=0.0286$). By contrast, in hearing non-signers, no significant effect was found in neither

of the two stimulus pairs (LOC-P: $p=0.375$; LOC-A: $p=0.181$).

In sum, RTs do not follow results in accuracy: we did not find the expected results for RTs since the shape on the graph did not fit our expectations. Statistical analyses show that in HS-P, both Deaf signers and hearing non-signers answered faster at the boundary compared to within categories. The same effect was observed in LOC-P for Deaf signers.

5.5.3 Summary of the results

Below we provide two tables summarizing the statistical results in accuracy (Table 5) and RTs (Table 6). We also indicate whether such results were or not expected based on our hypotheses (cf. Section 5.3.8). In accuracy, we expected to find the same results as in Emmorey et al. (2003), i.e. to find a CP effect in HS-P for Deaf signers, and no effect in any other condition. No effect at all was expected in hearing non-signers.

ACCURACY				
	HANDSHAPE		LOCATION	
	Phonemic (HS-P)	Allophonic (HS-A)	Phonemic (LOC-P)	Allophonic (LOC-A)
Deaf signers	$p < .05$	$p < .05$	n.s.	n.s.
	Expected	Unexpected	Expected	Expected
Hearing non-signers	n.s.	n.s.	n.s.	n.s.
	Expected	Expected	Expected	Expected

Table 5: Summary of results on Accuracy.

We expected RTs to follow accuracy. In the next table we therefore specify whether our results were expected or not based on the results reported in the table above. In other words, if results on RTs are identical to those on accuracy we indicate “expected”, otherwise “unexpected”.

REACTION TIMES (RTs)				
	HANDSHAPE		LOCATION	
	Phonemic (HS-P)	Allophonic (HS-A)	Phonemic (LOC-P)	Allophonic (LOC-A)
Deaf signers	$p < .05$	n.s.	$p < .05$	$p < .05$
	Expected	Unexpected	Unexpected	Unexpected
Hearing non-signers	$p < .05$	n.s.	n.s.	n.s.
	Unexpected	Expected	Expected	Expected

Table 6: Summary of results on RTs.

In the next section we provide an interpretation of these results.

5.6 Discussion

We conducted a CP experiment in French Sign Language, a sign language on which still little is known about its phonological system. By testing phonemic and allophonic pairs in two phonological classes, naming handshape and location, we aimed at understanding the perception of sign sub-units in both Deaf signers and hearing non-signers. The main objective was to disentangle the contradictory results obtained in previous studies and see whether the origin of the perception of phonological contrast is amodal, i.e. independent from the modality of the language, or if the visual perceptual system takes over CP. The implementation of the simultaneous presentation of our stimuli as well as the recording of RTs represent two major aspects of our experiment, bringing new insights into the role of perceptual cues in visual perception.

Results in accuracy provide evidence for CP in handshape but not in location, thereby suggesting processing differences across phonological classes of sign languages similarly to the ones observed between stop consonants and vowels in spoken languages (cf. Section 5.1, and see Repp, 1984). In handshape, Deaf signers performed significantly better across categories than within categories in both phonemic and allophonic continua, while this was not the case for hearing non-signers. This first result confirms that the absence of exposure to a contrast prevents its discrimination, although, based on the categorization task, we see that participants are able to identify phonetic categories. In location, no CP effect was found, neither in Deaf signers nor in hearing non-signers. In addition to confirming previous findings (Newport, 1982; Emmorey et al., 2003), this can be explained by the fact that the use of space in signing is less restricted than the use of an articulator (for example, see Uyechi, 1995, for a description of space in the visual-gestural modality). More clearly, even when signs are produced on the body compared to when they are produced in the neutral space, location is rarely targeting one specific point, which implies more variability in signs. Furthermore, the use of space varies across signers (see Mauk and Tyrone, 2012, p.10). The fact that location is not perceived in a categorical way can therefore be explained by its intrinsic continuous nature. Together, these results partially confirm the pattern observed by Emmorey et al. (2003) in ASL, suggesting that the perception of sign sub-categories is driven by modality-independent language mechanisms as it is sensitive to the linguistic knowledge of the target group, i.e. Deaf signers.

For the first time in sign language CP studies, the effect extends to the allophonic pair in handshape, an interesting yet surprising result. Indeed, we created the continua based on an allophonic variation between the two handshapes: we modulated the spreading of the selected fingers in the ‘Y’-handshape, i.e. the pinkie finger and the thumb. In signs using

this handshape, as PETIT in LSF, the finger spreading is allophonic in this particular phonological context. In other words, the (non)selection of the feature [spread] does not generate contrast in ‘Y’. As described in Section 5.3.3, we could not find a feature whose values are in absolute allophony in the language, and the feature [spread] is contrastive elsewhere in the lexicon, as for example in the minimal pair composed of the LSF signs ASSOCIATION and HANDY (Figure 59). The only alternative we had left was to use the handshape ‘Y’, which potentially prevented us from targeting a genuine allophonic feature.



Figure 59: Example of a minimal pair based on the finger spreading in LSF: ASSOCIATION (59a, [-spread]) ~ HANDY (59b, [+spread]).

From there, a new question arose. If this is true for [spread], why did not Emmorey et al. (2003) obtain the same result for [flexed], the feature that changes without generating contrast in their allophonic pair in ASL but that is still contrastive in other contexts (e.g., in their phonemic pair)? One possible explanation is that we used pseudo-signs, the context in which we make the feature vary does not exist. In their study, Emmorey et al. (2003) tested existing words; the contrastive handshapes they used are mapped into two lexical representations, i.e. they are based on two individual signs, while they chose an internal handshape change in one single lexical item to test allophonic variation. In this respect, actual lexical items could trigger a lexical recognition effect (Emmorey and Corina, 1990). When signers are shown the handshapes along the continuum, the latter correspond to actual steps of the internal movement represented by an existing combination of a handshape and a location. Signers probably identified the meaning of the sign and noticed that they were not part of two independent signs with distinct meanings but rather two forms belonging to the same sign.

Together with our results on handshape, we confirm Emmorey et al. (2003)’s main conclusion: sign languages seem to rely on their linguistic system to categorize phonemes, with variation across sign sub-categories. Handshape tends to be perceived categorically,

even more than previously thought, and location more continuously, echoing the variation of perception between consonants and vowels in spoken languages. However, it is still necessary to recall that, even if we observed a CP effect from a statistical point of view, participants did not show a heightened discriminability because they reached high accuracy scores within categories, suggesting a behavior more in line with a weak CP as seen in fricatives for example (i.e. the discrimination function did not show as high a peak as in stop consonants, see Best et al., 2010, for a discussion along these lines).

From a language-specific perspective, our data provide new evidence about the perception of phonological contrast in LSF. Our study is the only one to explore CP in LSF after Boutora (2008) who did not report any effect in handshape. The difference from our results can be motivated by the fact that we did not use the same experimental design. First, different from our study in which we used the entire upper body of the avatar, in that study stimuli were showing ‘U’ and ‘V’ handshapes in isolation, with no other body parts involved. Thus, those artificial stimuli, much closer to being non-signs than pseudo-signs, may have had an influence on the perception of language contrast. Second, she tested the ‘U’-‘V’ pair, which does not seem to activate CP. As a matter of fact, the ‘U’-‘V’ continuum generates a strong bias towards ‘V’; even if the two fingers are close to each other, as soon as the fingers start spreading, the configuration is perceived as opened and is automatically categorized as ‘V’ (see Best et al., 2010, for a discussion).

For the first time in the field of CP studies in sign language, we recorded RTs. While accuracy scores are supposed to show a significant distinction between across and within categories (i.e. with more accurate responses across boundary than within categories), RTs reflect the speed of response in correct answers only. This means that when participants are accurate, they are still able to answer faster in some conditions compared to others. While we hypothesized an alignment between accuracy scores and RTs, our results indicate that RTs do not simply follow accuracy but rather provide additional information related to the processing of sign-related stimuli. Indeed, if RTs were aligned with accuracy, an effect on handshape phonemic and allophonic pairs should have been observed in Deaf signers only. Contrary to this expectation, not only Deaf signers but also hearing non-signers were faster when the stimuli belonged to two distinct categories than to the same category and in the handshape phonemic pair only. At first glance, this is surprising as the hearing population is not supposed to be sensitive to phonological contrast in LSF. The absence of exposure to (the phonology of) the language should prevent any effect because hearing non-signers do not have the required phonological knowledge. However, a close inspection of the target pair in HS-P, i.e. stimuli #4 and #6 (see Figure 60 below) revealed the presence of one major perceptual cue distinguishing the two pictures: the

nails of the avatar were not visible on step #4 while they were on step #6. In fact, some participants reported on the presence of this perceptual cue at the end of the experimental session. Feedback from participants further support the idea that hearing non-signers may have used the perceptual/visual cue to elaborate a response strategy, and that such a cue might have helped in the categorization and discrimination of the visual stimuli. If one tries to bring the results in accuracy and RTs together, one can find a connection in line with perceptual cues. Indeed, when participants were presented with HS-P, they could use this visual detail to discriminate the two stimuli, make a quick decision and therefore answer faster than in the absence of the cue. This does not contradict the results obtained from the direct measure; even if hearing non-signers did not show any CP effect in HS-P, i.e. there is no distinct categories, they are faster when a visual cue is available. This may well have been reflected in the accuracy: even if the significant effect is not reached, hearing non-signers performed better across categories.



(a) Step #4 in the HS-P continuum.

(b) Step #6 in the HS-P continuum.

Figure 60: Items that compose the target pair in HS-P for hearing non-signers (#4 belongs to the category ‘B-bar’, and #6 to the category ‘A-bar’).

Interestingly, these results are not in line with findings from other visual domains, such as CP in colors for example (Bornstein and Korda, 1984). This could be explained by the fact that colors are uniform, while in our stimuli each body part of our avatar can be identified. Contrary to homogeneous/uniform stimuli, shapes have intrinsic delineations; the avatar has body boundaries, shades and landmarks that are visually salient and that cannot be removed.

The role of perceptual saliency can also explain the results obtained with RTs in location. Deaf signers were significantly faster at the category boundary than within categories in LOC-P (but not in LOC-A). Here again, the effect might have been triggered by a perceptually salient body landmark which, for this specific pair, was represented by the eyes. In LOC-P, the target pair is composed of steps #5 and #7 (the category boundary

was identified at step #6). As shown in Figure 61, the main difference between the two pictures was the position of the hands with respect to the eyes. In other words, the space between the two positions was enough for the participants to use the eyes as a landmark, thereby assisting their faster responses. Taken together, these points suggest that our visual task was trigger other response strategies based not on linguistic knowledge but rather on visual cues.



(a) Step #5 in the LOC-P continuum.

(b) Step #7 in the LOC-P continuum.

Figure 61: Items that compose the target pair in LOC-P for Deaf signers (#5 belongs to the category ‘forehead’, and #7 to the category ‘nose’).

In LOC-A, we would expect the same sensitivity as in the other conditions: in the target pair (steps #6 and #8), the space below the armpit is visually different. However, this is not what we observed since Deaf participants answered significantly faster within categories compared to across categories. When looking at the plot (Figure 62), one can see that values on the right part of the continuum are shorter and might be responsible for the direction of the effect, especially the next pair composed of steps #7 and #9. When looking at the differences across the steps while moving from the boundary (step #7) towards the right extreme (step #11) we found two potential explanations: participants might have based their answers on (1) the distance between the biceps and the non-dominant hand, or on (2) the covering of the fingers of the non-dominant hand.

