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The linguistic representation of number: Cross-linguistic and cross-modal perspectives

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The linguistic representation of number: Cross-linguistic and cross-modal perspectives

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy

in

Linguistics with a Specialization in Anthropogeny

by

Nina Semushina

Committee in charge:

Professor Rachel I. Mayberry, Chair
Professor David Barner
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Professor Eva Wittenberg

2021

The dissertation of Nina Semushina is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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Chapter 2 is partially based on the working paper in Semushina, N., Fairchild, A., Counting with Fingers Symbolically: Basic Numerals Across Sign Languages, San Diego Linguistic Papers (7) 2019. The dissertation author was the primary investigator and author of this paper.

Chapter 3, in full, is a reprint of the material as it appears in Semushina, N., Mayberry, R. I. (2019). Numeral Incorporation in Russian Sign Language: Phonological Constraints on Simultaneous Morphology. Sign Language Studies, Fall 2019, Vol. 20, No. 1 (Fall 2019), pp. 83-131. The dissertation author was the primary investigator and author of this paper. Reprinted with permission. This work was partially supported by NIH grant R01DC012797 to Rachel Mayberry. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. This work was also supported by a Malcolm Stacey Memorial Scholarship and CARTA Ph.D. Fellowship for Anthropogeny Students to Nina Semushina.

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Chapter 4, in full, has been submitted and may appear as a publication: Semushina, N. Mayberry, R. I. Number Stroop effect in Arabic digits and ASL number signs: The impact of age and setting of language acquisition. The dissertation author was the primary investigator and author of this paper.

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ABSTRACT OF THE DISSERTATION

The linguistic representation of number: Cross-linguistic and cross-modal perspectives

by

Nina Semushina

Doctor of Philosophy in Linguistics with a Specialization in Anthropogeny

University of California San Diego, 2021

Professor Rachel I. Mayberry, Chair

This dissertation investigated how the number systems of sign languages (SLs) of deaf people are similar to and different from the number gestures of hearing cultures and the number systems of spoken languages. Number representation in SLs was investigated here in its typological, morphological, and processing aspects. Additionally, the thesis explored the effects of early language deprivation on the acquisition of number, since it is common in the deaf community (90% of deaf children are born in hearing families, do not learn SL from their parents).

Culturally specific number gestures are often used by language speakers to indicate number. While SL numeral systems share the same articulatory and perceptual systems, SLs are linguistic systems, unlike number gestures. In the first study of the dissertation, a corpus of numeral systems

in 82 SLs was analyzed to investigate how they are similar to and different from spoken languages number systems and number gestures, and to discover the modality-specific, systematic properties of SL numeral systems, their use of iconicity, and the global distribution of one- and two-handed numeral systems. The second study investigated how the iconic two-handed numeral system in Russian SL interacts with the non-concatenative morphology of the language discovered some new phonological constraints in sign language.

The number systems of SLs are linguistic, but also visual – a property they share with Arabic digits. Using a Number Stroop Test, the third study revealed that the processing of number lexemes in American SL (ASL) is similar to that of spoken language number lexemes rather than Arabic digits. Both number formats are affected by early language deprivation in terms of processing speed. However, automatic magnitude representation still can be formed despite delayed language exposure.

Finally, the linguistic representation of number extends beyond the number systems to grammatical number marking. The last study investigated the impact of early language deprivation on the acquisition of plural classifier constructions, which are a complex morphological means of number marking in ASL. It revealed that late first language learners prefer morphologically simpler strategies over classifiers and make errors specific to their language acquisition background.

Chapter 1. Introduction and background

1.1. Introduction

The focus of this dissertation is on the nature of number representation in sign languages. Sign languages share the articulatory and perceptual systems of gesture, yet they are linguistic systems, whereas spontaneous gestures are not. Gestures are often used by language speakers to indicate number, and the means by which they do so varies widely across cultures. The overarching question investigated here is how the number systems of sign languages are similar to or different from both gestures that indicate number and the number systems of spoken languages. Given that the number systems of sign languages are linguistic, this leads directly to next question addressed here, namely whether and how the number lexemes of sign languages interact with their structure, morphologically in particular. Although the number systems of sign languages are linguistic, they are also visual, a property they share with number notations, such as Arabic digits. This raises the third question investigated here, which is whether the lexical processing of number lexemes in sign language is similar to that of digits, because they are represented in the visual modality, or to that of spoken language number lexemes, because they are linguistic. The linguistic representation of number extends beyond the number systems of languages to grammatical number marking, such as singular, plural, or dual. In sign languages, grammatical number can be marked morphologically by classifier predicates. Such grammatical number marking is acquired as part of linguistic structure. However, the age and setting of sign language acquisition is often atypical, so the last question investigated here is how these factors affect the learning of number representation, be it written digits, number lexemes, or grammatical morphology. In what follows, I situate the main questions investigated here in the theoretical context of what researchers mean when they investigate number.

1.2. Number systems and number notations

One cognitive ability that humans are thought to share with animals is the ability to perceive non-symbolic quantities of items or entities. This ability is referred to as numerosity, numeracy, or number. Although humans and other animals distinguish quantities, the underlying conceptual mechanisms may differ significantly. Núñez (2017) proposes a distinction between the terms quantical cognition (observed in human and non-human animals) and numerical cognition, which presupposes the existence of symbolic number and arithmetic. Quantical cognition is proposed to be biologically innate and be a prerequisite for numerical cognition. Numerical cognition, by contrast, is thought to arise from linguistic and cultural input which provides the basis for symbolic and exact number representation. Speakers of languages that do not have elaborate numerical system may not be skilled in matching quantities above the subitizing range (Everett & Madora, 2012; Frank, Everett, Fedorenko, & Gibson, 2008), suggesting that precise calculation is related to the way a particular language represents quantity, because it is the language that provides a cultural tool to keep track of set cardinality.

Precise recursive numerical systems are by no means required to represent quantity, however, and approximate or restricted numeral systems are by no means inferior. Xu & Regier (2014) provide a functional account for the variety of number system types: they hypothesize that numeral systems across languages form a continuum from approximate to recursive, representing tradeoffs between informativeness and simplicity. The approximate systems are near-optimal from the point of view of simplicity and require a minimum of cognitive load, while the highly informative recursive systems are on the opposite end. So, all numeral systems serve certain cultural purposes and satisfy the needs of their users.

Geographical factors also play an important role in the distribution of numerals – numeral systems with a less frequent base (such as vigesimal, or base 20) or structure (such as body-part) tend to cluster together. This is linked to both the typological relatedness of the languages that use such systems and to the contact of these populations: using the same representation of numerical concepts would facilitate trade and other interactions.

Consequently, numeral systems of languages can be borrowed, changed, or replaced due to sociolinguistic factors and cultural changes. For example, it has been reported that in languages with restricted numeral systems, numerals expanded with the increase of trade (Comrie, 2011, 2013; Omachonu, 2013). Comrie (2005) and suggests that, in fact, numeral systems of endangered languages, existing in the situation of diglossia, are even more endangered than the languages themselves. Languages may still have a large number of native speakers, but the number system may not be used by the younger speakers specifically in the domain of counting (Omachonu, 2013). Decimal systems are dominating the world and spreading to more and more societies through language contact and technology. Arabic digits are used almost everywhere; other systems of graphic number representations have a very restricted use. Roman digits are used in science in very limited terminological contexts; Hebrew numbers (corresponding to letters of Hebrew alphabet) are used in religious practices and in the Hebrew calendar.

As Chrisomalis (2004) explains, this kind of replacement of numeral systems and counting practices occur as a result of cultural and social changes and pressures, and he finds no uniform evolutionary trend leading to the decimal recursive system or place-value number notation: that is, there is no evidence that such systems are "better" or more efficient. The same trend can be observed with numerical notations as well (Chrisomalis, 2020).

Number can be represented in various ways: linguistically, with various numerical notations (which are trans-linguistic, as Arabic or Roman digits), or with number gestures, which vary between cultures. Bender & Beller (2012) presented a large typology of number gestures in different cultures around the world that vary in their use of the articulators (from finger phalanges to toes or the whole body) and the overall complexity of the system.

1.3. Number representation(s)

Since there are many ways to represent numbers that differ in functionality and context of use, the question is whether they designate the same concept. For instance, are number lexemes and conventional number symbols such as Arabic digits underlyingly represented in the same way? While some theoretical models assume the existence of an amodal abstract number representation (Dehaene, 1992; McCloskey, Caramazza, & Basili, 1985), others argue that the representation and processing of number depends on how it is expressed (Campbell & Clark, 1988; Campbell & Epp, 2004; Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Cohen Kadosh & Walsh, 2019; Myers & Szücs, 2015).

The most widely accepted model, the Triple-code model proposed by Dehaene (1992), postulates the existence of three different representational codes: a verbal form, a visual Arabic digit form, and an abstract, analogue magnitude representation code. According to this model, these three codes demonstrate different but interactive neural correlates (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene, Piazza, Pinel, & Cohen, 2003; Nieder & Dehaene, 2009). Both verbal and visual codes are connected to abstract number representation. A direct association between the number symbol (such as a digit) and the number word without accessing magnitude information is also possible. However, the semantics of number is processed in an abstract way, irrespective of the mode of presentation.

Although the existence of abstract number representation has largely been accepted, some researchers challenge this view (Cohen Kadosh et al., 2007; Cohen Kadosh & Walsh, 2009; Myers & Szücs, 2015). The existence of an abstract number representation would predict that the effects of representation should show similar patterns independently of format. Yet, this is not always the case. For example, Cohen Kadosh & Walsh (2009) hypothesized that magnitude representation itself is format-dependent, operation-specific, and that specific tasks can generate specific number representations. This hypothesis is based on multiple experimental results showing that qualitatively different patterns in magnitude processing tasks depend on the mode of presentation (digits, other types of symbolic non-linguistic notations, or the number words of one or several specific languages in bilinguals). Based on their review of neuroimaging studies, Cohen Kadosh & Walsh (2009) propose a Dual code model following Paivio (1976), Paivio & Begg (1971) and an encoding-complex model (Campbell & Clark, 1988). According to this model, abstract number representation may exist, but it is not a default strategy. Rather, implicit and automatic processing is format-specific. Abstract representation can be created online through interaction between formats for a particular task but it is not stored offline as a default one. However, the relation between acquisition and processing of digits and number lexemes is difficult to disentangle due to the relatively simultaneous acquisition of both.

1.4. Number Acquisition

In numerical cultures, language and number acquisition go hand in hand, and the child has access to both very early in life. During the initial learning stages, children probably use the same mechanism for the acquisition of linguistic number markers and the actual number lexemes

(Barner, 2017). Although children across different cultures go through the same stages of language and counting acquisition, it has been shown that cross-linguistic differences in number marking can influence number acquisition (Almoammer et al., 2013; Barner, Libenson, Cheung, & Takasaki, 2009; Colomé & Noël, 2012; Marušič et al., 2016; Meyer, Barbiers, & Weerman, 2018). It has also been proposed that Arabic digits are acquired through mapping onto linguistic numerals, which in turn are mapped onto a not human specific approximate number system (Le Corre & Carey, 2007). Other studies on the acquisition of Arabic digits (Hoffmann, Hornung, Martin, & Schiltz, 2013; Knudsen, Fischer, Henning, & Aschersleben, 2015; Park & Brannon, 2013) suggest that learning initially involves number lexemes, but later the link between two formats of representation, digits and lexemes, weakens with experience.

There is evidence that number gestures support counting acquisition as well (Alibali & DiRusso, 1999; Gibson, Gunderson, Spaepen, Levine, & Goldin-Meadow, 2019), and may be learned even earlier than number words (Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015). It has also been shown that the mismatch between the information represented linguistically and gesturally is a predictor of more successful learning in the domain of mathematics (Church & Goldin-Meadow, 1986). This is true for users of spoken and sign languages, since signers also gesture (Goldin-Meadow, Shield, Lenzen, Herzig, & Padden, 2012). The power of gestures thus is postulated to arise from the juxtaposition of information in analogue (gesture) and discrete (language) forms (Church & Goldin-Meadow, 1986), and may not be linked to the potential of iconicity in gestures. In fact, there is evidence that children are sensitive to the conventionality of number gestures, but not to their iconicity (Nicoladis, Pika, & Marentette, 2010) and thus not to the one-to-one mapping between the number of objects and the number of fingers.

The complex relations between number lexemes, Arabic digits, and iconicity of number gestures can be partially disentangled if we turn to a population who acquire iconic but linguistic number in manual modality, and may be exposed to Arabic digits prior to linguistic number markers.

1.5. Overview of this dissertation.

1.5.1. Why study number in sign languages and its acquisition?

One way to investigate the acquisition of number in various formats is to study the question in a different modality: sign languages. Deaf signers live in highly numerate cultures and are exposed to number in multiple formats. Number signs are produced with hands and may be iconic, but unlike number gestures, they form productive recursive numeral systems. However, sign language numerals remain largely ignored in the typology of numeral systems – while numerous studies have investigated exact quantification in a number of sign languages of deaf communities and in shared sign languages (Sagara, 2014; Sagara & Zeshan, n.d.; Yang, 2016; Yano & Matsuoka, 2018; U Zeshan, Escobedo Delgado, Dikyuva, Sibaji, & De Vos, 2013), this work remains overlooked by the broader number typology literature or works on number evolution (such as Chrisomalis, 2021; Comrie, 2011). Instead two sign languages were included in a large study of number gestures (Bender & Beller, 2012). While Bender and Beller acknowledged the high complexity and regularity of sign language numeral systems, it is important to distinguish gesture (even as conventionalized and culturally significant as number gesture are) from linguistic number instantiation, even if it is produced manually. Thus, one of the goals of this dissertation thus is to place sign language numeral systems in the context of the larger study of exact quantification in languages and discover what they have in common with both linguistic number systems and number gestures.

While sign languages have productive, complex numeral systems and linguistic plural marking, not all deaf signers have full access to language in early life. Only 10 % of deaf children are born to deaf parents in signing households (Mitchell & Karchmer, 2004). Many deaf children receive highly variable and often incomplete language input at an early age, and some do not have access to natural sign language until after childhood, creating severe language deprivation, which often is not prevented even by medical interventions, such as cochlear implantation (Humphries et al., 2012). Only within the congenitally deaf population can be found individuals who acquire little or no language in childhood prior to learning a sign language in later life.

We can approach the question of the role of language in number acquisition by studying individuals who learn signed language during childhood (early or native first language learners of sign language) and congenitally deaf individuals who were exposed to neither spoken nor signed language until adolescence (late first language learners). The latter group, while living in fully numerate culture, are exposed to conventional number lexemes and linguistic number marking after they encounter Arabic digits. The proposed dissertation is comprised of four studies using this unique situation to investigate the relations among language modality, language acquisition, the format of number representation, and numerical cognition.

1.5.2. The studies in this dissertation

To approach the questions identified above, I started by investigating modality-specific properties of sign languages that might be relevant for number acquisition, and then conducted two experimental studies investigating the effect of delayed first language exposure on number acquisition in three formats: Arabic digits, number signs, and linguistic plural number marking.

Chapter 2 of this dissertation presents an analysis of the general properties of numeral systems in sign languages to discover how these systems change over time, whether they rely on iconicity, and what common strategies they use to form basic numerals (atoms). By analyzing a corpus of number systems (82 sign languages), created from online materials, I show that sign language number systems rely on iconicity only in a limited way, and the age of a sign language does not predict the degree of this iconicity, i.e., younger sign languages are not more likely to have two-handed numeral systems where numbers are formed just by finger extension.

Next, I move to another modality-specific property of sign languages: non-concatenative simultaneous morphology. Chapter 3 presents the results of a several years of fieldwork with signers of Russian Sign Language. This study investigated numeral incorporation in a language with a two-handed iconic numeral system and showed that nevertheless it is regulated by the phonological constraints of the language when integrated into syntactic and morphological structures. The constraints operate on the phonological level: on the level of location, orientation, movement, and handshape. This study adds to typological studies of numeral incorporation, increasing our understanding of constraints on two-handed signs and the interaction of phonology and morphology in sign languages.

In Chapters 4 and 5 I explore how these linguistic means of symbolic number use and quantity reference – a partially iconic numeral system and non-concatenative plural morphology – are acquired by people who were deprived of language in their early life and thus were exposed to digits and numeric culture before they learned a language for number.

In two experiments presented in Chapter 4, I tested the automatic processing of numbers expressed both linguistically (through ASL number signs) and in conventional mathematical symbols (Arabic digits) using the Number Stroop Test paradigm where participants compared pairs of stimuli that differed both in physical size and magnitude, while the decision task focused on only one aspect (either size or magnitude). The stimuli varied in congruity. In congruent trials, size and number information aligned (3 5). In incongruent trials, size information contradicted the numerical dimension (3 5), and in neutral trials the digits differed only in the relevant dimension (3 5, 3 3). While the Number Stroop Effect is consistently found in Arabic digits, this is not the case for linguistic numerals, and results of my study show the same. It suggests that ASL number signs are processed more like linguistic number words than Arabic digits. For ASL signers who learned sign language from birth, performance with Arabic digits did not differ from that of the hearing control group, suggesting that deafness per se does not contribute to mathematical underachievement, but that a lack of early language access does. It affects the speed of processing, but automatic magnitude activation can be achieved despite this. Other factors that might influence magnitude activation in both formats (iconicity of the stimuli, frequency of the stimuli, spatial-numerical association of response codes) are also discussed.

Finally, Chapter 5 presents a series of three experiments (picture description, acceptability judgements, sentence-to-picture matching) that looked at the impact of language deprivation on the comprehension and production of plural classifier constructions in American Sign Language – a frequent and iconic, but highly constrained and morphologically complex type of plural marking. The results of the production experiment revealed that while post childhood language learners can produce these constructions, they do not exhibit a preference towards it, unlike native signers. Additionally, classifier use is motivated by the frequency of both the construction (particular classifier) and the entity described (cat vs sheep). As far as plural marking is concerned, post childhood language learners prefer morphologically simpler constructions or avoid plural marking altogether, which results in a loss of crucial information. Importantly, both second language learners and late learners of ASL demonstrated group-specific types of errors (L2: incorrect classifier handshape, LL1: incorrect number) and differed from the native signers on their choice of classifier plural constructions.

I then conducted an acceptability judgement experiment with a rating scale to investigate whether native signers confirm the preferences towards the maximally informative constructions shown in production, and whether the errors that second language learners produced make sentences ungrammatical. Both the production preferences and the ungrammaticality of incorrect classifiers were confirmed.

Finally, in a sentence-to-picture matching task I investigated how the two different types of errors, namely incorrect classifier handshape and incorrect number marking, affect understanding the descriptions. While the sentences with number mismatches were rejected with high accuracy by second language learners and native signers, sentences with incorrect classifier handshapes were often accepted by both groups, suggesting that in comprehending such constructions both groups of signers tend to rely on the plural movement morpheme more than on handshape[1].

All chapters of the dissertation were conducted and written as separate research studies with their own literature review, methods, results, and discussion, followed by figures, appendices, and references.

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1 - Due to the unforeseen circumstances (pandemic) we were only able to test the native signers and second language learners in the sentence-to-picture matching experiment: online studies with these participants were not possible. However, we hope to test the late learners of ASL in picture matching task as well once it is safe to conduct research in person

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Chapter 2. Counting with Fingers Symbolically: Basic Numerals Across Sign Languages

Abstract

In a corpus of numeral systems in 82 sign languages, we analyzed the distribution of one- and two-handed numeral systems as a function of language age and geographic factors and described the properties of two-handed and one-handed numeral systems in terms of iconicity and structural properties. We found that the age of a sign language does not predict the type of numeral system that it has, but geographic clustering is observed.

Sign languages use a more restricted set of articulators than the number gestures of hearing cultures. On the other hand, both one- and two-handed numeral systems demonstrate complexity and all the properties of numeral systems in spoken languages. Sign language numerals rely on several kinds of iconicity, but in a limited way. Similar to spoken languages and number notations, a limited set of common structural properties has been observed, but languages do not converge to one universal strategy.

2.1. Introduction

There is no universal way of encoding symbolic number: languages differ in the types of numeral systems they use, and number systems can change over time (Comrie, 1999, 2011, 2013). Besides linguistic number, various culture-specific number gestures are widely used (Bender & Beller, 2012). Many such gestural systems are elaborate and use a variety of articulators, from finger phalanges to the whole body, but are not linguistic. However, there are languages that use manual articulators to represent linguistic number – sign languages. An important question is, how are such systems similar to and different from both numeral systems of spoken languages and number gestures of hearing cultures.

In this study, we analyzed the basic numerals across a set of 82 sign languages using the video data available online as well as available linguistic descriptions. We investigated the following questions. What strategies do the two types of numeral systems (one- and two-handed) employ in terms of iconicity, numerical base, and morphological structure? How are they similar to and different from spoken languages and number gestures? Based on what we know about historical change in sign languages, do similar changes occur in sign language numeral systems during their language history?

We first present a brief overview of numeral systems in spoken languages and number gestures of hearing cultures. We then explain our methodology and describe our language sample in terms of phonological and morphological properties, base, iconicity, and variation. We then move to the analysis of the distribution of one- and two-handed numeral systems as a function of language age and geographic factors and describe the properties of two-handed and one-handed numeral systems (briefly discussing mixed cases) and compare them to spoken languages/number gestures.

We find that numeral systems of sign languages are more constrained than number gestures in the way they use the manual articulators. They demonstrate all the properties of numeral systems in spoken languages. Numeral systems of sign languages are predominantly vigesimal, but other types of bases (including rare ones) are attested as well. The age of the language does not predict whether the system is one- or two-handed, but there is geographic clustering. The numeral systems of sign languages rely on various kinds of iconicity, but in a limited way. In the general discussion, we summarize the findings and discuss how the inclusion of sign languages can enrich numeral typology and studies of number processing.

2.2. Number representations in hearing cultures.

2.2.1. Number systems in spoken languages.

Symbolic number representations allow humans to build numeral systems that allow the use of both precise numbers and corresponding linguistic quantifiers. However, there is no universal way to encode quantities; languages differ significantly in the grammatical representation, complexity, and even limits for number systems. Research with non-numerate cultures and speakers of languages that do not have an elaborate numerical system show that they may not be skilled in distinguishing quantities above the subitizing range in the tasks that require storing quantities in long-term memory (Everett & Madora, 2012; Frank, Everett, Fedorenko, & Gibson, 2008). The relationship is reciprocal: in a society that does not need to use exact quantities, a linguistic tool for keeping track of them does not develop.

Numeral systems differ in terms of base, or the value *n* such that numeral expressions are constructed according to the pattern ... $xn + y$, i.e., some numeral *x* multiplied by the base plus some other numeral (Comrie, 2013). Most of the world's known linguistic numeral systems are decimal. According to the WALS database, among the 196 languages included, 125 have a decimal numeral system; 20 are vigesimal; 22 are a hybrid vigesimal-decimal; 5 languages have other bases; 4 use extended body-part systems; and 20 have restricted numeral systems. These numeral systems are as follows.

Vigesimal systems have the structure x20 + y (as in the language Diola-Fogny (Niger-Congo). Hybrid systems (like French and Basque) combine these two types of bases.

Extended body-part systems (where pointing to body parts refers to certain quantities) are attested in Highland New Guinea (Comrie, 2013) and Australia (Howitt, 1904).

Restricted numeral systems, according to Comrie, do not have a base and are limited by a certain number, as the Kulin languages of Australia. This is not rare. Bowern & Zentz (2012) show that numerous indigenous languages of Australia have restricted numeral systems, with the limit (highest number) in 169 languages being as low as three. Numeral systems with a less frequent base, as well as restricted and extended body-part systems, tend to cluster in particular regions of the world. This phenomenon is related to both the typological relatedness of these languages and to the contact between their speakers: using the same representation of numerical concepts would facilitate trade and other interactions (Comrie, 2005, 2013). Cultural practices may also be involved, such as ceremonial routine yam-counting in Southern New Guinea, which arguably gave rise to the typologically rare senary (base 6) number systems in this region (Evans, 2009). One language, Pirahã, has been claimed to have no numeral system at all, but the data are controversial.

Languages change, and so do numeral systems and number words (Chrisomalis, 2019, 2020; Fedden, 2012). Consider an example from spoken Russian. In the course of history, number words underwent the same phonetic changes as other lexical categories. Compositional numerals merged into one unit (*pyat desyat* (five tens) -> *pyadesyat*). The distinct lexical category of numeral emerged: while Old Russian number words behaved as nouns or adjectives, contemporary Russian numerals have specific rules of agreement with nouns. The grammatical dual number was lost which resulted into the change of declension paradigms (Gorshkova & Haburgaev, 1997).

Language contact also can lead to change. Entire numeral systems may be borrowed, when in certain contexts the use of a new system becomes somehow beneficial or widespread, and often they eventually replace the older one (Comrie, 1999). This can happen even in languages with a large number of native speakers, which makes numeral systems even more “endangered” than the language itself (Omachonu, 2013).

Xu & Regier (2014) provide a functional account for the variety of number system types. They hypothesize that numeral systems across languages form a continuum from approximate to recursive, representing the tradeoff between informativeness and simplicity. The approximate systems are near-optimal from the point of view of simplicity and require a minimal cognitive load, while highly informative recursive systems are on the opposite end.

While number notations are trans-linguistic (i.e., the same Arabic digits can be used by speakers of different languages), they can also be replaced, as happened with Roman digits that were widely used in the past (Chrisomalis, 2020). However, Chrisomalis (2020) explains that replacement of numeral systems or notations happen not because one of the systems is less cognitively suitable, but because of the coincidence of linguistic, cultural, and social factors; no numeral system or numerical notation is inferior to others.

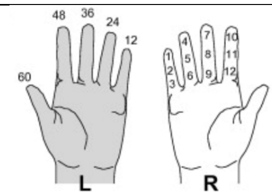
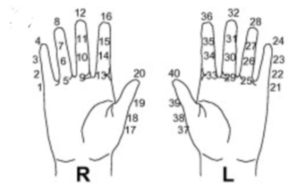
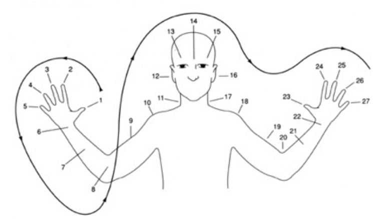
2.2.2. The number on the hands: number gestures in hearing cultures

Besides lexical numbers and conventional number notations, humans routinely express number with the help of number gestures. Some accounts link the evolution of number concepts and number words to the availability of iconic elements that have stable order, such as the fingers or other body tallies (Wiese, 2007). Experimental evidence shows that number gestures might support counting acquisition by enhancing the understanding of one-to-one correspondence (Alibali & DiRusso, 1999; Gibson, Gunderson, Spaepen, Levine, & Goldin-Meadow, 2019), and may be learned even earlier than number words (Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015). However, the ability to count with fingers is not innate and requires cultural input (Crollen, Seron, & Noël, 2011). Recent studies show that children may, in fact, be sensitive not to the iconicity of the number gestures, but to their conventionality (Nicoladis, Marentette, Pika, & Barbosa, 2018; Nicoladis, Pika, & Marentette, 2010), and the one-to-one mapping between the number of objects and the number of fingers may not be crucial. Bender and Beller (2011, 2012) claim that the structure of number gestures may have cognitive implications for number acquisition and therefore cross-cultural differences must be taken into account.

Indeed, although number gestures have the potential to be trans-linguistic, they are conventional and culture-specific (Bender & Beller, 2011, 2012). They may function as salient shibboleths, as exemplified by Tarantino in the movie *Inglourious Basterds* (Tarantino, 2009), where the use of the American gesture for THREE instead of the German one gives away a disguised character and results in a failure of the military operation.

In an extensive review, Bender and Beller (2012) build a typology of number gestures across the world. They show that such systems employ a great variety of strategies: even for counting from *one* to *five* with the extended fingers of one hand, there are at least 5 variants. However, number gestures are not limited to the fingers; the space between fingers can be used as well, as in Yuki, a Californian language (Kroeber, 1925); some gestural systems of the Americas and Africa extend counting to the toes; complex systems, such as the ones used in Indian schools and ancient Babylonia, use finger segments, and, finally, extended body-part systems can make use of the whole body.

Table 2.1. *The use of body in number gestures*

Strategy	Culture	Illustration
Finger segments	Babylonia	
Finger Segments	India	
Toes	Americas, Africa, Papua New Guinea	
Whole body	Oksapmin	

Source: Bender and Beller (2012)

While many systems of number gestures do rely on a one-to-one correspondence between the number of fingers extended and the number of objects counted, this is not always the case. In Eastern Africa, the widespread number gestures 4 and 5 are not based on such a principle. In body-part systems, the location itself serves as a tally, and so are the phalanges of fingers in Babylonian system.

Following Zhang & Norman (1995), Bender and Beller analyzed the structures of number gestures in terms of dimensionality, or base. Most of the number gesture systems in their data (across Eurasia, Africa, Americas) have no base, so these systems are not productive. Such systems include one or both hand gestures (usually limited by 5 or 10) and systems with linear extension to toes or body tallies.

Two-dimensional systems, such as old Chinese number gestures and an extensive number gesture system of Arusha Maasai in Tanzania, have a base. In such systems, the fingers of the first hand designate the numbers from one to five, but fingers of the second hand (or additional movements, or finger configurations) designate powers of the base. Information from both hands is combined. Importantly, the base does not necessarily need to be quinary (i.e., 5). For example, some number gestures are based on symmetry: the number 6 would be expressed by extending 3 fingers on each hand. Interestingly, in many countries of Africa, such symmetrical structures with compositional non-quinary bases (i.e., 3 + 3 for 6, 4 + 4 for 8) are observed not only in finger counting, but in linguistic number systems as well.

Finally, Bender and Beller (2012) discuss the possibility of a three-dimensional system that would have a sub-base use give an example from DGS, or German Sign Language. They also discuss the number system of American Sign Language, or ASL, and conclude that it is "extraordinary in various ways" and it is the most complex system in their sample. This is not surprising, given that the ASL number system is a productive numeral system. However, as we explain below, neither the DGS nor ASL number systems can be classified together with number gestures because these systems are composed of lexical numbers (just expressed in the manual modality) and therefore should be typologically grouped together with spoken languages. There is evidence that the processing of number lexemes in sign language is like the processing of spoken language number lexemes, rather than visual stimuli, such as digits, since they are linguistic (Semushina & Mayberry, under review; Vaid & Corina, 1989). At the same time, the numeral systems of sign languages do indeed use the manual articulators similar to number gestures and thus might have commonalities with them as well. Like number gestures, the numeral symbols of sign languages are constrained by the physical properties of the manual articulators. Not all hand configurations are anatomically possible, but the list of possible strategies is extensive. However, sign languages (as well as spoken languages) are governed not only by anatomic but also by linguistic, phonological constraints (Sandler, 2012). The number signs of sign languages also coexist with the numeral systems of spoken languages and the number gestures of hearing people.

Therefore, an important question is how sign language numeral systems differ from one another and what they have in common with both number gestures and numeral systems of spoken languages. There is fundamental work on number typology in sign languages (Zeshan & Palfreyman, 2017) and descriptions of numeral systems of individual sign languages (M Fuentes, Massone, Fernanez-Viader, Makotrinsky, & Pulgarin, 2010; Lanesman, 2016; H. Morgan, n.d.; Sagara, 2014; Yang, 2016; Yano & Matsuoka, 2018; Zeshan, Escobedo Delgado, Dikyuva, Sibaji, & De Vos, 2013). Sagara (2014) presents an extensive analysis of strategies attested in sign languages numeral systems.

However, more studies of the general properties of sign language numeral systems are needed. This information is crucial for understanding the interconnections of number and language, taking into account studies of number gestures and their role in early number development. We also know little about how the number systems of sign languages change, and whether the change can be predicted. Can we observe changes and replacements of the number systems in sign languages, and if so, does this occur due to the influence of other sign languages or other language-internal constraints?

We now turn to the description of the methodology we used to collect the data to answer the above questions.

2.3. Methodology and sources.

As a source for the video data for this study, we used the online international sign language dictionary *spreadthesign.com.* Spreadthesign is an international project, initially created by the European Sign Language Center that currently unites sign language users and researchers from different countries and includes a multilingual sign language dictionary with an option of comparison for the same lexical item across many sign languages. When available, we also used online dictionaries of individual sign languages (American Sign Language, Costa Rican Sign Language, Greek Sign Language, Hungarian Sign Language, Israeli Sign Language, Swedish Sign Language, Russian Sign Language, Ugandan Sign Language, Ethiopian Sign Language). When dictionaries were not available, we looked for educational sign language videos published on the internet, mostly from sign language teaching projects or Deaf-owned vlogs.

There is a distinction between deaf community sign languages (all mentioned above) and sign languages of shared communities – shared sign languages, also sometimes called "village sign languages" in the literature (Nyst, 2012). These types of languages differ in terms of their emergence circumstances and users. Deaf community sign languages emerge when deaf people who have no common means of communication form a community. This often happens with the rise of deaf education in the environment of school or vocational program for deaf individuals. Most of the first users of these languages were deaf and did not have a common language. This contrasts with shared sign languages, that usually emerge in closed communities with high level of hereditary deafness. In such communities almost every family has deaf members, but the majority of the population is hearing and proficient in one or more common spoken languages, although fluent in the emerging sign language to varying degree (Meir, Sandler, Padden, & Aronoff, 2012). For this study, we include information about both deaf community sign languages and shared sign languages.

When possible, we relied on the published linguistic analyses of the numeral systems. However, this was not always available. For some languages in the sample, we were only able to find materials from educational and popular science *YouTube* channels, as well as Deaf vlogs, including videos that explicitly compare different sign languages; in such cases we attempted to use as many videos as possible to assure consistency across sources. The list of the video sources with links is given in the appendix.

There are clear limitations of our study related to its methodology. These include the impossibility of controlling for the signer's proficiency and setting of language acquisition, the decontextualized nature of data, and difficulties controlling for dialectal or generational differences.

Another limitation relates to language status and community identification. For example, based on the lexicographic materials and educational videos, several sign languages of Post-Soviet countries bear significant resemblance to Russian Sign Language. Different sources consider Ukrainian Sign Language to be a dialect of RSL (Kimmelman, 2012) or possibly a closely related language (Bickford, 2005). Based on the data available on *spreadthesign*, the number signs for 1 – 10 are identical in Russian, Ukrainian, and Belorussian Sign languages, but for the purpose of this paper we consider them to be three separate languages, because that is how the Deaf communities of the three countries identify themselves.

Similarly, there are multiple sign languages on the Indian subcontinent described in the linguistic literature (Woodward & De Santis, 1977): Nepali Sign, Bangalore Sign, Indo-Pakistani Sign Language. However, educational videos with different signs are often called “Indian Sign Language," which complicates classification and prompted us to exclude such videos from the corpus.

Despite these challenges, the purpose of the following study is to give an overview of the strategies that sign languages use to form basic numerals (atoms) and assess their variation and potential language change. The possibility of an in-depth typological analysis of numeral systems across sign languages is currently limited by both the scarcity and quality of the available data.

We now provide a brief overview of the sign language numeral systems in this corpus in terms of phonology, morphology, iconicity, base structure, and variation.