Interestingly, hearing non-signers did not show the same pattern in LOC-P like Deaf signers. Indeed, they were not significantly faster at any stimulus interval. This result may be explained by potential differences between the two participant groups in visual accommodation. In the instructions, it was not specified whether the participants had to pay attention to handshape or location, they were just aware of the fact that we were investigating (parts of) signs with an avatar. Emmorey et al. (2009b) showed that native signers mostly look at the eyes of the signer, i.e. they perceive the sign components

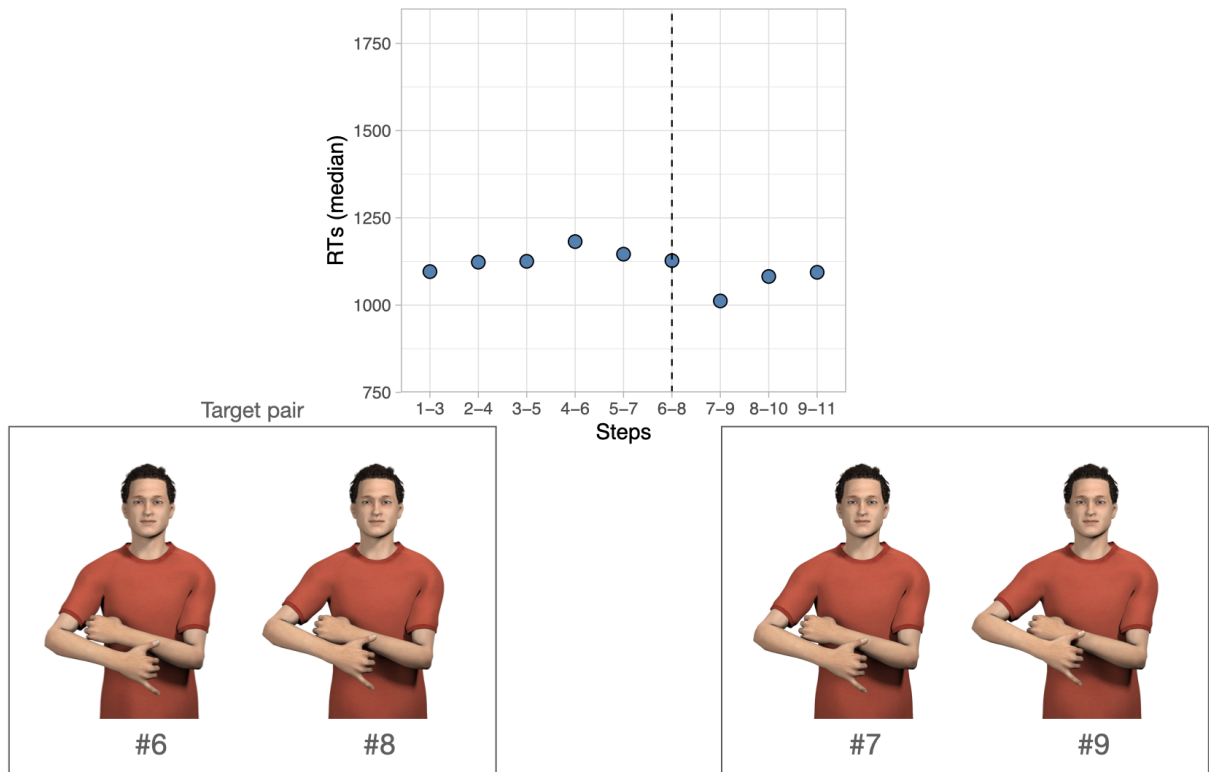


Figure 62: RTs in Deaf signers in LOC-A discrimination task. The target pair 6-8 (left) and the next pair 7-9 (right) show variation in perceptual cues.

all together, while non-signers also look at the hands. This may be the case for our participants too. Different from Deaf signers, hearing non-signers may have specifically focused on the hands (and in particular on the dominant hand) rather than other details cueing to changes in location.

From a methodological point of view, our study integrated one major innovation: the simultaneous presentation of our stimuli. Indeed, previous CP studies in sign language only used sequential presentation even though the visual modality allows simultaneity. In adapting the experimental design by showing two pictures at the same time, we inhibited further use of memory and rather tapped into the perception of language properties (cf. Section 5.3.2). Hence, we decreased the potential impact of memory load that might have appeared in studies that did not show CP effects in sign language (Morford et al., 2008; Boutora, 2008; Best et al., 2010). Our results therefore strongly confirm the studies showing CP effect in ASL (Emmorey et al., 2003; Baker et al., 2005) since we tapped directly into the psychological mechanisms of phonological categorization.

Several questions are left open with respect to experimental parameters and design. Indeed, while a great amount of data on the effects of variation in experimental parameters is available for spoken languages (see Repp, 1984), we remain unaware of the effects that the timing of the design (stimuli presentation, ISI, ITI...), mask, background color, *etc.* might

have on CP. For example, one Deaf participant reported to the experimenter that the light background was not easy for the eyes. In addition, the duration of the presentation of our stimuli was relatively long compared to Boutora (2008), which might explain the CP effect we found in HS-A (beside the methodological discrepancies discussed above). A drastically shorter presentation (e.g., 250ms) may be long enough to capture CP in phonemic pairs, but too short for Deaf signers to perceive the contrast present in the spreading in the ‘Y’-handshape from a more global perspective, i.e. the allophonic variation. Conducting a study aiming to vary the experimental parameters and evaluate their effects on CP would help address these questions. Additionally, we conducted our study online. While we know that online experiments replicated findings of studies conducted in labs (e.g., see Fairs and Strijkers, 2021, for an experiment on speech production), we do not know if this holds true for studies on CP in sign language. Ideally, the same study should be conducted in a laboratory such that potential effects of the environment can be identified. On the one hand, conducting an experiment at home may allow people to be more comfortable and less intimidated by the environment and, therefore, be more inclined to do the task. On the other hand, laboratory experiments allow for a better control of the set-up and avoid unwanted factors. In the specific case of our study, even though participants were tested in two separate short sessions to decrease attention drops as much as possible, our experiment was not exempted from interruptions in the participants’ environment, events that are less likely to happen in a lab environment. For instance, there could have been still a risk that internet connection and hardware problems occurred and generated some latency even though the figures were pre-loaded by the internet browser. With the decline of the pandemic, we plan to conduct the same experiment in a lab environment to check if these parameters had an impact on both accuracy and RTs.

And last but not least, our study on RTs highlighted the presence of confounding factors, namely the presence of the nails in HS-P, the eyes in POA-P and the armpit in POA-A. While we do not think that removing nails from an avatar would be a good solution as it would generate non-realistic stimuli (i.e. nails are always present on human hands), further CP studies should test a phonological contrast with less salient visual cues to check for replicability.

Finally, our study raises an important theoretical question about the notion of contrast at the featural level with respect to psycholinguistic measures. We found that the feature [flexed] in the ‘A-bar’-‘B-bar’ continuum carries categorical perception in LSF, as well as Emmorey et al. (2003) and Baker et al. (2005) did in ASL. We obtained the same result with the feature [spread] in the ‘Y’-handshape, speculating that we would obtain the same result in a ‘5’-handshape setting in which the variation is contrastive. However, Boutora (2008) and Best and Goldstone (2019) did not find any effect with the ‘U’-‘V’

continuum in which the feature [spread] is also involved. This suggests that some features may generate CP while others do not, and even more specifically, they may do so in specific contexts, e.g., in a specific finger selection but not in others. Moreover, visual cues may affect perception, either by boosting or hiding CP. Indeed, it is possible that the visual cue in the ‘A-bar’-‘B-bar’ continuum (i.e. the nails) helped Deaf signers in discriminating, while the salient opening between the index and middle fingers in the ‘U’-‘V’ continuum may interfere with CP. This leaves open additional directions for future work to understand which are the conditions where CP is more likely to be found and those where it is not. At a more global level, comparing two sign languages seems to be a crucial step for future research since it could allow to test the variation of a feature in a language in which it is contrastive and one in which it is not.

5.7 Conclusion

Our primary goal was to test CP in LSF and add to the literature on sign perception. In addition to achieving this goal, we also showed the important *finesse* of contrast perception in sign languages. By testing pseudo-signs, the allophonic variation that we thought we were targeting was actually not contrastive as it seemed to be uncorrelated from the context in which the contrast is tested.

Our results in accuracy are similar to those of spoken languages, i.e. minimal contrast is not driven by constraints related to the visual modality in sign language. They reflect the amodal linguistic organization responsible for the phonological structure of language. Contrary to results in accuracy relating the presence or absence of CP in the visual-gestural modality, additional data from RTs brought new insights on the effects of perceptual cues on the processing of complex visual stimuli.

General conclusion

This dissertation aimed at investigating LSF phonology at the theoretical, empirical and experimental level. While the number of studies on LSF morphology (Santoro, 2018), syntax (e.g., see Donati et al. 2017, and for an comprehensive work on LSF subordination see Hauser 2019), semantics (e.g., see Kuhn 2021, and for a general review of sign language semantics see, Schlenker 2020) *etc.* is increasing, the phonological system of LSF remains little studied. The objective was therefore to answer foundational questions about features, feature inventory and phonological contrast in LSF. More specifically, we investigated (1) the phonological status of one peculiar hand part, namely the webbing part of the fingers, and the (re)introduction of its corresponding feature [web] in the LSF phonological inventory (Chapter 2), (2) the place of phonological classes in linguistic theories, and precisely the one of orientation (Chapter 3), (3) articulatory complexity in the production of isolated signs (as elicited by a repetition task) and how theoretical models can predict complexity (Chapter 4), and (4) the categorical perception (henceforth CP) of handshape and location in an innovative experimental design (Chapter 5).

In sign language phonology, several theoretical models have been elaborated in order to capture the phonological representation of signs. The current research was developed within the scope of feature-based models (Clements, 1985; Clements and Hume, 1995; Hall, 2001) adapted to sign language phonology (van der Hulst and van der Kooij, 2021; Brentari, 1998; Sandler, 1989, to only cite a few). In Chapter 2, we showed that phonological processes long studied in spoken languages, such as saliency, assimilation, productivity, are necessary to the identification of distinctive features and their phonological status in LSF. From our study on the [web] feature, we highlighted the importance of adopting a cross-linguistic perspective. Indeed, while [web] was omitted/removed from the feature inventory of sign languages based on ASL data (Brentari, 1998), we provided evidence from LSF that this feature has to be part of the inventory so as to properly capture the phonological representation of signs. More importantly, this study led us in reconsidering hand-part features as orientation instead of location features.

In Chapter 3, the current status of orientation as a phonological class was revised. More

specifically, we proposed an analysis of orientation in a restricted type of signs, namely two-handed signs produced on the body. This provided us with enough evidence to consider both relative and absolute orientation to derive the phonological structure of these signs. While further investigation is necessary to prevent our theoretical implementation to overgenerate complexity in the structure, it once again proved that the structure and the content of existing theoretical models and feature inventories are not set in stone and need some readjustments.

Together, these two chapters allowed us to contribute to the debate about the status of orientation in phonological models of sign language. As described in both Chapter 2 and Chapter 3, orientation is treated as a phonological class in its own right, but while some models derive it from a specification in handshape and a specification in location (i.e. it is relative, e.g., see Crasborn and van der Kooij, 1997; Brentari, 1998; Liddell and Johnson, 1989), it is sometimes developed as an independent branch/parameter (i.e. it is absolute, e.g., see Battison, 1978; van der Hulst, 1993). Handshape is the most widely investigated phonological class, as well as movement, whereas location and orientation are still poorly understood. We then worked on both classes, with a special emphasis on orientation. At a more general level, these two studies on LSF provided further evidence that the definition and the constitution of phonological inventories in sign language still need to be explored for theoretical models to account for any sign language phonology.

Chapter 4 was devoted to the study of articulatory complexity in LSF. We provided a quantitative analysis of the ability for a theoretical model to assess articulatory complexity based on feature counting. The repetition task performed by hearing non-signers showed that handshape is the most difficult class to repeat accurately, closely followed by movement, while hand orientation and location are less hard to repeat. Correlations between scores obtained from feature counting in the theoretical structures of signs and the articulatory scores of the repetition task showed that phonological models are well-built to reflect the overall complexity of signs, as well as the complexity of handshape and location. Conversely, correlations were not found for movement, thereby suggesting once again the specific status of this phonological class among the other ones. Indeed, movement carries supra-segmental properties, as it is responsible for the syllabic structure of signs, and also visual prominence (e.g., see Brentari, 1998). Movement also plays a segmental role since it is responsible for phonological contrast (i.e. minimal pairs are found based on changes in movement). Future work might then be of interest to try to disentangle what is segmental and what is supra-segmental in movement.

Finally, in Chapter 5 we report the CP study we conducted to understand how contrast and allophony in handshape and location are perceived in LSF Deaf signers. Our results in accuracy proved that some phonological classes are perceived categorically but only

for the relevant linguistic population, i.e. Deaf signers who were exposed to LSF before the age of 6. We also showed differences in CP between the two phonological classes: CP effects were observed in handshape but not in location. This finding suggests that handshape may be perceived categorically while location more continuously. Previous findings by Emmorey et al. (2003) on ASL were therefore confirmed in our study. However, different from previous studies on CP in sign language, the simultaneous (instead of the sequential) presentation of our stimuli allowed us to tap more directly in the linguistic mechanisms and avoid potential short-term memory effects. Interestingly, our results brought to light a new aspect of the perception of contrast in sign language phonology: the use of pseudo-signs, i.e. stimuli with no existing but permissible lexical context, activated the perception of contrast in an allophonic pair in which the target feature was not contrastive in the specific context under investigation but was contrastive in others. Last but not least, RTs were recorded for the first time in the literature of CP studies in sign language. The divergence between accuracy scores and RTs captured in our study revealed the use of perceptual cues in the discrimination of complex visual stimuli.

Our studies allowed us to better understand the phonological processes of sign language and the methods for analyzing them, but also to identify the theoretical implementations necessary for the study of phonology with respect to the knowledge we have accumulated on other languages, especially ASL and many spoken languages. Future studies must include more sign languages to corroborate our findings and provide a more accurate picture about the use of features in sign language.