2.4. Numeral systems of sign languages (overview)

2.4.1. Phonology and morphology.

The numeral symbols of sign languages are constrained by the physical properties of the manual articulators, that have ten digits, the signing space has limits, and not all hand configurations are anatomically possible. This differentiates them from the extended body part, or body tally numeral systems that may use the whole body with pointing to certain locations (Bender & Beller, 2011, 2012; B. Comrie, 2013). Unlike such systems, sign languages have sublexical structure. This means that signs are comprised of features which form a finite number of discrete, contrastive units that are meaningless, but can be combined in an infinite number of meaningful combinations, just as phonemes in spoken languages (Sandler, 2012). The features include location, handshape, movement, and orientation, although orientation is sometimes regarded as inherent.

The combinations of the features are governed by phonological constraints and undergo changes such as deletion, epenthesis, reduplication, and others, very similar to the phonological processes in spoken languages (Sandler, 2012). However, while most constraints are applicable to all phonological structures, there is a special set of constraints that operate on two-handed signs (Battison, 1974; Eccarius & Brentari, 2007; Frishberg, 1975; Morgan, 2017; Morgan & Mayberry, 2012).

Two such constraints, the symmetry and dominance conditions (Battison, 1974), regulate the distribution of handshapes and movements across two-handed signs. The symmetry condition states that if both hands move independently during sign articulation, then both hands must be specified for the same location, same handshape, the same movement (performed simultaneously or in alternation), and the specification for orientation must be either symmetrical or identical. The dominance condition states that if the two hands do not share the specification for handshape, then one hand must be passive, while the active hand articulates movement. The handshape specification of the passive hand is restricted to a set of unmarked handshapes: A, S, B, 5, G, C, and O.

These constraints, found cross-linguistically (Sandler, 2012), restrict the number of strategies that can be present in two-handed numeral systems. For instance, consider the two-handed numeral system of Russian Sign Language, where the number 7 (Fig. 2.1.) is represented with five digits extended on the non-dominant hand, and the dominant hand with two fingers extended that moves to contact the palm of the non-dominant hand.

Figure 2.1. Number 7 in Russian Sign Language

This sign is well formed, according to the dominance condition: only the dominant hand moves, and the handshape on the non-dominant hand is unmarked. However, a sign with the same FIVE handshape on a static dominant hand with the moving non-dominant hand with a different handshape, TWO, moving towards it would not follow the dominance condition. All two-handed signs in the corpus for this study follow the symmetry and dominance conditions. Despite being iconic and similar to number gestures, two-handed numeral systems can follow other constraints of the language and are fully integrated in the phonological system, as exemplified by Russian Sign Language (Burkova, Filimonova, Kimmelman, Kopylova, & Semushina, 2018; Semushina & Mayberry, 2019)

Additionally, constraints can lead to language change. In her seminal work, Nancy Frishberg (1975) investigated location constraints and showed that in American Sign Language, two-handed signs articulated at the head tend to become one-handed with time, and asymmetrical two-handed signs in neutral signing space change towards symmetry. Importantly, most two-handed numeral signs are asymmetrical. We will come back to this in section 5.1, where we investigate whether sign language numeral systems undergo the same change, becoming one-handed over time.

Importantly, on other phonological levels, number signs can demonstrate exceptions to the general rule. For example, numeral systems have been shown to include handshapes that are not found elsewhere in the language. Such examples occur in numeral systems with orthographic iconicity (i.e., when a number sign bears a non-arbitrary, motivated relationship to some orthographic representation of number, for example, an Arabic digit), as SEVEN, EIGHT, NINE in Ugandan and NINE in Indo-Pakistani sign languages (Zeshan et al., 2013). Such cases are also attested in Australian Sign Language (Johnston, 1989) and American Sign Language (Zeshan, 2013), where number signs are not iconic, but follow systematic patterns of finger extension.

While the phonology of sign languages demonstrates many similarities with spoken languages, morphology has some modality-specific properties that are also important for the analysis of number systems. First of all, sign languages naturally allow for the prevalence of non-concatenative morphology, where instead of linearly following each other, morphemes are superimposed on each other simultaneously (Aronoff, Meir, & Sandler, 2005). For example, in English, the word *seventeen* contains morphemes that follow each other, while in American Sign Language, the specific wrist rotation movement will be simultaneously combined with the handshape for SEVEN. When combined with handshape SIX, the same movement will turn it into SIXTEEN.

Another example of such simultaneous morphology found across sign languages is numeral incorporation. Here, the lexeme (usually a time, measurement, calendric term, or numeral operator, such as THOUSAND) combines with the number sign, and the resulting sign retains the location, orientation, and movement of the lexical sign and the handshape of the numeral sign. Numeral incorporation is restricted both lexically (only a subset of signs can allow it) and phonologically (not all numbers can be incorporated; not all signs can incorporate them), but is often used in numeral systems across sign languages to form higher numerals (Burkova, Filimonova, Kimmelman, Kopylova, & Semushina, 2018; S. D. Fischer et al., 2011; Fuentes et al., 2010; Ktejik, 2013; Morgan, 2013).

2.4.2. Iconicity

The natural sign languages of deaf people around the world always exist in a situation of diglossia (coexisting with spoken languages that are often favored in educational contexts). Sometimes their numeral systems bear connection to the number gestures of the coexisting hearing culture, as has been described for Kenyan Sign Language and Yucatec Maya Sign Language (Morgan, 2017; Safar, Guen, Collí, & Hau, 2018), but in many cases they do not (Fuentes, Massone, Fernanez-Viader, Makotrinsky, & Pulgarin, 2010; Zeshan & Palfreyman, 2017).

One particular type of iconicity in sign languages is called *number-to-number* and is specific to number constructions. In such cases, numbers are represented by extending a corresponding number of fingers (Taub, 2001). However, different languages rely on this strategy to varying degrees, and its utility is limited by the number of naturally available articulators (10 fingers). Most sign languages in our database use this kind of iconicity for the number signs ONE to FIVE.

Another kind of iconicity that has been described in sign languages is orthographic: signs for numbers resemble the written forms of these numbers in a form conventional for their community. Examples include Arabic digits for Turkish Sign Language or spoken Russian number words for Russian Sign Language, where the signs THOUSAND and MILLION are initialized, and their handshapes correspond to the first letter of the corresponding Russian word (Semushina & Mayberry, 2019). This type of iconicity is not limited to handshape: the movement in Japanese Sign Language number signs fully mimics the writing of the Kanji symbols (Sagara, 2014; Zeshan

& Palfreyman, 2017) and Fischer & Gong (2010) describe partial movement iconicity with a tracing movement in large number signs that resembles the writing of the final stroke of a Kanji character.

Mediated iconicity that is not specific to numbers can be found in numeral systems as well. Hope Morgan (2017) mentions that the sign for THOUSAND in Kenyan Sign Language bears a resemblance to a particular currency bill that was red and was used in 1960 when the first Deaf school was founded. A similar kind of iconicity was also observed in Japanese Sign Language, but Sagara (2014) notes that it is disappearing.

This strategy has been found in spoken languages as well (Greenberg, 1978). For instance, in many languages, the numeral 5 may be related to the lexeme for *hand* (Calude & Verkerk, 2016). More specialized examples can also be found: the Russian number word for 40, "*sorok*", is allegedly related to the word meaning "garment" and originally it referred to the number of (squirrel) furs needed to make one garment (Gorshkova & Haburgaev, 1997). Cases of mediated iconicity are also present in the number systems of shared sign languages, but so far no shared sign language has been shown to employ orthographic iconicity (Zeshan et al., 2013).

It is important to distinguish between iconicity and transparency. The number system can be iconic and transparent, iconic but not transparent, or not iconic and not transparent, as shown in Figure 2.2. An iconic sign bears a non-arbitrary relation to its referent, but the meaning of the sign can be transparent (as in case of *number-to-number* iconicity in French Sign Language sign EIGHT) or not. For example, to understand the Turkish Sign Language sign EIGHT, it is necessary to be familiar either with the language, or with the Arabic-Indic numeral notation that the sign resembles. Finally, number signs in one-handed numeral systems can be both non-iconic and non-transparent, as the American Sign Language sign for EIGHT.

The kinds of iconicity present in one- and two-handed numeral systems will be discussed separately in chapter 5 of this paper.

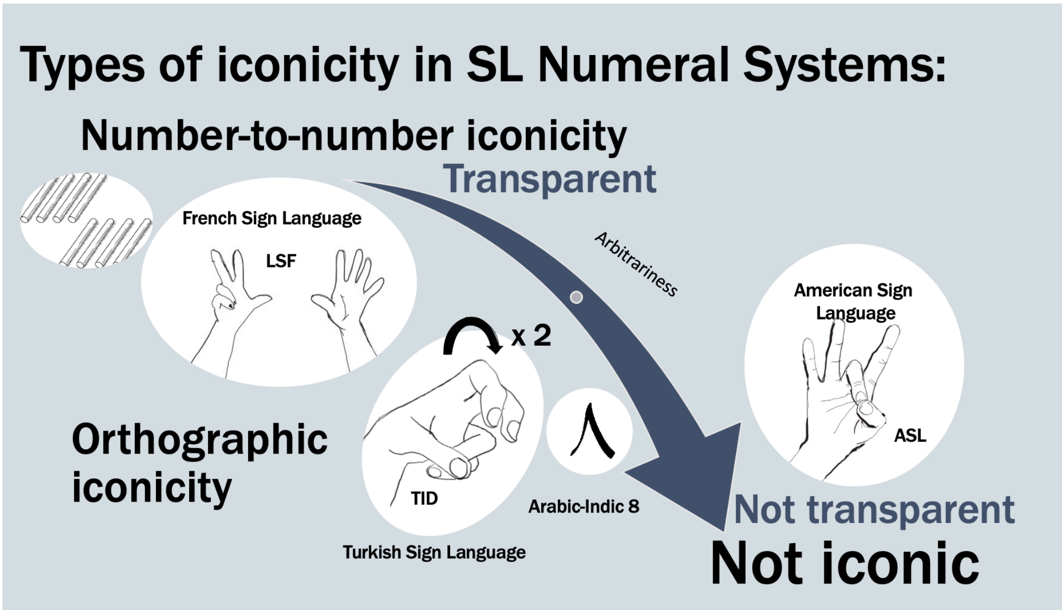


Figure 2.2. Examples of the possible relationship between iconicity and transparency in a sign language numeral systems. Exemplified by the number EIGHT in French, Turkish, and American Sign Languages. Systems with number-to-number iconicity are both the most iconic and the most transparent, systems with orthographic iconicity are less transparent and require familiarity to certain notation, and non-transparent non-iconic systems can't be interpreted without the knowledge of the system.

2.4.3. Numeral base

According to Calude & Verkerk (2016), the derivation of a compositional numeral in a language usually involves three components: atoms (already existing primary numerals), a base (an atom that is used serially to derive larger numerals), and an arithmetic operation, such as addition, subtraction, multiplication, division, or exponentiation2. This approach accounts for languages that have more than one base type (such as French). More importantly, different

[2] - For example, English number 84 (*eighty-four*) would have the structure of 8 x 10 + 4, where 8 is an atom, 10 is a base, and the operation is multiplication. In French, the same number (*quatre-vingt-quatre)* would have a structure 4 x 20 + 4, where the base is 20, and the atom is 4. In Russian Sign Language, 84 would have the same structure as in English.

operations can have different bases which may be morphologically derived from existing atoms or be separate unrelated lexemes, which Fuentes & Tolchinsky (2004) call "operators". According to Seiler, (1990), numeral bases share three fundamental properties. First, the bases are "turning points" on the number line where the linguistic rule for number formation changes. Second, irregularities in the derivation patterns of a given language tend to cluster around the base form. Finally, the choice among competing forms for representing the same number also tends to occur at the base.

The notion of the numeral base in sign languages appears to be problematic (Zeshan et al., 2013). The "base" is mostly defined as the value *n* such that numeral expressions are constructed according to the pattern ... $xn + y$, i.e., some numeral x multiplied by the base plus some other numeral (Comrie, 2013). However, there are other definitions: in some linguistic studies base is defined as numerals based on which other numerals are constructed (Lanesman, 2016; Zeshan et al., 2013). Several sign language studies (Fuentes & Tolchinsky, 2004; Leybaert & Van Cutsem, 2002) leave the notion of the base undefined. Several papers introduce the notion of sub-base for two-handed numeral systems. When evaluating the numeral bases of sign language numeral systems on videos and in published data, we followed the definition of Calude & Verkerk (2016).

Many sign languages of deaf communities emerged with the start of deaf education, which means that their first deaf signers spent considerable time in the school environment. It seems plausible that school curriculum included mathematics from the beginning. In the overview of the history of deaf education, Soviet authors Basova & Yegorov (1984) propose that Pedro Ponce de León, who allegedly invented fingerspelling in the 16th century, might have taught mathematics to his students. They also discuss that in the curricula of Russian deaf schools of the 19th century, four arithmetic operations with numbers under 20 were introduced in the first grade. Thus, sign language numeral systems might have evolved in close contact with written systems of number notations. This is reflected in the systems with orthographic iconicity (discussed in the corresponding section below). Importantly, this may be a factor influencing the type of numeral bases that the sign languages of deaf communities have. An overwhelming majority (77 of 82) of the numeral systems in our data sample are decimal. However, two-handed numeral systems have a sub-base of 5, which is naturally available because of the properties of manual articulators. We consider 5 to be a sub-base because the signs for the numbers 6 – 9 are formed from it by addition, using a rule similar to the way the Roman digits after five were formed (Chrisomalis, 2019). The sign FIVE is also the "turning point", where the modification of the existing morphological rule occurs to accommodate the two-handed signs (for example, the movement changes). An example of such a decimal system with a sub-base would be German Sign Language (Pfau, Steinbach, & Wall, 2012).

But other bases are attested as well. Algerian Jewish Sign Language has a quinary (base-5) numeral system (Lanesman, 2016). Shared sign languages have been reported to have bases higher than 10: Alipur Sign Language, Mardin Sign Language, and Chican Sign Language have base-50 numerals, Chican and Mardin Sign Languages have vigesimal (base-20) numerals. Alipur and Mardin Sign Languages have subtractive numerals, and Chican Sign Language has additive numerals (De Vos & Zeshan, 2012; Zeshan et al., 2013). Numeral systems of these types are attested in spoken languages (Comrie, 2013; Van Der Horst & Mussies, 1988; VAN DER HORST & MUSSIES, 1988) but not across the sign languages of deaf communities. Additionally, Alipur Sign Language creates numerals by spatial modification, which has not been attested in other languages (De Vos & Zeshan, 2012; Zeshan et al., 2013). Importantly, these rare bases are not a contact phenomenon: spoken languages that coexist with the shared sign languages with such bases have different bases (Zeshan et al., 2013).

Sign languages typically use movement morphemes to express a range of numerals, i.e., an arithmetic operation applied to it (1-10, 11-19, 20-90 etc.). For example, in Russian Sign Language the signs for 16, 60, 600, and 6 000 are derived from the sign SIX and differ from it (and from each other) only in movement. Each operation (multiplication by 10, exponentiation) has its own pattern. The sign for 66 would be a combination of SIXTY and SIX. Czech Sign Language has a different numeral system but employs this strategy as well.

There are sign languages that rely instead on a place-value strategy (i.e., 66 can be signed as SIX SIX), for example, South African Sign Language and Venezuelan Sign Languages: these languages have three different movement morphemes, as well as basic numerals, and are unrelated). Brazilian Sign Language relies on a place-value strategy even for round numbers. In German Sign Language (as well as in spoken German) the order is the inverse, and 23 is a combination of THREE and TWENTY (Pfau, Steinbach, & Woll, 2012). Shared sign languages with vigesimal and base-50 subsystems use more complex additive, subtractive and multiplicative strategies that are attested (although rare) in spoken languages (Comrie, 2013), but are not observed in sign languages of large deaf communities.

Sign languages also use operators – separate lexical signs to express a range or operation (Fuentes & Tolchinsky, 2004). For example, in Catalan Sign Language one way to sign 200 would be to use signs TWO and HUNDRED sequentially. However, as mentioned earlier, operators can participate in numeral incorporation. Most sign languages make use of both simultaneous morphology and operators. The phonological constraints of particular languages define whether a certain numeral will be expressed as an incorporating form or with an operator sequentially added:

for example, in Russian Sign Language THREE_THOUSAND would be one sign with a handshape of THREE and a specific movement, while SIX THOUSAND is expressed sequentially, using THOUSAND as an operator after the numeral SIX.

Brazilian Sign Language does not use movement to create ranges and relies on the place-value strategy even for round numbers, but still has lexical operators for THOUSAND, MILLION and BILLION.

As noted by De Vos & Zeshan (2012), the range of strategies employed by the numeral systems of sign languages is large, and some shared sign languages exhibit typological properties of numeral systems that are more readily found in spoken rather than sign languages. Finally, a number of spoken languages with restricted numeral systems do not have a base at all (Hammarstrom, 2010), which is not the case in any of the sign languages in this survey.

This is also the main difference between the numeral systems of sign languages and number gestures: unlike the gestures, number signs form productive and rule-governed systems. However, while some number gestures of hearing cultures do have bases and operators for powers, the strategies that such systems employ do not resemble the strategies that sign languages use. For example, in the number gestures used by Indian merchants, the extended fingers of the left hand designate 1, 2, 3, 4, 5, and the extended fingers of the right hand 5, 10, 15, 20, 25 (Bender & Beller, 2012). Only one system of number gestures, in Arusha, Tanzania, employed some movement modifications on the basic handshapes. All sign language in our sample employed morphological modifications or separately standing lexical operator strategies for such modifications.

2.4.4. Variation in Sign Language Numeral Systems

All numeral systems of signed and spoken languages are reported to have several irregularities (Gvozdanović, 1999). The irregularity may appear not only on a single number, but on part of a range. For instance, Russian Sign Language has two ways to refer to the numerals 11-15, a regular one-handed sign, with quick extension of the corresponding number of digits (Semushina & Mayberry, 2019), and a less regular two-handed sign, where the non-dominant hand has a handshape from the sign TEN and the dominant hand expresses the number that needs to be added to it by extended fingers (Geilman, 2001), as illustrated in Figure 2.3. This difference may be dialectal, but the source is unknown.

Figure 2.3. Two variants of the sign ELEVEN in Russian Sign Language.

McKee, McKee, and Major (2011) working on New Zealand Sign Language (NZSL), point out a high level of dialectal variation for the range from ONE to TWENTY across groups of NZSL signers as a function of age, gender, geographical location, and ethnicity. This situation contrasts with most studied spoken languages, according to the authors. This might be related to the fact that NZSL has dialectal variants centered around five centers of Deaf education in New Zealand.

Sociolinguistic variation specific to the language emergence setting is observed in other sign languages too (Valli, 1989). For example, in Russia, deaf and hard-of-hearing students were historically educated in different schools (Basova & Yegorov, 1984), which resulted in dialectal differences. In the USA, deaf education was segregated for a long time, and a distinct dialect developed in the Black Deaf community (Mccaskill, Lucas, Bayley, & Hill, 2011). In Argentina, education for deaf boys and girls was separate for a long time, which also impacted the numeral systems used by women and men (Fuentes et al., 2010). Gendered education affected Irish Sign Language as well (Matthews, 1996).

In shared sign languages variation is observed as well. For example, in Alipur Sign Language, the number FIVE can be expressed either with an O handshape or with 5 fingers extended. The variation exists both between signers and within the numeral system. Zeshan et al. (2013) propose that a lack of formal education can contribute to the variation in shared sign languages and prompts signers to rely on number-to-number iconicity instead of conventionality. Notably, the variation is higher for small numbers than for larger ones.

We now turn to the comparison of one- and two-handed numeral systems. First, we examine the possibility of language change from two-handed to one-handed numeral systems. Then we discuss the structural properties and strategies used by two-handed numeral systems and then one-handed ones.

2.5. One *vs* two-handed numeral systems.

2.5.1. Do the two-handed numeral systems become one-handed over time?

As noted earlier, two-handed numeral signs do have asymmetric handshapes, and it is possible to hypothesize that, because handshape asymmetry is not favored in sign language phonology (Frishberg, 1975), over time the two-handed numeral signs might change into a one-handed numeral system. At least one case where the two-handed numeral system changed into a one-handed one was described by Flaherty and Senghas (2011) in Nicaraguan Sign Language. At earlier stages of its development, the emerging Nicaraguan Sign Language had a two-handed numeral system, which by 1990 rapidly changed into a one-handed system (Flaherty & Senghas, 2011). In this case, we would expect older sign languages to have one-handed numeral systems more frequently than two-handed ones. Alternatively, however, the distribution of one- and two-handed numeral systems might be linked to language family and areal distribution, since both factors have been shown to contribute to similarities among the number systems of spoken languages (Bowern & Zentz, 2012; Epps, Bowern, Hansen, Hill, & Zentz, 2012).

To examine this possibility, we surveyed 82 sign languages around the world. Among them, 36 used two-handed numeral systems. Of these 36 languages, four are shared sign languages (Bengkala, Chican, Algerian Jewish and Mardin Sign Languages), and all the others are sign languages of Deaf communities.

Additionally, some languages had numeral systems with optional two-handedness. For this analysis, systems with optional two-handedness were grouped with one- or two-handed systems based on the numeral system presented in the dictionary (however, we discuss them separately below). As shown in Figure 2.4., two major geographic clusters can be seen: two-handed numeral systems in Central Europe and one-handed systems in Asia.

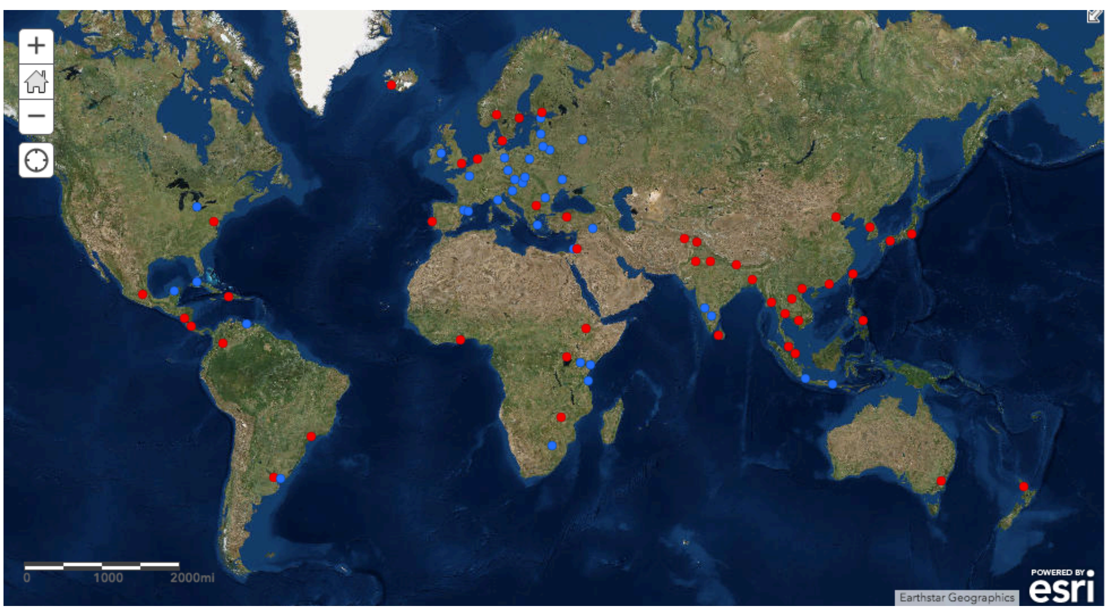


Figure 2.4. Geographic distribution of one- (red) and two-handed (blue) numeral systems across sign languages.

Next, we asked whether the age of the sign language can predict what type of numeral system it has. Although sign languages take time to develop and do not suddenly appear as full-fledged systems, their history is tightly connected to the history of Deaf communities, which often started to develop with the opening of the first deaf school in a country or locale. Therefore, the creation of the first deaf school was our point of reference for the language age in this study. We were able to find such data for 72 out of 82 languages in our sample presented in Table 2.2.

Table 2.2. The dates of the establishment of the first deaf school for the studied sign languages

Language	N system	First Deaf School	Source
Algerian Jewish SL	Two-handed	at least 3 generations/110 years ago	(Lanesman, 2016)
Alipur Sign Language	Two-handed	at least 6 generations	(Panda, 2012)
Austrian Sign Language	Two-handed	1779	(Dotter & Okorn, 2003)
Belorussian Sign Language	Two-handed	1806 (as RSL)	(Basova & Yegorov, 1984)
Bengkala Sign Language	Two-handed	5 generations	(De Vos & Zeshan, 2012)
Catalan Sign Language	Two-handed/One-handed	1800	(Frigola, 2010)
Chican Sign Language	Two-handed	3 generations	(Delgado, 2012)
Croatian Sign Language	Two-handed	1885	SIL
Czech Sign Language	Two-handed	1786	Ethnologue
Estonian Sign Language	Two-handed/One-handed	1866	(Hollman, 2016)
French Sign Language	Two-handed	XVII century	(Desloges & Deschamps, 1779)
German Sign Language	Two-handed	1778	(Günther, Hennies, & Hintermair, 2009)
Hungarian Sign Language	Two-handed	1802	(Bickford, 2005)

Table 2.2. The dates of the establishment of the first deaf school for the studied sign languages (continued)

Language	N system	First Deaf School	Source
Indonesian Sign Language	Two-handed	1930	(Palfreyman, 2015)
Irish Sign Language	Two-handed	1816	Ethnologue
Israeli Sign Language	Two-handed	1930	(Lanesman & Meir, 2012)
Italian Sign Language	Two-handed	1828	(Wittmann, 1991)
Kenyan Sign Language	Two-handed	1962	(H. Morgan, 2017)
Latvian Sign Language	Two-handed	1806	(Wittmann, 1991)
Lithuanian Sign Language	Two-handed	1945	Wiki
Oneida Sign Language	Two-handed	2016	Oneida SL Project
Polish Sign Language	Two-handed	1816	(Bickford, 2005)
Romanian Sign Language	Two-handed	before 1919	Asociația Națională a Surzilor din România, ANSR, 1995
Russian Sign Language	Two-handed	1806	(Basova & Yegorov, 1984)
Spanish Sign Language	Two-handed	1795	(Puente, Alvarado, & Valmaseda, 2009)
South African Sign Language	Two-handed	1863	(Aarons & Akach, 1998)
Tanzanian Sign Language	Two-handed	1963	(Lee, 2012; Tcherneshoff, 2019)
Ukrainian Sign Language	Two-handed	1805	(Basova & Yegorov, 1984)
Uruguayan Sign Language	Two-handed	1910	Ethnologue
Venezuelan Sign Language	Two-handed	1935	SIL
American Sign Language	One-handed	1817	(Shaw & Delaporte, 2011)

Table 2.2. The dates of the establishment of the first deaf school for the studied sign languages (continued)

Language	N system	First Deaf School	Source
Argentine Sign Language	One-handed	1880 - 1910	(Simon, Buscaglia, & Massone, 2003)
Australian Sign Language	One-handed	1860	(Johnston, 2002)
Brazilian Sign Language	One-handed	1857	Wiki
Bangladesh Sign Language	One-handed	1893	(Johnson & Johnson, 2016)
British Sign Language	One-handed	1760 - 1847	(Quinn, 2010)
Bulgarian Sign Language	One-handed	1898	Bulgarian Encyclopedia, ISBN 9789548104340.
Burmese Sign Language	One-handed	1904	(Kamei, 2004)
Cambodian Sign Language	One-handed	1997 (but probably existed before)	(Woodward, Bradford, Sokchea, & Samath, 2015)
Chinese Sign Language	One-handed	1887	(Gertz & Boudreault, 2016)
Colombian Sign Language	One-handed	1924	(Rodríguez & del Pilar Velásquez, 2000)
Costa Rican Sign Language	One-handed	1940	(Woodward, 1992)
Danish Sign Language	One-handed	1807	(Bergman & Engberg-Pedersen, 2010)
Dutch Sign Language	One-handed	1790	(Kimmelman, 2019)
Ethiopian Sign Language	One-handed	1956	(M. Morgan, 2009)

Table 2.2. The dates of the establishment of the first deaf school for the studied sign languages (continued)

Language	**N system**	**First Deaf School**	**Source**
Filipino Sign Language	One-handed	1907	https://web.archive.org/web/20071115152643/http://www.manilatimes.net/national/2007/feb/25/yehey/weekend/20070225week1.html
Finnish Sign Language	One-handed	1850	Ethnologue
Belgian French SL	One-handed	1819	http://dicto.lsfb.be/?lsfb=historique
Ghanaian Sign Language	One-handed	1957	SIL
Hong Kong Sign Language	One-handed	1949	Fischer & Gong (2010)
Icelandic Sign Language	One-handed	1910	(Thorvaldsdóttir & Stefánsdóttir, 2015)
Indian Sign Language	One-handed	1978	(Ulrike Zeshan, Vasishta, & Sethna, 2005)
Indo-Pakistani Sign Language	One-handed	1978	(Ulrike Zeshan et al., 2005)
Japanese Sign Language	One-handed	1878	(Sagara, 2014)
Jordanian Sign Language	One-handed	1964	(Hendriks, 2008)
Korean Sign Language	One-handed	1889	(S. Fischer & Gong, 2010)
Malaysian Sign Language	One-handed	1998	Ethnologue
Mardin Sign Language	One-handed (#10 two-handed)	1930	(Dikyuva, 2012)
Mexican Sign Language	One-handed	1869	Ethnologue
Miyakubo Village Sign Language	One-handed	at least 3 generations	(Yano & Matsuoka, 2018)
Nepali Sign Language	One-handed	1966	(Green, 2009)

Table 2.2. The dates of the establishment of the first deaf school for the studied sign languages (continued)

Language	N system	First Deaf School	Source
New Zealand Sign Language	One-handed	1880	(McKee, McKee, & Major, 2011)
Nicaraguan Sign Language	One-handed	1970	(Flaherty & Senghas, 2011)
Norwegian Sign Language	One-handed	1820	Ethnologue
Portuguese Sign Language	One-handed	1820	https://www.publico.pt/2017/11/14/p3/noticia/o-que-todos-deviamos-saber-sobre-lingua-gestual-em-dez-pontos-1828846
Singapore Sign Language	One-handed	1954	https://sadeaf.org.sg/about-deafness/about-sign-language/
Swedish Sign Language	One-handed	1809	Ethnologue
Taiwanese Sign Language	One-handed	1895	(S. D. Fischer et al., 2011; S. Fischer & Gong, 2010)
Thai Sign Language	One-handed	1950	(Reilly & Suvannus, 1999)
Turkish Sign Language	One-handed	1902	Deringil, S. (2002)
Ugandan Sign Language	One-handed (except #10)	1959	(Lule & Wallin, 2010)
Zimbabwean Sign Language	One-handed	1940	Ethnologue

Figure 2.5. shows that, in fact, among the oldest sign languages, two-handed systems are slightly more frequent; more languages that started to emerge between 1850 and 1900 have one-handed numeral systems, but overall, the regression line is flat.

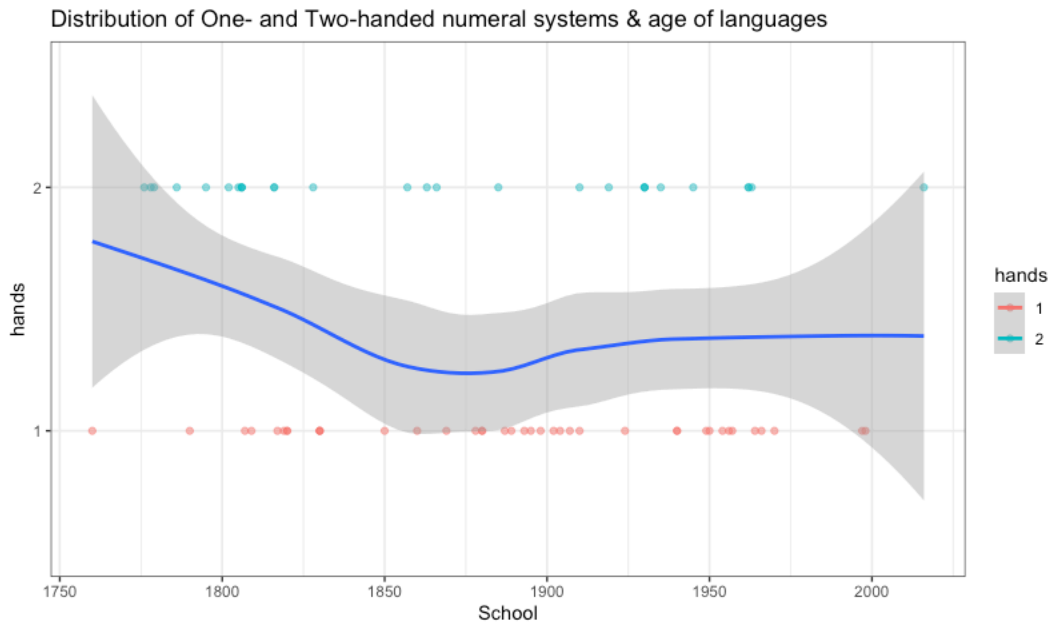


Figure 2.5. Distribution of one- and two-handed numeral systems as a function of language age. The X axis represents time. The top row (cyan) represents two-handed numeral systems. The bottom row (magenta) represents one-handed numeral systems. Every dot represents the date of the establishment of the first deaf school.

We built a binomial logistic regression model with a function *logit* in *R* (R CORE TEAM, 2016) to analyze the relationship between the type of the numeral system (dependent variable) and the date of the establishment of the first deaf school (predictor variable). The result was not statistically significant, suggesting that the age of sign language does not predict the type of numeral system it uses, and older sign languages are not more likely to have one-handed numeral systems.

Next, we examine two- and one-handed numeral systems, and numeral systems with optional two-handedness, in terms of the handshapes, types of iconicity, and structural properties they use, and identify the patterns that can be found inside and between groups.

2.5.2. Two-handed numeral systems

For the first five numerals, all languages with two-handed numeral systems use extended fingers, making use of number-to-number iconicity. The exception is Algerian Jewish Sign language that has a non-iconic handshape for FIVE (Lanesman, 2016). No language used bending fingers instead of extending for basic numerals (unlike the number gestures of Pekai-Alue in Papua New Guinea, according to Bender and Beller (2012).

Based on the way the signs SIX – TEN are formed, two-handed numeral systems can be divided into two subgroups: those that include contact between hands and those that do not. Unlike number gestures, two-handed number signs favored consistency over symmetry. For example, while in hearing cultures the gesture for the number 8 can be represented with four fingers extended on both hands (symmetrically), no deaf community sign language in our sample has a sign EIGHT with such a configuration. Instead, the consistency of the handshape on the non-dominant hand is preserved (i.e., it has FIVE handshape in all numerals from SIX to NINE), and the number of fingers extended on the dominant hand is three. However, cases of a symmetry preference over handshape consistency was found in shared Chican Sign Language, where the number sign for 8 is derived from 4 + 4 (Zeshan et al., 2013). Another shared sign language, Mardin Sign Language, also made use of a similar strategy to form the number sign EIGHT, using a sequential combination of FOUR handshape produced first with fingers facing up and then facing down (Zeshan et al., 2013).