Even though we think our work is a substantial contribution in LSF phonological and sign language linguistics, it is just the tip of the iceberg in relation to the phonological processes underpinning sign production and perception. Much work remains to be done to capture the underlying rules and mechanisms of phonological processes such as assimilation/reduction, enhancement, the role of non-manual markers in prosody *etc.* For example, which features are more prone to phonological assimilation or reduction? Are all phonological classes affected by them? Is the use of features the only way to assess sign language phonology? Assimilation and reduction can be partial, i.e. they are not binary but rather continuous phenomena. Their phonetic realization could therefore be exploited in more dynamic frameworks. Indeed, several phonological theories co-exist, and among them task-dynamic, i.e. non-segmental, models including *Articulatory Phonology* (Browman and Goldstein, 1992). Articulatory Phonology is a dynamic approach of *speech*, that explores the frontier between phonetics and phonology by investigating articulatory processes in speech communication. Feature-based and task-dynamic models are not in contradiction or in opposition but can rather be complementary. Features are discrete

entities primarily grounded in phonetic properties then on phonological contrast (Clements, 1989), and Articulatory Phonology studies the continuity in articulators' movements. More precisely, it aims at representing articulatory *scores*, i.e. measuring continuous articulatory gestures. For example, drawing a parallel between features and more gradient units could provide with the ordering/quantification of features based on their sensitivity to some phonological processes. Our work actually goes towards this direction. On the one hand, handshape and movement were more prone to errors in sign repetition, suggesting a more important articulatory complexity (cf. Chapter 4). On the other hand, we showed that some features generate contrast in some but not all phonological contexts, and that perception may vary depending on the target feature and phonological environment (cf. Chapter 5). Moreover, sign languages use the same articulators as in gestures and use space to communicate. Its continuous aspects could make the visual-gestural modality more attuned to a dynamic approach. Hence, investigating the same topics as we did during this PhD, such as phonological contrast or articulatory complexity, in a more dynamic framework could complement our findings and extend our work. Based on our knowledge, Articulatory Phonology was only applied to spoken languages, except for two studies conducted on sign language (Mauk and Tyrone, 2012; Silva and Xavier, 2018), thereby leaving an interesting avenue for future work.

Regardless of the theoretical context (whether feature-based or task-dynamic models) and the entity under investigation (feature, segment, syllable *etc.*), any additional study is a stepping stone towards the knowledge of sign languages, their phonological structure and the rules that are specific to them. Each study is necessary to better understand Human language, its amodal properties but also the modality-specific properties of the oral modality of spoken languages and the visual modality of signed languages. The accumulation of phonological expertise is necessary for a precise and complete study of morphological (morpho-phonological, morpho-syntactic), syntactic and semantic proprieties. Thus, our research enabled to enlarge the amount of information acquired so far and will allow us to get acquainted with other fields of research with a better phonological background.

From a more general point of view, more work on sign language linguistics is necessary for the recognition of sign languages as natural languages. Since Stokoe's seminal work 1960, we know that sign languages are endowed with a fully-developed linguistic system. Compared to spoken languages, this status is very recent, but it still goes back 60 years. Despite the increasing number of studies conducted since then, the lack of transparency between research and society maintains the under-representation of sign languages in most societies. Popular beliefs are still very limited as many people still assume that sign

language is universal, that it is a simplistic gestural system without complex structures and void of abstraction. Alternatively, it is perceived as a simple signed replication of the surrounding spoken languages. As far as LSF is concerned, Cuxas's (1983) work has brought the properties of LSF to the forefront of the linguistic scene, and thus started the fight towards the recognition of LSF in France. Unfortunately, the beliefs mentioned above are still very common in France; linguistic research must be pursued with hardness and perseverance in order to continue to promote the legitimacy of LSF and allow the Deafs of France to be recognized as a linguistic community in its own right. Actively participating in the recognition of LSF also serves to improve many aspects of the daily life of Deaf people in France, such as the development of language assessment tools to facilitate clinical diagnosis (e.g., see Bogliotti et al., 2020; Aristodemo and Friedmann, 2019, for recent studies), the detection of developmental or language acquisition disorders. By showing the richness of LSF and the Deaf culture, this could also help to cope with audism and fight for the legitimate recognition of the Deaf community. Thus, from the work carried out in this thesis, we sought to make a contribution by opening new avenues of research on the phonology of LSF.

Résumé substantiel

La Langue des Signes Française (LSF) est la langue majoritairement utilisée par les signants Sourds en France. Il s'agit d'une langue minoritaire aujourd'hui sous-représentée dans la littérature linguistique ; sa phonologie reste encore peu étudiée et les informations sur les processus phonologiques et la notion de contraste sont moins connues. Dans cette dissertation, nous avons tenté de combler ce manque en abordant le sujet d'un point de vue théorique, empirique et expérimental. Notre objectif était donc de comprendre les mécanismes qui sous-tendent la phonologie de la LSF et les fondements de la notion de *contraste* par l'analyse de la structure phonologique des signes, du statut des classes phonologiques, du lien entre la représentation théorique et l'articulation phonétique dans la complexité de perception et de production des signes, et de leur représentation mentale. Cela nous a donc permis de mieux comprendre les processus phonologiques des langues des signes ainsi que les méthodes pour les analyser, mais également d'identifier les adaptations nécessaires à l'étude de la phonologie vis-à-vis des connaissances que nous avons accumulées sur les autres langues, notamment les langues parlées.

Le cadre théorique de cette thèse évolue au sein du formalisme des traits distinctifs, avec ou sans géométrie, et c'est l'étude des traits et de leurs interactions qui nous a permis de conduire notre recherche sur la LSF. Nous nous sommes concentrés sur les inventaires de quatre classes phonologiques qui composent les signes : la configuration manuelle, l'emplacement, le mouvement et l'orientation. Les composants non-manuels (expressions faciales, plissement des yeux, *etc.*) constituent également une classe phonologique, mais nos questions de recherche ne portant pas sur leur étude en particulier, nous ne les considérons pas dans cette thèse.

Certains modèles théoriques des langues des signes utilisent les traits pour décrire la structure phonologique des signes, les différentes classes phonologiques sont donc décrites à partir d'ensembles de traits qui leur sont propres. Contrairement aux langues parlées, l'étude du contraste dans les langues signées n'est pas aussi évidente que celle des langues parlées. En effet, les paires minimales exactes sont difficiles à trouver dans les langues des signes, les méthodes d'analyse pour justifier la présence ou l'absence de traits dans

leurs inventaires phonologiques doivent donc être révisées et adaptées. Nous avons mené deux études sur la structure des signes en LSF et leur composition en termes de traits distinctifs, et elles nous ont permis de revoir les méthodes d'identification du contraste dans les langues des signes, étape nécessaire à la composition des inventaires phonologiques des langues signées, et dans notre cas celui de la LSF.

Dans notre première étude nous avons montré que le trait [web], qui fait référence à la partie palmée des doigts, devrait être inclus dans l'inventaire de l'emplacement/l'orientation à partir duquel les langues des signes peuvent créer un contraste. L'analyse de paires minimales approximatives ainsi que de processus phonologiques tels que la productivité dans les mots composés simultanés ou la neutralisation en LSF montrent que [web] devrait effectivement être (ré)introduit dans la liste des traits actifs. Grâce à cette étude, nous avons également souligné le rôle important que la saillance et la représentation de l'orientation jouent dans la composition des inventaires des traits. Ainsi, en plus de montrer qu'un trait distinctif a été omis ou retiré de façon prématurée de l'inventaire des traits des langues signées, notre étude est une étape majeure dans l'identification des mécanismes nécessaires à la perception du contraste dans les langues des signes. Cela montre également la nécessité d'étudier des données de plusieurs langues pour affiner les modèles théoriques existants, généralement établis à partir de l'étude approfondie d'une seule langue, et revoir leur contenu afin de rendre ce dernier plus précis. Enfin, grâce à l'étude de la distribution de [web], nous avons reconsidéré le statut des sous-parties du corps dont [web] fait partie. Alors qu'ils sont actuellement considérés comme des traits de l'emplacement, et plus particulièrement des sous-spécifications des parties majeures du corps (soit la main pour [web]), nous montrons qu'en les considérant comme des traits de l'orientation, non seulement nous allégeons les modèles en supprimant de la redondance dans la spécification des traits, mais surtout nous offrons une preuve concrète que l'orientation est une relation entre la configuration manuelle et l'emplacement.

Notre deuxième étude sur les traits nous a ensuite permis de revoir le statut de l'orientation dans la composition des signes, notamment les signes à deux mains produits sur le corps du signant. En tentant de dériver la structure phonologique de signes à deux mains dans le cadre du *Prosodic Model* de Brentari (1998), nous avons été confronté à de nouvelles difficultés. En effet, nous avons identifié des cas problématiques de signes à deux mains produits sur le corps du signant : lorsque les deux mains sont en contact avec une partie du corps autre que la main non-dominante, il est parfois impossible d'éviter les représentations phonologiques erronées dans des modèles qui représentent l'orientation de façon relative seulement. En effet, dans de nombreux modèles phonologiques l'orientation est dérivée à partir d'une spécification dans la configuration manuelle et d'une spécification dans

l'emplacement. Nos données sur [web] en LSF ont d'ailleurs appuyé cette relation entre les deux classes phonologiques. En revanche, d'autres modèles considèrent l'orientation comme une propriété absolue de la main, et nous apportons finalement la preuve qu'elle est également nécessaire à la représentation de signes à deux mains produits sur le corps du signant. De fait, nous montrons que l'orientation relative ne permet pas une description adéquate de ces signes lorsque l'orientation des deux mains doit être spécifiée, puisqu'elle peut capturer soit l'orientation entre les deux mains, soit l'orientation vis à vis du corps, mais pas les deux. Afin de modéliser l'orientation de ces signes dans un cadre formel, nous proposons l'implémentation de plans secondaires. Tandis que cette implémentation requiert des ajustements minimes dans les modèles formels actuels, son impact quant à la théorie générale de la phonologie segmentale des signes est, elle, importante. Les plans secondaires imposent des restrictions géométriques et forcent l'orientation absolue ; le concept d'orientation comme simple classe phonologique relationnelle n'est donc plus suffisant pour ces signes. Ce travail nous a ainsi permis de mettre en évidence le besoin d'une orientation absolue en plus d'une orientation relative pour une sous-catégorie de signes afin de décrire la phonologie segmentale des langues signées. L'implémentation de plans secondaires vient alors améliorer les modèles actuels et leur permettre de rendre compte de la phonologie de signes problématiques.

Après avoir revu la structure des signes dans un cadre formel, nous nous sommes interrogés sur la capacité d'un modèle théorique à refléter la complexité des signes en LSF. L'étude de la complexité articulatoire s'est avérée apporter des connaissances utiles sur les mécanismes phonologiques des langues parlées puisqu'il est prouvé que la complexité phonétique et la structure phonologique sont intimement liées. Dans les langues des signes, ce type de connaissance est peu documenté. Nous avons donc choisi de mener une étude en LSF dans le but de comparer une mesure de complexité basée sur les erreurs de répétition et une mesure de complexité basée sur un modèle phonologique/théorique. La première mesure est basée sur les taux d'erreur obtenus lors d'une tâche de répétition de signe en LSF réalisée par des entendants non-signants. Cette mesure comprend les erreurs produites sur la configuration manuelle, l'emplacement, l'orientation, le mouvement et la fluidité de répétition des signes. La seconde mesure est obtenue à partir de la structure phonologique de ce même ensemble de signes dérivée dans le cadre du *Prosodic Model* (Brentari, 1998), un modèle construit sur la base de la géométrie des traits (Clements, 1989). Nos résultats indiquent que la configuration manuelle est le constituant le plus difficile à reproduire, suivi de près par le mouvement, puis de l'orientation et de l'emplacement qui génèrent moins d'erreurs de la part des non-signants. En comparant les deux mesures, une corrélation significative est trouvée pour la complexité globale. En examinant les effets des classes phonologiques individuelles sur la complexité, une corrélation significative est observée

pour la configuration manuelle et l'emplacement, ce qui vient confirmer les résultats obtenus dans d'autres études de perception et de production des signes. Cependant, ce n'est pas le cas pour le mouvement pour lequel la corrélation n'est pas significative. Cela peut être lié au fait que le mouvement, en tant que composante dynamique des signes, ne peut être directement comparé à ses homologues statiques (c'est-à-dire la configuration manuelle et l'emplacement, ainsi que l'orientation). Ces résultats indiquent tout de même qu'un modèle théorique précis de la phonologie/phonétique des signes reflète le degré de complexité comme résultant des propriétés perceptives et articulatoires des signes. En utilisant la richesse des représentations phonétiques pour prédire les niveaux de précision dans une tâche de répétition de signes, notre étude marque une étape importante dans l'avancée de nos connaissances sur le rôle d'un système théorique dans l'évaluation de la complexité des signes.