Importantly, two-handed numeral systems always used a consistent strategy: the extended finger always corresponds to one unit, but does not designate a power or a larger number, as for example, in the number gestures used by Indian merchants, where the extended fingers of the left hand designate 1, 2, 3, 4, 5, and the extended fingers of the right hand – 5, 10, 15, 20, 25 (Bender & Beller, 2012), as illustrated by Table 1. Unlike number gestures, in the numeral systems of sign languages there was no segmentation beyond extended fingers, as opposed to, for example, an ancient Babylonian system, where each phalange of each finger was a tally for a different number.

Next, we consider numeral systems that have and do not have contact between two hands and observe common patterns that emerge in such systems.

2.5.2.1. Numeral systems with no contact between hands

In most of the numeral systems with no hand contact (26 of 36), such that the sign SIX is expressed by the extension of five fingers on the non-dominant hand and one on the dominant hand, for the subsequent numerals, the necessary number of fingers on the non-dominant hand is extended, using the strategy of *number-to-number iconicity* (Taub, 2001). The languages that make use of this strategy are mainly clustered in Europe (Italian Sign Language, French Sign Language, German Sign Language, and others), but such numeral systems are also found in Asia (Bangalore Sign Language), and South America (Uruguayan Sign Language, Venezuelan Sign Language and others). As far as the sociolinguistic situation and circumstances of language emergence are concerned, we find this pattern in sign languages of large Deaf communities, as well as in shared sign languages (Zeshan et al., 2013). The languages differed in terms of hand orientation (palm out or inward), but orientation in this group is consistent throughout the counting list (i.e. all numerals SIX – NINE have the same orientation).

One shared sign language that uses this strategy, Mardin Sign Language (Zeshan et al., 2013), has a very particular numeral system. The non-dominant hand only appears in the sign for 10 (all fingers simultaneously extended, using number-to-number iconicity), but the numerals from one to nine are one-handed. Several numbers are expressed through the sequential combination of the sign 5 with other numbers (so that the sign that designates the number 7 is a compound FIVE^TWO). Thus, the system combines simultaneous and sequential means to express number through finger extension.

Sequential combinations also were attested in Chican Sign Language, another shared community sign language (Zeshan et al., 2013). As mentioned earlier, this language also has an instance of symmetry preferred over handshape consistency, where the number sign for 8 is derived from 4 + 4 (Zeshan et al., 2013).

2.5.2.2. Numeral systems that do have contact between hands

Among the ten sign languages that do have contact between the two hands while articulating numbers, we found three distinguishing patterns: contact with open palm, contact with fingers, and contact with the fist (as illustrated in Table 2.3).

Russian Sign Language exemplifies the first pattern (Moroz, 2015; Semushina & Mayberry, 2019). The non-dominant hand with the handshape 6 is oriented palm out, and the dominant hand with corresponding handshape (1 for SIX, 2 for SEVEN) contacts it. This pattern can be observed not only in the sign languages of the former USSR that are historically related to Russian Sign Language (Ukrainian and Belorussian Sign Languages), but also in Tanzanian Sign Language. Tanzanian Sign Language emerged when the first school for the Deaf was established in 1963 (Lee, 2012) and is not historically related to Russian Sign Language. It possibly experienced influence from Finnish Sign Language (Tcherneshoff, 2019), but the numeral systems of these languages are entirely different (Finnish Sign Language has a one-handed numeral system).

The second pattern is found in Irish Sign Language, where the fingers of one hand contact the fingers of the other with both handshapes being different. Additionally, Irish Sign Language makes use of different types of hand contact to form higher numerals: for example, in the sign ELEVEN the dominant hand with one handshape slides on the open palm of the horizontally placed non-dominant hand in the direction away from the signer.

The third pattern was found in Rwandan and Kenyan Sign Languages (H. Morgan, 2017). We were not able to find any available information about Rwandan Sign Language history (although it is an established sign language with a published dictionary), but Kenyan Sign Language traces its history to 1962, when two Deaf schools were first opened in Kenya. While the education was oralist, sign language emerged among the Deaf students. Unlike the Nicaraguan school for the Deaf where Nicaraguan Sign Language originated, Kenyan schools were residential, where the children lived at least nine months of the year, which might have influenced the pace of language emergence. The Kenyan Sign Language numeral system probably emerged in contact with gestures that hearing people in West Kenya (where the first schools were situated) used in the 1960s (Morgan, 2017).

Table 2.3. The number 7 in sign languages, using contact between two hands

Rwandan Sign Language	
Russian Sign Language	
Irish Sign Language	

In Kenyan Sign Language, the hand palm faces the signer, with an extended index finger for ONE, an extended index and middle fingers for TWO, an extended pinky, ring and middle fingers for THREE, pinky + ring and middle + index in V-like form for FOUR, and fist for FIVE. For numbers after 5, Kenyan Sign Language uses two-handed signs where the extended fingers of the dominant hand (with ONE, TWO, THREE, FOUR handshapes) touch the fist (which is FIVE), and TEN is two fists contacting each other (Morgan 2013). Rwandan Sign Language has a different sign for FOUR, with the 4 extended fingers, but other number signs below 10 are the same as in Kenyan Sign Language.

Importantly, although the influence of the hearing number gestures on the numeral systems of these languages can be traced, this influence was likely limited by phonological constraints. As Bender and Beller (2012) discuss, the two-handed number gestures used across Africa often favor symmetry of the handshapes on two hands (6 = 3 + 3), but both Kenyan and Rwandan Sign Languages instead followed the pattern of consistency of the non-dominant hand handshape (instead of symmetric strategy with three fingers extended on each hand, the sign for SIX has FIVE handshape on the non-dominant hand and ONE on dominant hand).

To sum up, in our data two-handed numeral systems in sign languages seem to rely a great deal on *number-to-number iconicity* (Taub, 2001). Despite the wide range of anatomically possible finger combinations and positions, most of the languages under consideration used one common strategy, namely finger extension with an unmarked 5 handshape on the non-dominant hand in two-handed signs.

Note that the consistency of the dominant hand handshape is valued more than handshape symmetry. Although the number 8 could be represented symmetrically by extending four digits on each hand, in our sample this construction is only attested in shared, but not deaf community sign languages. Finally, the strategies that include contact between hands (such as Russian, Ukrainian, Belorussian, Rwandan, Tanzanian, Kenyan, Irish sign languages) also rely on *number-to-number iconicity*, but less transparently.

All sign languages of deaf communities preferred simultaneity over sequentiality in the basic number signs (atoms): there were no handshape changes. However, in shared sign languages sequential strategies were observed.

Overall, we found less variability in the strategies that sign languages use than Bender & Beller (2012) observed across number gestures of hearing cultures.

We now move to the description of one-handed numeral systems and the strategies they use in terms of iconicity, systematic patterns, and phonological contrasts.

2.5.3. One-handed numeral systems

Forty-six sign languages in our data have one-handed numeral systems. If two-handed numeral systems cluster in central Europe, one-handed numeral systems are frequent in Asia and America. The distribution and frequency may be influenced by multiple factors, such as contact with number gestures of hearing cultures or other sign languages. For example, there might be an influence of American Sign Language on local sign languages through the migration of American educators, as happened in Thailand (Woodward, 1996), Costa Rica (Woodward, 1991) and several countries of Asia and Africa (Fenlon & Wilkinson, 2015). Several sign languages in our data have numeral systems identical or similar to that of ASL: Ethiopian Sign Language, Costa Rican Sign Language, Danish Sign Language (signs for numbers from 6 – 9), Filipino Sign Language, Ghanaian Sign Language, Icelandic Sign Language, Singapore Sign Language. We note that in these languages the higher numbers differ from ASL, although based on the same handshapes.

In our sample, there was only one shared sign language with a one-handed numeral system: Miyakubo Sign Language, signed on an isolated community in Japan (Yano & Matsuoka, 2018).

This language has a very particular numeral system with signs for 1 – 5 represented by extended fingers and for numbers 6 – 10 articulated on the signer's cheek. In the sign SIX, the signer contacts the cheek with an extended index finger, in the sign SEVEN with two fingers extended together (not spread), and the pattern continues. The cheek therefore serves as a sub-base but is different from the sign for FIVE.

All the sign languages in our data do rely on number-to-number iconicity for at least some of the first five numbers. The exception was the numeral systems in Argentinian Sign Language. The language has two numeral systems (Johnson & Massone, 1992). The historical roots of this particularity can be found in the separate schooling for deaf boys and deaf girls in Argentina. The currently dominant Argentinian Sign Language numeral system comes from the schools for boys and does not rely on any kind of iconicity; it also extensively uses contact with body, neck, and face in different locations. These signs are not identifiable as numerals by a non-signer, and their meaning is not transparent. They do not seem to be derived from manual counting. Sagara (2014) provides the interpretation that these numerals can be related to the name signs of particular people in the first deaf school, but little is known about the origin of this numeral system.

The majority of other one-handed numeral systems still make use of number-to-number iconicity for numbers from 1 to 5 (however, several languages stop at 4), but then the strategies start to differ dramatically, either relying on orthographic iconicity or using some arbitrary pattern. We now discuss these strategies separately.

2.5.3.1. Othographic iconicity in one-handed numeral systems

While we might expect that sign languages might rely on iconicity in a similar and straightforward way, it is not the case. The system might rely on some number notation (Arabic digits; Eastern Arabic Digits) or written forms of the linguistic numbers (THOUSAND in Russian

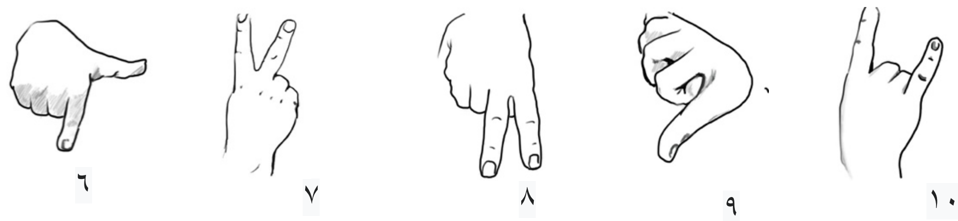
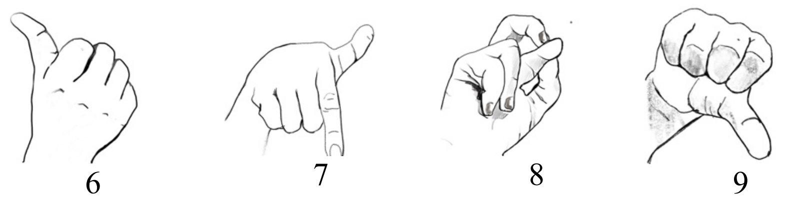
Sign Language has the T handshape, which is the first letter of *тысяча*, the Russian word for *thousand*). The relationship can become less evident with time: it has been reported that the American Sign Language sign for THOUSAND used to have a distinct M handshape, with M representing thousand in Roman numerals and being the first letter of the French *mille* (Fischer & Gong, 2011), but later the handshape mutated to the bent B.

In our sample, we found that for basic numerals sign languages tend to use iconicity representing numeral notations, but not the letters of the written number word, which are frequently used for operators instead. The iconic strategy may be borrowed for a range of numbers or for individual number.

Several sign languages in Asia base their numeral systems on the conventional number gestures of the hearing Chinese speakers, either completely borrowing the set of handshapes (as in Hong Kong Sign Language, which uses number gestures from North China) or borrowing some individual gestures, most frequently 6 (as Sri Lankan Sign Language).

A group of languages relies on orthographic iconicity. In our data, seven sign languages have numeral systems that rely entirely on number-to-number iconicity for the numbers 1 – 5 and on orthographic iconicity for the numbers 6 – 9. For example, Turkish Sign Language and Pakistani Sign Language base iconicity on Arabic-Indic numerals. Chinese and Hong Kong Sign Languages integrated the Chinese number gestures that bear some degree of hieroglyphic system resemblance (Yang, 2016). Jordanian Sign Language numerals iconically resemble the Eastern Arabic Numerals that are currently used in conjunction with Arab alphabet, while Ugandan Sign Language bases its numbers from 6 to 9 on Arabic digits (with the exception of 10, which is a combination of two fists which are FIVE handshapes in this language (Table 2.4).

Table 2.4. Examples of numeral systems with orthographic iconicity

Jordanian SL (Eastern Arabic Numerals)	
Ugandan Sign Language (Arabic Digits)	

As noted by Zeshan et al (2013), shared sign languages do not employ orthographic iconicity in their numeral systems, unlike the deaf community sign languages that developed in close contact with education. Thus far our data confirm this observation.

2.5.3.2. Arbitrary patterns

Many one-handed sign languages use the iconic (number-to-number iconicity) numerals for the numbers 1 to 5 and then employ a pattern of finger extension that is not based on number notation and is not transparent to those who are not familiar with the language. Alternatively, numbers from 6 to 9 can use different arbitrary handshapes without a predictable systematic pattern.

An example of a systematic pattern can be Bulgarian Sign Language, where the numbers 1 – 5 are signed with palm out: TWO has middle and index fingers extended, THREE extends the index, middle, and ring fingers, for FOUR all fingers are extended (but not the thumb), all demonstrating number-to-number iconicity. The sign SIX is signed with the thumb up, palm facing out, the number sign SEVEN is formed through extension of thumb and index finger; for EIGHT the thumb, index, and middle finger are extended; NINE has the thumb and all the fingers extended except for the pinky finger, which is bent, while TEN has index and pinky fingers extended, while the other fingers form a fist with thumb on top of other fingers.

Numbers can be formed through finger extension starting either from the thumb (as in Bulgarian and Mexican Sign Languages) or the pinky finger (as in Finnish and Cambodian Sign Languages), or through contact between the fingers, as in American Sign Language and several languages related to it.

Brazilian Sign Language, on the other hand, also uses a non-iconic and non-transparent numeral system, but there is no predictable finger extension pattern (Madalena, Correa, & Spinillo, 2019). Signs from ONE to FOUR are based on number-to-number iconicity, the sign FIVE is not iconic (index and middle fingers bent, palm out), number SIX is signed with a thumb up, number SEVEN with index finger pointing to the left, EIGHT with the fist (palm out), and NINE with thumb facing down. The number 10 is signed as a sequence ONE ZERO. Table 2.5. illustrates five non-iconic and non-transparent strategies to sign the number 8.

Table 2.5. The sign for 8 in Bulgarian, Finnish, American, Brazilian, and Cambodian Sign Languages.

Bulgarian SL Finnish SL American SL Brazilian SL Cambodian SL

It was mentioned earlier that number signs can demonstrate exceptions to the general rule and include handshapes that are not found elsewhere in the language. We see such examples both in numeral systems with orthographic iconicity (Ugandan and Indo-Pakistani sign languages, according to Zeshan et al., 2013) and with systematic patterns of finger extension, as in Australian Sign Language (Johnston, 1989) and American Sign Language (Zeshan, 2013).We can argue that the systematicity of the pattern inside the system (i.e., fingers being extended/contacting each other in a certain order) required the use of some unusual handshapes.

How are the one-handed numeral systems different from the number gestures (mostly two-handed)? In their analysis of number gestures, Bender & Beller (2012) do not distinguish between arbitrary forms (not based on any other number notation) and iconic ones (based on some other form of number notations) and group together the symbolic systems that do not rely on number-to-number iconicity. An example of an arbitrary system could be the one used by Arusha Maasai in Tanzania, and an example of an iconic system could be the Chinese number gesture system discussed above. They hypothesize that the systems that do not rely on number-to-number iconicity could provide a cognitive advantage for working memory (Bender & Beller, 2012; Zhang & Norman, 1995), but among the number gestures, such systems constitute a minority. Sign languages, on the other hand, rely on such strategies abundantly.

Having described some of the iconic and not iconic strategies, we now turn to the description of the phonological contrasts that are used in numeral systems to form a set of basic numerals with the one hand.

2.5.3.3. Handshape and movement contrasts in one-handed numeral systems

As discussed above, in one-handed numerals the number of extended fingers often is not predictive of the numerical value: three extended fingers can represent both 3 and 8, as in Australian, Bulgarian and several other sign languages. To distinguish between the two interpretations, sign languages use different strategies.

The most frequent strategy is changing selected fingers: for example, in Finnish Sign Language numbers ONE – FIVE are signed through extension of fingers starting with the index, while to sign SIX, the pinky is extended, and then for subsequent numbers fingers are extended in the opposite direction (Takkinen, Jantunen, & Seilola, 2016), and the sign for TEN is a thumbs up. Among the languages that also use different selected fingers to distinguish between, for example, THREE vs. EIGHT and FIVE vs. NINE are British Sign Language, Cambodian Sign Language, Dutch Sign Language, Nepali Sign Language, and Vietnamese Sign Language.

Interestingly, in some two-handed numeral systems, such as Russian Sign Language, the numbers TWO and THREE can be signed with different selected fingers (using the thumb or not). As soon as the number of fingers equals three, it is interpreted as the number 3 (Semushina, 2015). However, in New Zealand Sign Language, variation is found inside a one-handed system, and differences with signs with three fingers extended (whether it represents 8 or 3) may depend on mouthing (McKee et al., 2011).

Another strategy is a change of orientation, where the signs THREE and EIGHT will have the same selected fingers but would be minimal pairs by the palm facing either away or towards the signer. This strategy can be exemplified by the one-handed numerals of Catalan Sign Language (Fuentes & Tolchinsky, 2004). This strategy can be used for all numbers 6 – 10, or for some, as in Norwegian Sign Language (9 vs. 4, 8 vs. 3), and Dutch Sign Language (5 vs. 10).

We previously explained that sign languages typically use movement morphemes to express a range of numerals (such as tens, thousands), but not numbers under 10. However, Colombian Sign Language (Castro Pinto, 2019) does use internal movement to form the numerals SIX – TEN. In this language, with a number system that appears to be quinary, the sign ONE is an extended index finger, and the sign SIX is an extended index finger that bends twice, for SEVEN , an extended index and middle fingers bend twice. Thus, ONE – SIX, and TWO – SEVEN, THREE – EIGHT, FOUR - NINE are minimal pairs in movement.

Swedish Sign Language and Nicaraguan Sign Language also have internal movement in basic numbers, but these movements do not seem to be morphemes for specific arithmetic operation, such as ($5 + n$) as in Colombian Sign Language.

Unlike sign languages, in the number gestures of hearing cultures the resolution of ambiguity is often connected to the use of spoken language; for example, when using Arusha Maasai finger counting system, the listener has to repeat the number that is shown to them (Bender & Beller, 2012; Gulliver, 1958).

We now consider the last category of numeral systems: ones that have optional two-handedness and therefore can't be categorized with one or two-handed systems.

2.6. Variation: numeral systems with optional two-handedness

The numeral system of Catalan Sign Language was described as optionally two-handed. In this language, the number 8 may be signed both by two hands (FIVE handshape on the non-dominant, THREE handshape on the dominant hand, both palms facing out) or by one hand (dominant, with 3 handshape). In this case, signs for THREE and EIGHT are minimal pair in orientation, as well as pairs FOUR and NINE, or TWO and SEVEN (Fuentes et al., 2010). Asian Sign Bank lists both two- and one-handed variants for Indonesian Sign Language used in Jakarta.

A similar pattern can be observed, if we consider language change in Russian Sign Language (Semushina, 2015). As described in the previous chapter, Russian Sign Language has a two-handed numeral system; numbers 6 – 9 are signed with two hands in contact, where the sign for SIX is composed of a non-dominant hand FIVE handshape, and a dominant hand with a ONE handshape. However, younger signers of RSL in the data collected for that project also produced one-handed versions of the numbers SIX – NINE. In this case, as in Catalan Sign Language, the signs ONE – FOUR become minimal pairs in orientation for signs SIX – NINE.

In Estonian Sign Language, two-handed numerals are also used alongside with one-handed numerals, but the signs ONE – FOUR and SIX – NINE have different selected fingers, while having the same orientation (Hollman, 2016).

Although several younger signers report using one-handed version as their default way to refer to numbers, older singers of Russian Sign Language often reject this version as informal. They understand it, but do not accept it to be used in any formal context such as public speaking or interpreting for someone who is not the signer's close friend or family (Semushina, 2015). In Estonian Sign Language, one-handed numerals are reported to be more widespread among younger signers, but a difference in register is not described (Hollman, 2016). For Catalan Sign Language, such a difference in register is not reported either, nor are the potential sources of variation.

In Nicaraguan Sign Language, the one-handed numeral system replaced the older two-handed one. Flaherty & Senghas (2011) explain that residual traits from original two-handed signs can still be observed in the new numeral system, although *number-to-number* iconicity is lost. The new one-handed number signs that they documented also have specific movements that one-handed numerals did not have. Such a pattern is not observed for the one-handed numerals Russian, Estonian and Catalan Sign Languages: they only differ from their two-handed counterparts by the drop of the non-dominant hand.

However, coexisting numeral systems might be completely different. As mentioned earlier, Argentinian Sign Language also has two co-existing numeral systems, one- and two-handed, but they might be etymologically unrelated. The two-handed system, relying on number-to-number iconicity, is only found in older women who went to a girls-only deaf school in Buenos Aires

(Fuentes et al., 2010). The one-handed numeral system of Argentinian Sign Language is not iconic at all.

In Argentinian Sign Language, the two-handed system might be disappearing together with the dialect that it belongs to. However, although the data is limited, in Catalan, Russian, and Estonian Sign Languages the two numeral systems seem to coexist, and so far the tendency towards replacing two hands with one has not been reported by researchers. Thus, these data do not support the hypothesis that numeral systems evolve towards less iconic one-handed form either.

2.7. Discussion

Overall, our data show that numeral systems of the world's sign languages demonstrate many similarities to each other. Despite the wide variety of possibilities that the manual articulators and the human body offer, they use a limited number of strategies. This is especially evident in two-handed numeral systems, where only a small subset of languages used strategies with hand contact. Even among languages that are unrelated to each other, the strategies converge.

Only two sign languages use a location other than the hands and neutral signing space: Argentinian Sign Language and Miyakubo Sign Language have number signs that contact the head.

This contrasts to the number gestures of hearing cultures that demonstrate a wider variety of strategies, both in terms of articulator (from finger segment to the whole body) and in the use of articulators to express power/range (from finger segmentation to the body tally).

At the same time, even though the iconic strategy of fingers extension is available, not all languages use it. Forty-six out of eighty-two languages use one-handed numeral systems, where the use of number-to-number iconicity is limited. Sometimes number signs bear iconic resemblance to a specific number notation, but most systems rely on that strategy only partially, if at all. This also contrasts with the number gestures of hearing cultures, which are mostly iconic – but, as Bender & Beller note, not all of them, and despite iconicity, number gestures vary tremendously across cultures.

The degree of number-to-number iconicity present in sign language numeral systems also does not correlate with sign language age and setting of emergence; the oldest sign languages in our sample have both one- and two-handed numeral systems, and do not seem to "evolve" away from such iconicity and asymmetry, although that tendency does exist for lexical signs (Frishberg et al., 1984). If anything, older sign languages use two-handed systems slightly more often (the relationship was not statistically significant). While some languages have optionally two-handed systems, our data do not support the idea that two-handed systems are generally quickly replaced by one-handed ones. The case of Nicaraguan Sign Language stands out as an exception, not a rule.

Sign languages attributed to the same family may have very different numeral systems. For example, Russian Sign Language and French Sign Language have two-handed numeral systems (that also differ from each other), and American Sign Language has a one-handed system. All three languages are attributed to the Old French Sign Family (Frishberg et al., 1984.; Grenoble, 1992). However, the data on sign language families was not always available, and often there is no agreement in the literature about the status of some languages. Claims are often made based exclusively on historical information, but the sources are often conflicting. For example, while Grenoble (1992) and Wittmann (1991) describe Russian Sign Language as a member of the French Sign Language family, Bickford (2005) contests this relationship. Promising lexicostatistic approaches might shed more light on sign language families (Abner et al., 2020; Yu, Geraci, & Abner, 2018) and make more detailed analysis of their numeral systems possible.

In our data, a geographic clustering of numeral systems was observed: numeral systems of the same type are likely to be neighboring, with two-handed numeral systems being frequent in Central Europe and one-handed systems prevailing in Asia and America. A similar phenomenon was observed in spoken languages (Comrie, 2013). However, these data should be interpreted with caution because of the issues of potential language contact and linguistic imperialism. The influence of American Sign Language on the local sign languages or even replacement of them by the foreign-based variants has been documented extensively in Asia and Africa, where foreign educators established schools or otherwise influenced education (Edward & George Akanlig-Pare, 2021; Woodward, 1992, 1996). Thus, in some areas the prevalence of currently used one-handed systems, sometimes directly borrowed from ASL, does not give us information about the numeral systems that might have preceded them in indigenous communities.

We have identified several common principles that numeral systems of different sign languages employ. First of all, simultaneous combinations are preferred over sequential ones. While one-handed numeral systems with several number handshapes sequentially produced within one sign can exist and are observed in two shared sign languages, 80 sign languages in our data set instead have number signs without handshape change, even if this produces asymmetrical two-handed signs that are in general dispreferred by sign language phonology. None of the deaf community sign languages demonstrated sequential constructions in basic numerals.

Second, handshape consistency is favored over symmetry. While in hearing cultures the gesture for number 8 can be represented with four fingers extended on both hands (symmetrically), no deaf community sign language has a sign EIGHT with such a configuration. Instead, the consistency of the handshape on the non-dominant hand is preserved (it is always a FIVE handshape which is not necessarily iconic, as in Algerian Jewish Sign Language). However, sequential and asymmetrical strategies were attested in shared sign languages, as well as in a number gestures of hearing cultures. On the other hand, shared sign languages demonstrated a variety of complex numeral bases that were attested neither in deaf community sign languages nor in number gestures. Importantly, such rare bases were described in spoken languages.

Third, in signs with number-to-number iconicity, selected fingers are always neighboring (i.e., there are no sign languages where the pinky finger and thumb selected can mean TWO, but there are languages where such a hand configuration is not iconic and means SIX).

Fourth, the overwhelming majority of sign languages (79 out of 82) do not have internal movements in basic numeral signs, or atoms. Even when movement is present, it is not morphemic (with the exception of Colombian Sign Language). Instead, in one-handed numeral systems, handshape and orientation contrasts that distinguish different number signs are more widespread. Movement in number systems usually appears to form numbers after 10 and is usually morphemic in both one-handed and two-handed numeral systems.

In his cognitive typology of numeral notations, Stephen Chrisomalis (2004, 2019) describes several cross-cultural patterns of numerical notation that independently emerged in unrelated societies. He also discusses the diachronic change in number notation in terms of transformation and replacement and concludes that there are a limited number of patterns observed across systems, but no linear trend and no final, best cognitively optimal notation. We argue that this is true for the number systems of sign languages as well: despite a wide variety of available strategies, only a limited set of patterns is used but, crucially, there is no single strategy that all languages converge on.

Often the theories that link the body and hand representations of number to its acquisition and processing operate on the premise that these representations are iconic (Alibali & DiRusso, 1999; Gunderson et al., 2015). However, our work shows that the numeral systems of sign languages do not necessarily rely on iconicity. In fact, most of the sign languages in our sample only use it in a limited way. Crucially, even if iconicity is present, it is not always transparent to the naive user, such as a young child learner of Turkish Sign Language who isn't yet familiar with Arabic Indic digits.

However, there can still be language-specific differences in the acquisition of number, as has been demonstrated in spoken languages (Almoammer et al., 2013; Barner, Libenson, Cheung, & Takasaki, 2009; Marušič et al., 2016; Meyer, Barbiers, & Weerman, 2018; Miller, Major, Shu, & Zhang, 2000). The manual modality or structure of the numeral system might also affect number acquisition or processing independently of iconicity. For example, it has been shown that the structure of two-handed numerals influences parity judgments in German and Italian Sign Languages (Chinello, de Hevia, Geraci, & Girelli, 2012; Iversen, Nuerk, Jäger, & Willmes, 2006; Iversen, Nuerk, & Willmes, 2004). In similar tasks, notation effects are found in spoken languages with various orthographies. For example, studies of the spatial numerical association of response codes (SNARC effect) show that users of languages written from left to right respond faster on larger numbers when they are represented on the right part of the screen and to smaller numbers on the left side (Dehaene, Bossini, & Giraux, 1993), but the effect differs in languages written from left to right (Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017). Two-handed finger counting practices were also shown to contribute in the SNARC effect (Fischer, 2008). However, in the one-handed numeral system of American Sign Language, a SNARC effect was not found (Bull, Blatto-Vallee, & Fabich, 2006; Semushina & Mayberry, under review). Thus, when processing a two-handed numeral sign, there might be a direction of "reading", while this would not be the case for one-handed numerals.

While these notation or language effects are mild and obviously do not mean that some languages or some gestures give their users a cognitive advantage over others (Chrisomalis, 2021), studying these effects and controlling for them in studies of number acquisition can shed more light onto the nature of number representation. The structure of sign language numeral systems can yield unique insights in number processing. For example, Friedmann, Haluts, & Levy, (2021) recently identified a particular number processing deficit that affects reading and production of decimal structures, but not of place-value structures. Identifying this deficit became possible because it was studied in a user of the numeral system of Israeli Sign Language. This system allows two ways of signing multidigit numbers: one with the use of powers (84 – EIGHT-TENS FOUR), and one relying on place-value (84 – EIGHT FOUR).

In conclusion, we suggest that because numeral systems of sign languages are systematic, conventional, productive, and integrated to the structure of language (i.e., the signs follow the same phonological constraints) just as numeral systems of spoken languages are, that theories of numerical cognition and acquisition must accommodate sign languages as well while taking into account the possibility of modality-specific properties.

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Chapter 3. Numeral Incorporation in Russian Sign Language: Phonological Constraints on Simultaneous Morphology

Abstract

This paper looks at numeral incorporation in Russian Sign Language (RSL). Numeral incorporation is the simultaneous combination of a numeral and a base sign into one sign. Incorporating forms typically use the numerical handshape combined simultaneously with the movement, location, and orientation of the base lexical sign; for example, “three months” will be expressed through an incorporating form 3_MONTH. RSL is a language with a two-handed numeral system. Investigating two-handed numeral incorporation in RSL provides important insights into the constraints on numeral incorporation across languages as well as into the phonological structure of RSL.

Numeral incorporation is a general preference in RSL that is highly constrained: not all calendric terms can incorporate, and not all numbers can be incorporated. For example, the sign MONTH incorporates numbers one through nine (one through five are one-handed, and six through nine are two-handed). The incorporating one-handed form 5_MINUTE exists, while the two-handed *6_MINUTE form does not occur (that is, its meaning is expressed sequentially), and the sign DAY does not incorporate numbers at all. These limits are conditioned for semantic (lexical frequency, pragmatics) and phonological reasons. Because the numeral system of RSL is two-handed, the results show, first, that numeral incorporation is not limited to one-handed numerals. In addition, the results indicate that limits on numeral incorporation are not universal across sign languages. In RSL, each paradigm shows specific numeral incorporation limits that are phonologically conditioned. These limits are explained by the interaction of phonological rules at all levels of sign

sublexical features for both the numeral and lexical sign: location, orientation, handshape, and movement.

The location and orientation parameters of sign, however, have not been previously noted as being factors that limit numeral incorporation and sign complexity in a sign language. Our analyses, from both the numeral incorporation data and from elicitation and RSL corpus data, show that location and orientation function as phonological constraints in the composition of two-handed signs. Specifically, location and orientation operate in handshape symmetry restrictions. Our analyses also show that signs located on the head do not allow two-handed numeral incorporation. The corpus analyses corroborated this finding: all two-handed signs on the head that we found in our RSL corpus were symmetrical and frequently included weak drop, such that we found no asymmetrical two-handed signs on the head. Another symmetry restriction relates to orientation. Analyses of the RSL numeral incorporation data and the RSL corpus data and dictionaries show that RSL disprefers asymmetrical handshapes in two-handed signs having lateral orientation (palm facing the central line) (Fenlon et al. 2013).

3.1. Introduction

One of the particularities of sign languages (in comparison to the spoken ones) is the presence of two independent articulators. Although in principle the simultaneous articulation of two signs is possible, in reality it occurs only in highly constrained conditions, such as in the case of weak freeze, or passive hand hold that may be phonetically, syntactically, or semantically motivated (Kimmelman, Safar, and Crasborn 2016), in classifier constructions (Eccarius and Brentari 2007), or in poetic discourse (Crasborn 2006). Independent of simultaneous articulation, there exist two-handed signs that require both hands to be involved in the expression of a single sign. Anatomically, the signer's two hands are identical, yet even in two-handed signs not all combinations of handshapes, locations, and movements are allowed on both hands. Several constraints limiting sign complexity have been described for sign language phonology. Some constraints are claimed to be applicable to all signs (for a review, see Sandler 2012), while other constraints have been described specifically for two-handed signs (Crasborn and Van der Kooij 2013; Eccarius and Brentari 2007; Kimmelman, Safar, and Crasborn 2016; Morgan and Mayberry 2012). Although initially observed in different sign languages, such as American Sign Language (Battison 1978), Sign Language of the Netherlands (van der Kooij and Crasborn 2008) or Kenyan Sign Language (Morgan and Mayberry 2012), many of these constraints are relevant to other sign languages as well (Sandler 2012). The goal of the present study is to describe complexity constraints on one- and two-handed signs in Russian Sign Language (RSL), looking specifically at numeral incorporation. Numeral incorporation is a morphophonological phenomenon attested in most sign languages of *large Deaf communities* (a term used by Nyst, 2012); specifically, it is a combination of a numeral and a base sign into one sign. Typically, incorporating forms insert the numerical handshape into the movement, location, and orientation of the base lexical sign. Numeral incorporation shows typological similarities across different sign languages: it mainly occurs in calendric or measurement terms (Sagara and Zeshan 2013), such as year, month, or hour, which all incorporate numbers in RSL. Being a moderately productive and highly constrained process, it can yield unique insights into the morphophonology of sign languages, especially when compared cross-linguistically.

The present study describes numeral incorporation in contemporary RSL by focusing on sign complexity constraints that restrict numeral incorporation both in terms of lexical roots and numbers. RSL uses a two-handed numeral system, while calendric terms are usually one-handed. Little is known about the morphophonological structure of RSL (Grenoble 1992; Kimmelman

2017; Zaitseva 2000), so the present study represents a first step towards a phonological analysis of RSL. The paper is structured as follows. First, we briefly describe numeral incorporation in sign languages and constraints on sign phonological complexity. Next, we present the RSL numeral system, calendric terms and their variation. Third, we describe and explain the RSL paradigms that allow (or disallow) numeral incorporation, along with the phonological constraints they reveal. By paradigms, we mean a set of linguistic items that form mutually exclusive choices, formed through numeral incorporation, such as WEEK, 2_WEEK, 3_WEEK, 4_WEEK, 5_WEEK).[3] Finally, we consider alternative explanations of the observed phenomena.

3.2. Background

3.2.1. Numeral incorporation

Aronoff, Meir, and Sandler (2005) point out a peculiarity of sign language morphology: these languages have both sequential (where the morphemes are organized in a linear way) and simultaneous (where morphemes are simultaneously superimposed) morphology. Comparing ASL and Israeli Sign Language, they argue that simultaneous morphological processes seem to be similar across these two languages, while sequential morphological processes differ significantly.

One simultaneous morphological processes attested to in most developed sign languages is numeral incorporation. First described for ASL by Stokoe (1965), it is generally defined as the inclusion of a numeral marker within another single sign (Liddell 1996). Numeral incorporation has been described to occur in Japanese Sign Language (Ktejik 2013), Kenyan Sign Language (Morgan 2013), Catalan and Spanish Sign Languages (Fuentes et al. 2010), Taiwan Sign Language (Fischer, Hung, and Liu, 2010), and Argentine Sign Language (Johnson and Massone

[3] - The term paradigm is adopted from Liddell (1996).

1992), among others. After examining data from 21 sign languages, Sagara and Zeshan (2016) observed typological similarities in numeral incorporation cross-linguistically. The most frequent paradigms of numeral incorporation are signs for time units and calendric terms, money or currency, and school grade. Calendric terms are lexemes that define different parts of the calendric cycle, both man-made and natural (Petruck and Boas 2003). Although Sagara and Zeshan (2013) propose that numeral incorporation may be restricted to sign languages, similar phenomena have also been attested in the spoken languages of Kabardino-Cherkessian, Adygean (Moroz 2015), and Nootka (Stonham 1998). In these languages, numeral incorporation is sequential and is not restricted to calendric terms (unlike in sign languages), but nouns and incorporated numerals also become one phonological unit. Despite evidences that shared (or village) sign languages—which emerge in areas of a high incidence of deafness and are used by both the deaf and hearing members of the local community—often lack simultaneous constructions (Nyst 2012), simultaneous morphology in the derivation of numerals, multiplication strategies, and restrictive numerals (such as “only two”) have been observed in Alipur Sign Language (APSL) and Mardin Sign Languages (MarSL) (Zeshan et al. 2013). Data on numeral incorporation in calendric terms in village sign languages are scarcer. Le Guen (2012) mentions that Yucatec Maya Sign Language (YMSL) productively uses numeral incorporation for the sign DAY (not observed in the spoken language of this community) and has lexicalized items for IN ONE DAY, IN TWO DAYS, or IN THREE DAYS, but not *IN FIVE DAYS. However, the examples given are sequential, rather than simultaneous, in nature where a number sign precedes a lexical one.

A distinguishing characteristic of numeral incorporation is that it is highly phonologically constrained in all sign languages. Not all time signs can incorporate numerals (for example, in

RSL MINUTE allows numeral incorporation, while SECOND does not), and not all numerals can be incorporated. For example, the number two is incorporated by most time signs in RSL, the number twelve is only incorporated by one sign, and the number twenty is never incorporated. Being partially lexically restricted, numeral incorporation is regularized by the general phonological constraints of a given language.

Although several RSL studies mention numeral incorporation (Korolkova 2013; Moroz 2015; Zaitseva 2000), formal analyses of numeral incorporation in RSL have not been conducted to date. When a numeral limit has been mentioned in the literature, it has been assumed to be five for all paradigms (Korolkova 2013). The numbers one through five are one-handed in RSL, while the numbers six through ten are articulated with two hands. This assumption would predict that two-handed numerals are not incorporated. That is, the form 5_HOUR (five hours) or 5_MINUTE (five minutes) would be possible, while 6_HOUR (six hours) or 6_MINUTE (six minutes) would not be. However, as we find in the present analyses, this is not always the case. Rather, paradigms vary significantly in RSL in relation to phonological constraints on numeral incorporation. Some signs allow incorporation of two-handed numerals (for example, HOUR). Some signs only allow incorporation of one-handed numerals (for example, MINUTE). Other signs never incorporate (for example, DAY). The question we address here is what specific phonological constraints explain the limits on these paradigms.

Our fieldwork on numeral incorporation in RSL revealed thirteen measurement signs typologically expected to incorporate numbers: eleven incorporate numerals, and two do not (see Table 1 for a summary). We compared and contrasted the numeral incorporation paradigms as a function of their incorporation limits. The hypothesis we tested here is that limits on numeral incorporation are conditioned by the interaction of phonological constraints at all featural levels of sign: orientation, location, handshape, and movement. Discovering numeral incorporation constraints as a function of featural level can open the door to future phonological analyses of RSL. This approach also allows us to determine the degree to which featural complexity constrains simultaneous morphological processes across sign languages.

Previous research (Kubuş 2008; Mathur and Rathmann 2010) has proposed that the level of phonological complexity allowed in a sign language explains numeral incorporation limits. Constraints on movement and handshape complexity have been described as a major limiting factor for numeral incorporation in ASL and German Sign Language (DGS; Mathur and Rathmann 2010), as well as Turkish Sign Language (TID; Kubuş 2008). Here we investigate the impact that each feature of sign has on numeral incorporation in RSL, not only movement and handshape, but also location, orientation, and contact preservation.

While location is considered one of the most salient features in sign language phonology (Rozelle 2003), orientation (Battison 1978) and contact (Friedman 1975; Mandel 1982) are now traditionally regarded as secondary parameters (Sandler 2012). However, they also may play a major role in phonotactic constraints. Contact is one of the subordinate categories of location (Sandler 2012). According to Battison (1978) and Rozelle (2003), contact may serve as a "diagnostic test" for markedness: signs with marked handshapes are more restricted in where and how they can contact the place of articulation.

Orientation is considered an inherent feature of hand configuration and location (Brentari 1998; van der Hulst 1996). As our work shows, when interacting with other features, orientation limits the handshapes that can occur in two-handed forms of numeral incorporation. We now examine the constraints on two-handed signs in more detail before turning to our data and analyses.

3.2.2. Complexity Constraints in Sign Languages: One- and Two-Handed Signs

Not all combinations of the articulators' movements and positions are allowed in the world's sign languages. As Sandler (2012) points out, following Hockett (1960), these constraints reflect duality of patterning (meaningful units are composed from meaningless elements), which is a design feature of all human languages and not found in any animal communication systems. Several constraints have been described for the world's sign languages that limit the overall complexity of any sign: for example, symmetry and dominance conditions for two-handed signs (Battison 1978), selected and unselected finger constraints (Mandel 1981) and internal movement constraints (Mandel 1981; see Sandler 2012, 2017 for a review). Although initially proposed for particular sign languages, these constraints were later argued to be applicable to sign languages of large Deaf communities (Sandler 2012), although cross-linguistic violations have been found for initialized signs (Sandler 2017). Constraints may operate at the level of a free morpheme or a syllable (which in sign language is understood as a movement segment or simultaneous movements), which constitutes the visual equivalent of sonority (Brentari 1998; Perlmutter 1992; Sandler 2010). Constraints also operate on all featural levels. We turn now to the constraints relevant for two-handed signs.

While investigating the phonological structure of ASL, Battison (1978) noted that not all handshapes and movements can occur in two-handed signs. The restrictions mainly apply to the non-dominant hand and the way it interacts with the dominant hand in sign production. Based on these observations in ASL, Battison formulated the Symmetry and Dominance conditions for monomorphemic signs that were later argued to be relevant for the structure of many sign languages (Sandler 2012):

> <u>Symmetry condition:</u> If both hands move independently during sign articulation, then both hands have to be specified for the same location, same handshape, the same

movement (performed simultaneously or in alternation), and the specification for orientation must be either symmetrical or identical.

Dominance condition: If the two hands do not share the specification for handshape, then one hand must be passive, while the active one articulates movement. The handshape specification of the passive hand is restricted to a set of unmarked handshapes: A, S, B, 5, G, C, and O.

The so-called unmarked handshapes have common properties. First, they are the most frequent in ASL (and in other sign languages too), geometrically distinct, and perceptually salient. Second, these handshapes are among those first acquired by children (Boyes-Braem 1990; Henner, Geer, and Lillo-Martin 2013; Marentette and Mayberry 2000). Based on the symmetry and dominance condition for movement and handshape, Battison proposed a classification of ASL two-handed signs: type 1 signs are balanced for both handshape and movement; type 2 signs have the same handshape but are unbalanced for movement (only the dominant hand moves); and type 3 signs have different movement but the same handshape. According to Battison (1978), signs in which both hands move but have different handshapes are very rare and unnatural. For example, TOTAL-COMMUNICATION has different handshapes (T and C) performing alternating movement near the chin. This sign came to ASL through the influence of signed English. Frishberg (1975) notes, however, that these signs were more common in nineteenth-century ASL and later evolved in a way that satisfies the symmetry and dominance conditions. Further research on ASL and other sign languages has revealed sign types that do not follow the symmetry and dominance conditions and yet are part of natural sign language. These new data prompted a revision of the originally proposed symmetry and dominance conditions (Channon 2004; Eccarius and Brentari 2007; Napoli and Wu 2003). For example, Napoli and Wu (2003) investigated ASL vocabulary and found nineteen two-handed signs with different handshapes in which both hands move as a unit. From the point of view of the original dominance condition proposal, these signs are impossible. Signs of this type have also been described in Sign Language of Netherlands (NGT) by van der

Hulst (1996). After investigating the handshape distribution of these signs, Napoli and Wu (2003) proposed a reformulated version of the dominance condition:

> Expanded dominance condition: in a two-handed sign in which the two hands have different handshapes, the non-dominant hand must have an unmarked handshape.

Investigating signs of this type cross-linguistically, Rozelle (2003) introduced a contact condition:

> Contact Condition: if one hand moves and the other remains still, there must be contact (or proximity) between the two hands at some time during the articulation of the sign.

Rozelle proposes this constraint to be phonotactic and not anatomical. Signs that violate this constraint are possible to produce but do not occur in the lexicons of ASL, Korean Sign Language, New Zealand Sign Language, and Finnish Sign Language (Rozelle 2003).

In the sign language literature, the behavior of classifiers under symmetry and dominance conditions has been analyzed differently. Aronoff et al. (2003) claimed that classifiers often violate both conditions. Eccarius and Brentari (2007) analyzed two-handed classifiers across Hong Kong, American, and Swiss German sign languages (including the large proportion of signs that violate the original symmetry and dominance conditions). Based on their analysis, they proposed another revision to the symmetry and dominance conditions that accounts for classifiers:

> Maximize symmetry and restrict complexity in the handshape features of the two hands.
>
> Modified dominance condition: Handshape on the non-dominant hand must be a simple structure morphosyntactically and phonologically in order to achieve word-like prosody.
>
> Modified symmetry condition: To achieve word-like prosody, a form must have symmetrical timing (i.e., be articulated simultaneously).

All of the numeral-incorporating, two-handed forms in our data follow these revised conditions as well as the modified dominance condition proposed by Napoli and Wu (2003), while some two-handed incorporating forms contradict the original symmetry condition. Although the present study does not allow us to draw conclusions about the possible classifier nature of calendric terms, our analyses provide support for the above described revisions to the symmetry and dominance conditions proposed to account for classifiers, cross-linguistic data, and various kinds of symmetry that are possible in sign languages.

It is important to note here that incorporating forms are by definition polymorphemic (i.e., a number sign is combined with a calendric or measurement sign). At the same time, as we will show, all the RSL forms we analyze here are predicted by the expanded dominance condition and contact conditions. This finding underscores the proposal that these constraints not only govern complexity within a morpheme, but also their simultaneous combination.

3.3. Numeral Incorporation in RSL: What Combines?

3.3.1. Russian Sign Language (RSL)

Russian Sign Language (RSL) is a sign language of a very large Deaf community, used in the territory of Russia, in many—but not all (Kibrik 2008)—countries of the former Soviet Union (Grenoble 1992). Wittmann (1991) and Zeshan (2006) categorize RSL as a member of the Old French Sign Language Family. The first Deaf school in St. Petersburg was founded in 1806 and used the French method of teaching, promoting signing. The process was led by the French instructor who was a student of Roch-Ambroise Sicard, the successor of Jean-Michel de l'Epée in Paris (Basova and Yegorov 1984). According to the Russian National Census in 2010, 120,500 Russians mentioned RSL among the languages they use daily. However, the census data need to be interpreted with caution because the questionnaire did not have a separate option for RSL in the list of languages available to check. According to other sociolinguistic analysis, RSL is used by two million signers in the territory of Russia (Voskresensky 2002).

3.3.2. Data Collection

Data were gathered from eight language consultants (two of whom were males) from Moscow, St. Petersburg, Novosibirsk, and Kirov in Russia from 2015 through 2016 via face-to-face, video-recorded interviews and Skype. All the language consultants were native signers (one hearing signer with deaf parents), and all indicated that they interact daily in RSL with their families, friends, and at work. The data were collected through translation elicitation (from Russian to RSL), a picture description task, and metalinguistic questions.[2] The interviews were conducted by the first author using RSL and Russian; RSL interpreters assisted with three interviews. Two signers recorded themselves during translation elicitation and shared these recordings with the first author. The language consultants were first asked to show their signs for calendric or measurement terms and time units. They were then given a list of sentences in Russian to translate into RSL. The sentences contained time, measurement, and calendric units in different contexts. Next, the language consultants were asked to describe a series of pictures. (For example, one picture displayed an enthusiastic young man with a bouquet of flowers standing under a street clock showing noon. In a second picture, the same man stands under the same clock, now showing 3 o'clock, with faded flowers and a sad face). Finally, the language consultants were interviewed about their intuitions and metalinguistic judgments of numeral incorporation, limits of incorporation (what numbers can be incorporated, what signs can incorporate), any regional variations they were aware of, and any situations of RSL use in which numeral incorporation could or could not be used. The RSL interpreters were familiar to the language consultants and contributed to the discussions (i.e., suggesting more contexts).

The interviews were then transcribed by the first author using ELAN 4.9.3 with separate tiers for transcription, Russian and English translation, and comments. In most cases, the decision as to whether a certain form is incorporated was straightforward. In three cases in which it was unclear, the same RSL language consultants were asked to clarify. All their metalinguistic judgments were consistent. All the consultants had strong intuitions about numeral incorporation.

Once the transcriptions were complete, each informant's consistency in use of numeral incorporation was checked for each particular sentence and for every construction (across sentences). Before we describe the detailed analyses of the gathered data, we describe the numeral system of Russian Sign Language.

3.3.3. RSL Numeral System

The numeral symbols of sign languages are constrained by the physical properties of the manual articulators: we only have two hands with ten digits, the signing space has limits, and not all hand configurations are anatomically possible. This differentiates sign language numeral signs from the extended body part numeral systems that use the body with pointing. A certain degree of iconicity is present in all the numeral systems of natural sign languages described to date (Zeshan et al. 2013). The numeral systems of sign languages may use one hand (as does ASL) or two hands, as does DGS (Pfau, Steinbach, and Woll 2012). Taub (2001) describes sign language numeral systems as being a special case of iconicity, that is, *number-to-number iconicity*: the number of fingers is in one-to-one correspondence with the number of referents for some numerals. This kind of iconicity is limited by the number of available articulators and can be observed in pluralized classifiers, grammatical dual number, and numeral incorporation (Taub 2001). The degree of number-to-number iconicity in the number systems of sign languages varies. In RSL, as in most sign languages, numbers from one through five are represented iconically by extending the corresponding number of fingers on the dominant hand. Another type of iconicity found in sign languages is orthographic iconicity: signs for numbers represent the written forms of these numbers in the spoken language, such as Kanji for Japanese Sign Language (JSL) numbers (Zeshan and Palfreyman 2017). This kind of iconicity also can be found in RSL in the signs THOUSAND and MILLION.

Figure 1.
Gesture for 9, commonly used in Russia.

Figure 3.1. Gesture for 9 commonly used in Russia

Although the natural sign languages of Deaf people around the world typically have existed in the situation of diglossia (with spoken languages), their numeral systems do not always reflect the type of numeral systems of the spoken languages within which they are embedded despite their close proximity (Pfau, Steinbach, and Woll 2012)—although there is some dependency in many sign languages (Safar et al. 2018; Zeshan et al. 2013). Nor do the numeral signs of RSL seem to depend on the common gestural representations of numbers. The common Russian gesture for nine would be an iconic extension of five digits on one hand and four on the other (figure 2.1), but RSL has a different sign for the number that is less transparently iconic. The sign NINE, for instance, is two-handed; the dominant hand with the FOUR handshape contacts the palm of the non-dominant hand, which is held in neutral signing space with a handshape FIVE, as illustrated in figure 2.2.

The RSL numeral system has a base of ten with a sub-base of five, as does DGS (Iversen et al. 2006; Pfau, Steinbach, and Woll 2012). The base of a numeral system is the value *n* such that numeral expressions are constructed according to the pattern ... $xn + y$ (Comrie 2013). Multiples of ten (such as tens, hundreds, thousands) in sign languages are often formed through a multiplication strategy (Sagara and Zeshan 2013). In RSL, simultaneous morphological processes are used to create higher-magnitude representations: the basic handshapes ONE through NINE are combined with a specific movement that indicates, for example, thousand. The number signs FIFTEEN, FIFTY, FIVE HUNDRED, and FIVE THOUSAND are derived from FIVE and differ from it (and from each other) only in movement. The number FIFTY differs from FIVE by the diagonal movement downwards. The number fifty-five is signed as FIFTY FIVE, in which both hands have a FIVE handshape, but FIFTY contains diagonal movement.

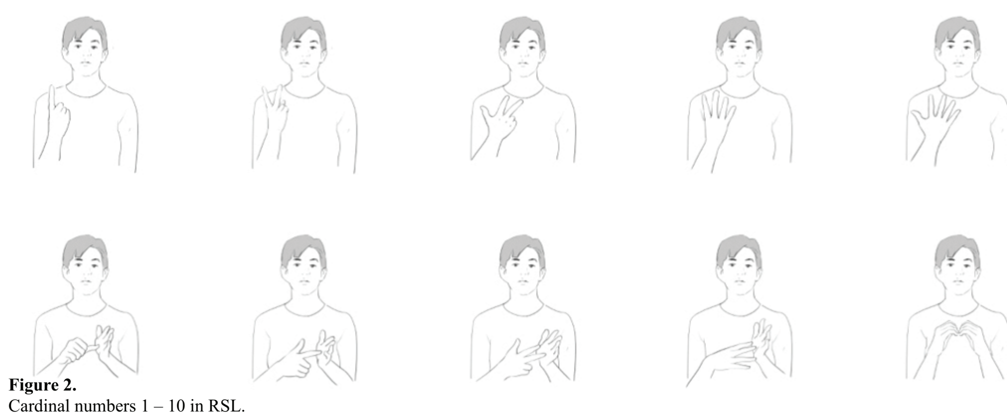


Figure 3.2. Cardinal numbers 1 - 10 in RSL

This patterning is not universal across sign languages. In some of the ASL number signs, digits can be signed in linear finger order, but round numbers (for example, EIGHTY) have a specific movement. While some numbers have specific movement patters (as TWENTY-THREE), other numbers are signed as a sequence of digits (EIGHTY-THREE is a combination of EIGHT and THREE, and not EIGHTY and THREE). In DGS the order is inverse, and TWENTY-THREE is a combination of THREE and TWENTY (Pfau, Steinbach, and Woll 2012).

In RSL, the cardinal numbers ELEVEN through FIFTEEN begin with a fist and have a quick extension of the selected fingers. The numbers SIXTEEN through NINETEEN have a distinct arc movement: the dominant hand touches the non-dominant palm twice, as shown in figure 3.3. Round numbers TWENTY through NINETY have a diagonal downward movement (figures 3.4 and 3.5). Cardinal numbers ONE HUNDRED through NINE HUNDRED have a quick single bending movement (in two-handed numerals it begins with the fingers of the dominant hand touching the palm of the non-dominant one). The RSL sign for FIFTY-FIVE is a sequential combination of FIFTY and FIVE; 555 is a combination of FIVE HUNDRED, FIFTY and FIVE, and so on. The signs THOUSAND and MILLION are both initialized; forms ONE THOUSAND through FIVE THOUSAND are formed through numeral incorporation with suppletion and are discussed below in section 4.4.

Figure 3.
Cardinal number 17 in RSL.

Figure 3.3. Cardinal number 17 in RSL

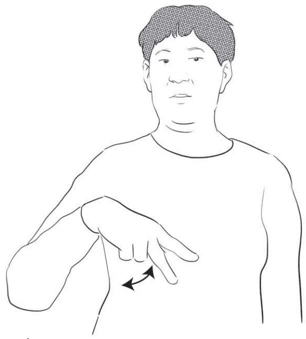


Figure 4.
Cardinal number 20 in RSL.

Figure 3.4. Cardinal number 20 in RSL

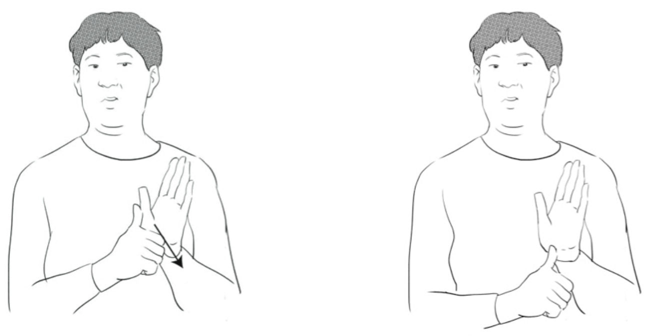


Figure 5.
Cardinal number 60 in RSL.

Figure 3.5. Cardinal number 60 in RSL

According to our consultants, this numeral system is common and universally understood in all regions of Russia, but there exists some variation on the numbers eleven through fifteen. Besides one-handed numerals with a quick extension of selected fingers, there is also a two-handed version in which the non-dominant hand holds the same handshape as in TEN, while the number of fingers is extended on the dominant hand (for example, three for THIRTEEN), while the other fingers are held in the TEN handshape. According to our language consultants, these variants for eleven through thirteen are less common in contemporary RSL, and the source of this variation is unknown. However, in his RSL textbooks, Iosif Geilman (Geilman 1957, 1980, 2001), presents the following rule for the numbers ELEVEN and TWELVE: first, the number TEN should be signed, and then ONE or TWO. This rule is close to the two-handed numerals that was described above and may be the predecessor of the current version. One-handed variants for these numerals are not represented in Geilman's work.

Figure 6.
Cardinal number 11:
Left - from Geilman (2000, p. 25), right – from Fradkina (2001, p.20)

Figure 3.6. Cardinal number 11 in RSL

However, other RSL Dictionaries (Bazoev et al. 2009; Fradkina 2001) issued by the Moscow Deaf Society and Zaitseva (2000), do not list the two-handed variants and only present one-handed numbers with internal movement for the range ELEVEN through FIFTEEN. As our fieldwork shows, both variants are understood by native signers of RSL, but most people today use the one-handed versions.

The difference may be generational or dialectal: Geilman, a hearing native signer, grew up in St. Petersburg, while the group of Deaf authors working on the dictionary (Bazoev et al. 2009) and Fradkina (2001) publish and work in Moscow. Further discussion is beyond the scope of this paper. However, as the two versions of these numbers behave differently in the context of numeral incorporation, it is important to keep both versions in mind.

This kind of variation in number signs has also been attested for British Sign Language (BSL) (Stamp et al. 2014). In addition, McKee, McKee, and Major (2011) working on New Zealand Sign Language (NZSL), point out a high level of dialectal variation for the numbers one through twenty across groups of NZSL signers as a function of age, gender, region, and ethnicity. This might relate to the fact that NZSL has dialectal variants associated with five centers of Deaf education in New Zealand. Sociolinguistic explanations may also be relevant for RSL variation, taking into account both the factors of geography and the fact that Deaf and hard of hearing students were historically educated in different schools in Russia (Basova and Yegorov 1984).

3.3.4. Signs Allowing (and Not Allowing) Numeral Incorporation

According to Sagara and Zeshan (2016), the most frequent paradigms of numeral incorporation are time signs such as years, hours, and minutes (which are attested for in twenty sign languages); money or currency (attested for in fifteen sign languages); and school grade (attested for in thirteen sign languages). Although RSL generally fits this pattern, there are some peculiarities. Numeral incorporation is a general preference for time signs (YEAR_a [*a* stands for *age*], MONTH, WEEK, HOUR_1, WORKING_HOUR, $\text{O'CLOCK}_{old,new,Novosibirsk}$, $\text{MINUTE}_{1,2}$, TIME [occurrence], YESTERDAY, TOMORROW). In addition, numeral incorporation occurs in one measurement sign (KILOGRAMS), currency (RUBLE), and one paradigm that has not been described to incorporate numerals in other sign languages, namely PERSON/PEOPLE. At the same time, not all calendric terms in RSL incorporate number: the signs DAY, SECOND, YEAR_c (*c* stands for *calendar*, the glosses will be discussed later in the subchapter about signs allowing numeral incorporation) and some others do not allow it. As for school grades, we did not manage to elicit any forms allowing numeral incorporation. There are several ways to sign school grade, but our language consultants mainly used the sign ROOM (in spoken Russian, *класс* means both school grade and room, and RSL may have borrowed this lexeme), which does not allow numeral incorporation in any context.

RSL has a complex and elaborate system of time expressions and calendric terms that do not mirror spoken Russian (see Burkova et al. 2018)[4]. Numeral incorporation is systematic and consistent in RSL, but there is some variation in our data. Because it was not always immediately clear whether this variation was lexical (different signs), phonological (within one sign), or diachronic (between different generations), we briefly discuss these variants and give examples below. Note that all of these types of variation have been described for other sign languages (Frishberg 1975; Lucas et al. 2001; Stamp et al. 2014). Table 3.1 summarizes the numeral incorporation paradigms analyzed for the present RSL data set.

With respect to variation, some signs differ only by handshape: for example, the signs HOUR$_1$ and HOUR$_2$ (figures 3.7a and 3.7b) have the same circular clockwise movement in neutral signing space, but HOUR$_2$ is initialized (it has a handshape Ч, which is the first letter of the spoken Russian word *hour* – *час*), while HOUR$_1$ has a handshape 1, typical for most calendric terms (Burkova et al. 2018). The RSL dictionary by Fradkina (2001) has separate entries for these signs. In our data, both signs were understood, but our consultants tended to consistently use only one of them, either HOUR$_1$ or HOUR$_2$. HOUR$_1$ more frequently appeared in our data. Importantly, these signs behave differently in the context of numeral incorporation: HOUR$_1$ incorporates numbers up to five, while HOUR$_2$ in our data does not allow any numeral incorporation, presumably due to the initialized handshape. In our data, HOUR$_1$ and HOUR$_2$ were considered phonological variants.

[4] - For detailed analyses of calendric and time signs of RSL, see Burkova et al. 2018.

Table 3.1. Numeral-incorporating paradigms of RSL

The first column gives an English translation of the time or measurement sign. The subtitles indicate variants or dialectal differences. The second column illustrates the sign in citation form (usually beginning and final location). The third column indicates whether the sign is one- or two-handed, while the fourth and the fifth columns indicate whether the sign allows incorporation and, if so, the numeral incorporation limit.

The source videos for the last 3 illustrations are from *spreadtesign.com*.

Calendric term	**Lexical base sign**	**One/two-handed in citation form**	**Incor-poration**	**NumLimit**
YEAR$_c$		1	-/2,3,4	4
YEAR$_a$		1	+	5
MONTH		1	+	9
WEEK		1	+	5

Table 3.1. Numeral-incorporating paradigms of RSL (continued)

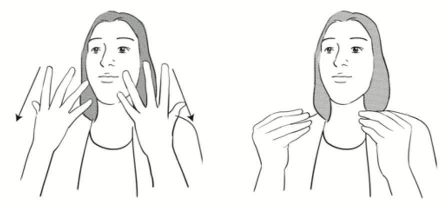
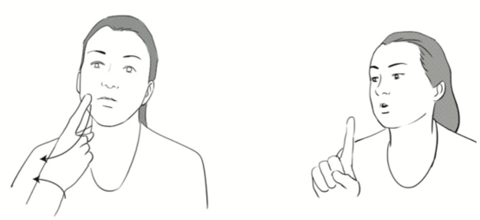
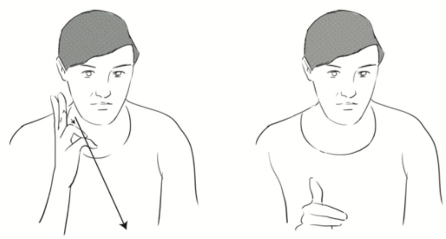
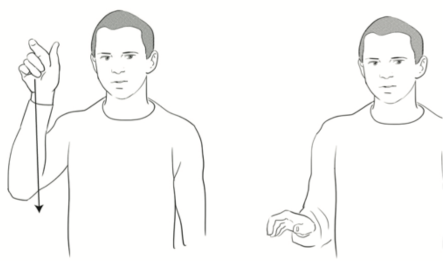
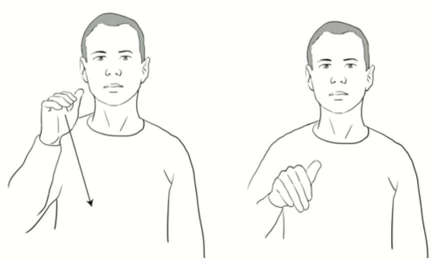
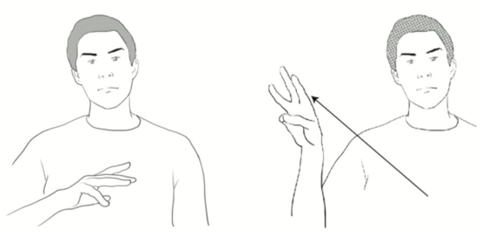
Calendric term	Lexical base sign	One/two-handed in citation form	Incor-porati on	Num. Limit
DAY		2	-	-
HOUR		1	+	4
O'CLOCK		1	+	5
WORKING HOUR (example: 8_WH, incorporated form)		No citation form	+	9

Table 3.1. Numeral-incorporating paradigms of RSL (continued)

Calendric term	**Lexical base sign**	**One/two-handed in citation form**	**Incor-poration**	**Num. Limit**
MINUTE		1	+	5
SECOND		1	-	-
TIME (occurrence, incorporated form 3_TIMES)		1	+	5
RUBLE (Russian currency)		1	+	1, 3, 5, 10

Table 3.1. Numeral-incorporating paradigms of RSL (continued)

Calendric term	**Lexical base sign**	**One/two-handed in citation form**	**Incor-porati on**	**Num. Limit**
KG		1	+	5
PEOPLE		1	+	5
THOUSAND		1	+	5
MILLION		1	-	-

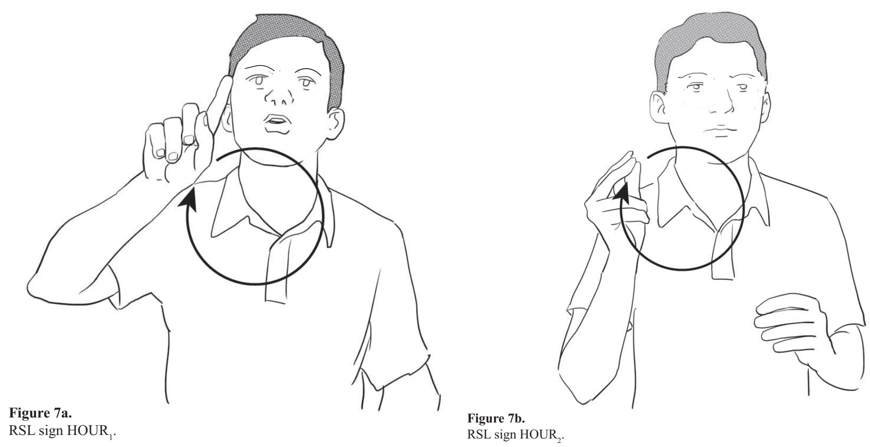


Figure 3.7. RSL sign for HOUR (two versions)

In another case, the difference between the two variants is in location, as in O’CLOCK$_{old}$ and O’CLOCK$_{new}$ (figures 3.8 and 3.9, respectively). In this case, our language consultants explicitly labeled the sign that starts at the forehead as the old sign and the sign that starts on the cheek as contemporary (the same distinction is made by lexicographic sources). Zaitseva (2000) describes the old sign, while contemporary online RSL dictionaries provide only the new version. As for numeral incorporation, both variants incorporate the numbers one through five. These signs were considered diachronic variants.

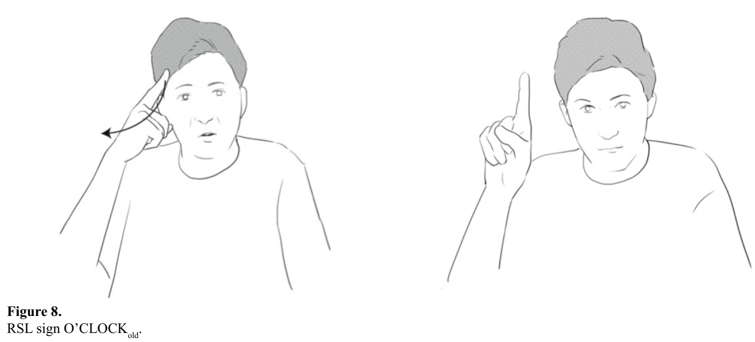


Figure 3.8. RSL sign O'CLOCK $_{old}$

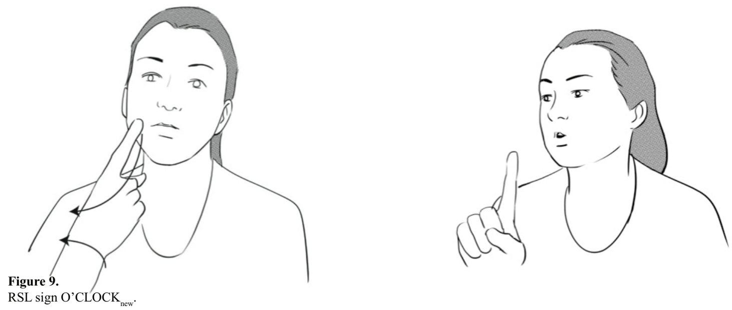


Figure 3.9. RSL sign O'CLOCK$_{new}$

Besides these two diachronic variants, there exists a third variant, O'CLOCK$_{Novosibirsk}$ (figure 10), which has both a different movement and place of articulation and is used by our consultants from Novosibirsk. It is signed in neutral signing space and contains a slight repetitive movement of the wrist to the right and to the left. This sign also allows numeral incorporation (one through five) and was understood but never used by our language consultants from Moscow.[5] Thus, O'CLOCK has two diachronic and one regional variants.

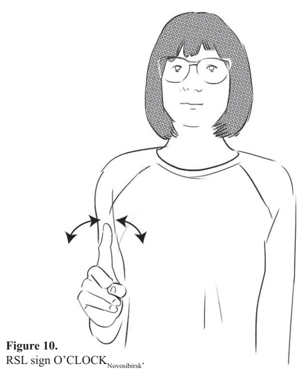


Figure 3.10. RSL sign O'CLOCK (Novosibirsk variant)

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[5] - Moscow and Novosibirsk are also two dialectal centers. More information about differences between Siberian and Moscow dialects of RSL can be found in Burkova and Varinova (2012).

Finally, there are signs that have a similar meaning but are used in different contexts in RSL (figure 3.11). Two signs refer to year (a period of 365 days) but occur in different contexts. The sign YEAR$_c$ (where *c* stands for *calendar*) refers to a period of 365 days and is used in calendric contexts (e.g. *year 1965*) and frozen expressions (e.g., *New Year*). When referring to an age (*ten years old*) or a period (*the three years that I have spent in Moscow* or *three years of famine*) the sign YEAR$_a$ is used (*a* in our glossing stands for *age*). Native signers from both Novosibirsk and Moscow had strong unanimous intuitions that these signs are not variants. In this case, numeral incorporation occurs only in YEAR$_a$; YEAR$_c$ does not usually incorporate numbers and does not occur in contexts of plurality. Instead, the sign TIME is used, which functions as a suppletive form for both YEAR$_a$ (when sequential forms are used) and YEAR$_c$. However, in our data and on the Internet, we can observe cases of numeral incorporation in YEAR$_c$, which we discuss below in relation to the influence of spoken Russian on RSL.