Enfin, pour approfondir notre démarche et mieux comprendre les mécanismes psychologiques qui sous-tendent la perception du contraste dans les signes en LSF, nous avons mené une expérience de perception catégorielle. La majeure partie des études ont été réalisées sur la Langue des Signes Américaine (ASL) et les résultats obtenus sont contradictoires. En effet, certaines études montrent un effet de perception catégorielle dans la configuration manuelle (Emmorey et al., 2003; Baker et al., 2005), tandis que d'autres non (Newport, 1982; Morford et al., 2008; Best et al., 2010). Pour l'emplacement, en revanche, les deux études qui ont inclus cette classe phonologique à leur recherche n'ont montré aucun effet de perception catégorielle (Newport, 1982; Emmorey et al., 2003). Seule Boutora (2008) a testé la perception catégorielle de la configuration manuelle en LSF à partir de la paire U-V et n'a reporté aucun effet chez les signants. Notre étude est donc la deuxième en LSF, et surtout la première à tester l'emplacement dans cette langue. Nous avons créé des pseudo-signes avec un avatar et généré deux continua par classe phonologique, l'un créé sur la base d'une paire de signes contrastifs (configurations phonémiques), l'autre sur la base d'une paire non contrastive (configurations allophoniques). Pour la première fois dans la littérature des langues des signes, nous avons présentés nos stimuli en simultané dans notre tâche de discrimination afin de tirer avantage de la modalité visuo-gestuelle des langues des signes et éviter tout effet lié à l'ordre de présentation des stimuli. De plus, nous avons su nous adapter aux contraintes liées à la crise sanitaire de la COVID-19 en menant notre expérience en ligne. Enfin, une autre innovation majeure parmi les études sur la perception catégorielle dans les langues des signes était l'enregistrement des temps de réponse. Des participants Sourds signants ont participé à notre étude et constituent notre groupe cible. En ayant été exposés à la LSF depuis la naissance ou les premières années de vie, les signants Sourds ont eu accès à la langue et à son système phonologique pendant les périodes critiques d'acquisition, ils

sont donc sensés être sensibles au contraste (ou l'absence de contraste) dans leur langue. Notre groupe contrôle est lui composé d'entendants non-signants, une population jamais exposée à une langue des signes et donc théoriquement non sensibles à la phonologie de la LSF. D'après nos résultats, les Sourds signants montrent un effet de perception catégorielle dans la configuration manuelle, contrairement aux entendants non-signants. Pour l'emplacement, nos résultats confirment ceux des études antérieures puisqu'aucun effet de perception catégorielle n'a été identifié, quelque soit la tâche et quelque soit la population testée. Nous confirmons donc les résultats obtenus dans l'étude de Emmorey et al. (2003) en ASL, à une exception près. En effet, contrairement à nos attentes, un effet pour la paire allophonique chez les Sourds signants s'est avéré être significatif. Une explication possible est qu'en faisant varier l'écartement entre les doigts, qui n'est pas contrastif dans la configuration manuelle 'Y' que nous avons testée, nous avons finalement ciblé un trait contrastif puisque le trait [écarté] est distinctif dans d'autres contextes. Ces derniers sont d'ailleurs plus nombreux que les allophones, puisqu'on trouve cette distinction [+écarté]/[-écarté] entre les configurations U-V, 5-B, *etc.* En testant des pseudo-signes, nous avons mis en évidence le caractère indépendant du contexte de la perception. En d'autres termes, quand testée dans un environnement inconnu, la perception ne tient pas compte d'un contexte spécifique mais fait appel au système phonologique dans son intégralité. Cela ne vient donc pas contredire les résultats de Emmorey et al. (2003) qui n'ont pas reporté d'effet pour leur paire allophonique puisque, contrairement à nous, les auteurs ont utilisé des signes lexicaux, ce qui a pu provoquer un effet lexical chez les signants qui auraient alors reconnu que les deux extrêmes du continuum ne sont pas porteurs de sens.

L'enregistrement et l'analyse des temps de réponse ont également montré des résultats intéressants. En effet, contrairement à nos attentes, ils n'étaient pas alignés avec les taux d'erreurs. Cela nous a permis de mettre en évidence un effet des indices perceptifs liés à la forme physique du corps sur la perception du contraste dans les langues des signes. Des repères tels que la visibilité des ongles, par exemple, a permis aux participants de discriminer des stimuli plus rapidement quelque soit leur groupe linguistique (Sourd signant ou entendant non-signant).

Notre objectif principal était de tester la perception catégorielle en LSF dans un cadre expérimental solide et d'étoffer la littérature sur la perception des signes. En plus d'avoir atteint cet objectif, nous avons également montré l'importante finesse de la perception du contraste dans la modalité visuo-gestuelle. Enfin, d'un point de vue plus global notre travail est un tremplin dans le domaine expérimental et ouvre la voie de la phonologie de laboratoire en LSF. Des études supplémentaires sont bien sûr nécessaires pour étudier la perception des autres classes phonologiques, notamment le mouvement et l'orientation,

mais aussi pour connaître les effets de la variation de certains paramètres expérimentaux, tels que les durées de présentation des stimuli, des intervalles inter-stimuli et inter-essais, ou encore l'utilisation des masques.

Les travaux théoriques et empiriques effectués tout au long de cette thèse nous ont permis de comprendre comment les traits distinctifs saisissent le contraste dans les langues des signes et identifier leur rôle en LSF. Les innovations théoriques qui en découlent vont ainsi guider la recherche dans la compréhension de la composition de l'inventaire phonologique des signes. D'un point de vue quantitatif, nous nous sommes concentrés sur les caractéristiques des signes et leur degré de complexité. Enfin, nous avons examiné la notion de contraste en psycholinguistique à partir de méthodes expérimentales, nous permettant de mettre en avant ses propriétés associées à la modalité visuo-gestuelle. De plus, à travers les différentes thématiques que nous avons abordées dans cette thèse, nous avons montré que l'étude de la LSF va au-delà de l'intérêt de la langue elle-même ; elle nous informe sur les langues des signes de façon globale mais surtout sur les langues humaines en général, et ainsi sur les propriétés qu'elles partagent et celles qui leurs sont propres.

L'étude des traits permet donc d'étudier la phonologie des langues signées, au même titre que les langues parlées. Il s'agit cependant d'un cadre théorique parmi d'autres, il serait donc intéressant d'étendre nos études à d'autres cadres, tels que la phonologie articulatoire (Browman and Goldstein, 1992). Par exemple, mener une recherche sur la complexité articulatoire dans un cadre où les marqueurs phonétiques sont identifiés, à la fois en production et en perception, serait donc une perspective intéressante pour venir poursuivre et compléter nos travaux.

Communications

Articles

Published

- Justine Mertz, Chiara Annucci, Valentina Aristodemo, Beatrice Giustolisi, Doriane Gras, Giuseppina Turco, Carlo Geraci, and Caterina Donati (2022). “Measuring sign complexity: Comparing a model-driven and an error-driven approach”. *Laboratory Phonology, Special Collection on Phonological Categories*. <https://doi.org/10.16995/labphon.6439>
- Justine Mertz (2020). “Représentation phonologique des signes à deux mains en LSF : faut-il reconsidérer l’orientation absolue dans les modèles phonologiques des langues des signes ?” *JEP 31st edition, ATALA*.
- Natasha Abner, Carlo Geraci, Shi Yu, Jessica Lettieri, Justine Mertz, and Anah Salgat (2020). “Getting the Upper Hand on Sign Language Families: Historical Analysis and Annotation Methods”. *FEAST proceedings*.

Submitted or to be submitted

- Justine Mertz and Carlo Geraci (*under review*) “What [web] reveals about contrast and feature inventory of (French) sign language”.
- Justine Mertz (*in prep.*) “Categorical perception in French Sign Language (LSF)”.

Conferences

Oral presentations

- “Categorical perception in French Sign Language (LSF)” (Mertz J, Turco G, Geraci C), Incontro di Grammatica Generativa (IGG 47), Catania, Italy.
- “Structural Phylogenetics and the Reconstruction of Sign Language History” (Abner N, Geraci C, Yu S, Lettieri J, Mertz J, Salgat A), Formal and Experimental Advances in Sign Language Theory (FEAST), Paris - Online, France.
- “Représentation phonologique des signes à deux mains en LSF : faut-il reconsidérer l’orientation absolue dans les modèles phonologiques des langues des signes ?” (Mertz J), Journées d’Études sur la Parole (JEP-TALN-RECITAL), Nancy - Online, France.
- SIGNopsis - “Articulatory evidence for sign language typology and history” (Abner N, Geraci C, Mertz J, Yu S), Theoretical Issues in Sign Language Research (TISLR 13), Hamburg, Germany.
- “On how to measure phonological complexity of sign languages” (Aristodemo V, Annucci C, Geraci C, Giustolisi B, Gras D, Mertz J, Donati C), Phonetics and Phonology in Europe (PaPE), Lecce, Italy.
- “Typological and Historical relations across sign languages - The view from articulatory features” (Geraci C, Mertz J, Lettieri J, Yu S, Abner N), Phonetics and Phonology in Europe (PaPE), Lecce, Italy.
- “Theory-Description-Theory: A round trip in French sign language phonology.” (Mertz J, Geraci C), Theoretical and Formal Linguistics (TFL), Nantes, France.
- “Investigation of sign language phonology: On how LSF makes us reconsider absolute orientation and timing units” (Mertz J), Paris-Cologne Collaborative Meeting (PCCM 6), Cologne, Germany.
- “On how to measure phonological complexity of sign languages” (Aristodemo V, Annucci C, Geraci C, Giustolisi B, Gras D, Mertz J, Donati C), Generative Linguistics in the Old World (GLOW 42), Oslo, Norway.
- “Typological and Historical relations across sign languages - The view from articulatory features.” (Geraci C, Mertz J, Yu S, Lettieri J, Abner N), Incontro di Grammatica Generativa (IGG 45), Padova, Italy.
- “La famiglie linguistiche nelle lingue dei segni” (Geraci C, Abner N, Lettieri J, Yu S,

Mertz J), 4o Convegno Nazionale LIS, Rome, Italy.

Posters

- “Categorical Perception in French Sign Language (LSF)” (Mertz J, Turco G, Geraci C), Architectures and Mechanisms for Language Processing (AMLaP 2021), Paris - Online, France.
- “Measuring phonological complexity in Sign Languages” (Mertz J, Aristodemo V, Annucci C, Geraci C, Giustolisi B, Gras D, Donati C), Theoretical Issues in Sign Language Research (TISLR 13), Hamburg, Germany.
- “Theory-Description-Theory: A round trip in French sign language phonology” (Mertz J, Geraci C), Theoretical Issues in Sign Language Research (TISLR 13), Hamburg, Germany.
- “Theoretical and Empirical issues of phonemic inventories in French Sign Language” (Mertz J, Geraci C, Turco G), Phonetics and Phonology in Europe (PaPE), Lecce, Italy.
- “Typological and Historical relations across sign languages - The view from articulatory features” (Geraci C, Mertz J, Lettieri J, Yu S, Abner N), Generative Linguistics in the Old World (GLOW 42), Oslo, Norway.
- “Questions théoriques et empiriques sur les inventaires phonémiques des langues signées : le cas de la LSF” (Mertz J), Journée d’Ouverture à la Recherche en LSF (JORLSF - dissemination day), Paris, France.

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Appendices

A Appendix to Chapter 4

A1 List of the items tested in our experiment in French sign language

- ALCOHOL
- BAND-AID
- BAR
- BED
- BLUE
- BONE
- BOYFRIEND
- BREAD
- BROWN
- CANDIES
- CASTLE
- CHICKEN
- CHOCOLATE
- CHRISTMAS
- COMPASS
- COMPUTER
- DANCE
- DIAMOND
- DOLPHIN
- EGG
- ELECTRICITY
- ELEPHANT-1
- ELEPHANT-2
- ELEVATOR
- EXERCISE-1
- EXERCISE-2
- FEAR-1
- FEAR-2
- FEAR-3
- FIRE
- FLOWER
- FLY
- FOOTBALL
- FRIES
- FRUIT
- GLASS
- GRASS
- GREEN
- GREY
- HAM
- HEDGEHOG
- INTERNET
- INTERPRETER
- IRON
- LAMP
- LEAF
- LION-1
- LION-3
- LIZARD
- MATCH
- MEAT-1
- MEAT-2
- METER
- MILK
- MOM
- MOVIE
- MUSHROOM
- NURSE-1
- NURSE-2
- NURSE-3
- NUT
- OIL
- PEAR
- PEN
- PENCIL
- PIG

-
- PINEAPPLE
 - PLASTIC
 - POLICE
 - POPE
 - RED
 - RULER
 - SAUCE
 - SHEEP
 - SKIN
 - SOCKS
 - STAR-1
 - STAR-3
 - STATUE
 - SUN
 - THEATRE
 - THERMOMETER
 - TICKET-INSPECTOR
 - TOILET
 - TRAIN
 - TREE
 - UNIVERSITY
 - VIOLET
 - WALLET
 - WIND
 - WINDOW
 - WINE
 - WOMAN
 - YELLOW

A2 Tested items and their partial and total scores from both model- and error-driven measures

item	overall-Model	HS-Model	L-Model	M-Model	overall-Error	HS-Error	L-Error	M-Error	O-Error	Fluency
ALCOHOL	27	14	8	5	4.75	1	0.95	0.9	1	0.9
BAND-AID	18	12	3	3	4.55	0.9	1	0.75	0.9	1
BAR	26	14	6	6	4.2	0.8	0.65	0.95	0.9	0.9
BED	30	20	4	6	4.05	0.5	0.95	0.9	1	0.7
BLUE	19	14	3	2	4.55	0.75	1	0.85	1	0.95
BONE	38	19	9	10	4.5	0.8	1	0.85	0.95	0.9
BOYFRIEND	31	16	9	6	3.65	0.35	0.9	0.95	0.6	0.85
BREAD	32	15	9	8	4.35	0.6	0.95	0.95	0.95	0.9
BROWN	17	7	6	4	4.85	1	1	0.85	1	1
CANDIES	24	11	7	6	4.85	0.95	0.95	0.95	1	1
CASTLE	32	19	4	9	4.1	0.55	1	0.75	0.95	0.85
CHICKEN	22	14	6	2	3.9	0.45	0.95	0.7	1	0.8
CHOCOLATE	29	13	9	7	4.45	0.75	1	0.85	0.95	0.9
CHRISTMAS	28	12	6	10	4.8	0.95	1	0.95	1	0.9
COMPASS	33	16	9	8	3.35	0.05	1	0.35	1	0.95
COMPUTER	29	17	4	8	4.45	0.75	1	0.7	1	1
DANCE	31	19	8	4	3.95	0.85	0.95	0.25	1	0.9
DIAMOND	24	8	9	7	3.9	0.95	1	0.25	0.95	0.75
DOLPHIN	30	13	4	13	4.55	0.85	1	0.85	0.95	0.9
EGG	26	14	9	3	3.25	0.85	0.95	0.05	0.9	0.5

Table A2.1 continued from previous page

item	overall-Model	HS-Model	L-Model	M-Model	overall-Error	HS-Error	L-Error	M-Error	O-Error	Fluency
ELECTRICITY	26	16	4	6	4.8	0.9	1	0.9	1	1
ELEPHANT-1	26	12	6	8	4.75	0.95	0.95	0.9	1	0.95
ELEPHANT-2	32	14	6	12	4.5	0.7	1	0.85	1	0.95
ELEVATOR	32	20	3	9	4.45	0.65	1	0.9	1	0.9
EXERCISE-1	29	19	4	6	4.25	0.65	1	0.8	0.95	0.85
EXERCISE-2	25	16	3	6	4.45	0.65	0.9	0.95	1	0.95
FEAR-1	27	13	8	6	4.55	0.85	1	0.8	1	0.9
FEAR-2	20	13	3	4	4.95	1	1	1	1	0.95
FEAR-3	26	17	3	6	4.55	0.85	1	0.85	0.85	1
FIRE	23	10	3	10	4.75	0.95	1	0.85	1	0.95
FLOWER	29	14	6	9	4.9	1	1	0.9	1	1
FLY	32	18	8	6	4.35	0.5	1	0.85	1	1
FOOTBALL	27	10	9	8	3.85	0.45	0.95	0.7	1	0.75
FRIES	29	14	9	6	4.4	1	1	0.55	1	0.85
FRUIT	23	16	3	4	3.7	0.45	1	0.4	0.95	0.9
GLASS	30	15	9	6	4.2	0.7	0.85	0.9	0.9	0.85
GRASS	26	13	8	5	3.75	0.5	1	0.5	1	0.75
GREEN	25	15	4	6	4.65	0.75	1	0.9	1	1
GREY	25	13	4	8	3.7	0.45	1	0.45	0.95	0.85
HAM	25	10	9	6	5	1	1	1	1	1
HEDGEHOG	32	17	9	6	3.15	0.2	0.8	0.55	0.95	0.65
INTERNET	32	17	3	12	3.3	0.55	1	0.15	0.75	0.85
INTERPRETER	28	12	9	7	4.45	1	0.95	0.7	0.95	0.85

Table A2.1 continued from previous page

item	overall-Model	HS-Model	L-Model	M-Model	overall-Error	HS-Error	L-Error	M-Error	O-Error	Fluency
IRON	23	13	7	3	4.45	0.7	0.9	0.95	1	0.9
LAMP	21	14	3	4	4.7	0.9	1	0.8	1	1
LEAF	37	18	9	10	3.95	0.65	1	0.3	1	1
LION-1	19	9	7	3	4.25	0.8	1	0.6	0.9	0.95
LION-3	15	9	3	3	4.8	0.95	0.95	0.95	1	0.95
LIZARD	31	18	4	9	4.3	0.6	1	0.8	1	0.9
MATCH	21	15	3	3	4.9	0.95	1	0.95	1	1
MEAT-1	31	20	9	2	4.2	0.45	1	0.85	1	0.9
MEAT-2	26	16	8	2	4.7	0.9	1	0.85	0.95	1
METER	35	18	9	8	3.7	0.8	1	0.25	0.85	0.8
MILK	38	23	9	6	4.05	0.4	0.9	0.95	1	0.8
MOM	25	11	8	6	4.55	0.75	0.9	0.9	1	1
MOVIE	27	12	9	6	3.3	0.9	0.55	0.6	0.5	0.75
MUSHROOM	41	26	9	6	3.65	0.1	0.9	0.95	0.95	0.75
NURSE-1	27	9	9	9	3.55	0.65	1	0.25	1	0.65
NURSE-2	23	8	9	6	4.8	0.95	1	0.85	1	1
NURSE-3	26	9	8	9	4.55	0.75	1	0.9	1	0.9
NUT	28	18	8	2	3.9	0.4	0.85	0.75	1	0.9
OIL	24	14	4	6	4.1	0.8	0.95	0.8	0.75	0.8
PEAR	31	14	8	9	4.55	0.9	0.9	0.85	1	0.9
PEN	41	24	8	9	3.9	0.2	1	0.9	1	0.8
PENCIL	32	20	9	3	4.2	0.75	0.95	0.6	1	0.9
PIG	29	17	8	4	4.75	0.9	1	0.9	1	0.95

Table A2.1 continued from previous page

item	overall-Model	HS-Model	L-Model	M-Model	overall-Error	HS-Error	L-Error	M-Error	O-Error	Fluency
PINEAPPLE	26	11	9	6	4.5	0.7	1	1	0.95	0.85
PLASTIC	28	20	3	5	4.5	0.75	1	0.75	1	1
POLICE	27	16	9	2	3.95	0.85	0.95	0.3	1	0.85
POPE	29	12	8	9	4.25	0.9	0.95	0.55	0.9	0.95
RED	26	13	6	7	4.7	0.85	0.95	0.95	1	0.95
RULER	34	18	9	7	4.45	0.55	0.95	1	1	0.95
SAUCE	25	15	4	6	3.6	0.15	1	0.75	0.85	0.85
SHEEP	24	9	9	6	4.95	1	0.95	1	1	1
SKIN	26	16	8	2	4.8	0.9	1	0.95	1	0.95
SOCKS	31	14	4	13	4.5	0.9	0.95	0.8	1	0.85
STAR-1	26	16	8	2	4.55	0.75	1	0.85	1	0.95
STAR-3	30	18	7	5	4.1	0.6	1	0.5	1	1
STATUE	22	9	6	7	4.7	0.85	1	0.95	0.95	0.95
SUN	24	14	7	3	4	0.7	1	0.3	1	1
THEATRE	38	20	9	9	3.85	0.1	0.95	0.85	0.95	1
THERMOMETER	23	16	3	4	4.35	0.55	1	0.9	1	0.9
TICKET-INSPECTOR	36	18	8	10	4.2	0.6	1	0.7	1	0.9
TOILET	28	14	8	6	4.55	0.75	1	0.9	1	0.9
TRAIN	27	16	7	4	4.5	0.75	0.95	0.8	1	1
TREE	25	14	9	2	4.4	0.9	0.85	0.85	0.95	0.85
UNIVERSITY	30	17	9	4	4.4	0.8	1	1	0.75	0.85
VIOLET	26	13	4	9	3.85	0.65	0.95	0.3	1	0.95
WALLET	24	13	9	2	4.5	1	1	0.85	0.75	0.9

Table A2.1 continued from previous page

item	overall-Model	HS-Model	L-Model	M-Model	overall-Error	HS-Error	L-Error	M-Error	O-Error	Fluency
WIND	29	16	4	9	4.65	0.95	1	0.8	0.9	1
WINDOW	25	18	3	4	4.35	0.6	1	0.8	1	0.95
WINE	28	13	8	7	4.5	0.8	1	1	0.75	0.95
WOMAN	26	11	8	7	4.55	0.95	0.9	0.85	0.95	0.9
YELLOW	32	15	8	9	4.2	0.65	0.9	0.75	1	0.9

A3 Models computed and resulting parameters

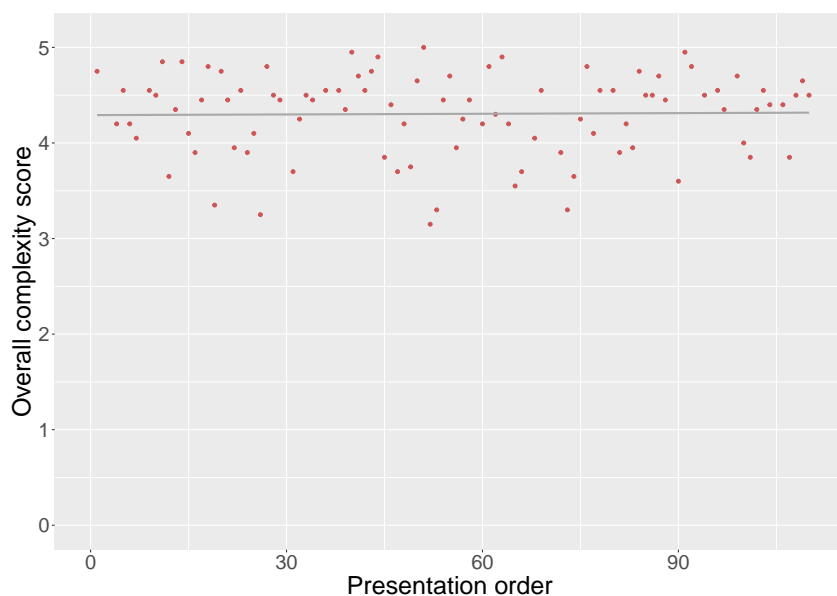
Here we report the results of the step-up procedure.

A3.1 Effect of the order of presentation of stimuli on overall accuracy

```
clmm(overall-Error ~ ORDER + (1|participant) + (1|item), data = df)
```

Items = 94; Participants = 20

AIC = 3597.59



A3.2 Effect of chronological age on overall accuracy

```
clmm(overall-Error ~ AGE + (1 | participant) + (1 | item), data = df)
```

Items = 94; Participants = 20; Pseudo- $R^2 = 0.270$

AIC = 3593.61

AGE	β	SE	z value	p value
	-0.021	0.010	-2.103	<0.05

A3.3 Effect of model-driven overall complexity on error-driven overall complexity

clmm(overall-Error ~ overall-Model + AGE + (1|participant) + (1|item), data = df)
Items = 94; Participants = 20; Pseudo- $R^2 = 0.278$
AIC = 3578.52

overall-Model	β	SE	z value	p value
	-0.112	0.026	-4.289	<0.001
AGE	β	SE	z value	p value
	-0.021	0.01	-2.107	<0.05

A3.4 Effect of model-driven HS complexity on error-driven HS complexity

glmer(HS-Error ~ HS-Model + AGE + (1|participant) + (1|item), data = df, family = binomial(link = "logit"))
Observations = 1880; Items = 94; Participants = 20; Marginal $R^2 = 0.162$; Conditional $R^2 = 0.446$
AIC = 1807

HS-Model	β	SE	z value	p value
	-0.25	0.038	-6.473	<0.001
AGE	β	SE	z value	p value
	-0.026	0.01	-2.534	<0.05

A3.5 Effect of model-driven Location complexity on error-driven Location complexity

glmer(L-Error ~ L-Model + (1|participant) + (1|item), data = df, family = binomial(link = "logit"))
Observations = 1880; Items = 94; Participants = 20; Marginal $R^2 = 0.072$; Conditional $R^2 = 0.377$
AIC = 546.6

L-Model	β	SE	z value	p value
	-0.266	0.096	-2.745	<0.05

A3.6 Effect of model-driven Movement complexity on error-driven Movement complexity

glmer(M-Error ~ M-Model + (1|participant) + (1|item), data = df, family = binomial(link = "logit"))

Observations = 1880; Items = 94; Participants = 20

AIC = 1709.33

A3.7 Effect of each model-driven phonemic class on error-driven overall complexity

clmm(overall-Error ~ HS-Model + L-Model + AGE + (1|participant) + (1|item), data = df)

Items = 94; Participants = 20; Pseudo- R^2 = 0.278

AIC = 3579.77

HS-Model	β	SE	z value	p value
	-0.134	0.035	-3.797	<0.001
L-Model	β	SE	z value	p value
	-0.127	0.055	-2.303	<0.05
AGE	β	SE	z value	p value
	-0.021	0.01	-2.105	<0.05

A3.8 Ad-hoc analysis: Effect of model-driven Movement complexity on error-driven Movement complexity for 5 easiest and 5 most complex signs