Figure 11a.
RSL sign YEAR$_c$, used to refer to year as a calendar unit.

Figure 11b.
RSL sign YEAR$_a$, used to refer to age.

Figure 11c.
RSL sign 3 YEAR$_c$, incorporated form.

Figure 3.11. RSL signs for year

In the present analyses, we treat the pair YEAR$_a$ and YEAR$_c$ as unrelated signs; the signs HOUR$_1$ and HOUR$_2$ as different, but historically related (as they share the same movement); and O'CLOCK$_{old}$ and O'CLOCK$_{new}$ as diachronic variants of one sign, while O'CLOCK$_2$ is a dialectal sign with the same meaning.

3.4. Phonological constraints on numeral incorporation in RSL.

Functional complexity is defined as a hierarchy of principles that govern a system and the corresponding degrees of freedom that are allowed in that system (Gierut 2007). Phonological complexity limits the number and structure of forms allowed in a language. The level of complexity allowed in a language has previously been described as a constraint on numeral incorporation limits. Mathur and Rathmann (2010) concluded that both ASL and DGS show a preference towards simultaneous forms over sequential ones, which favors numeral incorporation, but in some cases simultaneous forms are blocked by constraints arising from the complexity of articulation.

Mathur and Rathmann (2010) formalize their finding in an Optimality Theory (OT) framework that explains the surfacing of linguistic forms as the result of optimal satisfaction of conflicting constraints. Faithfulness constraints require that a certain feature present in the input be preserved in the output, while markedness constraints impose limits on what the possible output can be (de Lacy 2011). Mathur and Rathmann explain the preference towards simultaneity by the markedness constraint, which they named *SEQ and which prefers forms with one movement over ones with a sequence of movements. However, not all incorporating forms are possible because *SEQ interacts with other constraints.

This has been observed cross-linguistically (Ktejik 2013). In RSL numeral incorporation, this is also a general preference. If there is a possibility of numeral incorporation, it is done obligatorily. Below we discuss the calendric paradigms of RSL in detail and propose that the constraints that govern numeral incorporation arise from all featural levels. The order of presentation is as follows: first, we discuss the constraints on movement, then handshape, location, and orientation.

3.4.1. Movement constraints.

Constraints on movement complexity have been posited as a major limiting factor for numeral incorporation in ASL, DGS (Mathur and Rathmann 2010), and TID (Kubuş 2008). These authors suggest that no more than one movement specification is allowed per sign, which disallows incorporation of numerals that have internal movements. This constraint also operates in RSL, as our data show. Numerals that have internal movements (both two-handed, as seventeen, figure

3.12, or one-handed, as twenty, figure 3.13) are never incorporated in RSL. If these numeral signs were to be incorporated, their internal movement would have to coincide with the path movement of the lexical sign.

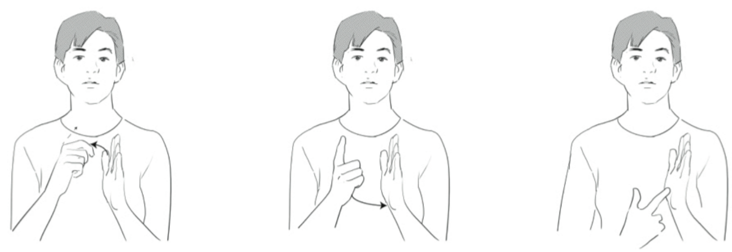

Figure 12.
Cardinal number 17 in RSL.

Figure 3.12. Cardinal number 17 in RSL

One possible solution would be to delete the movement segment from the numeral, but movements cannot be deleted without a loss of information. One-handed numerals of different ranges (for example, three, thirteen, and thirty) share a handshape and differ only in movement, so movement deletion would make the forms of 3_MINUTE and 13_MINUTE indiscernible. At the same time, deletion of the path movement from the lexical base sign would result in the loss of lexical meaning. Thus, to refer to the period of three minutes, the incorporating form 3_MINUTE is used, while thirteen minutes is referred to with the sequential noun phrase 13 MINUTE.

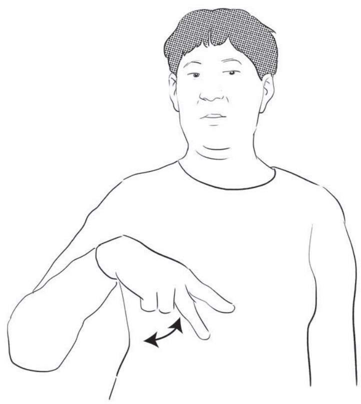

Figure 13.
Cardinal number 20 in RSL.

Figure 3.13. Cardinal number 20 in RSL

Only one paradigm in RSL has a double movement specification (i.e., both path and internal movement): PERSON/PEOPLE. However, in this case the lexical sign itself has two specifications for movement: the active fingers bend, and simultaneously the hand moves down (figure 3.15). Thus, the incorporating form 2_PEOPLE is a minimal pair with the sign 200: the two signs differ only in path movement, while the internal movement is shared. Correspondingly, the same is true for the numeral-incorporated signs 3_ PEOPLE through 5_ PEOPLE and the number signs 300 through 500. Thus, even in this particular case of unusual complexity, it is important to note that both movements come from the lexical base time sign and not the numeral.

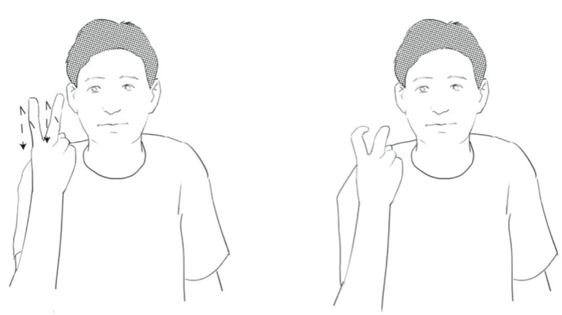

Figure 14.
Cardinal number 200 in RSL.

Figure 3.14. Cardinal number 200 in RSL

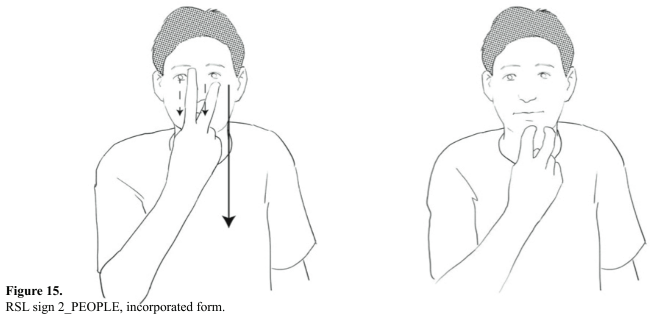

Figure 3.15. RSL sign 2_PEOPLE, incorporated form

The two-handed numerals eleven through fifteen (older version discussed above) are a special case. Having peculiar combinations of handshapes that are distinct from all other numerals, these number signs can lose their internal movement specification without creating ambiguity. We argue that this characteristic allows these numerals to be incorporated. Indeed, the sign HOUR1 (one-handed sign with circular clockwise movement in neutral signing space) incorporates one- and two-handed numerals up to fifteen. This paradigm shows the highest limit in RSL (see figure 3.16a-d). Next, we ask what distinguishes this paradigm from the other paradigms to allow for such robust incorporation.

As noted above, two-handed signs like 7_HOUR or 10_HOUR would not be possible from the point of view of the classic definition of the dominance condition (Battison 1978). However, the expanded dominance condition (Napoli and Wu 2003), motivated by the necessity to account for two-handed signs in ASL in which the hands move as one unit, accounts for these forms in RSL as well. It is important to note that these forms are polymorphemic.

Figure 3.16. Incorporated forms of RSL sign HOUR

3.4.2. Handshape Constraints

As discussed above, in RSL, as in many other sign languages described to date (Fischer, Hung, and Liu 2010; Fuentes et al. 2010; Ktejik 2013; Mathur and Rathmann 2010; Morgan 2013), numeral incorporation is a general preference for calendric terms and measurement units, and simultaneous expression of morphemes is preferred over sequential expression. At the same time, in RSL—as in ASL, DGS, TID and other sign languages—time and measurement signs exist that do not allow any incorporation. Mathur and Rathmann (2010) proposed that this is due to a faithfulness constraint that preserves the marked featural specification in the input from deletion. In their example, the DGS sign MINUTE does not incorporate numerals because of its marked F handshape, which cannot be deleted. To be preserved, the handshape requires that all the fingers be selected, i.e., fingers that can change their aperture during the articulation of a sign (Brentari 2010).

The role of the handshape is also crucial in RSL. In their bare forms, most calendric and measurement signs in RSL have an unmarked 1 handshape with index or thumb extended (which was interchangeable both across and within our consultants). All of these signs allow numeral incorporation. However, several signs have handshapes with all fingers selected: DAY (figures 3.17 and 3.18), SECOND, HOUR$_2$, MINUTE, and KILOGRAM. The first three of these signs do not allow numeral incorporation. In contrast, suppletion occurs for the MINUTE (figure 3.19) and KILOGRAM paradigms: both signs change handshape and movement direction, and then numerals are incorporated.

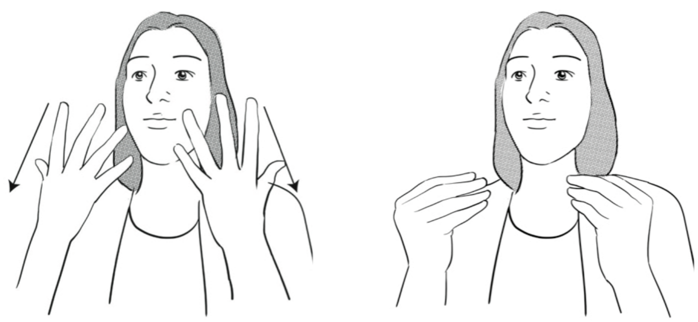

Figure 17.
RSL sign DAY.

Figure 3.17. RSL sign DAY

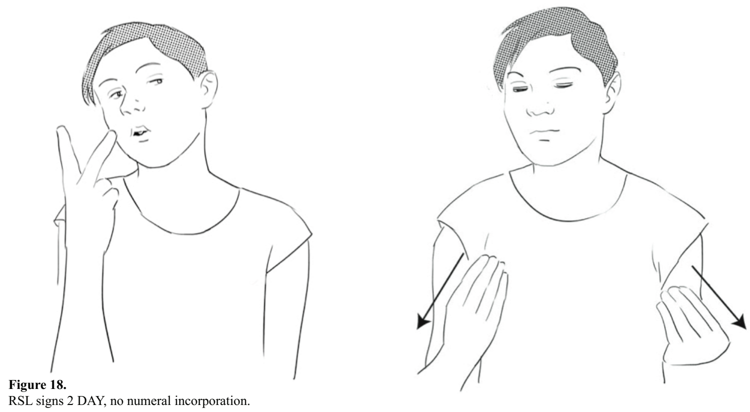

Figure 3.18. RSL signs TWO DAY

The sign MINUTE is initialized (it has the M handshape with palm facing down orientation) and has horizontal ipsilateral movement, while the incorporating forms change orientation (palms face the central line) and movement direction (the hand moves forward), as illustrated in figure 19.

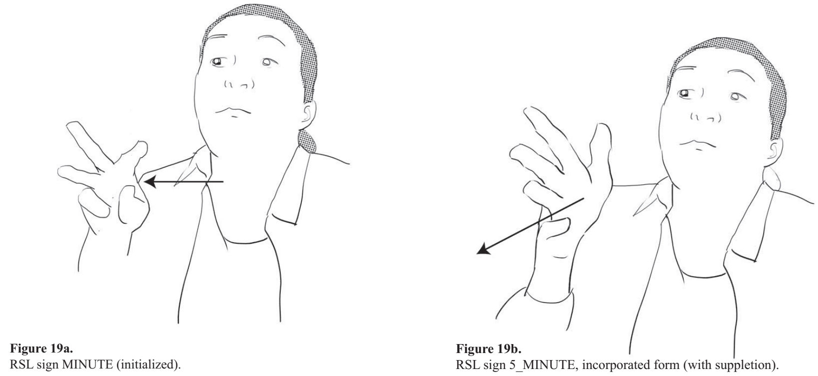

Figure 3.19. RSL sign MINUTE

Comparison of the signs HOUR$_1$ (HS 1) and HOUR$_2$ (HS Ч) shows that, although the movement, location, and orientation of these signs are the same, they behave differently in relation to numeral incorporation. We discussed earlier that our consultants tended to systematically use one of the variants, but not both. While signers who typically used the sign HOUR$_1$ incorporated numerals one through fifteen, in our data the consultants who systematically used only the sign

HOUR2 never incorporated numerals,[6] signing instead a sequential combination (for example, THREE HOUR2). Since handshape constitutes the only difference between these signs, we assume that the meaningful handshape with all fingers selected in the sign HOUR2 prevents it from incorporating numbers.

It is important to note here that initialized numerals (for example, MILLION that has the handshape M, or THOUSAND that has the handshape T) either do not allow incorporation or have suppletion. For example, the incorporated forms TWO THOUSAND through FIVE THOUSAND recruit suppletion. Beyond the number five, only the initialized sign THOUSAND (with the T handshape) is used in sequential combination with a numeral.

One paradigm in RSL that allows more than one finger specification is the currency paradigm, RUBLE. This sign is initialized (the bare form has P handshape, as in Russian word "Ruble"; thumb and middle finger contact each other twice). When incorporating the numerals one, two, and four, suppletion of the lexical sign occurs: the numeral handshape is incorporated and the movement is changed to wrist twisting. However, the forms 3_RUBLE, 5_RUBLE, and 10_RUBLE have specific forms that allow double handshape specification, as shown in figure 3.20. In other cases, meaning is expressed sequentially without numeral incorporation.

Figure 20a.
RSL sign RUBLE.

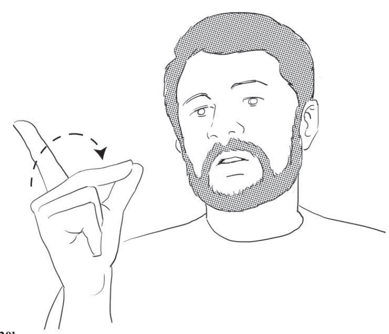

Figure 20b.
RSL sign 3_RUBLE, incorporated form.

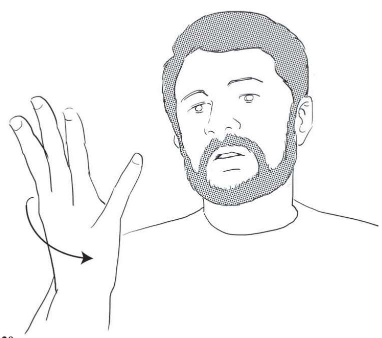

Figure 20c.
RSL sign 4_RUBLE, incorporated form (with suppletion).

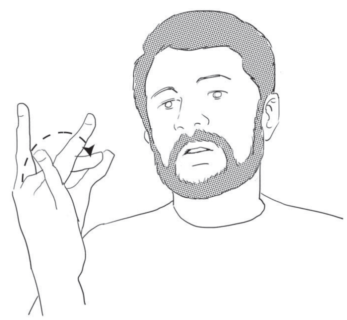

Figure 20d.
RSL sign 5_RUBLE, incorporated form.

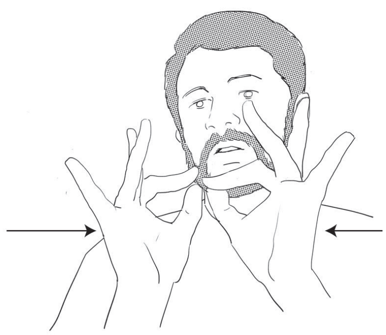

Figure 20e.
RSL sign 10_RUBLE, incorporated form.

Figure 3.20. RSL sign RUBLE

In 3_RUBLE, the 3 handshape is produced and then the middle finger contacts the thumb (turning to original P handshape); the same pattern is followed in 5_RUBLE. In 10_RUBLE, both hands touch each other in the P handshape, thus maintaining the original handshape and the movement and orientation from the sign 10. Because the original handshape of RUBLE has only three fingers selected rather than all fingers, these forms manage to maintain both finger specifications from the input.[6]

Another possible explanation for signs that do not incorporate may lie in the nature of calendric terms. Fuentes et al. (2010) in their analysis of numeral incorporation in Catalan Sign Language (LSC) and Argentine Sign Language (LSA) note that across sign languages the distribution of paradigms that allow numeral incorporation resembles the distribution of numeric classifiers in spoken languages. Fuentes et al. analyze numeral incorporation as a simultaneous compounding of classifiers (calendric terms) and numerical roots. The signs that have specific handshapes and do not allow numeral incorporation in this framework do not resemble classifiers. We note that this approach does not fully account for the individual limits of paradigms. The question of whether the morphology of calendric terms is akin to classifier morphology awaits future research.

3.4.3. Location Constraints

Thus far we have described the phonological constraints that prevent certain numerals from being incorporated (internal movement) and certain calendric terms from incorporating (handshape with all fingers selected). However, most time signs in RSL incorporate numerals but show limits arising from different phonological constraints. For example, the paradigm HOUR_1, discussed above, incorporates the numbers one through fifteen; the paradigm MONTH incorporates the numbers one through nine; and YEAR_a and MINUTE allow incorporation up to five. How are these limits conditioned? This becomes apparent by comparing the signs HOUR, YEAR_a, and MONTH.

[6] - According to one of our language consultants, these incorporated forms may soon disappear from RSL discourse for extralinguistic reasons related to economic inflation.

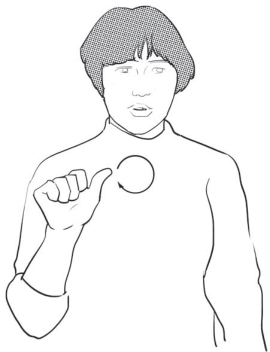

Figure 21a.
RSL sign HOUR_1.

Figure 21b.
RSL sign YEAR_a.

Figure 21c.
RSL sign MONTH.

Figure 3.21. RSL signs HOUR, YEAR, MONTH

The sign HOUR is located in neutral signing space, while MONTH and YEAR_a are signed on the head, and both start with contact. As is the case for the sign DEAF in ASL and RSL, MONTH can start either in its higher (ear) or lower (chin) location, depending on the preceding and following signs. The sign YEAR_a only allows incorporation up to five. Incorporation of the two-handed numerals six through nine would result in asymmetric two-handed signs located on the head, and signs of this type are never observed in RSL in either the present data set, the RSL Swadesh-Woodward list for the RSL dialect project (Davidenko et al. 2013), or in RSL dictionaries (Bazoev et al., 2009; Fradkina 2001; Geilman 2001). The sign O'CLOCK_{new}, also signed on the head and discussed above, behaves like YEAR_a in that it only incorporates one-handed numerals.

The sign MONTH, however, behaves differently. If the original location (figure 3.22) is preserved, it cannot incorporate numerals six through nine. But suppletion occurs in this case; the sign's location lowers to neutral signing space and changes orientation (see figure 3.23). The movement of the original lexical sign (movement down, or up in case of location metathesis, if the previous sign was articulated lower) between the two contact points (forehead and chin) is preserved. The number handshape, while incorporated, also changes; both contacts are substituted with two holds in neutral signing space, and both palms now face outward. This new orientation is part of neither the lexical sign, nor the number sign.

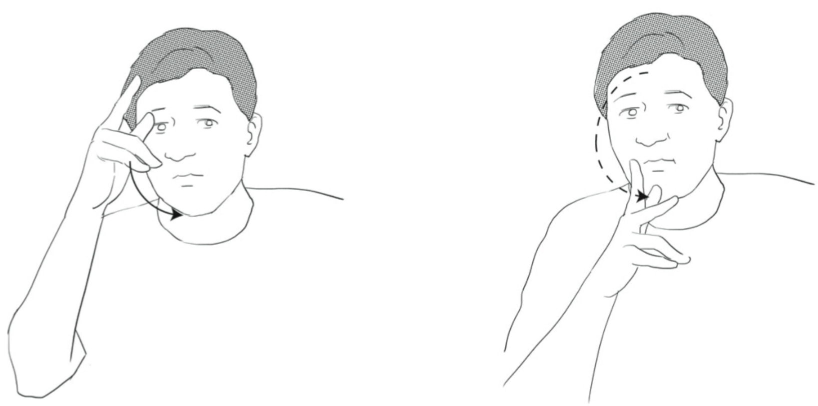

Figure 22.
RSL sign 3_MONTH, incorporated form.

Figure 3.22. RSL sign 3_MONTH, incorporated form

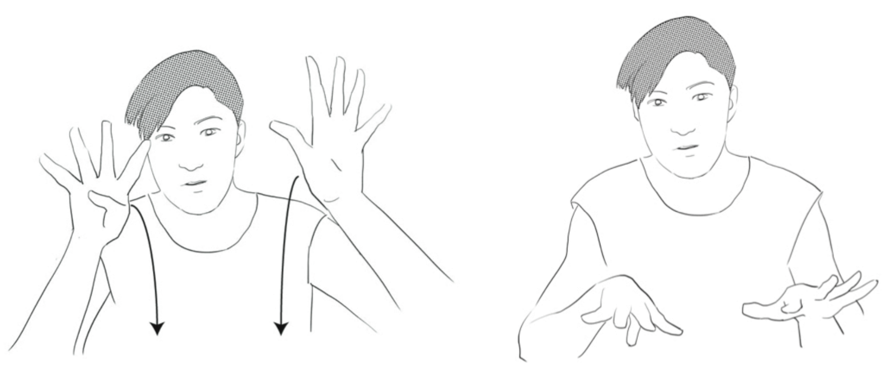

Figure 23.
RSL sign 9_MONTH, incorporated form (with suppletion).

Figure 3.23. RSL sign 9_MONTH

When we discussed this suppletion with our language consultants, all of whom consistently used suppletion, they mentioned that some people may also use non-incorporating sequential forms to refer to six through nine months instead of the suppletive forms and that it is also acceptable except for the numbers two through five months, for which only incorporating forms may be used. Importantly, they noted that incorporation of two-handed numerals without suppletion is ungrammatical and both location and orientation are obligatorily changed.

3.4.4. Orientation Constraints

The sign MONTH, discussed above, allows incorporation of the two-handed numerals six through nine. Through incorporation, it changes not only location but also orientation. This led us to hypothesize that orientation might also be involved in the articulatory constraints preventing two-handed numerals from incorporation. When analyzing all the calendric and measurement signs that have an orientation facing the central line (lateral to the body), MONTH, MINUTE, and KILOGRAM, we discovered that none of these signs incorporate two-handed numerals.

The signs MINUTE and KILOGRAM are signed in neutral signing space and, yet, incorporate only one-handed numerals. This contrasts with the paradigms $HOUR_1$, which incorporates two-handed numbers six through thirteen, and WORKING_HOUR (figure 3.24), which has an outward orientation and allows incorporation of two-handed numerals up to ten (we describe this lexicalization process in more detail below in the discussion). This observation indicates that no paradigm that has lateral orientation allows two-handed signs with asymmetrical handshapes.


Figure 24.
RSL sign 8_WORKING-HOUR (8 hours of working day).

Figure 3.24. RSL sign 8_WORKING_HOUR

Checking RSL dictionaries and the Swadesh-Woodward list of RSL signs, we again found no signs with lateral orientation and asymmetrical handshapes. If a sign has two hands with this orientation, then it also has identical handshapes and movements that are synchronized (for example, READY) or alternating (COOK). If the handshapes are different, then one hand also has a different orientation (KILL; BREAD). Preliminary analysis of 321 signs collected and published online by Davidenko et al. (2013) as a part of the RSL dialect project (signs from the Swadesh list, including regional variants from different parts of Russia) revealed a low frequency of two-handed signs with lateral orientation (palms facing each other). Among the 321 signs examined, only twenty-nine have an orientation facing the central line, and only 4 percent (or nine) of these signs are two-handed. All nine signs have either an internal separate movement of the dominant hand or do not have contact. The handshapes occurring in this orientation are also highly restricted and include only handshapes that are unmarked, according to Battison's classification (1978). We propose that these handshapes are sufficiently perceptually salient to be distinguishable even when the hand faces the central line.

In addition, no two-handed signs have the same orientation (facing the central line) with different handshapes in either the Swadesh list or any of the RSL dictionaries we consulted (Bazoev et al. 2009; Fradkina 2001; Geilman 1957, 1980, 2001). So, signs like *6_MINUTE are apparently ill-formed, not only for a particular numeral incorporation paradigm but also for RSL in general. This suggests that asymmetry in sign languages is compositional, that there are asymmetries on different featural levels that interact with other parameters. Therefore, we propose that, together with a location constraint, a constraint for orientation exists in RSL phonology that disallows signs with asymmetric handshapes to appear with an orientation lateral to the signer's body. The preliminary corpus data and analysis of RSL dictionaries provide additional support for our finding that orientation facing the central line in RSL strongly disprefers handshape asymmetry.

Another orientation restriction applies to the sign THOUSAND (figure 3.25) which has a downward palm orientation. This sign incorporates numbers one through five. After the number five, sequential phrases are used with a suppletive initialized form: ONE_THOUSAND versus EIGHT THOUSAND (see figure 3.26). This constraint may be anatomical and perceptual, that is, a two-handed sign with downward orientation in which one palm completely blocks the other from the interlocutor's sight is both hard to produce and impossible to distinguish.

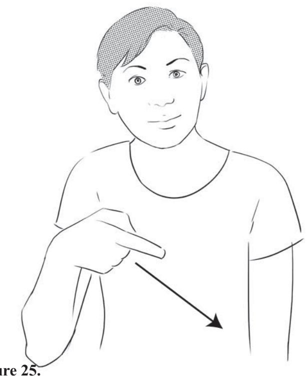

Figure 25.
RSL sign 1_THOUSAND, incorporated form.

Figure 3.25. RSL sign 1_THOUSAND

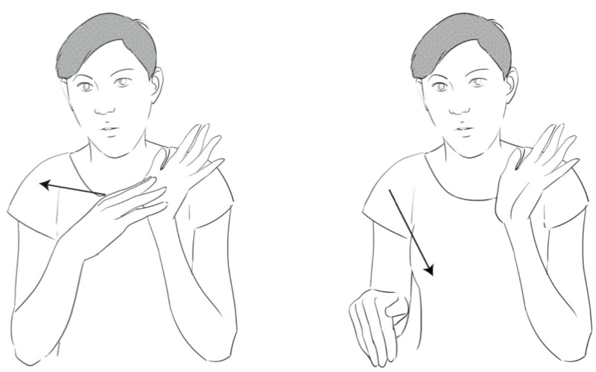

Figure 26.
RSL signs 8 THOUSANDS (initialized sign), no numeral incorporation.

Figure 3.26. RSL signs 8 THOUSAND

Thus, our analyses show that the parameter of palm orientation serves as one major factor that constrains the numeral incorporation limits of the various paradigms in RSL. This is an important finding, especially taking into account the controversial status of this parameter in the sign language literature. In Stokoe's (1960) original analyses, orientation was not included as a sign parameter. Battison (1978) later added palm orientation as a sign parameter, but its status remains a matter of some debate. Some phonological models of sign language consider orientation to be a parameter by itself, while others analyze it as a subcomponent of hand configuration (Brentari 1998; Sandler 2012; van der Hulst 1996). We argue, based on the analyses presented here, that orientation is not redundant and does not inherit its specification from location. To the contrary, orientation mostly interacts with handshape, in line with Sandler's Hand-Tier model (Sandler 1986).

3.4.5. Contact Preservation

In addition to the constraints discussed above, other factors may condition incorporation limits. Thus far, we have only discussed one-handed lexical signs, but among paradigms allowing numeral incorporation there is one paradigm that is two-handed: TIME.

The sign TIME refers to the number of occurrences of a certain event (as in, "She failed the statistics test three times"). It is articulated in neutral signing space, with the dominant hand moving down to contact the non-moving, non-dominant hand and then returning to the initial position, as figure 3.27 shows. This sign only incorporates one-handed numerals; two-handed numeral incorporation would cause the sign to lose the contact present in the input. Analyses of weak drop and compounding in ASL (Brentari 1998; Del Giudice 2007) have shown that a segment with a contact feature is always preserved in the output. Apparently, this is also true for RSL, although specific analyses of compounds in RSL are required to confirm this hypothesis.

Figure 27.
RSL sign 3_TIMES, incorporated form.

Figure 3.27. RSL sign 3_TIME

3.4.6. Alternative Explanations: Frequency, Borrowings, and Lexicalization.

Other factors may also impact numeral incorporation patterns in RSL. However, none of them fully account for numeral incorporation in RSL. Productivity is often considered an opposing factor with frequency and lexicalization. Highly frequent units are stored together as a holistic gestalt (and are thus lexicalized), while word formation is the product of combination of less frequent units (Fernández-Domínguez 2010). Word formation has to "overcome" numerous phonological, syntactic, semantic, and pragmatic constraints, as Fernández-Domínguez puts it.

Calendric paradigms in RSL differ in frequency as do the individual members of the paradigm. The question is whether the frequency of occurrence of particular combinations of numbers and particular lexical items lead to numeral incorporation and thus account for the limiting conditions described here. For example, the paradigm WORKING_HOUR, discussed above, incorporates only the two-handed numerals six, seven, and eight. Our language consultants explained that this sign does not have a bare, non-incorporating form and refers to the typical length of the working day. Thus, "ten-hour working day" or "ninth working hour" do not typically occur in RSL discourse. Although our language consultants reported never producing such forms, they could imagine them. Thus, even if these forms are lexicalized, all the incorporating forms of the paradigm are faithful to all of the phonological constraints described here. Moreover, the pattern is productive.

Another group of signs that may have been influenced by spoken Russian in a way that impacts numeral incorporation limits, for example, is the sign YEAR_a, discussed above. According to five of our RSL consultants, this sign never incorporates numerals because it refers to one calendar unit and is never used in plural contexts. However, three of our younger language consultants noticed that incorporation of the numbers two, three, and four in this sign may be used when referring to a child's age but that the incorporation of the number five does not occur. This may be an influence from spoken Russian. When referring to an age or a period of time, the lexeme *год* [got] is used together with numbers one through four, while other numbers require a different lexeme, *лет* [let]. Thus, it is likely that RSL borrowed this paradigm from spoken Russian, as other numerals (even the phonologically possible five) cannot be incorporated.

It is important to note, however, that neither lexicalization and frequency nor the influence of spoken Russian alone can account for the variety of numeral incorporation paradigms and limits in RSL we have found here, which are highly consistent and predictable from a phonological standpoint. Together, our data and analyses demonstrate that, even in the case of lexicalization or language contact, phonology is always in play. Phonological constraints on numeral incorporation are apparent even in highly similar signs. For example, HOUR_1 allows numeral incorporation but HOUR_2 does not because the phonological form of the lexical sign specifies that all fingers are selected.

3.5. Summary

In this paper, we have described how phonological constraints occur across different featural levels to govern the numeral incorporation process in RSL. The present findings thus extend our understanding of the phenomenon. These results (paradigms, limits, and constraints responsible for the limits) are summarized in Table 2.

Our results extend previous work on these morphological processes in sign language. First, constraints on movement complexity have been posited as a major limiting factor for numeral incorporation in ASL, DGS (Mathur and Rathmann 2010), and TID (Kubuş 2008). The fact that no more than one movement specification is allowed per sign disallows incorporating numerals that have internal movements. As our data show, this constraint also operates in RSL. Handshape complexity has also been posited as a constraint on numeral incorporation in sign languages. Calendric terms that have a handshape with all fingers selected do not incorporate numerals in DGS (Mathur and Rathmann 2010). This is also the case for Russian Sign Language. The location and orientation parameters of sign have not been previously described as constraints, either in numeral incorporation limits or the maximum sign complexity allowed in a sign, but Frishberg (1975) mentions that two-handed signs on the head are less preferred in ASL than one-handed signs, and they often change in this direction. However, based on our present analyses of the data, both from our language consultants about numeral incorporation and RSL lexicographic materials, we find that location and orientation also operate as constraints in the composition of two-handed signs. Specifically, they interact with symmetry restrictions. Two-handed signs with asymmetrical handshapes are not allowed in RSL if they have an orientation lateral to the body (facing the central line) or are signed on the head location, or both. At the same time, two-handed signs with asymmetrical handshapes exist in numeral incorporation paradigms and in the RSL lexicon in general, but only if they have other orientations (such as palm outwards) and locations (neutral signing space). Finally, an important factor that also influences numeral incorporation is contact preservation; a contact segment present in the input cannot be deleted, consistent with previous research (Del Giudice 2007).

In sum, the results of our data and analyses add to typological studies of numeral incorporation, increasing our understanding of constraints on two-handed signs and the interaction of phonology and morphology in RSL. Our results also underscore the importance of sign orientation and its interaction with other parameters, such as handshape and location, in sign language phonology.

Table 3.2. The limits of numeral incorporation for individual paradigms

The first column contains English translations of RSL signs, and the second column shows whether a particular sign incorporates one-handed numerals. The third column shows whether this sign incorporates two-handed numerals six through nine. The fourth column indicates whether the sign incorporates two-handed numerals ten through fifteen. If incorporation does not occur, the columns also explain which constraint prevents it.			
Lexical base sign	**1–5 (one-handed)**	**6–9 (two-handed)**	**10–15**
$HOUR_1$	+	+	+ (only two-handed)
MONTH	+	+ suppletion: orientation change	-movement
MINUTE	+	-blocked by orientation	-movement
KG	+	-blocked by orientation	-movement
$YEAR_a$	+	-blocked by location	-movement
O’CLOCK	+	-blocked by location	-movement
TIME(occurrence)	+	-blocked by contact preservation	-movement
PEOPLE	+	-movement	
WEEK	+	-orientation	
DAY	-handshape with all fingers selected		
SECOND	-handshape with all fingers selected		
MILLION	-handshape with all fingers selected		
$HOUR_2$	-handshape with all fingers selected		
$YEAR_c$	-semantic reason		
RUBLE	+ suppletion		-movement
WORKING HOUR	+ (lexicalized)		-movement
THOUSAND	+ suppletion		-orientation

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Chapter 4. Number Stroop effect in Arabic digits and ASL number signs: The impact of age and setting of language acquisition.

Abstract

We investigated automatic magnitude processing in two formats (Arabic digits and American Sign Language number signs) and the influence of age of first language exposure on both by using two versions of the Number Stroop Test. We compared deaf people who experienced early language deprivation to both deaf native signers and hearing second language learners of ASL and found that when magnitude is represented by Arabic digits, late first language learners exhibit robust Number Stroop Effects, suggesting automatic magnitude representation. However, they demonstrate slower reaction times.

In an experiment with ASL number signs, Number Stroop Effects were not found in any group, suggesting that magnitude representation might be format-specific, in line with the results from several other languages. Late first language learners also demonstrate unusual patterns and slower reaction times.