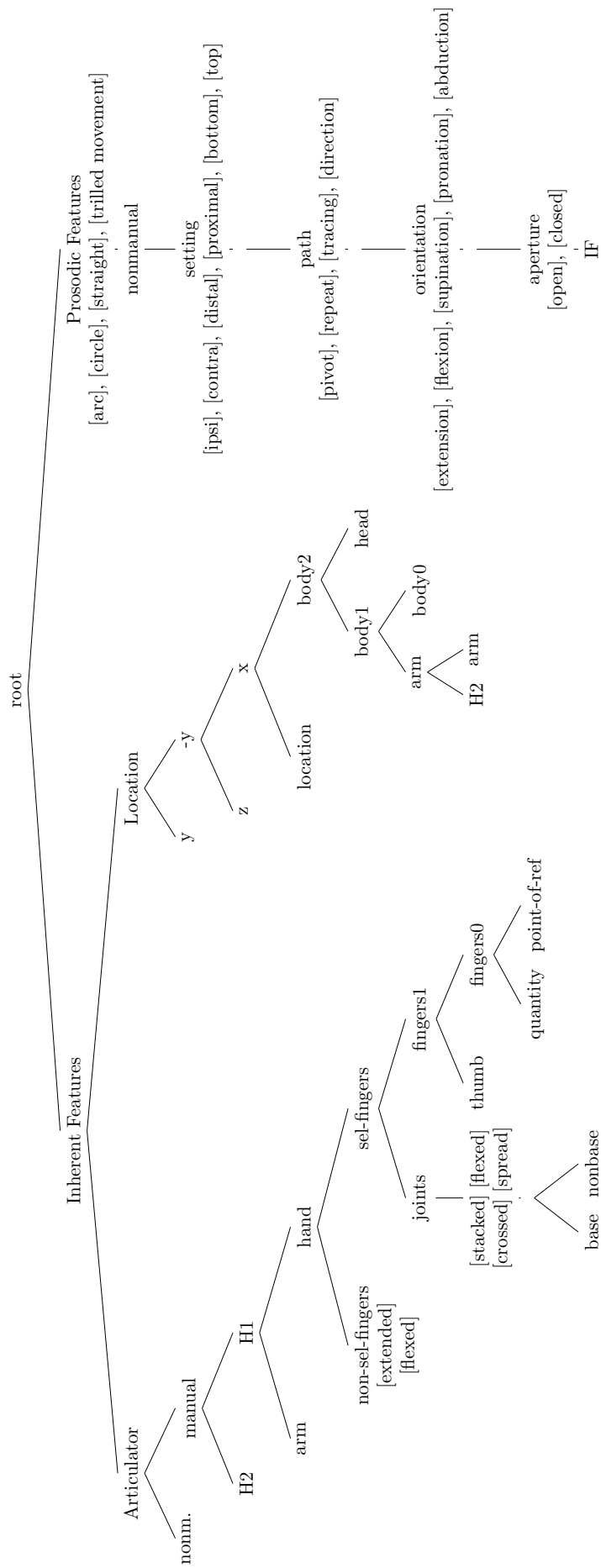
glmer(M-Error ~ M-Model + (1|participant) + (1|item), data = df, family = binomial(link = "logit"))

Observations = 200; Items = 10; Participants = 20

AIC = 133.16

A4 Fully-expanded structure of the Prosodic Model (Brentari, 1998) with every possible nodes and features

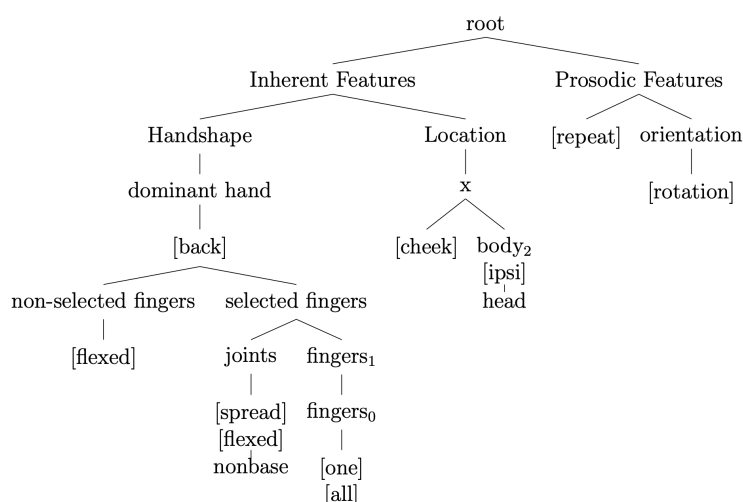
Adapted from Brentari (1998).



A5 Detailed description of the model-driven measure for the sign TRAIN (Figure 10): Step-by-step procedure

Please note that we *literally* applied Brentari’s framework as in her book, she defines sign complexity based on the definition provided in Dependency Phonology (Anderson and Ewen, 1987; Drescher and van der Hulst, 1993): “Structures that have daughters are more complex than those that do not (...), and structures with branching daughters are more complex than those with nonbranching daughters (...).” (Brentari, 1998, p. 213).

Sign train and its phonological structure

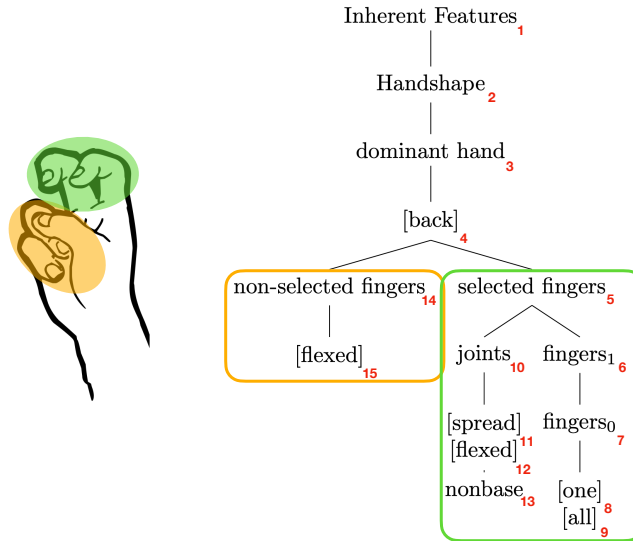


A5.1 Step 1: Handshape

The handshape is developed under the major node “Inherent Features” (# 1-2). In TRAIN, as only one hand is used the branch for the dominant hand is developed (# 3) while the one for the non-dominant hand is not. The feature [back] (# 4) here refers to the back of the fingers, the specific hand part facing the location (i.e. the cheek, see below). Two fingers are selected, the index and the major fingers. They are represented under the selected fingers node (# 5). The branch on the right specifies that the thumb is not selected (not thumb branch developed under fingers1 #6) and that two fingers are selected: [one] and [all] in this order specify the number “2”, and since no specific point of reference is developed under fingers0 (# 7) it means that the referent is the index finger

(the second finger is therefore the major finger, [# 8-9]). Then, the branch for the joints (# 10) specifies the shape of the selected fingers: they are [spread] and [flexed] at the nonuse joint (# 11-14).

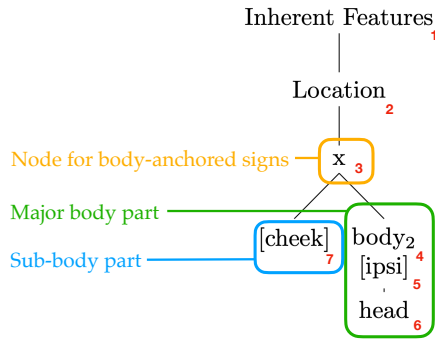
We therefore end up with a score of 15 for the handshape branch of structure.



A5.2 Step 2: Location

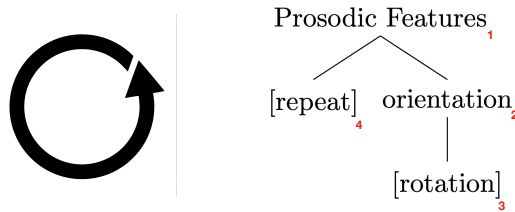
Reminder of Footnote 7: Notice that in order to independently compute the number of nodes necessary to capture both handshape and location, the Inherent Feature node was counted twice. While this increases by one point the overall complexity of a sign, it does so uniformly across all signs. Since we did not compare the complexity of the Inherent and Prosodic branches this move does not affect any of the statistical analyses conducted in the study.

Under the Location node (# 2, also referred to as Place of Articulation and hence POA) the x node is selected as it is the default node to represent the body in body-anchored signs (# 3). The right branch under the x-plane specifies the major body part selected, here the ipsi side of the head (# 4-6). On the left branch, the feature for the sub-part of the major body part is specified: in TRAIN, it is produced on the cheek. We thus end up with a total score of 7 for Location in TRAIN.



A5.3 Step 3: Movement

Finally, the Prosodic Features branch represents the movement (# 1). In TRAIN, the movement is a simple circular movement. Hence, it is an orientation change (# 2) as it is a rotation of the wrist (# 3). A feature for repetition is also specified as there are several rotations of the wrist in TRAIN (# 4). The total score for movement is then of 4 in TRAIN.



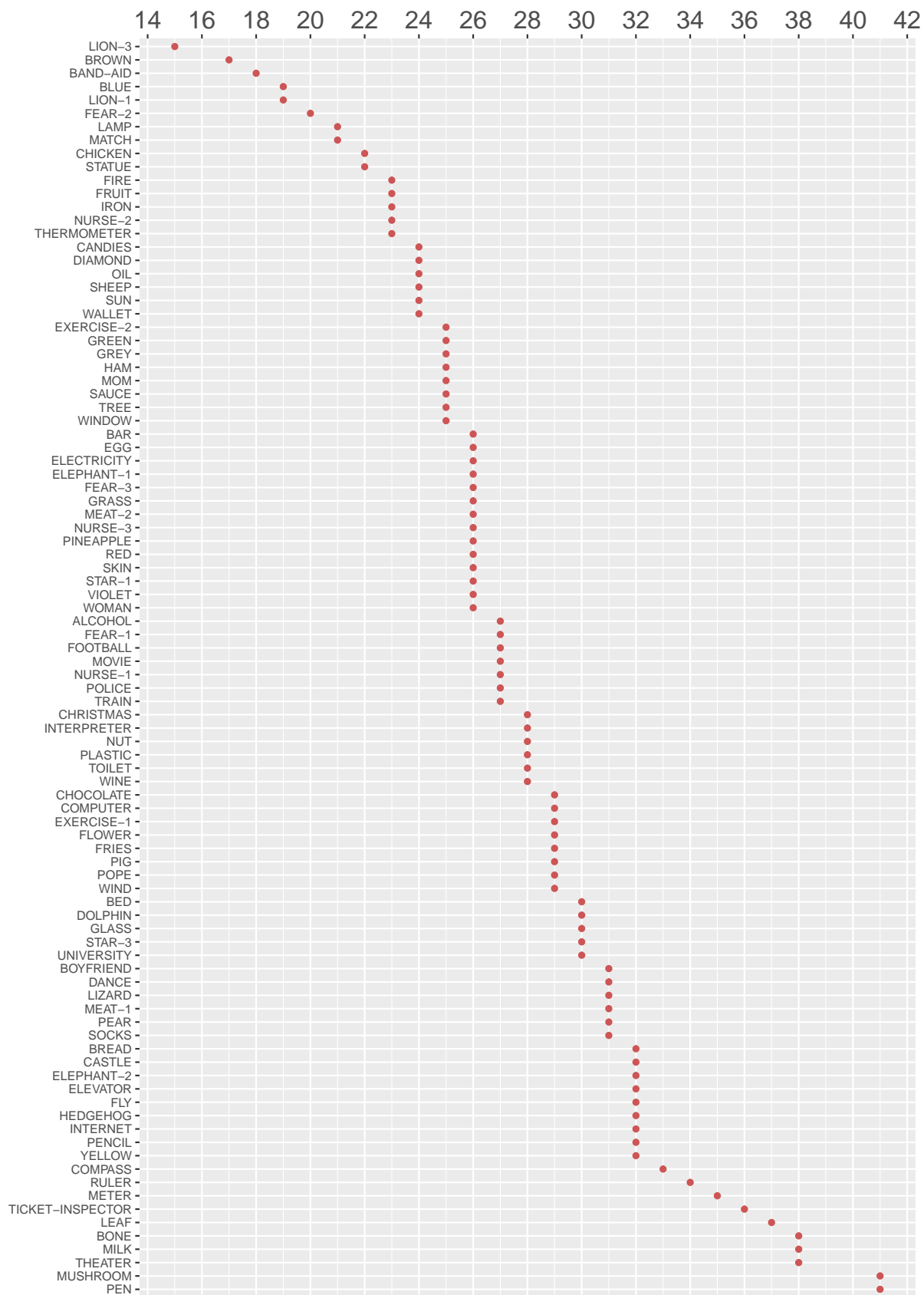
A5.4 Step 4: Counting

The final scoring TRAIN is thus as follows:

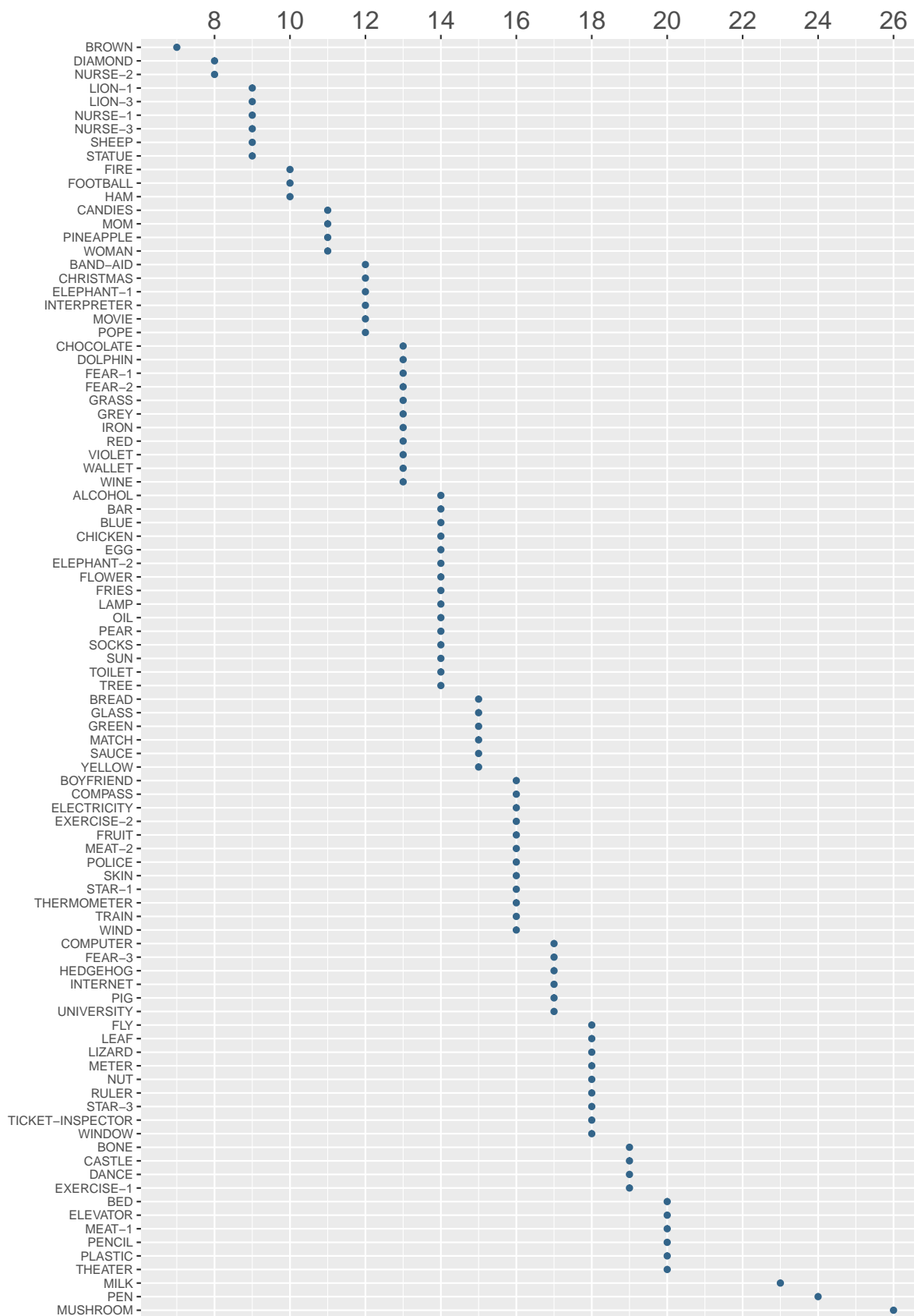
	TRAIN
Handshape	15
Location	7
Movement	4
TOTAL	26

A6 Complexity scores for each sign from the annotation in the framework of the Prosodic Model (Brentari, 1993)

A6.1 Overall complexity score



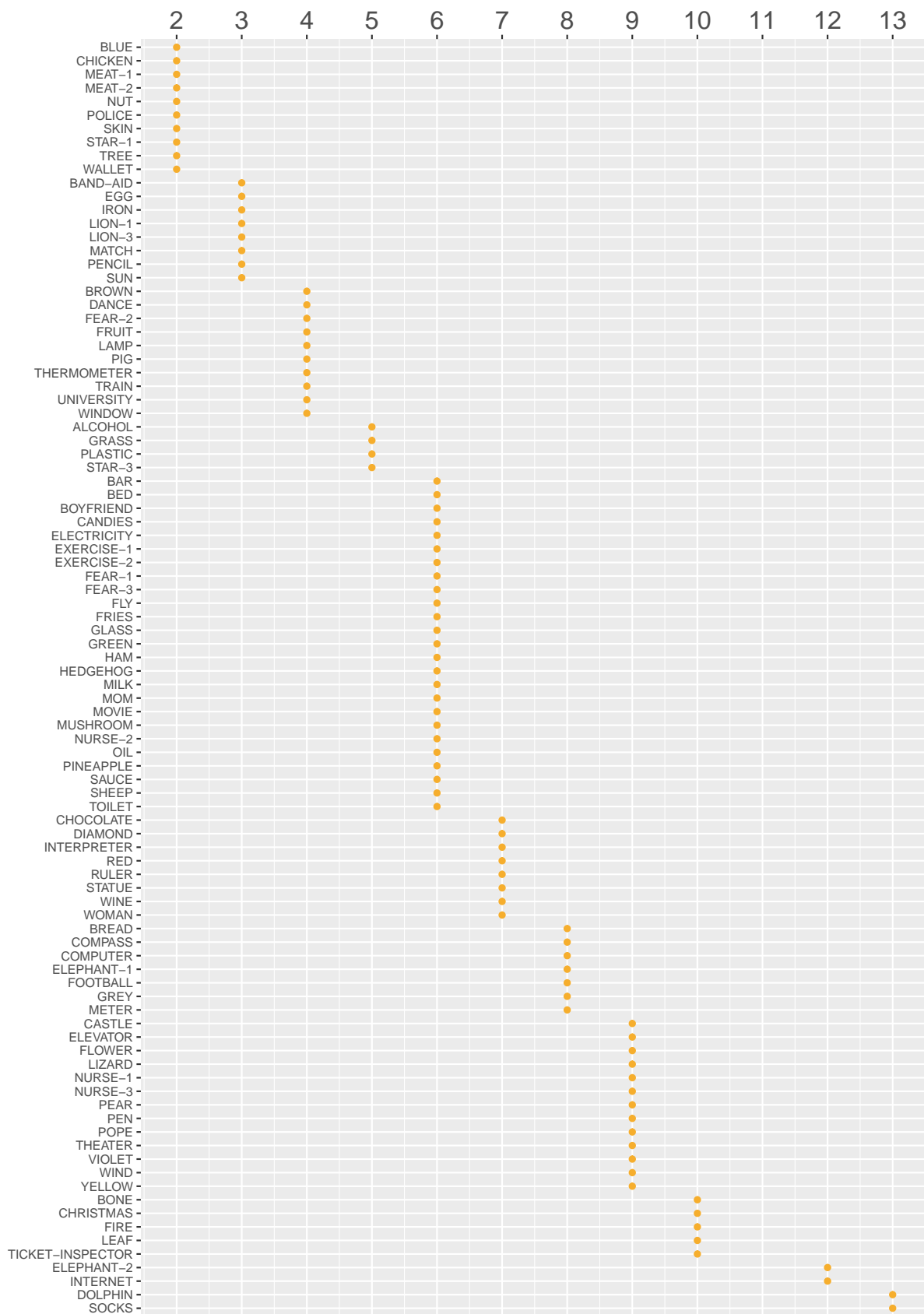
A6.2 Complexity score for Handshape



A6.3 Complexity score for Location



A6.4 Complexity score for Movement

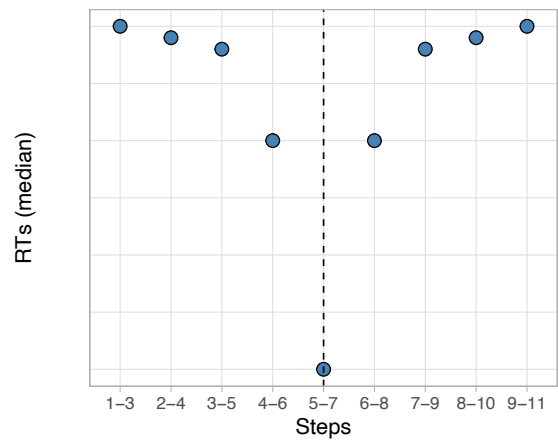
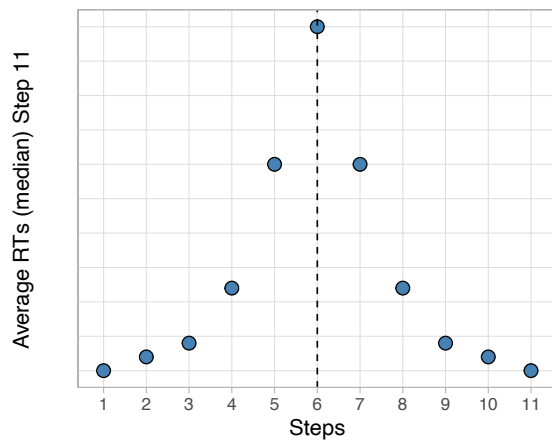
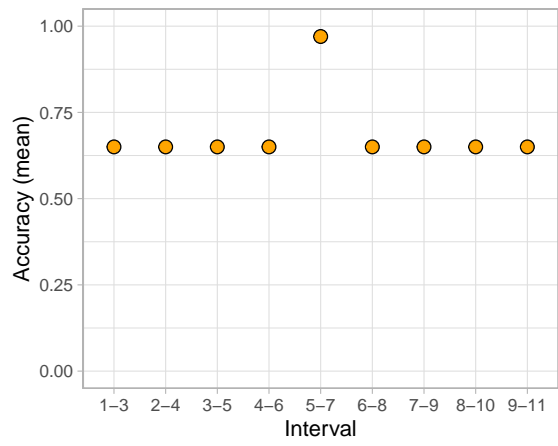
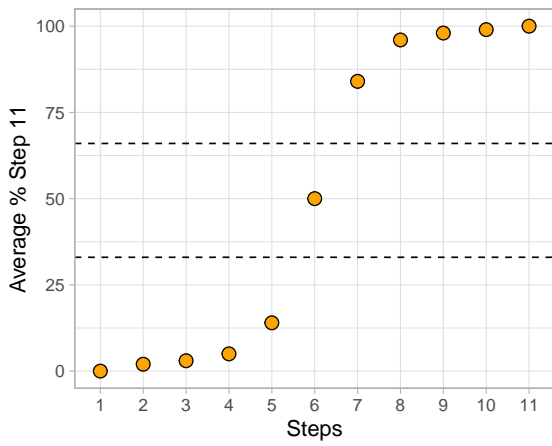


B Appendix to Chapter 5

B1 Idealized results in CP studies

Below we provide idealized results of a CP effect, i.e. results we would expect in both categorization (left) and discrimination (right) functions in accuracy (top) and RTs (bottom). These are built based on a XAB categorization task with a 33-66% threshold (cf. Section 5.3.1). Figures for accuracy are adapted from (Morford et al., 2008): in a categorization task one would expect to find a clear sigmoid, with the first steps of the continuum belonging to one category (average percentage below 33%), a steep slope, and the last steps of the continuum belonging to the other category (average percentage above 66%). One step would ideally fall in between, with a percentage of answer at chance ($\sim 50\%$), which would be identified as the category boundary. In this case, in the discrimination task the target pair would be the stimulus pair 5-7 as it crosses the boundary #6. One would then expect the percentage of accuracy to be visually and significantly higher at the target pair (across categories) compared to all the other pairs (within category). In other words, we would expect to find a “peak” at the category boundary as shown in (a) on the right.

Results in RTs are expected to be aligned with accuracy, i.e. that they should strongly increase when the task is harder and strongly decrease when the task is easier. In other words, RTs should be longer at the category boundary in the categorization task as it is supposedly more difficult to categorize the boundary in either one or the other category. In the discrimination task, RTs are expected to be shorter across categories as the two steps composing the target pair should be discriminated more easily as opposed to the pairs within category.



B2 *Poser Pro* (Bondware, 1995) - Animation software used to create our avatar: Technical parameters

Several parameters were manipulated to create the avatar with the software *Poser Pro* (Bondware, 1995). To facilitate replication, we provide them below.

Avatar: Pre-loaded avatar named *Rex* with its respective accessories (t-shirt, pants, hair etc.)

Light: Poser superfly and loop

Render: Firefly (Auto)

Main camera (dolly): $z = -2$, $y = 5$, $x = 0$, x-orbit = -4°

Resolution: 300 PPI (pixel/in)

Export size: 13cm×13cm (1535×1535px)

Focus of centering: center of the avatar (not the hand to keep homogeneity across stimuli)

To create postures and handshapes, two strategies were used:

1. We took pictures (of the experimenter and/or Deaf consultant) while signing the pseudo-signs as reference model to copy natural poses,
2. We used the pre-loaded library of ASL handshapes: unfortunately it was from a previous version of the software and the parameters were incompatible with the version (v.11) we used. We still used the visuals to compare with our own productions.

B3 *Labvanced* (Finger et al., 2017) - Platform to create and conduct online experiments: Specifications

In this section, we provide several details about the parameters and settings used in the CP experiment built with *Labvanced* (Finger et al., 2017).