In both experiments, late first language learners demonstrated high accuracy. Together, the results show that the ability to automatically judge quantities represented linguistically can be acquired later in life. Contrary to previous studies that find differences in speed of number processing between deaf and hearing participants, we show that when the language was acquired early in life, native signers perform identically to hearing participants.

4.1. Introduction.

Several studies have reported delays in number acquisition and mathematical development in deaf students. The delays are often attributed to hearing loss, unrelated to setting of education (Kritzer, 2009; Traxler, 2000; D. Wood, Wood, & Howarth, 1983; H. A. Wood, Wood, Kingsmill, French, & Howarth, 1984), and are hypothesized to persist into adulthood, since deaf college students in several experiments processed magnitudes more slowly than hearing students (Rebecca Bull, Marschark, & Blatto-Vallee, 2005; Epstein, Hillegeist, & American, 1994). These delays are often found in studies that use standardized school tests with spoken language (Gottardis, Nunes, & Lunt, 2011). However, other studies do not identify such delays in children or adults who are deaf, especially when looking at individual aspects of mathematical development (R. Bull, Blatto-Vallee, & Fabich, 2006; Gottardis et al., 2011; Iversen, Nuerk, & Willmes, 2004). Moreover, deaf preschoolers can outperform their hearing counterparts in some spatial tasks (Arfé et al., 2011; Zarfaty, Nunes, & Bryant, 2004), which indicates that hearing loss per se does not impact quantity discrimination and number reasoning at young ages.

What can impact quantity discrimination and number acquisition is early language deprivation. Importantly, deaf and hard of hearing people do not constitute a homogenous group, but vary in life experience and cultural and language background. Less than 10% of deaf children are born in deaf families using sign language (Mitchell & Karchmer, 2004) and thus experience reduced language exposure early in life. Not only does a lack of language exposure limit access to early number exposure (such as number words or signs, grammatical plural markers, context for numbers in reading and storytelling) that are foundational (Anderson, Anderson, & Shapiro, 2005), it might also negatively affect working memory (Marshall et al., 2015), which is necessary for successful acquisition of numbers and mathematics (Holmes & Adams, 2006). It has been shown that the working memory of deaf children from deaf families (6 – 11 years old) who had early access to sign language is not impaired and is not different from hearing controls on non-verbal working memory assessments, whereas deaf children with later input scored significantly lower (Marshall et al., 2015).

Proficiency in sign language positively correlates with mathematical achievement in deaf children (Henner, Pagliaro, Sullivan, & Hoffmeister, in press.; Hrastinski & Wilbur, 2016). Moreover, a positive impact of bimodal bilingual education on school performance has been demonstrated for deaf children with various language backgrounds: in mathematics specifically (Lange, Lane-Outlaw, Lange, & Sherwood, 2013) and in other aspects such as reading and spoken language proficiency (Henner, J., Hoffmesiter, R., Fish, S., Rosenburg, P., & DiDonna, 2015; Hermans, Knoors, Ormel, & Verhoeven, 2008). Deaf children from deaf families who have access to sign language at home show an advantage in standardized mathematic assessments, scoring on par or even better than their hearing counterparts (Henner, Pagliaro, Sullivan, & Hoffmeister, in press).

However, not all deaf individuals receive access to a natural sign language, even by school age. Late first language learners are congenitally deaf individuals who did not have early access to natural sign language and/or early spoken language intervention and thus began first language acquisition around or post puberty. These individuals do not demonstrate cognitive impairments. They were not socially deprived, unlike cases of isolated children (Fromkin, Krashen, Curtiss, Rigler, & Rigler, 1974; Koluchová, 1972, 1976). Some late first language learners develop homesigns – gestural communicative systems used with their families before they begin learning their first language later in life. However, delayed exposure to the first language has long-lasting detrimental effect on language proficiency and language outcome in comparison to both first and second language learners (Cheng & Mayberry, 2019, 2020; Ferjan Ramirez et al., 2016; Rachel I Mayberry & Lock, 2003). In late first language learners, years of experience does not predict language proficiency: if language acquisition is begun late, native-like proficiency is not achieved even after considerable exposure to language, suggesting the effect of a critical period. It has been shown that initially the language acquisition progress of LL1 learners follows the same milestones as children learning language in the acquisition of vocabulary and word combinations (Berk & Lillo-Martin, 2012; Ferjan Ramirez, Lieberman, & Mayberry, 2013). Late learners are able to successfully master some mono-clausal, but not more syntactically complex syntactic structures (Boudreault & Mayberry, 2006; Cheng & Mayberry, 2019; Fromkin et al., 1974; Mayberry, Cheng, Hatrak, & Ilkbasaran, 2017.; Mayberry, Davenport, Roth, & Halgren, 2018; Newport, 1990). However, there have not been systematic studies of the effect of severe language deprivation on number reasoning.

Being immersed in a numerate society, late first language learners often learn Arabic digits earlier than they acquire language and conventional number lexemes. Work with deaf Nicaraguans (Flaherty & Senghas, 2011) showed that some of the participants who lacked early access to language were able to produce and interpret large numbers written with Arabic digits, while they were not able to recite a counting list in Nicaraguan Sign Language. While performing well on matching tasks with stimuli physically present (i.e., when the participants had to match the number of items that the experimenter physically presented to them in real time), at least one such participant did not perform well on an ephemeral matching task (when the items that the participants had to match were no longer physically present after they were presented). Thus, Flaherty and Senghas (2011) concluded that knowledge of Arabic digits alone is insufficient for successful mental tracking of quantities. At the same time, by testing a diverse group of subjects with various backgrounds, they also showed that when a language is finally available, the counting sequence can be learned at an adult age. However, number processing following severe language deprivation has not yet been studied.

There are many ways to represent number symbolically, and number acquisition from an initial stage involves the interaction between different types of representation: number lexemes, gestures, digits. Arabic digits are acquired through mapping linguistic numerals, which in turn are mapped onto an approximate number system (Le Corre & Carey, 2007). This process is not automatic. Children learn counting lists before they can understand the cardinal principle and can successfully apply it (Condry & Spelke, 2008), and often fail to map newly learned number words onto abstract concepts (Huang, Spelke, & Snedeker, 2010). Studies on acquisition of Arabic digits (Hoffmann, Hornung, Martin, & Schiltz, 2013; Knudsen, Fischer, Henning, & Aschersleben, 2015; Park & Brannon, 2013) suggest that initially it involves number lexemes, but later the link between the two modes of representation weakens with experience. The relation between acquisition and the processing of digits and linguistic numbers is difficult to disentangle due to the relatively simultaneous exposure to both, and, overall, the relationship between language and number remains a topic of considerable debate (Carey, 2009; Gelman & Butterworth, 2005; Spelke, 2017). Research with individuals who acquired number lexemes and Arabic digits on different developmental timelines can contribute to our understanding of this relationship.

In the current study, we investigated the impact of delayed first language exposure on automatic magnitude processing, one of the fundamental aspects of number acquisition. We compared performance in two modes of representation (number lexemes and Arabic digits) in late first language learners of ASL and two control groups, deaf early childhood ASL learners and hearing second language learners of ASL. We used the Number Stroop Paradigm (Algom, Dekel, & Pansky, 1996; Besner & Coltheart, 1979; R. Bull et al., 2006; Gebuis, Cohen Kadosh, De Haan, & Henik, 2009; Henik & Tzelgov, 1982; Kaufmann et al., 2008; Liu, Wang, Corbly, Zhang, & Joseph, 2006; Pansky & Algom, 2002; Razpurker-Apfeld & Koriat, 2006; Schwarz & Heinze, 1998), where participants compare pairs of stimuli that differ both in physical size and magnitude, but the task focuses only on one aspect (size or magnitude). The stimuli vary in congruity: in congruent trials, size and number information aligns (3 5). In incongruent, size information contradicts the numerical dimension (3 5), and in neutral trials the digits differ only in a relevant dimension (3 5, 3 3). Reaction times (RT) across studies show a facilitation effect (RT in congruent trials are faster than in neutral trials), as well as interference effects (RT in incongruent trials are slower than neutral). This size congruity effect (SCE) has been interpreted as evidence in favor of automatic parallel processing of both magnitude and size information: irrelevant information was accessed even in the trials where it was not beneficial. A size congruity effect emerges in children after the start of schooling (Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; White, Szucs, & Soltész, 2012) and has been studied to assess automatic magnitude representation in children with varying degrees of mathematical achievement (Heine et al., 2010a) or mathematical disabilities (Ashkenazi, Rubinsten, & Henik, 2009; Rousselle & Noël, 2007; Rubinsten & Henik, 2005). To date, automatic magnitude representation has not yet been studied in adults who learned their first language late in life.

However, magnitudes can be expressed symbolically, not only through conventional mathematic symbols as described above, but also linguistically through numerals. Studies with Arabic digits unambiguously suggest automaticity of unintentional number processing, but when numbers are represented linguistically, results show great variability. The presence of a Size Congruity Effect when participants are reading number words appears to be specific to a language, or even a particular writing system. In Japanese, it has been found only in ideographic Kanji script, but not the syllabic Kana script (Takahashi & Green, 1983). In Hebrew, it has been found only with gematric numerals, which are letters of the alphabet that stand for numbers (Razpurker-

Apfeld & Koriat, 2006), but not with number words spelled out (Cohen Kadosh, Henik, & Rubinsten, 2008). While the first linguistic Number Stroop Effect study did not find it in English (Besner & Coltheart, 1979), later Vaid (1985) found such an effect and hypothesized that size congruity in number words may be language-specific, such that its processing depends upon the particular orthographic strategy of the language. The higher the phonological transparency of the writing system, the less pronounced the effect would be, so the Stroop effect would be primarily expected in ideographic notations. Similar to English, experiments with ASL have also yielded conflicting results: while one study has found it (J Vaid & Corina, 1989), no effect was reported in a later study (R. Bull et al., 2006).

Besides the size congruity effect, other indices of automatic number representations, such as the distance effect, were shown to be different when stimuli were presented as number words (Cohen Kadosh, 2008). Given the conflicting results of linguistic automatic magnitude processing research, including Number Stroop studies, it has been suggested that the format may fundamentally affect numerical processing (Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007a; Cohen Kadosh & Walsh, 2009), as opposed to the commonly accepted proposal that there is an abstract, format-independent processing of number (Dehaene, Dehaene-Lambertz, & Cohen, 1998). Indeed, numerical notation systems (such as Arabic digits) and number lexemes (such as number signs or words) may represent the same magnitudes, but their use is often governed by different constraints (Chrisomalis, 2019, 2020). Their use in different contexts can also influence processing and retrieval efficiency: for example, doing math problems with written numerals poses more difficulties compared with doing them with digits (Campbell & Alberts, 2009; Campbell & Epp, 2004; Campbell & Fugelsang, 2001), but the skill improves with practice (Metcalfe & Campbell, 2007).

In case of the ASL Number Stroop effect, the conflicting results may also relate to methodological differences. Vaid & Corina (1989) investigated the Number Stroop effect in Arabic digits, English number words, and ASL number signs. They compared results from deaf native signers exposed to ASL from birth, hearing children of deaf adults, and hearing second language learners of ASL. Because the ASL number signs from ONE to FIVE (the number system of ASL is illustrated in Fig.4.1) are transparent and similar to the number gestures from hearing American culture, only the signs SIX – NINE were used, to avoid confusion with number gestures of hearing people. Vaid and Corina found the effect in all conditions in all groups. Most importantly, they also investigated visual field asymmetry in the Stroop effect and found a greater left visual field Stroop effect for numerical size judgments involving digits. A larger right visual field Stroop effect was found for number words/signs trials, leading the researchers to conclude that there might be hemispheric differences in numerical comparison that depend on the mode of representation (linguistic/digits).

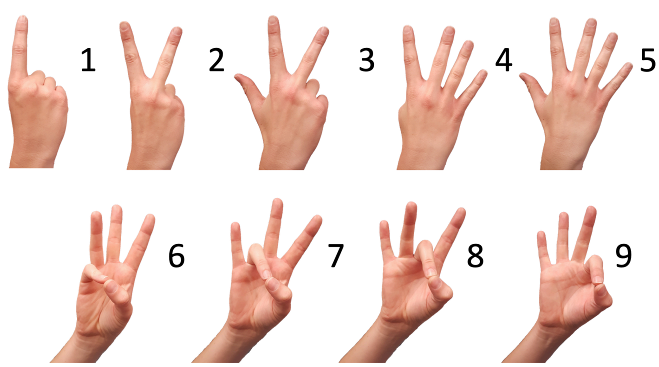


Figure 4.1. ASL number signs ONE - NINE.

In another study using ASL stimuli with deaf signers (Bull et al., 2006), a Size congruity effect was not found. Unlike the Vaid and Corina (1989), this study used only the number signs

ONE – FIVE, which make use of number-to-number iconicity (Taub, 2001) and therefore were intelligible to the hearing controls as well. This study compared number activation in deaf college students with hearing college students, not exposed to ASL, but there was no control for the age and setting of ASL acquisition by deaf participants. The mathematic test scores were comparable to the mean scores of deaf college students, but lower than the national norms. The study showed that the deaf and hearing participants demonstrated similar reaction times in processing magnitudes. Both groups showed the expected Size congruity effect for Arabic digits only. The number Stroop task was a part of a large battery of tests used in this study to investigate different aspects of magnitude processing: both groups of participants were tested in other tasks accessing automatic magnitude representation (subitizing, magnitude estimation) and showed overall similar patterns of performance.

It is possible that methodological differences between these two studies can explain the difference in results. First, the different choice of stimuli in these two studies might influence reaction times: number signs ONE – FIVE are more iconic and more transparent than the signs SIX – NINE. Although it has been shown that iconicity does not facilitate lexical sign processing in native deaf signers (Bosworth & Emmorey, 2010), it may help beginners, or inhibit the processing of experienced second language learners (Baus, Carreiras, & Emmorey, 2013). Moreover, the cross-linguistic frequency of the first five numerals exceeds the frequency of the subsequent ones (Dehaene & Mehler, 1992), and the frequency of the stimulus items may influence the choice of strategy, as discussed earlier.

In addition, the experimental procedure differed between the studies. Vaid and Corina (1989) presented their stimuli sequentially, while Bull et al. (2006) used a more traditional simultaneous digit comparison. Bull et al. discuss the possibility that presentation format may have influenced reaction times in previous work as well, since several findings of slower number processing in deaf individuals were obtained using sequential presentation of stimuli. Using sequential presentation, their deaf and hearing participants reacted equally fast and accurately with no significant differences in RTs.

Importantly, none of the Number Stroop Effect studies reported here used a control stimulus, that is, a neutral pair of stimuli (such as 3 5 for the number condition, or 3 3 for the size condition), which makes it difficult to evaluate the facilitation effects (as opposed to interference effects).

Finally, differences in results may be related to the likely difference in the language backgrounds between the participants of the two studies. Vaid and Corina (1989) tested deaf native signers of ASL, with hearing non-signers and hearing children of deaf adults as controls. The language background of participants in the Bull et al. (2006) study was not specified, and some participants may have learned ASL as a second language or experienced language deprivation early in life. The authors report the age of hearing loss (0 – 3) and that participants used ASL as their preferred means of communication, but the setting of acquisition of sign language was not reported.

In the present study, we control for both the issues discussed above. To assure that experimental stimuli fully represent the numeral system of ASL, with both transparent and non-transparent number signs, we included all numbers from TWO to NINE, with the number ONE excluded following the original experiment by Henik & Tzelgov (1982) due to its frequency.

To control for age and setting of language acquisition, we compared three groups of participants: first language learners of ASL who acquired language from birth, late first language learners of ASL who first acquired language after the age of 9, and hearing adults acquiring ASL as a second language in a college setting. Doing so allowed us to disentangle the effects of age of exposure versus language deprivation: second language and late language learners both began learning ASL late in life, but their prior language experience differed dramatically.

We conducted two Number Stroop experiments, with Arabic digits and ASL number signs, to investigate three questions: whether ASL number signs elicit the Number Stroop Effect, whether this effect is influenced by age of acquisition and/or years of exposure, and whether this effect is similar for both number formats. In addition, we analyzed the possible effects of stimuli: the iconicity or the frequency of the numeral and Spatial Numerical Association of Response Codes (SNARC effect). The SNARC effect is an association of the right side with larger magnitudes and of the left side with smaller ones that is attested in cultures reading and writing from left to right (Dehaene, Bossini, & Giraux, 1993). Table 4.1a lists the possible outcomes of the Arabic Digit experiment and their potential explanations, and Table 4.1b lists possible outcomes of the ASL experiment.

Table 4.1. Possible outcomes of the study.

a. Possible outcomes of Experiment 1.

Number Stroop Effect with Arabic Digits	*Possible Interpretation*
Found in all groups; no differences	Age of acquisition does not affect automatic magnitude representation
Found in all groups, but there are specificities in late first language learners	Age of acquisition affects automatic magnitude representation, but it still can be formed despite incomplete early input (i.e., only digits)
Found in all groups but late learners	Age of acquisition affects automatic magnitude representation, without early language exposure automatic magnitude representation is not achieved
Found only in hearing second language learners	Something other than language deprivation affects automatic magnitude representation in deaf participants

b. Possible outcomes of Experiment 2.

Number Stroop Effect with ASL signs	*Possible Interpretation*
Found in all groups	ASL number lexemes activate magnitudes in the same way as Arabic digits, supporting the common number representation hypothesis
Not found in all groups	ASL number lexemes activate magnitudes in a different way from Arabic digits, supporting the modality-specific activation hypothesis
Late first language learners differ from other groups	Age of acquisition rather than years of exposure influences automatic magnitude representation with number lexemes
Hearing signers differ from other groups	Years of exposure rather than age of acquisition influence automatic magnitude representation with number lexemes
Early first language learners differ from other groups	Both years of exposure and age of acquisition influence automatic magnitude representation with number lexemes

4.2. Methods
4.2.1. Participants

29 adult users of American Sign Language were recruited. 11 were second language learners of American Sign Language (all female, mean age (SD): 21.5 (1.08), mean AoA (SD) 15.2 (4.8), mean duration of exposure (SD) 6.1 (5.15)), who acquired ASL in an educational setting (college, university, or high school).

10 participants were late first language learners of ASL (6 females, mean age (SD): 33.1 (12.9), mean AoA (SD): 19.6 (6.12), mean duration of exposure (SD) 13.4 (14.45). These individuals were born deaf and did not have accessible language input during childhood. Due to various circumstances, these individuals did not have access to natural sign language or spoken language but were not socially deprived. Currently, they are using ASL daily. Two more participants in this group were excluded from the analysis: one did not satisfy the background inclusion criteria (they were exposed to another sign language prior to ASL[7]), and one demonstrated unusually slow reaction times, which suggested that the participant did not perform the task automatically.

8 participants were deaf early signers of ASL (mean age (SD): 39.7 (13.29)); 7 were exposed to ASL from birth, learning it from their deaf parents, and one participant from a hearing family was exposed to ASL from 1 month of age through an early intervention program. Participants who were not UCSD students received financial compensation for their time, while the students participated in the experiment for class credit (the experimenters were not involved in teaching any of the classes that the extra credit was used for). Participants signed the Informed Consent that was approved by UCSD Institution Review Board.

[7] - background criteria for late first language learners: being born deaf, not exposed to sign/spoken language prior to the age of 10, not being socially deprived.

4.2.2. Materials

4.2.2.1. Structure

Each participant performed a computer-based task in two conditions: size comparison (the relevant dimension was physical size) and number comparison (the relevant dimension was number). There were two blocks of each condition: Arabic digits followed by ASL number signs. The order of the size and number conditions was counterbalanced across participants. Within both conditions, stimuli were fully randomized.

Each block contained 12 congruent, 12 neutral, and 12 incongruent stimuli, repeated three times with 108 trials per block (ASL or digits) for a total of 216 trials per condition. The structure of each trial was as follows: a white fixation dot appeared in the middle of the screen for 450 ms, followed by the stimulus (digit/sign array). The stimulus remained on the screen until the participant pressed the key (right or left). Before each block, the participant received instructions in ASL from the experimenter along with explanations from an individual familiar to the participants if needed (in case of late first language learners, a native signer of ASL) and in written English on the screen. In the Arabic digit experiment, for the number condition, the instructions stated "In this condition, you need to choose a digit that is numerically bigger. To choose the variant on the left, press Z. To choose the variant on the right, press M"; for size "In this condition, you need to choose a digit that is physically bigger. To choose the variant on the left, press Z. To choose the variant on the right, press M". In the ASL condition, "digit" was replaced by "handshape".

Instructions were followed by three examples (congruent, neutral, incongruent): participants saw each example stimulus for 700 ms, after which the correct answer was indicated with green arrows. After the example trials, the participants performed 6 practice trials followed by feedback, and then began the experiment. Based on the pilot results, to avoid boredom that may lead to inadequate effort on cognitive tasks completed exclusively for credit (DeRight & Jorgensen, 2015) and increase motivation, each block was followed by feedback as well: the percentage correct and mean reaction time (RT). The participants were encouraged to respond as fast as possible.

4.2.2.2. Stimuli

The Arabic digits 2 – 9 and the ASL signs TWO – NINE were used as stimuli. Each digit/number sign was paired with itself for a neutral comparison in physical size, or with a different number that was always numerically smaller or bigger by two (for example, 5 was paired with 3 or 7). The signs/digits differed in physical size and numerical magnitude. The bigger item size was 3.2'', the smaller item size was 2.9''. Digit stimuli were created using standard font Calibri (Body). The stimuli were presented on a black background. The ASL handshape illustrations were created from photographs of a native signer signing numbers. Examples of the stimuli for each block are shown in Figures 2 and 3. To avoid right/left hand biases, each digit/number sign appeared on each side of the screen an equal number of times.

4.2.3. Results

4.2.3.1. Age.

Given the small size and heterogeneity of the groups of participants in terms of age, we first explored whether age influenced the overall reaction times (RT) independently of the Stroop interference and language acquisition circumstances, since several studies have suggested that the Color Stroop Effect changes with chronological age, namely participants who are older generally respond more slowly (Bugg, DeLosh, Davalos, & Davis, 2007; West & Baylis, 1998), although other studies contest this effect (Verhaeghen & De Meersman, 1998).

For each numerical format (digits and ASL), we built linear regression models (using *lm* function in *R* (R CORE TEAM, 2016)) with mean reaction time for each participant as a dependent variable and age of participant as a predictor variable. For both formats, the effect of age was not significant.

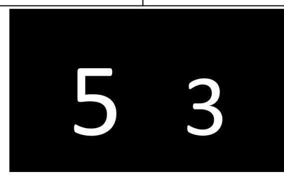
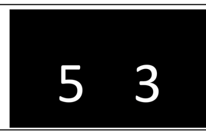
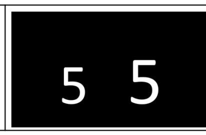
Type of stimulus	Number condition	Size condition
Congruent		
Neutral		
Incongruent		

Figure 4.2. Examples of stimuli for Arabic Digit block.

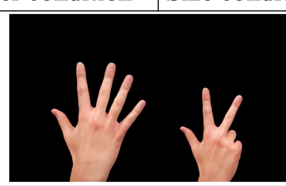
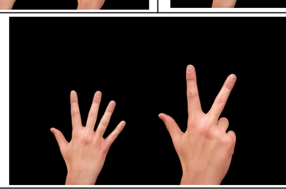
Type of stimulus	Number condition	Size condition
Congruent		
Neutral		
Incongruent		

Figure 4.3. Examples of stimuli for ASL block.

4.2.3.2. Number Stroop Effect: data processing.

The experimental within-subject factors were size comparison (physical vs. semantic), notation, i.e., type of stimuli (Arabic Digits vs ASL number signs), congruity (congruent, incongruent, neutral). The between-subject factors were condition and Age of acquisition (AoA). All the variables were categorical (for this analysis, AoA included three groups – early first language learners, late first language learners, second language learners).

Data analyses for response time were conducted for correct response trials only. The outliers for each subject were removed using an interquartile rule 1.5 x (IQR). Some previous Number Stroop Effect studies have used a cutoff method and included only the trials with reaction times under a specified threshold (for example, 150 - 2000 msec) in the analysis (Cohen Kadosh, Gevers, & Notebaert, 2011; Szucs & Soltész, 2007). However, we did not use a cut-off method here because, in relatively small sample sizes with large variation, as in the present study, a general threshold may affect the power and introduce asymmetric biases (Whelan, 2008), because there was a high degree of individual variation within our sample, especially for the late first language learners.

In the following sections, the results for each experiment are presented separately, first for the Arabic Digit experiment, then for the ASL number sign experiment.

4.3. Experiment 1: Arabic Digits.

4.3.1. Mean Reaction Times.

Overall accuracy was high for all groups, with the late first language learners showing somewhat lower accuracy, that was still above chance (Early language learners: 0.96, Second language learners: 0.95, Late first language learners: 0.88). Mean reaction times for each group for the Number Strop task in Arabic digits are presented in Table 1. The deaf early first language learners and hearing ASL students showed comparable performance. By contrast, the mean RTs for the LL1 group were slower (Table 4.2).

Table 4.2. Mean RT (SD), digits

Arabic digit task.			
	L1	L2	LL1
Number	612 (189)	602 (165)	893 (448)
Size	450 (127)	432 (116)	672 (343)

4.3.2. Stroop Effect: Mean Reaction Times as function of congruity.

Mean reaction times (SD) data for Arabic Digits are shown in Table 4.3. In all groups, a Number Stroop Effect was observed: congruent stimuli were processed faster than neutral stimuli, and incongruent stimuli were processed slower than neutral stimuli.

Table 4.3. Mean RT (SD) as a function of congruity.

Arabic digits						
	Size mean RT (SD)			Number mean RT (SD)		
	congruent	incongruent	neutral	congruent	incongruent	neutral
L1	438 (112)	473 (153)	437 (106)	549 (146)	678 (208)	613 (188)
L2	424 (104)	450 (138)	422 (96)	558 (162)	652 (156)	601 (163)
LL1	674 (378)	698 (360)	642 (279)	823 (386)	942 (458)	931 (494)

To estimate congruity effects in both conditions (size/number), we performed a mixed-effects regression model in R (Team, 2015), using the package *lme4* (Bates et al., 2016). The predictor variables were the within-participants factors of congruity (congruent, incongruent) and condition (size, number), and the between-participants factor was Age of Acquisition (early first language learners, late first language learners, hearing second language learners). The interactions of congruity and condition with AoA were included in the model. We included random intercepts for block order, number or size first, and participants (nested) and stimuli (every stimulus was seen by each participant three times). The model was tested for multicollinearity (for all effects VIF < 3.5). Confidence intervals were verified through the *confint ()* function with a bootstrapping resampling technique, based on 1000 bootstrapping replicates. All the significant effects were confirmed, so we report the CI obtained through bootstrapping.

We first fit the model that included Task, Congruity, and AoA with no interactions as predictors, followed by a model that included interactions of AoA with condition and AoA with congruity. We compared these two models based on the results of previous studies. In adults, congruity effects with Arabic digits have been shown reliably across populations. At the same time, in children, the emergence and nature of the congruity effect change with the amount of number exposure (Girelli et al., 2000; Heine et al., 2010b; Rubinsten et al., 2002). Difference in RTs between size and number conditions may also change with the amount of exposure, and therefore age and setting of language exposure might influence both the congruity effect and condition differently across groups. Since the Akaike Information Criterion (estimator of out-of-sample prediction error) was lower for the second model including interactions (76805 and 76792), the analysis was performed using this model. The graph representing reaction times for the Arabic digit experiment can be found on Figure 4.4. The results of the model are presented in Table 4.4.

The main effect of congruity was significant for both facilitation (congruent being faster than neutral) and interference (incongruent being slower than neutral). There was also a main effect of comparison condition, with size judgments being faster than number judgments.

Table 4.4. Results summary for Number Stroop Effect with Arabic digits.

Results summary for Number Stroop Effect with Arabic digits.
Reference categories: congruity = neutral, AoA = L1, condition = number.

	Response time		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	604.64	483.59 – 725.68	**<0.001**
congruity [congruent]	-31.98	-57.55 – -6.42	**0.014**
congruity [incongruent]	49.94	24.15 – 75.74	**<0.001**
AoA [L2]	-10.47	-176.92 – 155.99	0.902
AoA [LL1]	306.88	140.28 – 473.48	**<0.001**
condition [size]	-158.63	-176.82 – -140.44	**<0.001**
congruity [congruent] * AoA [L2]	11.69	-18.05 – 41.43	0.441
congruity [incongruent] * AoA [L2]	-12.53	-42.68 – 17.61	0.415
congruity [congruent] * AoA [LL1]	-7.22	-37.62 – 23.17	0.641
congruity [incongruent] * AoA [LL1]	-12.05	-43.29 – 19.19	0.450
AoA [L2] * condition [size]	-6.73	-31.12 – 17.66	0.589
AoA [LL1] * condition [size]	-55.63	-80.99 – -30.27	**<0.001**
Random Effects			
σ^2	37529.17		
$\tau_{00\ stimulus}$	384.04		
$\tau_{00\ block\ order:subject}$	33433.23		
ICC	0.47		
$N_{stimulus}$	48		
$N_{block\ order}$	2		
$N_{subject}$	29		
Observations	5728		
Marginal R^2 / Conditional R^2	0.262 / 0.612		

4.3.2.1. Differences in the Stroop Effect between groups

While the reaction times of the deaf early first language learners (L1) and hearing second language ASL learners (L2) groups did not significantly differ, the late first language learners group (LL1) demonstrated significantly slower reaction times. Besides that, the interaction between condition and age of acquisition (AoA) was also significant: the mean difference in speed between size and number judgments for the late first language learners group was significantly larger than it was for the early first language learners.

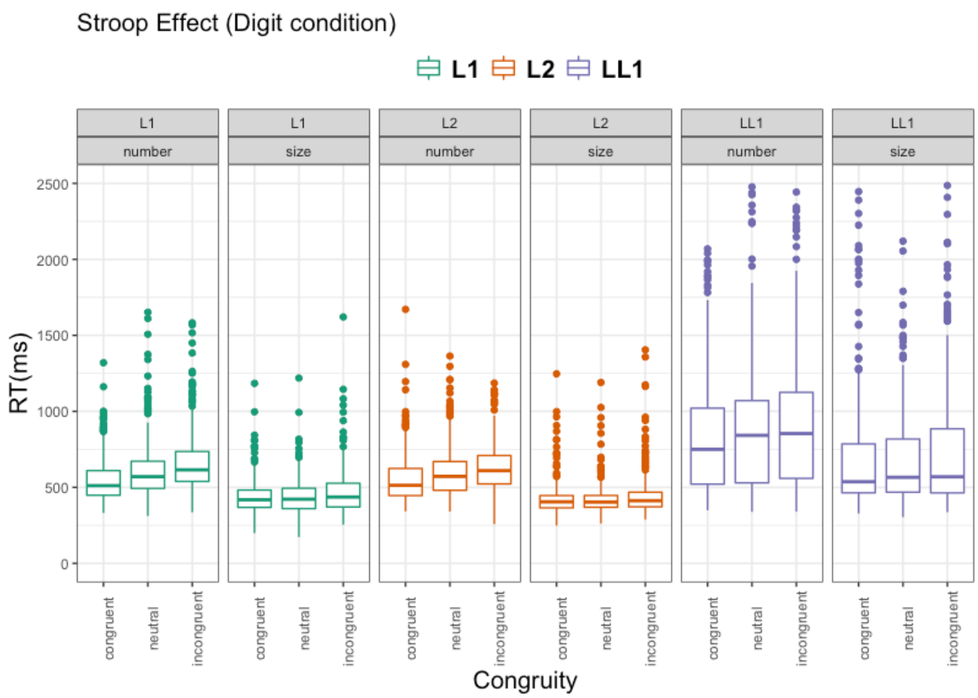


Figure 4.4. Response times for the trials with Arabic Digits. The head of the facet and the color indicate a group of participants (L1, L2, or LL1) and the condition (type or number). The top of the box plot shows the higher quartile (75%), the bar shows the median (50%), and the bottom of the box shows the lower quartile (25%); the dots show outliers outside the 1.5 interquartile range.

4.3.3. Random effects

4.3.3.1. Stimuli: SNARC effect and perceptual similarity

Since the effect of stimuli was significant (CI obtained by bootstrapping 11.119 – 26.631), we performed additional analyses to evaluate if the difference in reaction time was caused by the structure of the stimuli that elicited the Spatial–Numerical Association of Response Codes, or the SNARC effect (Dehaene et al., 1993). In cultures that write numbers from left to right, people react faster to larger numbers that require rightward response, and to smaller numbers that require leftward response (Fias, 2001; G. Wood, Willmes, Nuerk, & Fischer, 2008). Several studies suggest that SNARC effect depends both on left to right (or right to left) reading habits (Shaki & Fischer, 2008; Shaki, Fischer, Petrusic, & Shaki, 2009) and immediate spatial experiences (Fischer, Shaki, & Cruise, 2009). While the SNARC effect is usually assessed through number parity judgments without size incongruities involved, there was a possibility that it can influence the processing times for particular stimuli.

For the purpose of the subsequent analysis, we defined the stimuli as SNARC-congruent if numerical and size information aligned in terms of the SNARC effect (for example, in 3 5 the right number is bigger both size and number, and in 7 5 the right number is smaller in both dimensions) and as SNARC-incongruent if the size and numerical information did not align (as in 3 5 or in 7 5). The stimuli that only had one dimension of comparison (e.g., 5 5) were excluded from the analysis.

Using *lm* function in *R* (R CORE TEAM, 2016), we built a linear regression model with reaction time per each stimulus in as a dependent variable, and SNARC congruity, group (early first language learners, late first language learners, or hearing second language learners of ASL), and the interaction between SNARC congruity and group. The main effect of SNARC congruity was significant with SNARC-incongruent stimuli being processed more slowly (*β*= 136.22, *CI* = 39.75 – 232.70, *SE*= 48.79, *t* (144) = 2.792, *p* = **0.006**). The main effect of group was also significant: the late learners of ASL were significantly slower than other groups in both SNARC-congruent and incongruent trials (*β*= 289.81, *CI* = 185.61 – 394.01, *SE*= 52.70, *t* (144) = 5.499, *p* < **0.001**). The interactions were not significant. The results are illustrated by Figure 7.

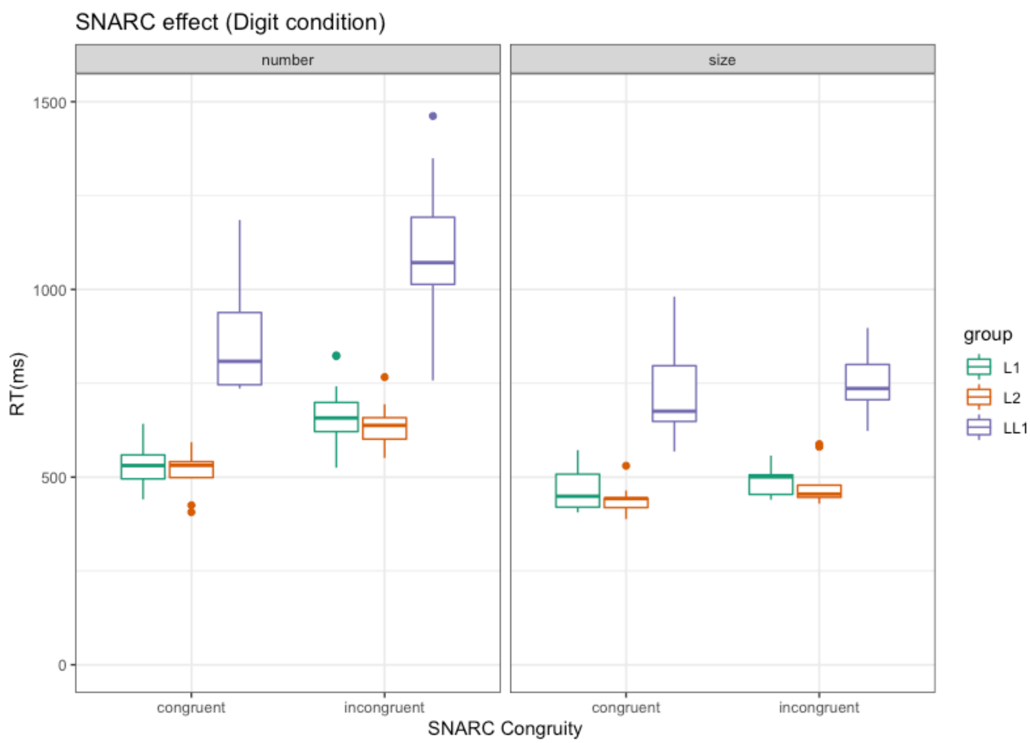


Figure 4.5. SNARC effect with Arabic Digits. The colors indicate a group of participants (L1, L2, or LL1) and the columns show SNARC congruity (congruent or incongruent). The top of the box plot shows the higher quartile (75%), the bar shows the median (50%), and the bottom of the box shows the lower quartile (25%); the dots show outliers outside the 1.5 interquartile range.

Additionally, the stimuli including the digits 6 and 8 as SNARC-congruent were processed 40 ms slower than the baseline. It has been suggested in previous literature that processing speed for larger and smaller numbers might differ (Girelli et al., 2000; Tzelgov, Meyer, & Henik, 1992). Using the linear regression model, we analyzed whether mean reaction times for the stimulus depended on magnitude (small (1-5), large (6 – 9) or mixed (stimuli containing both), but the effect of magnitude was not significant.

However, it has been previously shown that perceptual similarity between digits can significantly influence the speed of their discrimination, and 8 differs from 6 with only one line compositional element (Cohen, 2009), and this might explain the difficulty of distinguishing 6 and 8 specifically.

4.3.3.2. Individual differences: delayed first language acquisition and language experience

The nested random effect of order/participant was significant (CI obtained by bootstrapping 134.43 – 232.77). Since participants in the late first language acquisition group varied greatly in their age of acquisition and years of exposure, we analyzed the potential impact of these factors on the reaction times. We built a linear regression model (using *lm* function in *R* (R CORE TEAM, 2016)) with mean reaction time for each participant as a dependent variable. The predictor variables were the exact age of first language acquisition (AoA), number of years of exposure (YoE) and their interaction. For this analysis, AoA and YoE were continuous variables. Only the main effect of years of exposure was weakly significant (β= 64.96, *CI* = 5.70 – 124.22, *SE*= 24.21, t (10) = 268, p = 0.036): the more years of experience the late learners had, the slower they were.

4.3.4. Summary of the Experiment 1 results

Overall, the results showed the expected size congruity Stroop effect (both interference and facilitation only for the number judgment task) and condition effects, but they differed depending upon the group. Deaf and hearing participants who learned a first language early in life performed identically. In contrast to the deaf early signers, deaf participants who experienced highly delayed exposure to language showed slower reaction times and larger time differences between number and size judgments.

With more years of language experience, late first language learners did not become faster, but demonstrated the tendency towards slower reaction times. Exact age of first language acquisition did not correlate with the processing speed.

Additionally, all groups demonstrated a SNARC congruity effect, and, unlike with Stroop, there were no differences between groups in the SNARC effect. Other characteristics of stimuli (frequency and magnitude size) did not significantly affect reaction times.

Together the results of Experiment 1 suggest that early language deprivation affects automatic magnitude representation, but it was still achieved despite incomplete early input (i.e., only digits, but no language).

4.4. Experiment 2: ASL number signs

4.4.1. Mean Reaction Times.

Overall accuracy was high for all groups, with the LL1 showing somewhat lower accuracy (ASL: L1 0.96, L2 0.96, LL1 0.92). Mean reaction times for the ASL number signs are shown in Table 4.5. Here, RTs differ greatly between groups and conditions, although size judgements are made at comparable speed by deaf early first language learners and hearing second language learners.

Table 4.5. Mean RT (SD), ASL

ASL Task.			
	L1	L2	LL1
Number	827 (207)	1047 (331)	1112 (418)
Size	450 (152)	476 (180)	802 (458)

4.4.2. Stroop Effect: Mean Reaction Times as a function of congruity.

Mean RT (SD) data are shown in Table 4.6 (for ASL).

Table 4.6. Mean RT (SD) as a function of congruity.

ASL signs.						
	Size mean RT (SD)			Number mean RT (SD)		
	congruent	incongruent	neutral	congruent	incongruent	neutral
L1	445 (145)	452 (164)	452 (146)	808 (204)	841 (197)	832 (219)
L2	455 (147)	473 (194)	498 (192)	1049 (335)	1063 (329)	1030 (330)
LL1	802 (444)	755 (445)	846 (481)	1079 (412)	1134 (391)	1130 (446)

Following the same rationale described above for Experiment 1, we first fit the model that included Task, Congruity, and AoA with no interactions as predictors, followed by a model that included interactions of AoA with condition and AoA with congruity. Since Akaike Information Criterion for the model with interactions was smaller (75000 and 74729), it was used for the subsequent analysis. Multicollinearity was checked through VIF (all VIF < 2.5). The ASL RTs are shown on Figure 4.6, and the full results of the model are shown in the Table 4.7.

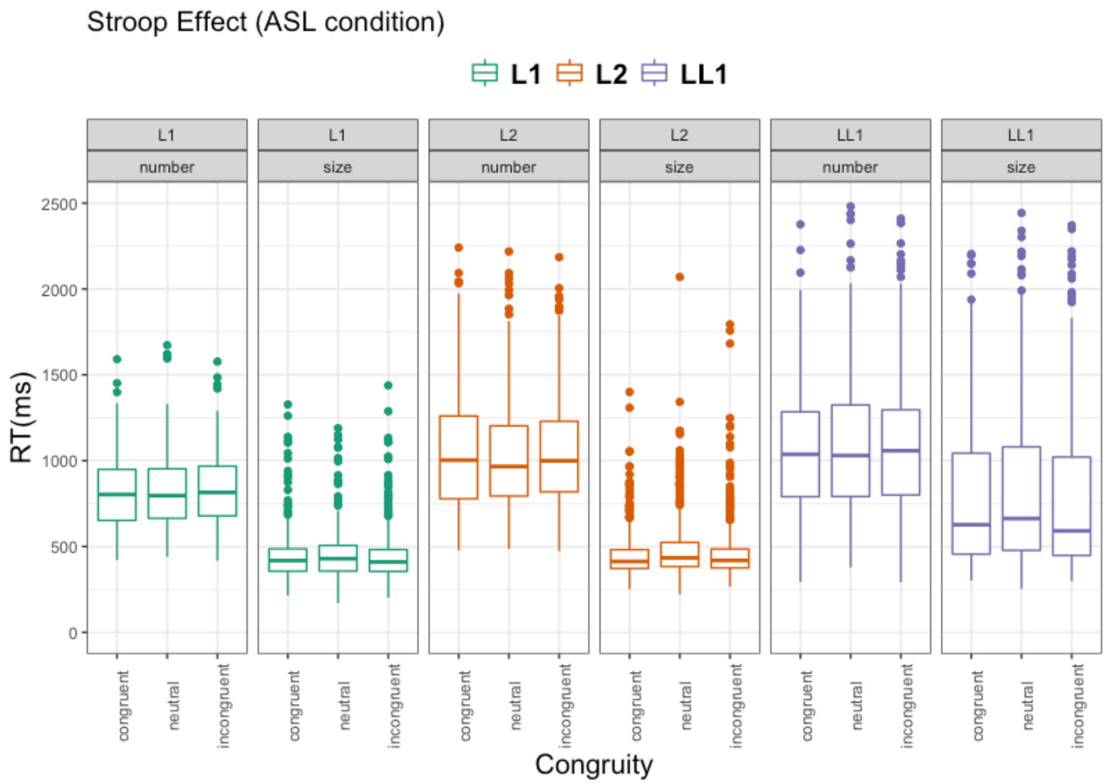


Figure 4.6. Response times for the trials with ASL signs. The head of the facet and the color indicate a group of participants (L1, L2, or LL1) and the condition (type or number). The top of the box plot shows the higher quartile (75%), the bar shows the median (50%), and the bottom of the box shows the lower quartile (25%); the dots show outliers outside the 1.5 interquartile range.

Table 4.7. Results summary for Number Stroop Effect with ASL signs.

Results summary for Number Stroop Effect with ASL signs. Reference categories: congruity = neutral, AoA = L1, condition = number.			
		response_time	
Predictors	*Estimates*	*CI*	*p*
(Intercept)	821.75	684.71 – 958.80	**<0.001**
AoA [L2]	213.19	28.84 – 397.54	**0.023**
AoA [LL1]	262.67	78.55 – 446.79	**0.005**
congruity [neutral]	14.37	-32.27 – 61.02	0.546
congruity [incongruent]	18.88	-32.46 – 70.22	0.471
condition [size]	-385.58	-409.98 – -361.19	**<0.001**
AoA [L2] * congruity [neutral]	8.61	-31.06 – 48.28	0.670
AoA [LL1] * congruity [neutral]	40.26	1.17 – 79.34	**0.044**
AoA [L2] * congruity [incongruent]	3.69	-35.96 – 43.34	0.855
AoA [LL1] * congruity [incongruent]	0.75	-38.88 – 40.37	0.971
AoA [L2] * condition [size]	-190.91	-223.70 – -158.12	**<0.001**
AoA [LL1] * condition [size]	84.03	51.53 – 116.54	**<0.001**
Random Effects			
σ^2	60460.57		
$\tau_{00\ \text{stimulus}}$	2875.92		
$\tau_{00\ \text{block order:subject}}$	40513.65		
ICC	0.42		
N_{stimulus}	48		
$N_{\text{block order}}$	2		
N_{subject}	29		
Observations	5379		
Marginal R^2 / Conditional R^2	0.387 / 0.643		

In contrast to the Arabic Digit experiment, the main effect of congruity was not significant when magnitudes are represented by ASL signs. However, there was an interaction effect of congruity with age of acquisition: in the late first language group the neutral stimuli were processed significantly more slowly than the congruent stimuli. Differences between congruent and incongruent stimuli were not significant for any other group.

However, the main effect of condition was significant: size judgments were faster than number. The main effect of age of acquisition group was significant as well: both the hearing second language learners and deaf late first language learners significantly differed from the early deaf first language learner group. In the size condition, mean reaction times of the hearing second language learner group were very close to those of the early first language group, but in the number condition hearing second language learners performed as slowly as the late learners.

The significant interaction between condition and age of acquisition indicated that all three groups showed contrasting reaction time patterns as a function of size and number. The largest difference in performance between the number and size conditions was shown by the hearing second language learners. By contrast, the smallest difference in performance between the number and size conditions was shown by the late first language learners, due to their slowed performance in the size condition.

4.4.3. Random effects

4.4.3.1. Stimuli: ASL SNARC effect and iconicity

Since the random effect of stimuli was significant (CI from bootstrapping 40.454617 – 67.66368), we performed an additional analysis identical to the one described in Experiment 1 to detect a possible SNARC effect and its interaction with language acquisition group. However, SNARC was not significant, and the only significant result was that late learners demonstrated slower reaction times (β= 380.49, *CI* = 190.28 – 570.71, *SE*= 96.20*, t* (144) = 3.955*, p* < **0.001**). None of the interactions were significant.

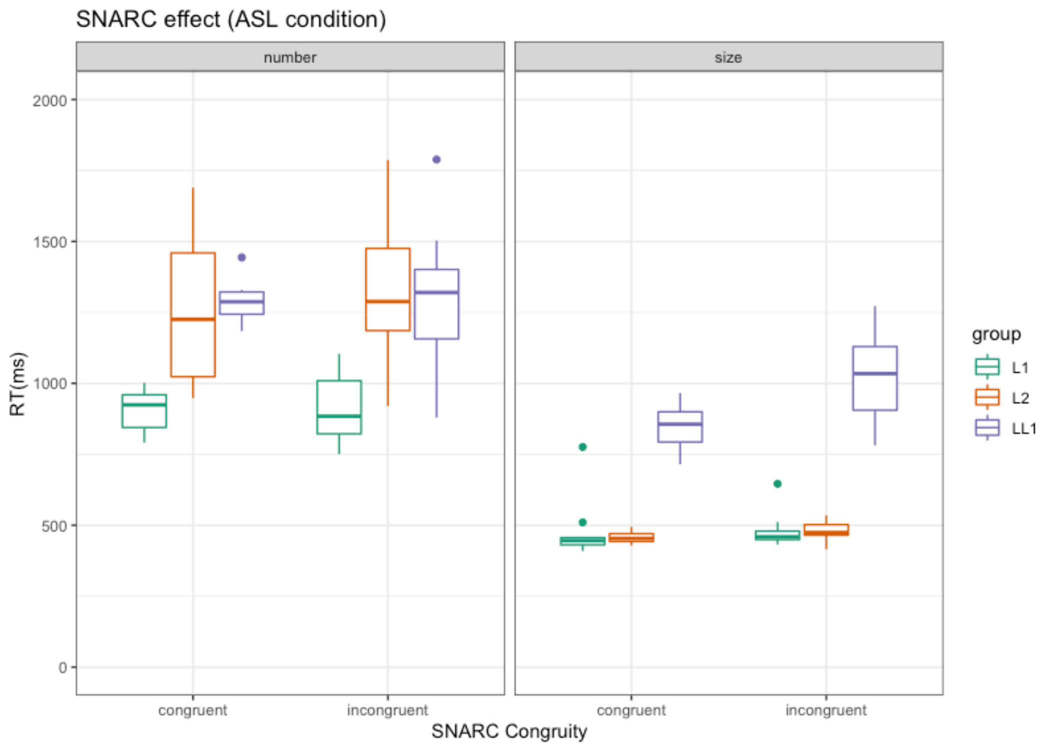


Figure 4.7. SNARC effect with ASL signs. The color indicate a group of participants (L1, L2, or LL1) and the columns show SNARC congruity (congruent or incongruent). The top of the box plot shows the higher quartile (75%), the bar shows the median (50%), and the bottom of the box shows the lower quartile (25%); the dots show outliers outside the 1.5 interquartile range.

Another potential source of variation can be the transparency of the stimulus, or whether it abides to number-to-number iconicity. The combinations of number signs in our stimulus set can be divided in 3 groups: only transparent numerals (THREE FIVE, TWO FOUR, FIVE THREE, FOUR TWO), a mix of transparent and non-transparent (FOUR SIX, FIVE SEVEN, SIX FOUR, SEVEN FIVE), and non-transparent (SIX EIGHT, SEVEN NINE, EIGHT SIX, NINE SEVEN). To evaluate the effect of this transparency, we used the *anova* function of R to compare two linear regression models. One included mean reaction time for the particular stimulus as a dependent variable and Stroop congruity, Age of acquisition group, and condition as predictor variables, the other model also included transparency of the stimulus (transparent, non-transparent, or mixed); the model that included transparency had better R^2 / R^2 adjusted. Table 7 presents the results of the models. Alongside the main effects of group and condition, the main effect of number transparency was significant: the stimuli with transparent (iconic) number signs TWO to FIVE were processed faster than the mixed stimuli that included a combination of transparent and non-transparent number signs, but the stimuli with non-transparent signs SIX to NINE did not differ from the mixed stimuli. However, there is a possibility that the effect was produced not by transparency, but by higher crosslinguistic frequency of the first five numbers (Dehaene & Mehler, 1992): the non-transparent number signs in ASL all designate higher magnitudes that are less frequent.

Table 4.8. Results summary for Iconicity Effect with ASL signs.

Results summary for Iconicity Effect with ASL signs.
Reference categories: congruity = congruent, AoA = L1, condition = number, iconicity = mix

		rt			**rt**	
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	932.44	870.77 – 994.11	**<0.001**	950.29	879.48 – 1021.11	**<0.001**
congruity_stroop [neutral]	61.27	-0.40 – 122.94	0.051	65.55	7.06 – 124.04	**0.028**
congruity_stroop [incongruent]	33.29	-28.38 – 94.96	0.288	34.84	-23.65 – 93.33	0.242
AoA[L2]	192.56	130.89 – 254.22	**<0.001**	192.56	134.12 – 250.99	**<0.001**
AoA [LL1]	455.17	393.51 – 516.84	**<0.001**	455.17	396.74 – 513.61	**<0.001**
condition [size]	546.62	596.98 – 496.27	**<0.001**	-544.80	-592.61 – 496.99	**<0.001**
iconicity [-]				37.20	-23.79 – 98.19	0.231
iconicity [+]				-102.79	-165.62 – -39.95	**0.001**
Observations	216			216		
R^2 / R^2 adjusted	0.763 / 0.757			0.789 / 0.782		

4.4.3.2. Individual differences: delayed first language acquisition and language experience

Since the random effect of participant was significant (CI obtained by bootstrapping 149.482 – 255.979), we performed additional analyses to compare the influence of age of ASL acquisition and Years of Exposure on number sign processing in deaf late learners and hearing language learners of ASL. The linear regression model included reaction time as a dependent variable and exact age of acquisition, exact years of exposure (both were continuous variables), and their interactions. The only effect that was marginally significant was years of exposure (β= 52.57, CI = 4.34 – 100.80, SE = 22.860, t (21) = 2.300, p = 0.034); participants demonstrated high variation in reaction time patterns, but in both groups, there were several individuals with longer exposure to ASL who performed slower than people with comparable or less exposure.

4.4.4. Summary of the Experiment 2 results.

We did not find the typical Number Stroop Effect in the ASL condition. Age and setting of ASL acquisition also impacted the performance: while in the size condition second language learners performed no differently from early signers of ASL, in the number condition they were significantly slower. Late learners, on the other hand, were slower in both conditions. Hence, unlike in the Arabic Digit experiment, the largest difference between size and number judgments was demonstrated by hearing second language learners of ASL.

The SNARC effect was not attested in the ASL condition as well, but another effect of stimuli was significant: stimuli with frequent and transparent number signs TWO to FIVE were processed faster than stimuli with less frequent non-transparent number signs and mixes of transparent and non-transparent ones.

Some of the deaf late learners and hearing second language learners of ASL demonstrated a tendency towards slower reaction times despite their longer experience with the language. Exact age of first language acquisition did not correlate with the processing speed.

4.5. Discussion

In the current study, we conducted two Number Stroop experiments, with Arabic digits and ASL number signs, with three groups of participants (deaf early learners, deaf late learners, and hearing second language learners of ASL) to investigate three questions: whether automatic magnitude estimation is influenced by age of acquisition and/or years of exposure, whether the Number Stroop Effect is found in ASL number signs as well, and whether the effect of age of acquisition is similar for both number formats.

Revisiting the possible outcomes in Table 1, in Experiment 1, the results showed the Number Stroop Effect with Arabic digits found in all groups, but there were specificities in late first language learners, suggesting that age of acquisition affects automatic magnitude representation, but can still be formed despite incomplete early input.

The Results of Experiment 2 suggest that, since the Number Stroop Effect in ASL was not found in any group, ASL number lexemes activate magnitudes in a different way from Arabic digits, supporting the modality-specific activation hypothesis. At the same time, both late and second language learners differed from the early first language learners, suggesting that both years of exposure and age of acquisition influence automatic magnitude representation with number lexemes.

The results of the two experiments are discussed separately, followed by the general discussion.

4.5.1. Magnitude Estimation and Age of Acquisition: Arabic Digits

The results showed the expected size congruity Stroop effect (incongruent stimuli were processed more slowly than neutral, and congruent were faster than neutral in number condition) and condition effect (the size comparison was faster than the number comparison) in all groups, but age of acquisition influenced the results. Deaf and hearing participants who learned language early in life performed identically, but late first language learners showed slower reaction times and a larger time difference between number and size judgments.

The large difference in speed between size and number judgments was previously attested in children at the early stages of schooling: it differed significantly between first graders and older children (Girelli et al., 2000). However, young children not experienced with numbers also did not show the canonical Number Stroop Effect: neutral stimuli in the number condition were processed almost as slowly as the incongruent ones, suggesting that the task was hard rather than the interference being strong (Girelli et al., 2000; Rubinsten et al., 2002). Adults with developmental and acquired dyscalculia (Ashkenazi, Henik, Ifergane, & Shelef, 2008; Rubinsten & Henik, 2005) have also demonstrated an atypical Stroop pattern with the absence of facilitation. In contrast, in the present study late first language learners demonstrated a robust Number Stroop effect in the number task. This result suggests that the difference between size and number conditions in late first language learners and in children requires different explanations. While first graders may have not fully developed automatic magnitude representation, the fact that late first language learners demonstrated robust congruity effect in number judgments suggests that both dimensions are salient for them. It is possible that late learners might experience greater difficulties resisting interference.

The difference between unexperienced children and late first language learners is underscored by the fact that with more years of language experience, late first language learners did not become faster, but demonstrated a tendency towards slower reaction times. This result suggests that, while more exposure leads to automaticity of magnitude processing (and a strong Stroop effect), delayed first language acquisition may affect the inhibition of irrelevant information and thus slow down the decision. However, taking into account the small sample and the variety of life experiences of the participants, this result needs to be interpreted with caution. Exact age of first language acquisition did not correlate with processing speed, suggesting that the effect of language deprivation is not gradual after early childhood, but abrupt, in line with previous research, showing the absence of correlation between exact age of acquisition and performance on linguistic and cognitive task battery (Mayberry, Hatrak, Ilkbasaran, Cheng, & Hall, in prep).

Additionally, all groups demonstrated a SNARC congruity effect, which is not surprising, since all participants come from cultures that write and read numbers from left to right. It is important to note that, while there have been claims that the association of the right side and bigger quantity is innate, the SNARC effect differs in cultures that write numbers, number words, or both from right to left. Unlike the Stroop effect, there were no differences between groups in the SNARC effect, with both late and early deaf signers of ASL experiencing the same effect as the hearing participants.

Importantly, it has to be noted that canonically, the SNARC effect is studied with number comparison or parity judgment tests, but not Stroop-like tests, and therefore this result might be a byproduct of the particular methodology. For instance, one previous study did not find significant SNARC effects in a different Stroop paradigm in both hearing and deaf participants (R. Bull et al., 2006). On the other hand, another study did find the SNARC effect in deaf individuals in a number comparison task, but with slower reaction times (Rebecca Bull et al., 2005).

Together the results of Experiment 1 suggest that early language deprivation may affect automatic magnitude representation, but that it still can be formed despite incomplete early input. When the language is acquired on a typical timeline, deaf participants score identically to the hearing participants, challenging the results of the studies that link a slowdown in number processing to deafness itself.

4.5.2. Number Stroop Test in ASL: no Stroop Effect.

The typical Number Stroop Effect was not attested in the ASL experiment. Predictably, age and setting of ASL acquisition impacted performance: while in the size condition the second language learners performed with no differences compared with the early signers of ASL, in the number condition they were significantly slower, which can be related to the lack of proficiency. Late learners, on the other hand, were slower in both conditions.

Additionally, late learners of ASL demonstrated the slowest reaction times for neutral stimuli in the size condition, which is an unusual pattern that has not been described in previous studies. Previous studies (using digits) with participants with developmental dyscalculia have reported abnormal patterns in size conditions, but these effects were related to the absence of facilitation effect (Ashkenazi et al., 2008), which was the case for the late language learners in digit, but not the ASL condition. The comparison in question involved pictures of the same number handshapes (for example, two FIVE handshapes) that only differed in size; the numerical difference was not present at all. We hypothesize that late language learners might experience difficulties because of all comparisons on the test, this one is the most unusual. While people do in fact see number words and Arabic digits written with various contrasting font sizes in real life (for example, in advertising), this doesn't happen with sign language perception: signer's hands do not change size, and the contrast between photos is perhaps not as salient as with printed digits. Other groups might have adapted to the unusual task easier than late learners.

The SNARC effects were not attested in the ASL condition as well. However, previous studies have identified SNARC effect in German (DGS) and Italian (LIS) sign languages, using parity judgment tasks (Rebecca Bull et al., 2005; Chinello, de Hevia, Geraci, & Girelli, 2012; Iversen, Nuerk, Jäger, & Willmes, 2006; Iversen et al., 2004).

We attribute the difference between our results to the experimental paradigm: the Stroop paradigm is less efficient for detection of spatial association of magnitudes. Since there are two interacting dimensions of SNARC congruity (size and number), the canonical numerical only SNARC effect cannot be assessed. Indeed, another Stroop paradigm study with ASL number signs did not report significant SNARC effect either (R. Bull et al., 2006). Alternatively, the explanation might be related to the structure of the numeral system: LIS and DGS have two-handed numeral systems, and in these languages the compositional structure of two-handed numerals has a sub-base of 5, which influenced parity judgments. In two-handed number signs, the non-dominant hand has the same handshape (FIVE), while handshape on the dominant hand changes, and there is a direction of sign perception than can be compared to the direction of reading. ASL number signs are one-handed.

Another effect of the stimuli was significant: stimuli with frequent and transparent number signs TWO to FIVE were processed faster than stimuli with the less frequent non-transparent number signs and than mixes of transparent and non-transparent ones. The difference in RT could be attributed either to iconicity or to the frequency of the first five numbers, since their frequency crosslinguistically exceeds the frequency of the subsequent ones (Dehaene & Mehler, 1992). There are two arguments in favor of the frequency hypothesis. The frequency ratings from the ASL-Lex database (Sehyr, Caselli, Cohen-Goldberg, & Emmorey, 2021) confirm that for ASL, this relationship also holds. Moreover, a similar effect (with faster reaction times for smaller numbers) was found in Italian Sign Language, which has a fully iconic and transparent two-handed numeral system (Chinello et al., 2012). This is another argument in favor of frequency but not iconicity being a facilitating factor. Finally, if iconicity alone was in play, then mixed stimuli would also be processed faster, since all non-transparent number signs refer to larger magnitudes than transparent iconic ones, and there would be no need to even interpret them to answer the question of which is larger, and yet it does not facilitate the decision.

Finally, we examined whether the exact age of ASL acquisition and exact number of years of experience influenced the processing of ASL numbers in late and second language learners. Exact age of ASL acquisition for late learners did not correlate with the processing speed, suggesting the existence of the critical period. Once it had passed, the exact age of language acquisition does not have a significant effect, in line with the result previously shown by Mayberry et al. (in prep). Success of second language learning may not depend on age of acquisition as well. We found a marginally significant effect of years of exposure, but, similar to the digit condition, it is the opposite of what one might expect: some of the late learners and second language learners of ASL demonstrated a tendency towards slower reaction times despite their greater experience with the language. An explanation might be related to the life experience of participants: both second language learners who are currently acquiring ASL in a classroom setting and the late learners who are immersed in the Deaf community and were taking ASL or English classes more recently, might have more fresh experience with timed tasks and therefore perform faster than participants that had this experience longer ago. However, the small sample and the variety of life experiences of the participants are serious limitations to this generalization.

Overall, the results of Experiment 2 show that magnitude activation by ASL number signs and Arabic digits differs. Similar results have been obtained for spoken languages with non-ideographic writing systems, such as Hebrew, Hindi, and Japanese when written with syllabic script (Besner & Coltheart, 1979; Kadosh et al., 2008; Kadosh & Walsh, 2009; Takahashi & Green, 1983; Vaid, 1985) . The significant difference between the language background groups suggests that both years of exposure and age of acquisition influence automatic magnitude representation with number lexemes. There was no gradual effect of age of acquisition in late first language learners: if the language was learned post childhood, the outcomes were similar. However, high accuracy demonstrated by both second and late ASL learners shows that ASL numbers were successfully acquired by both groups.

4.5.3. General discussion

Together the results of the two experiments suggest that magnitude information is accessed differently depending on the format (number lexemes or digits). The results further show that late first language learners can acquire and use both formats. However, their ability to do so is affected by language deprivation in both formats. While specific patterns of late first language learners' performance appear to be format-specific (a large difference between size and number in the digit condition, the longest reaction times for the neutral stimuli in the size condition), this group performs slower in both formats.

It has been shown that late first language learners performed more slowly than native ASL signers in various ASL tasks, but faster than second language learners, or at a comparable speed (Ferjan Ramirez, N., Leonard, M.K., Halgren, E., Mayberry, 2013; Ferjan Ramirez et al., 2016;

Mayberry, Davenport, Roth, & Halgren, 2018), and their performance in non-verbal cognitive tasks is comparable to hearing controls (Mayberry et al, 2018) . Therefore, we hypothesized that the slow performance in our experiments was not a general property of the late first language learner group, but may represent the specifics of their magnitude processing. Slower reaction times may be associated with difficulties inhibiting irrelevant information – but it could as well be associated with educational deprivation and little experience with timed tasks, although by the time of testing all the late first language learners had already had the educational experience of a classroom setting, taking exams, and playing games where time and reaction are important. The effects of language deprivation and educational deprivation are hard to disentangle, since one inevitably creates the other. However, the finding that delayed first language deprivation may be associated with slower response times on mathematic magnitude processing tasks may help explain the conflicting results of earlier studies. Effects of language acquisition setting that are often not controlled for (see Hall & Dills (2020) for a detailed analysis of this issue) may be relevant for the interpretation of studies that report a slowdown in magnitude tasks in deaf people (for example, Bull et al., 2005; Epstein et al., 1994).

At the same time, in comparison to the detrimental effects of early first language deprivation on language proficiency that have been described in the literature (Boudreault & Mayberry, 2006; Cheng & Mayberry, 2020; Cheng & Mayberry, 2019; Fromkin et al., 1974; Mayberry et al., 2017; Mayberry et al., 2018; Newport, 1990), the acquisition of basic numbers appears to be more intact: late first language learners perform with high accuracy with Arabic digits, and they demonstrate strong evidence of automatic magnitude activation, typical of adults in a numerical culture. With ASL number signs, late first language learners demonstrate even higher accuracy than with digits. What makes numbers so special? Perhaps, the numerical culture that the participants live in makes number so fundamental that, despite the absence of conventional language input, from an early age the late learners still had to operate quantities, rely on numbers, watch hearing people use number gestures and communicate number information to them. The studies of homesigners in Nicaragua, another example of a highly numerate culture, documented the quantity-tracking devices emerging in homesign systems without language models (Coppola, Spaepen, & Goldin-Meadow, 2013), even though these devices function more similarly to indexes of items within sets rather than cardinal representations of sets (Spaepen, Coppola, Flaherty, Spelke, & Goldin-Meadow, 2013), and conventional signs for large exact numbers may not be developed (Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011). While it has been shown that a counting list is needed to form the representation of larger numerosities, the concept of exactness is engrained in the numerical culture in which late first language learners grew up. Besides language, number development also requires approximate number system to be intact. Finally, our experiments only assessed automatic number representation, and more research is needed to establish how language deprivation affects more complex mathematic operations.

The results of the Number Stroop Test with ASL numerals did not reveal a Number Stroop Effect in any age of acquisition group. These results are in line with the results by Bull et al (2006), but not those of Vaid and Corina (1989). This may be due to methodological differences. As discussed earlier, Vaid and Corina presented their stimuli sequentially, while our experimental procedure included simultaneous presentations of stimuli, as in Bull et al (2006). This might indicate that, due to differences in experimental design, these studies detect different automatic processes. The absence of a size congruity effect in simultaneously presented linguistic Stroop stimuli is in line with the results of several experiments on spoken languages and supports the hypothesis that mechanisms of automatic magnitude processing may be format-dependent (Cohen

Kadosh & Walsh, 2009). According to this hypothesis, the processing of linguistic numerals may be less automatic even if unintentional, since it requires more processing resources. This prevents interference from size information. Neuroimaging research suggests some modality-specific differences in processing as well (Cohen Kadosh et al., 2007).

Although, in line with previous studies, automatic magnitude representation by linguistic numbers produces reaction time patterns that differ from the Stroop Effect observed with Arabic digits, the decreased speed of magnitude processing in late first language learners suggests a link between the two formats of number representation. However, in line with research conducted in Nicaragua with deaf and hearing adults of various backgrounds (Flaherty & Senghas, 2011), numbers can be successfully acquired later in life. Despite the unusual speed and pattern of reaction time, the late first language group performed with high accuracy and demonstrated automatic magnitude activation, needed for skilled calculation.

Together the data from both formats (digits and linguistic numerals) suggest that early first language exposure matters for number acquisition, and when language is acquired early in life, its modality does not have an effect on number representation: deaf early signers are as fast and accurate as hearing controls. This result once again underscores the importance of early access to natural sign languages for deaf children. Our results also call for adequate control for language background in studies of deaf education: when ignored, the effect of language deprivation can be confounded with other factors.

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Chapter 4, in full, has been submitted and may appear as a publication: Semushina, N. Mayberry, R. I. Number Stroop effect in Arabic digits and ASL number signs: The impact of age

and setting of language acquisition. The dissertation author was the primary investigator and author of this paper.

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Chapter 5. Learning Plural classifier constructions in ASL

Abstract

Plural classifier morphologically is complex and also iconic. Despite this iconicity, deaf children learning sign language from deaf parents acquire these constructions slowly and not without error, while adult second language learners have been shown to benefit from iconicity in some respects. But does iconicity help deaf signers who began learning their first language post childhood? This study investigated the production and comprehension of plural classifier constructions by second, early and late first language learners of American Sign Language (ASL). Using picture description, acceptability judgements, and sentence-to-picture matching tasks, we find that while deaf early first language learners prefer a maximally informative plural marking strategy (number sign and plural classifier movement morphemes: hold-stamping, hold-sweeping and sweeping-tracing), both second and late first-language learners opt for less complex constructions, use classifiers less often overall, and make errors specific to their language acquisition background.

5.1. Introduction

Classifier predicates have been attested in most sign languages and exhibit many cross-linguistic similarities, one of them being plural marking. In such cases, a movement morpheme from a restricted set modifies the classifier handshape, along with location and orientation depending on the arrangement of the scene described. Similarities in terms of location and movement have been observed among classifiers in various sign languages (Schembri, 2003; Zwitserlood, 2003, 2012). Classifier predicates are also iconic on multiple levels. They have been observed to be similar to the iconic gestures used by hearing people in descriptions when not allowed to use speech (Schembri, Jones, & Burnham, 2005) and hearing individuals never exposed to sign languages may still understand them (Marshall & Morgan, 2015).