Experiments: Two independent experiments were built to have two separate links: one for Deaf signers, one for hearing non-signers

Tasks: Each task was created as an independent bloc.

Color background: Light grey (RVB: 221-221-221, Hex code: DDDDDD)

Size frames text and instructions: Full-screen

Size frames stimuli: Fixed at 800px×450px

Size stimuli: Fixed at 10×10cm (from the top of the head to the bottom of torso of the avatar)

B4 Instructions in written French (with English translation)

In this section we illustrate the instructions that were provided directly on the experimental platform for hearing non-signers. On the left we replicate the sequence of slides for the French version and on the right we provide the English translation. The same slides were presented to Deaf signers with videos of a Deaf consultant signing the instructions in LSF.



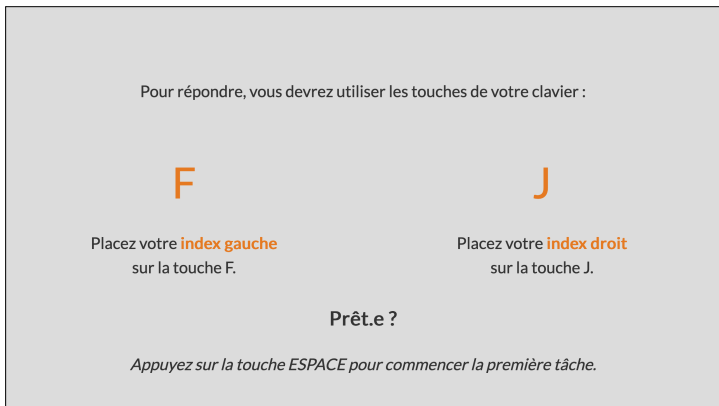
GENERAL INSTRUCTION AFTER THE CONSENT (1/2)

Let's start!

Here is Nico, our avatar:

This experiment is composed of two tasks in which you will see multiple pictures of Nico.

Press SPACE to continue.



GENERAL INSTRUCTION AFTER THE CONSENT (2/2)

To answer, you will have to use the keys of your keyboard:

F: put your left index on the key F.

J: put your right index on the key J.

Ready?

Press SPACE to start the first task.

Commençons par la première tâche

Dans cette tâche, vous verrez apparaître une image de Nico au centre de l'écran de façon très rapide.

Vous verrez ensuite deux images de Nico l'une à côté de l'autre : vous devrez indiquer laquelle des deux est identique à celle que vous avez vue précédemment.



Cliquez sur ESPACE pour continuer.

INSTRUCTION OF THE DISCRIMINATION TASK (1/2)

Let's start with the first task

In this task, you will see a picture of Nico appear in the center of the screen very quickly.

You will then see two pictures of Nico next to each other: you will have to indicate which of the two is identical to the one you saw before.

Press SPACE to continue.

Pour cela vous utiliserez soit la touche F pour indiquer l'image de gauche, soit la touche J pour indiquer l'image de droite.

F

Image de **gauche**.

J

Image de **droite**.

Cela sera répété plusieurs fois avec à chaque fois des images différentes.
Attention, il faut répondre **le plus vite possible** !

Commençons par un entraînement.

Quand vous êtes prête, appuyez sur la touche ESPACE.

INSTRUCTION OF THE DISCRIMINATION TASK (2/2)

To do this, use either the F key to indicate the left image, or the J key to indicate the right image.

F: Picture on the left.

J: Picture on the right.

This will be repeated several times with different pictures every time.

Be careful, you must answer **as fast as possible**!

Let's start with a training session.

When you are ready, press the SPACE key.

Passons à la seconde tâche

Dans cette tâche, vous verrez apparaître deux images de Nico l'une à côté de l'autre pendant plusieurs secondes.

Vous verrez ensuite une image de Nico au centre de l'écran de façon très rapide : vous devrez indiquer à laquelle de celle de droite ou de gauche elle ressemble le plus.



Cliquez sur ESPACE pour continuer .

INSTRUCTION OF THE CATEGORIZATION TASK (1/2)

Let's move on to the second task

In this task, you will see two pictures of Nico next to each other for several seconds.

You will then see an image of Nico in the center of the screen very quickly: you will have to indicate which of the one on the right or the one on the left it looks like the most.

Press SPACE to continue.

Pour cela vous utiliserez soit la touche F pour indiquer l'image de gauche, soit la touche J pour indiquer l'image de droite.

F

Image de **gauche**.

J

Image de **droite**.

Cela sera répété plusieurs fois avec à chaque fois des images différentes.
Attention, il faut répondre le **plus vite possible** !

Commençons par un entraînement.

Quand vous êtes prête, appuyez sur la touche ESPACE.

INSTRUCTION OF THE CATEGORIZATION TASK (2/2)

To do this, use either the F key to indicate the left image, or the J key to indicate the right image.

F: Picture on the left.

J: Picture on the right.

This will be repeated several times with different pictures every time.

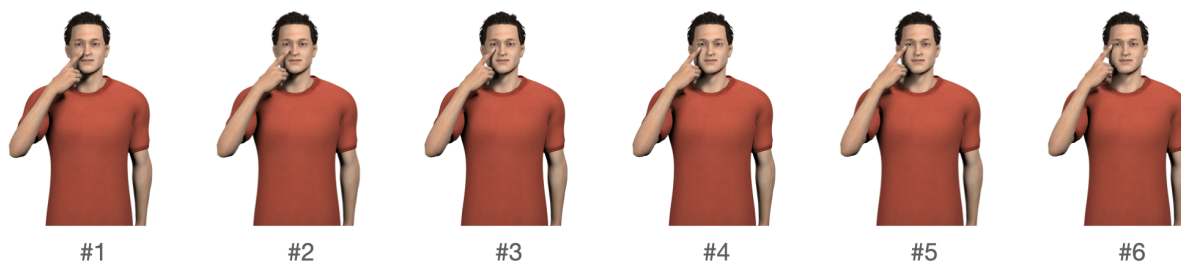
Be careful, you must answer **as fast as possible**!

Let's start with a training session.

When you are ready, press the SPACE key.

B5 Items used in the training phases

Both categorization and discrimination tasks were preceded by a training phase that included two 6-step continua built for this purpose; the extremes of the handshape continuum (top) are composed of the ‘U’-handshape (#1) and the ‘V’-handshape (#6), and the extremes of the location continuum (bottom) are located on the nose (#1) and the eye (#6). As for the items used for the experiment, we used the interpolation function in *Poser Pro* (Bondware, 1995) to generate equal steps between the extremes.



B6 Statistical analyses: models computed and results

Here we report the results of our statistical analyses. One model was computed for phonological class (handshape-HS / location-LOC), stimulus pair (phonemic-P / allophonic-A) and population (Deaf signers-LSF / hearing non-signers-FR), resulting in 8 models in Accuracy and 8 models in RTs. We provide the output of each model below. In the last section we provide the command that we used to run large models that failed to converge (cf. Section 5.5).

Once the paper will be submitted, data sets and scripts will be uploaded on an open-source repository (OSF). In the meantime, the script that was used with all steps and annotations can be downloaded here: <https://mycore.cnrs.fr/index.php/s/zi3o1qiT5rC4PJJ>.

B6.1 Effect of the target pair on Accuracy

B6.1.1 Model HS-P in Deaf signers (LSF)

```
glmer(accuracy ~ 1 + target + (1|participant), data = HS-P-LSF, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
Participants = 24
AIC = 591.0
```

<i>targetwithin</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-1.5317	0.7124	-2.150	0.0316	*

B6.1.2 Model HS-A in Deaf signers (LSF)

```
glmer(accuracy ~ 1 + target + (1|participant), data = HS-A-LSF, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
Participants = 24
AIC = 1706.4
```

<i>targetwithin</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.4487	0.2079	-2.159	0.0309	*

B6.1.3 Model HS-P in hearing non-signers (FR)

```
glmer(accuracy ~ 1 + target + (1|participant), data = HS-P-FR, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
```

Participants = 23

AIC = 989.7

target <i>within</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.6431	0.3366	-1.911	0.0561	n.s.

B6.1.4 Model HS-A in hearing non-signers (FR)

glmer(accuracy ~ 1 + target + (1|participant), data = HS-A-FR, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 23

AIC = 1972.4

target <i>within</i>	β	SE	<i>z</i> value	<i>p</i> value	
	0.04342	0.17452	0.249	0.803516	n.s.

B6.1.5 Model LOC-P in Deaf signers (LSF)

glmer(accuracy ~ 1 + target + (1|participant), data = LOC-P-LSF, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 21

AIC = 591.4

target <i>within</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.5848	0.4387	-1.333	0.182	n.s.

B6.1.6 Model LOC-A in Deaf signers (LSF)

glmer(accuracy ~ 1 + target + (1|participant), data = LOC-A-LSF, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 21

AIC = 696.8

target <i>within</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.04587	0.33541	-0.137	0.891	n.s.

B6.1.7 Model LOC-P in hearing non-signers (FR)

glmer(accuracy ~ 1 + target + (1|participant), data = LOC-P-FR, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 22

AIC = 780.8

<i>targetwithin</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.4355	0.3559	-1.224	0.221	n.s.

B6.1.8 Model LOC-A in hearing non-signers (FR)

glmer(accuracy ~ 1 + target + (1|participant), data = LOC-A-FR, family = binomial(link = "logit"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 22

AIC = 1226.2

<i>targetwithin</i>	β	SE	<i>z</i> value	<i>p</i> value	
	-0.0885	0.2420	-0.366	0.715	n.s.

B6.2 Effect of the target pair on RTs

B6.2.1 Model HS-P in Deaf signers (LSF)

glmer(RT ~ 1 + target + (1|participant), data = HS-P-RT-LSF, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 24

AIC = 25070.2

<i>targetwithin</i>	β	SE	<i>t</i> value	<i>p</i> value	
	0.08003	0.03114	2.57	0.0102	*

B6.2.2 Model HS-A in Deaf signers (LSF)

glm(RT ~ 1 + target, data = HS-A-RT-LSF, family = gaussian(link = "log"))

Participants = 24

AIC = 20160

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	-0.02616	0.04142	-0.631	0.528	n.s.

B6.2.3 Model HS-P in hearing non-signers (FR)

glmer(RT ~ 1 + target + (1|participant), data = HS-P-RT-FR, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 23

AIC = 21867.5

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	0.07616	0.02677	2.845	0.00444	*

B6.2.4 Model HS-A in hearing non-signers (FR)

glm(RT ~ 1 + target, data = HS-A-RT-FR, family = gaussian(link = "log"))

Participants = 23

AIC = 17345

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	-0.01704	0.04828	-0.353	0.724	n.s.

B6.2.5 Model LOC-P in Deaf signers (LSF)

glmer(RT ~ 1 + target + (1|participant), data = LOC-P-RT-LSF, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 21

AIC = 21741.2

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	0.10509	0.03473	3.026	0.00248	*

B6.2.6 Model LOC-A in Deaf signers (LSF)

glmer(RT ~ 1 + target + (1|participant), data = LOC-A-RT-LSF, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))

Participants = 21

AIC = 21596.6

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	-0.07132	0.03259	-2.189	0.0286	*

B6.2.7 Model LOC-P in hearing non-signers (FR)

```
glmer(RT ~ 1 + target + (1|participant), data = LOC-P-RT-FR, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
```

Participants = 22

AIC = 21598.8

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	0.02277	0.02567	0.887	0.375	n.s.

B6.2.8 Model LOC-A in hearing non-signers (FR)

```
glm(RT ~ 1 + target, data = LOC-A-RT-FR, family = gaussian(link = "log"))
```

Participants = 22

AIC = 20834

target <i>within</i>	β	SE	<i>t</i> value	<i>p</i> value	
	0.05402	0.04040	1.337	0.181	n.s.

B6.3 Large models that failed to converge

Following Barr et al. (2013), we ran larger models, but as mentioned in Section 5.5, the number of participants was not high enough for the models to run, resulting in convergence issues.

B6.3.1 Effect of target pair on Accuracy in Handshape, all variables included

```
glmer(accuracy ~ 1 + target * group * condition * rcs(interval, 3) + age + (1|participant), data = HS-accuracy, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
```

B6.3.2 Effect of target pair on Accuracy in Location, all variables included

```
glmer(accuracy ~ 1 + target * group * condition * rcs(interval, 3) + age + (1|participant), data = LOC-accuracy, family = gaussian(link = "log"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 2e5)))
```

B6.3.3 Effect of target pair on RTs in Handshape, all variables included

```
glmer(accuracy ~ 1 + target * group * condition * rcs(interval, 3) + age + (1|participant),  
data = HS-RT, family = gaussian(link = "log"), control = glmerControl(optimizer =  
"bobyqa", optCtrl = list(maxfun = 2e5))
```

B6.3.4 Effect of target pair on RTs in Location, all variables included

```
glmer(accuracy ~ 1 + target * group * condition * rcs(interval, 3) + age + (1|participant),  
data = LOC-RT, family = gaussian(link = "log"), control = glmerControl(optimizer =  
"bobyqa", optCtrl = list(maxfun = 2e5))
```