At the same time, classifier constructions are also morphologically complex, and some of the iconic elements (such as classifier handshapes or plural movement morphemes) are conventional and categorical. There is evidence that iconicity may help adult second language (L2) learners of sign languages acquire classifier constructions (Marshall & Morgan, 2015), but not children learning sign language as a first language (Conlin-Luippold & Hoffmeister, 2013; Kantor, 1980; T. R. Supalla, 1983). And classifiers are still hard to learn for both types of learners. Acquisition of classifiers is also influenced by early language experience: late learners may use "frozen forms" instead of productively creating new constructions (Newport, 1988), or demonstrate a reduced preference for the use of classifiers (Karadöller, Sümer, & Özyürek, 2017). Early language experience may affect the use of classifiers in view-dependent picture descriptions but have no effect in view-independent descriptions (Karadöller, Sümer, & Özyürek, 2020). Plural marking adds another level of complexity to classifier predicates.

In this study we investigated the production and comprehension of plural classifiers by early first language (L1), late first language (LL1), and second language (L2) learners of American Sign Language (ASL). After reviewing the linguistic peculiarities of classifiers and their acquisition, we report three experiments. Experiment 1 was a picture description task, which showed that deaf, early L1 learners of ASL demonstrate a strong preference for the use of classifiers, while hearing L2 learners and deaf late L1 learners do not demonstrate such a preference and make errors specific to their age and setting of language acquisition. In Experiment 2, we used an acceptability judgment task to test whether the production preferences of the early first language learners hold in comprehension tasks and how the typical production error patterns of L2 and late L1 learners would be rated. Finally, Experiment 3 used a sentence-to-picture matching task to investigate how signers (both early L1 and L2 signers) interpret picture descriptions with varying plural classifier constructions when they are correct or contain the error patterns observed in Experiment 1.

5.2. Classifiers in sign languages

Classifier predicates (alternatively called in the literature depicting verbs or polycomponential verbs/signs) have been described in most sign languages studied to date, and crosslinguistic studies show many similarities (Slobin et al., 2003; Zwitserlood, 2012). These signs are predicates of movement and location with complex morphological structure.

The handshape refers to a class or other semantically relevant properties of an entity, while the hand of the signer moves from one location to another (alternatively, either movement, or location, or both can be indicated). There are several approaches to the typology of classifiers in sign languages. Zwitserlood (2012) propose a distinction between two major types of classifiers: whole entity classifiers and handling classifiers (see Cormier, Quinto-Pozos, Sevcikova, & Schembri, 2012; Kimmelman, Pfau, & Aboh, 2020; Schembri, 2003; Supalla, 1986; Zwitserlood, 2012 for discussions of other classifications).

Whole entity classifiers refer to the whole object related to certain semantic properties and can be further subdivided into semantic classifiers, size and shape specifiers, and body part classifiers. Semantic classifiers refer to a particular class of objects (e.g., vehicles, animals, upright entities, humans). Size and shape specifiers (SASS) that represent some of the characteristics of the object's form (e.g., round, flat, thin). In body part classifiers, an articulator refers to a part of the body, such as a leg or head. Finally, in handling classifiers the articulators represent the hand or other manipulator holding or using the object.

It is commonly accepted in the literature as well that classifier predicates in sign languages are iconic. Iconicity in linguistics is defined as a non-arbitrary relationship between a linguistic form and its meaning, where the phonetic form structurally preserves a mapping to some mental image that is associated with a referent (Taub, 2000). In classifier predicates, iconicity can be seen on several levels: most evidently, on the level of location and movement that can represent the spatial location of the entities described, the direction or the path of movement. Iconicity can also be seen on the handshape level. For example, an ASL classifier CL V:bent (Fig.5.1) resembles bent legs (we can map the parts and the positions of fingers to the position of legs) and is used to refer to four-legged animals or sitting humans. At the same time, classifier handshapes constitute a finite set of restricted handshapes that are perceived categorically (Brentari & Benedicto, 1999).

The same noun can be described with multiple classifiers or a combination of them, but the semantic properties of the entity constrains the choice of classifier (Wilbur, Bernstein, & Kantor, 1985). For example, a sitting cat can be described by using the whole entity CL:V-bent (); the body part CL:S () can be used to indicate the position of the cat's head; and various size and shape specifiers can be used to describe cat's fur. On the other hand, the vehicle classifier CL:3 (), shown in Fig.5.2, can be used to describe a car, a bike, a boat, but not a cat. The use of a classifier can be "metaphorically extended" to describe a novel object based on the characteristics of the object. For example, in an experimental production study, the R2D2 robot from "Star Wars" was described with a classifier for upright entity or walking entity, even though it has wheels and no legs (Wilbur et al., 1985).

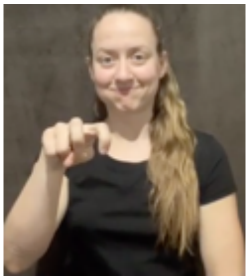


Figure 5.1. ASL CL:V bent (four-legged creatures; sitting humans)

Figure 5.2. ASL CL:3 (vehicle)

Classifier constructions are in some sense paradoxical: from one point of view, they are highly iconic and can use a gradient, analogue information representation, which makes them similar to gestures (Emmorey & Herzig, 2003; Schembri, Jones, & Burnham, 2005a; Singleton, Morford, & Goldin-Meadow, 1993). At the same time, the use of handshapes is highly constrained lexically and morphosyntactically (Brentari & Benedicto, 1999; Emmorey & Herzig, 2003; T. Supalla, 1986; Wilbur et al., 1985). Classifier predicates are also morphologically complex and can be further modified to also mark pluralization in different sign languages (Liskova, 2017; Roland Pfau & Steinbach, 2006; Zwitserlood, 2003; Zwitserlood, Perniss, & Özyürek, 2012).

5.3. Plural classifier constructions in ASL

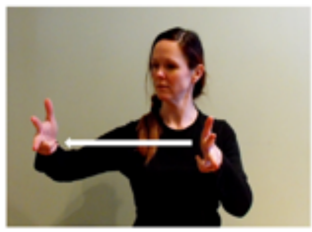
Pluralization can be expressed several ways. One means is through reduplication of the classifier handshape. Such classifier constructions not only contain numerical information, but also represent the spatial arrangement of the objects (Roland Pfau & Steinbach, 2006). The number of reduplications can be both exact (i.e., representing the actual number of objects and their locations) and a not exact (indicating a more generic plural).

Several plural morphemic movements are described in ASL. One of them is *extension* (Engberg-Pedersen, 1993). To designate a non-exact plural, where the number of objects creates a "whole mass", the sweeping-tracing movement is used (Conlin-Luippold & Hoffmeister, 2013; T. R. Supalla, 1983). This movement is then combined with a specific handshape: for example, a CL:5-bent signed with two hands for a flock of animals (Baker-Shenk & Cokely, 1991; Conlin-Luippold & Hoffmeister, 2013). Similar movement has been documented in other sign languages (Zwitserlood, 2003; Zwitserlood et al., 2012). The other plural morpheme is a sweeping movement on a straight line or arc, often combined with the hold of the same handshape on the non-dominant hand (Conlin-Luippold, 2015; Conlin-Luippold & Hoffmeister, 2013). For example, such movement combined with a CL:4  can be used to describe a long line of people.

The third type of plural morpheme is a contact movement (T. R. Supalla, 1983), also defined as position (Engberg-Pedersen, 1993) or stamping (Conlin-Luippold & Hoffmeister, 2013). It can be performed by one or both hands and, unlike tracing and sweeping movements which are used for mass plurals, contact can mark both exact and mass plural.

To sum up, plural classifier movements are both iconic and highly constrained, with each movement type being used for a specific type of plural and spatial arrangement. Additionally, plural classifier constructions can be combined with other types of plural marking, such as the use of a number sign or quantifier. To date, no study has investigated which manner of plural marking with classifier constructions is preferred in ASL and how much it depends on context. Examples of plural classifier morphemes are given in Table 5.1.

Table 5.1. Plural CL morphemes in ASL

The Plural CL morphemes in ASL		
		Sweep-trace
		Hold-sweep
		Hold stamp
		Dual-stamp
		Sign illustrations source: Conlin-Luippold & Hoffmeister, 2013)

5.4. Acquisition of classifiers

In their study of second language acquisition of ASL, McKee & McKee (1992) cite a deaf teacher who characterized the use of classifiers in expressive ASL as "*the heart of the language*" and “*a defining characteristic of fluency*”. However, acquiring such constructions is challenging both for deaf children learning ASL and for the adult hearing second language learners.

5.4.1. Acquisition of classifiers by first language learners

Deaf children who learn ASL from their signing parents start using classifier constructions early, but do not fully acquire the classifier system until ten or eleven years of age (Kantor, 1980; Lillo-Martin & Henner, 2021; Slobin et al., 2003; T. R. Supalla, 1983). Children first acquire the location, which is then followed by movement patterns, and finally the handshape. Besides that, in classifier constructions, children struggle to use some of the handshapes that they successfully use in other types of signs. Unmarked handshapes are acquired earlier than the marked ones, and movements are often deleted or substituted (T. R. Supalla, 1983). This leads Kantor to suggest that classifier acquisition is constrained linguistically rather than motorically (Kantor, 1980). The acquisition of morphologically complex forms, such as plural classifier constructions where a hold movement is combined with sweeping or stamping movements, can take even longer (Conlin-Luippold & Hoffmeister, 2013). The comprehension of such complex constructions is also influenced by the quantity and quality of language input: it takes longer for deaf signing children from hearing families to acquire them.

In these studies, iconicity did not facilitate the acquisition of classifiers. While Slobin et al. (2003) found spontaneous iconic/gestural mapping and classifier-like handling and depicting constructions not only in deaf signing children but also in homesigners between one and four years of age, they argue that such cases of spontaneous iconic innovation may be mistaken for classifier use. A study of homesigners in Turkey did not find developed spatial descriptions in children who were not exposed to language; these children demonstrated poor performance in non-linguistic spatial tasks as well (Gentner, Özyürek, Gürcanli, & Goldin-Meadow, 2013), suggesting that such constructions do not emerge on their own in the absence of input.

5.4.2. Acquisition of classifiers by second language learners

L2 learners of ASL (both college students taking ASL for credit and hearing parents learning ASL to communicate with their deaf children) experience difficulties using the correct classifier handshape and selecting it with appropriate movement and location. Even after several years of exposure to ASL, they use a smaller variety of classifiers and produce more mistakes (Lindert, 2001; McKee & McKee, 1992). Previous research suggests that in the early stages of learning, hearing second language learners can benefit from iconicity (Baus, Carreiras, & Emmorey, 2013; Lieberth & Gamble, 1991), and a study with second language learners of British Sign Language (BSL) showed that while iconicity did not help the acquisition of classifier handshapes, it facilitated expressing and understanding topographic relations (Marshall & Morgan, 2015). Importantly, the second language learners in these studies started acquiring sign language as adults.

5.4.3. Acquisition of classifiers by late first language learners

However, there are people who acquire their first language as adults. When language acquisition does not start at birth, the individual may experience severe language deprivation. Sometimes it happens due to extreme parental neglect and social deprivation (Fromkin, Krashen, Curtiss, Rigler, & Rigler, 1974; Koluchová, 1972, 1976), but this situation may also happen to congenitally deaf children who are not socially deprived, yet born into hearing families and do not have access to natural sign language and spoken language therapy. Their language acquisition does not start until their first immersion into the Deaf community, which might happen as late as post childhood. These individuals do not demonstrate any cognitive impairments. However, delayed language exposure has long-lasting detrimental effects on language learning outcomes in comparison to both first and second language learners, especially at the syntactic level (Boudreault & Mayberry, 2006; Cheng & Mayberry, 2019; Ferjan Ramirez et al., 2016; Mayberry, Cheng, Hatrak, & Ilkbasaran, n.d.; Mayberry, Davenport, Roth, & Halgren, 2018).

The acquisition of complex classifier predicates by late first language learners is understudied. A study by Newport (1988) investigated the acquisition of motion classifier predicates in ASL and found that young children (both those who received parental input from an early age and late learners of ASL) were sensitive to morphological patterns in complex motion predicates, which allowed them to productively change and use them in novel contexts. The late learners who started acquiring language around the age of 12 and were tested as adults, however, learned the motion predicates holistically, and neither group demonstrated sensitivity to iconicity. Interestingly, child and adult first language learners had different error patterns. While children omitted morphemes or combined then sequentially rather than simultaneously, late first language learners tended to use frozen forms that were not modified based on novel contexts.

Recent work by Karadöller, Sümer, & Özyürek (2017) analyzed the use of spatial classifier predicates in Turkish Sign Language (TID) and found that, although children and adults who are late learners use classifier constructions to encode spatial locations, they do not demonstrate a strong preference towards doing so (unlike the native signers), and tend to choose morphologically simpler forms and other strategies (such as lexical verbs or pointing). In a following study (Karadöller et al., 2020), they found a distinction between view-dependent (left/right) and view-independent (containment) locative descriptions: view-independent constructions were mastered quickly and in a native-like way, but view-dependent constructions (cognitively more challenging) were affected by delayed language exposure: for these descriptions (but not view-independent ones) adult and child late learners used fewer classifiers and preferred morphologically simpler forms. Overall, however, late learners were able to correctly and clearly communicate spatial relations in TID.

Plural markers add one more layer of complexity to the classifier predicate. The acquisition of plural classifiers requires the conceptual understanding of number, the skill to choose the conventional classifier handshape and the appropriate plural morpheme, plus the ability to encode spatial relations (i.e., use correct location and orientation of the classifier construction). ASL plural classifier forms require specific movements from a restricted set; there are several movements, each having a specific meaning. Thus, the acquisition of plural classifiers can be even more challenging both for second language learners and for late first language learners. The acquisition of linguistic plural marking by late learners has not been described to date and can help illuminate the relation of number concepts to the acquisition of linguistic number.

Several studies have investigated the impact of early language deprivation on the acquisition and processing of number and show that language is needed for exact quantification, but that it can be learned late in life, once language is finally available. As far as the conceptual understanding of number is concerned, homesigners from Nicaragua, who did not know a conventional number system, had difficulties with exact number matching tasks (Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011), but when language was acquired, even late in life, the concept of number was acquired as well (Flaherty & Senghas, 2011). Adult late learners of ASL show typical automatic magnitude activation by Arabic digits and ASL signs and are highly accurate in a Number Stroop task, even though they demonstrate unusual speed and reaction time patterns (Semushina & Mayberry, under review). A case-study of an adolescent acquiring ASL shows that already at the initial stages of language acquisition the understanding of number signs, Arabic digits, and basic math was possible, while linguistic and non-linguistic spatial abilities were affected by language deprivation (Hyde et al., 2011). This finding contrasts with the results obtained by Karadöller et al. (2020) with late L1 participants, who had multiple years of experience with TID. Finally, plural morphology can be challenging. Studies with Genie, a hearing child who suffered from extreme linguistic and social deprivation, showed that she learned to understand lexical number marking (*many, a lot*) earlier than morphosyntactic means (plural morphemes and copula in English), and acquisition of morphology required extensive instruction (Curtiss et al., 1974).

On the other hand, plural classifier constructions can be iconic on all featural levels: movement, orientation, location, and handshape. This iconicity may help the adult learner. In the previously mentioned study of the second language acquisition of BSL, the signers with one to three years of experience were highly accurate in encoding information with location and orientation, but not handshape. In a comprehension experiment, they performed well even on the handshape contrast (Marshall & Morgan, 2015). The question is whether deaf LL1 learners and hearing L2 learners of ASL benefit from iconicity as well, or does the additional morphological complexity prompt them to make errors or choose different constructions.

5.5. The current study

In the current study, we analyzed the impact of various settings of ASL acquisition on the use of plural classifier constructions in ASL and asked the following questions. What plural marking strategies do early deaf L1 signers of ASL use and how do their preferences change in relation to the availability of context? How are L2 and late L1 learners different in terms of their classifier use? Is there an asymmetry between production and comprehension in terms of the errors that participants with certain language acquisition background produce?

In Experiment 1, we compared the production of classifier constructions of late first language learners (LL1) to that of deaf early L1 signers and hearing L2 learners of ASL, (Experiment 1). We analyzed general preferences for the use of classifiers, errors in relation to type of language acquisition (i.e., first, second or late language acquisition), the potential impact of context, and finally differences in preferred strategies for plural marking across the groups. This experiment also provided data on the preferred ways of plural marking by the early L1 learners of ASL, which we further investigated. In Experiment 2 we used an acceptability judgment task to discover whether the most frequent plural marking strategies in ASL shown by early L1 signers in production would also be preferred in comprehension, and how the typical production error patterns of L2 and late L1 learners would be rated. The sentences for this task were created based on the Experiment 1 results, and only deaf, early L1 deaf signers participated in this experiment.

In Experiment 3, we used the same stimuli as in Experiment 2, but in a sentence-to-picture matching task, and compared sentences with correct marking strategies to the sentences with errors of two types to determine how participants with various language backgrounds understand sentences with errors. Deaf early L1 signers and hearing L2 learners of ASL participated in this experiment. (Due to the COVID-19 pandemic, testing the late L1 learners was not possible.)

5.6. Experiment 1: Production of plural classifiers.

5.6.1. Methods.

5.6.1.2. Participants.

Participants were recruited with three contrasting backgrounds and settings of language acquisition. 1) Early L1 signers: n = 5 (4 females, 1 male) signers; 4 acquired ASL from birth from deaf parents, and one from the age of 1 month in an intervention program. 2) Hearing L2 signers: n = 5, all female), mean AoA =18.4 (SD =1.81); mean Years of exposure, or YoE = 2.2 (SD = 2.68), took ASL classes in college/university. 3) Late L1 signers (n = 5, 2 females, 3 males), mean

AoA = 17.6 (SD = 6.4), mean YoE = 11.8 (SD = 13.5) were not exposed to sign or spoken language prior to their immersion in the Deaf community and onset of the ASL acquisition.

5.6.1.3. Procedure

We selected 38 stimuli from stock photos available on the Internet. The photos included different arrangements of 5 types of entities: animals, vehicles, people (usually described with whole entity CLs), and cups and buildings (usually described with SASS). Table 1 presents the illustrations of target classifier handshapes that we expected to be used for each type of entity. To elicit spontaneous description strategies, we used photos from different countries (including USA, Russia, Cuba, India). For entity classifiers, we included different types of entities usually described with the same classifier: cats and sheep, cars and bikes, adults and children. Every entity was represented in 5 arrangements: singular, unusual singular (ex: car upside down), two exact plurals, a non-exact plural (cars parked in a row), and a mass plural (ex: traffic). Table 5.2 shows the classifiers expected for each type of entity. The participants saw the stimuli on a computer screen and were asked to describe each picture, while they were filmed. No specific instructions about classifiers were given, since we were interested in the naturally preferred strategies of plural marking and choice of classifiers. The participants decided when to proceed to the next picture. The deaf L1 and LL1 learners of ASL were interviewed in person, while the interviews with the hearing L2 learners were recorded online through the Zoom program.

Table 5.2. The expected target classifiers for the production experiment.

Entity	**Conventional name**	**Illustration** (source: https://www.lifeprint.com/asl101/pages-signs/classifiers/classifiers-frame.htm
Animals (cats, sheep)	CL:V bent	
Flock of animals, crowds of people, traffic	CL:5 bent	
Vehicle (car, bike)	CL:3	
People: sitting	CL:V bent	
People standing in line	CL:4	
Buildings and houses	CL:B, CL:A open, CL:C	  
Cups/mugs	CL:C, CL:F, CL:G	 

The videos were then analyzed by two deaf consultants, proficient signers from deaf families (one familiar with the background of the participants, one not). The deaf consultants evaluated both the grammatical well-formedness of the sentence and the relation to the picture (i.e., whether the spatial arrangement was correct and all the important elements were described). In addition, the data were coded for the use of particular classifiers, plural strategies and consistency across participants for each construction and sentence. All the statistical tests and plots were created in R (Team, 2015).

First, the quantitative and qualitative results on the use of classifiers as a function of AoA and YoE are presented (analyzing the N of classifiers used, types of errors, the choice of classifier, and the effect of the entity) followed by an analysis of plural marking strategies.

5.6.2. Results.

5.6.2.1. Use of classifiers as a function of AoA and YoE.

Using a linear regression model, we found that AoA affects the use of classifiers: LL1 signers used classifiers significantly less than the early L1 group ($\beta = -17.00$, CI = -24.04 – -9.96, SE= 3.23, $t = -5.26$, $p < 0.001$). L2 learners also used classifiers significantly less than L1 signers ($\beta = -10.60$, CI = - 17.64 – -3.56, SE= 3.23, $t = -3.28$, $p = 0.007$). The model's R^2 was 0.70. Post-hoc multiple pairwise comparison performed using the package *multicomp* (Hothorn, Bretz, & Westfall, 2008) showed no significant difference between LL1 and L2 learners. Both groups demonstrated more variation than the L1 group. While the L1 group preferred classifiers, the L2 and LL1 groups used them much less often (Fig. 5.3a).

Then we conducted a separate analysis to see the possible effect of YoE, since the individual variation in this parameter was high in both the L2 and LL1 groups, and the amount of experience with ASL might play important role. We fitted a linear regression model for YoE and compared only LL1 and L2 learners, since the L1 group had used ASL their entire lives. However, YoE did not predict the use of CLs in the LL1 or L2 groups (the difference was not significant, R^2

= 0.02), and individual LL1 participants who had used ASL for 10 years or more than 30 years produced classifiers with a similar frequency (Fig. 5.3b).

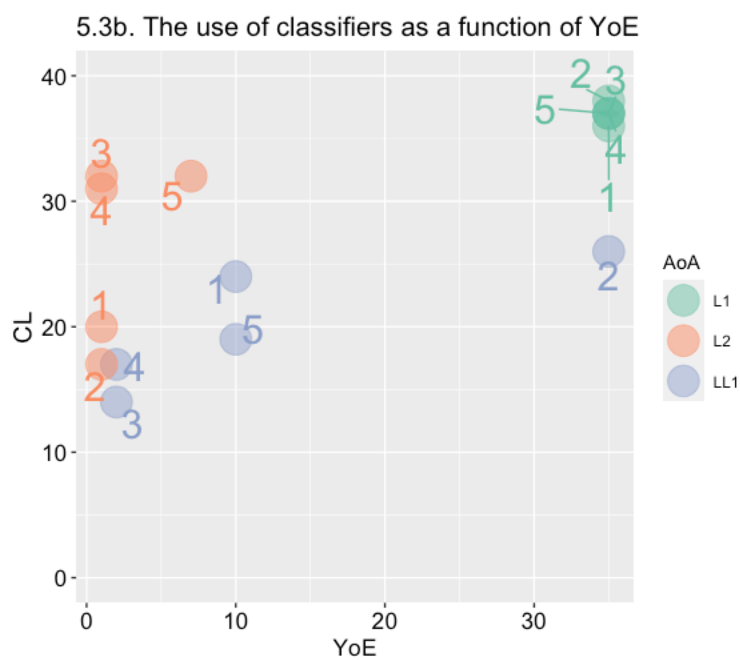


Figure 5.3. Use of classifiers as a function of AoA (3a) and YoE (3b). AoA group is indicated by color: deaf early first language learners (L1), second language learners (L2), and deaf late first language learners (LL1). The Y axis shows the total number of cases where classifiers were used. The X axis shows AoA group (5.3a) or individual YoE (5.3b)

5.6.2.2. Types of errors.

The errors in the picture descriptions were identified by two deaf native consultants; for each picture description, they answered questions about the use of the classifier (whether the classifier was chosen appropriately and articulated correctly, and if not, what the error was), spatial arrangement (correct or not, and if not, what the error was), the correct articulation of other lexical signs, and the overall informativeness of the description (on a scale of 1 – 7). The results revealed that the AoA groups differed in the errors they made.

Early L1 signers of ASL demonstrated only minor errors: unclear spatial positioning when signing fast (occurred in all signers), occasional misarticulation of a lexical sign in fast signing (occurred once), and fingerspelling error (occurred once). No classifier errors were detected.

Both L2 learners (four participants) and LL1 (five participants) systematically missed spatial positioning when it was not canonical (for example, a small house (art object) on the roof of the building, or a line of people winding around a corner). However, LL1 learners appeared to be confused with such arrangements, and one LL1 participant skipped the description of one such picture, signing that it is weird, and proceeded to the next one. Both groups also tended to use a more generic classifier instead of a more specific one: for example, CL:A open ( ) and CL:B ( ) were both used for cars and cats. Both groups occasionally misarticulated lexical signs. However, the L2 and LL1 learners produced several non-overlapping types of errors.

L2 learners (and only they) often used the wrong classifier: for example, CL:V ( ) instead of CL:3 ( ) when describing a vehicle; CL:3 for humans (instead of CL:1,) or animals (instead of CL:V ()). These errors occurred in four out of five participants. One of the participants also demonstrated wrong segmentation: CL:A open () was used to describe both the building (signer pointed at the fist) and the small house on top of it (pointed at the thumb). Articulation errors in classifiers were also observed: one-handed forms where two-handed would be more appropriate, misarticulation of handshapes, or wrong movement pattern.

LL1 learners (and only they) often missed an important part of the scene: for example, a picture with a man fixing a car was described just as "CAR" (four participants systematically produced errors of this type). In addition, all participants often omitted plural marking, such as describing a picture with a flock of sheep with one sign: SHEEP. Additionally, three of the participants used incorrect lexical signs in their descriptions, such as CITY instead of HOUSE.

Overall, L2 learners tended to give lengthy explanations and descriptions, while LL1 learners often omitted important information and gave incomplete descriptions. Descriptions by early L1 learners were usually brief but complete.

5.6.2.3. Choice of classifier.

We analyzed the data for consistency of use of each entity classifier by each AoA group. Since CL:V bent () can be used to describe both animals and people, we analyzed the two types separately. The use of size and shape classifiers for the description of buildings and cups is discussed in the next section.

The early L1 signers used the expected target classifiers for all stimuli with high convergence (Fig. 5.4). The only construction where variation occurred was CL:C () that was sometimes substituted for more nuanced SASS classifiers. The other groups, however, demonstrated more variation and less use of classifiers. CL:3 ( ) for vehicles, and CL:4 ( ) for people in line were used the most consistently by the L2 and LL1 learners, alongside with CL:C ( ) for cups. CL:5-bent ( ) with sweeping-tracing movement and CL:V-bent ( ) for people were used the least consistently by both LL1 and L2 learners.

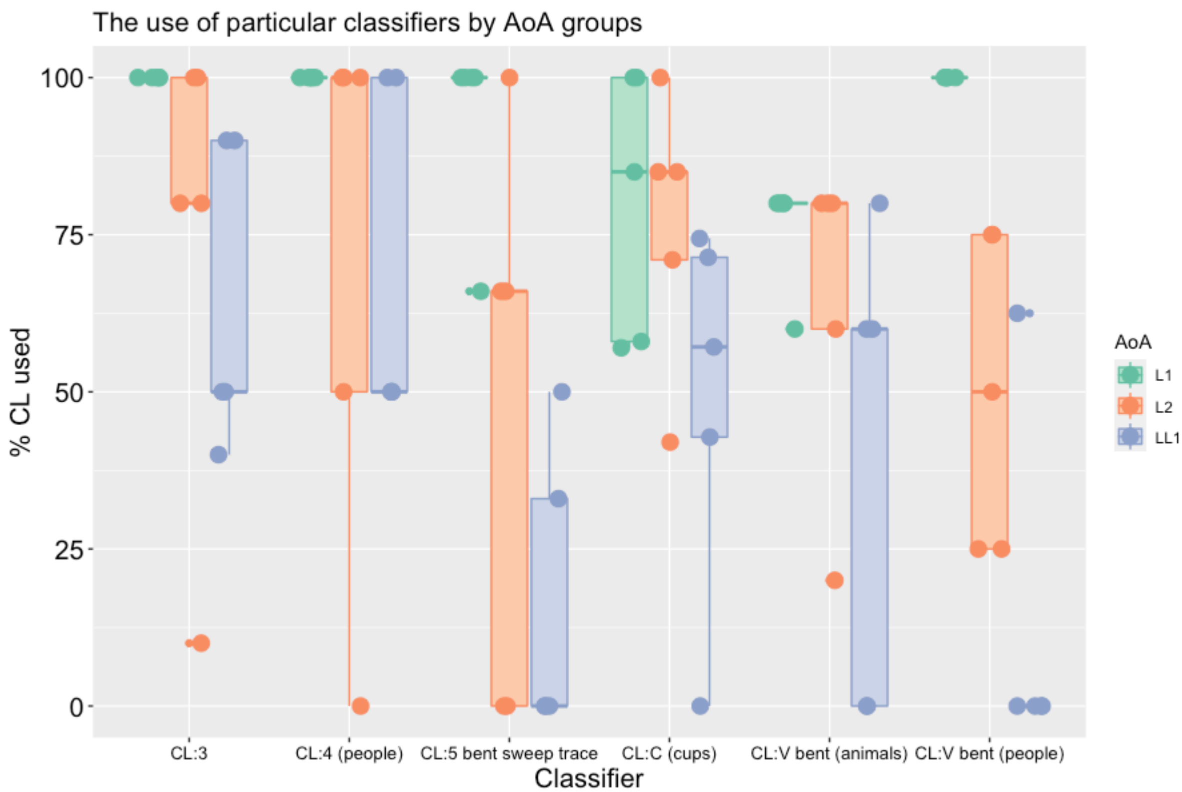


Figure 5.4. The use of each CL by the AoA groups, L1, L2 and LL1. The dots represent individual participants. The Y axis indicates the % of cases where the target classifier was used. The X axis represents the particular classifiers. Individual dots represent participants. The top of the box plot shows the higher quartile (75%), the bar shows the median (50%), and the bottom of the box shows the lower quartile (25%); the show outliers indicate the 1.5 interquartile range.

5.6.2.4. Effect of particular entity on classifier use.

When describing an entity which has a prototypical form (such as cars, bikes, cats, or sheep) early L1 signers demonstrated consistency and converged on the same conventional, most specific classifier. However, both LL1 and L2 learners demonstrated variation: the more generic classifier (for example, locative CL:A-bent () or CL:B ()) can be used instead of the most specific classifier. For LL1 and L2 language learners, the particular entity also determined their use of classifiers: bike and sheep were often described without the use of a CL (both groups), or with a wrong/non-conventional classifier (L2 learners only), while cat and car were more consistently described with the correct classifiers. All groups tended to use CL:V () bent less than expected, sometimes using the verb to describe the animal's action (the sheep running) or quality (the cute black cat), which may be related to our choice of stimuli.

With the entities that belong to the same class (cups/mugs; buildings) but vary in size and shape and thus can be described with size and shape specifiers, the data showed the opposite trend. Although the early L1 signers used the most generic classifier (such as CL:C () for cups), they also used a variety of different classifiers to better describe the particular form of the object. L2 and LL1 learners also demonstrated variation, depending on the form of the object, but tended to use the most generic classifier and sometimes avoided using it altogether.

Overall, LL1 learners used classifiers less than L2 learners, but the influence of the particular entity type on the choice of classifier was similar in both groups. The choices of classifiers for each entity are presented in Table 5.3.

Table 5.3. The use of classifiers for particular entities in different AoA groups.

Entity	**L1**	**L2**	**LL1**
Cat	bent, (head)	bent	, bent, open
Sheep		, , no CL	no CL
Car		, bent,	,
Bike		, no CL	, no CL
Cup/mug	, open, , claw, ,	, open, claw, no CL	, , round, no CL
House	open, , , round, no CL	no CL, , open	, claw, no CL,
Tall building	, , with sweep trace (Pl), round	, open, bent, , no CL	, no CL, claw, with hold sweep (Pl)
Sitting people	bent	bent, no CL	no CL
Crowd of people	bent with sweep trace, upright and palm down	with sweep trace, no CL, ,	no CL, with hold sweep
Flock of animals	bent	with sweep trace, dual stamp,	no CL, with hold sweep,
Line of people		, , , no CL	with hold sweep, bent
Traffic	bent with sweep trace, dual stamp	, , dual stamp	bent with sweep trace, , no CL

5.6.2.5. Plural marking strategies.

In our stimuli, 26 out of 38 pictures contained plural arrangements. We coded these descriptions by plural marking and found three main strategies in our data: number and plural classifier construction; plural classifier construction alone; other, morphologically simpler strategies that included a quantifier or number with a singular classifier, reduplication, lexical marking (ex: blue car, red car, green car), or a combination of those. Additionally, in a number of cases plural marking was omitted, which was coded as a fourth strategy.

The data were analyzed with a linear mixed effect model function with a *lmer,* package *lme4* (Bates et al., 2016), using the number of sentences with each plural marking produced by each participant as the dependent variable. AoA (L1, L2, or LL1), the strategy of plural marking (Number + CL + Pl, CL + Pl, other, no marking), and their interactions were the predictor variables. Random intercepts were included for participants. The results of the model are presented in Table 5.4.

The main effect of Plural marking strategy was significant: L1 signers marked plural with CL and number significantly more frequently than with plural CL alone. The plural CL, however, were used significantly more frequently than other strategies or no plural marking.

The main effect of AoA also was significant. L2 learners marked plural by plural classifier alone significantly less frequently than the L1 learners, the difference between L1 learners and LL1 in the use of classifier alone learners was not significant.

The interaction between AoA and plural marking strategy was significant as well. Both LL1 learners and L2 learners avoided plural marking significantly more frequently than the early L1 signers (note that the early L1 signers always marked plural in our data). While L2 learners did not significantly differ from the L1 signers in their use of Number + CL + Pl strategy, the LL1 learners used this strategy significantly less often. Both LL1 and L2 learners used other ways to mark plural significantly more frequently than the early L1 signers.

Table 5.4. The strategies of plural marking & AoA

The strategies of plural marking & AoA Reference categories: AoA = L1, plural marking = CL, condition = number.			
Predictors	*Estimates*	*CI*	*p*
(Intercept)	9.80	6.24 – 13.36	**<0.001**
AoA [L2]	-6.60	-11.64 – -1.56	**0.010**
AoA [LL1]	-1.20	-6.24 – 3.84	0.640
Plural [no marking]	-9.80	-14.84 – -4.76	**<0.001**
Plural [Number + CL + Pl]	5.40	0.36 – 10.44	**0.036**
Plural [other]	-8.80	-13.84 – -3.76	**0.001**
AoA [L2] * Plural [no marking]	8.60	1.48 – 15.72	**0.018**
AoA [LL1] * Plural [no marking]	7.20	0.08 – 14.32	**0.048**
AoA [L2] * Plural [Number + CL + Pl]	3.00	-4.12 – 10.12	0.409
AoA [LL1] * Plural [Number + CL + Pl]	-12.40	-19.52 – -5.28	**0.001**
AoA [L2] * Plural [other]	13.60	6.48 – 20.72	**<0.001**
AoA [LL1] * Plural [other]	10.20	3.08 – 17.32	**0.005**
Random Effects			
σ^2	16.50		
$\tau_{00\ participant}$	0.00		
$N_{participant}$	15		
Observations	60		
R^2	0.571		

For between-group comparisons, post-hoc multiple pairwise comparisons were performed using the package *multicomp* (Hothorn et al., 2008). It showed a significant difference between the L2 and LL1 learners in their use of Number + CL + Pl: LL1 learners used this strategy less frequently ($\beta = -10.000$, SE = 2.569, $z = -3.892$, $p < 0.001$). L1 signers used Number + CL + Pl strategy significantly more frequently than late learners (β = 13.600, SE = 2.569, z = 5.294, $p < 0.001$), but the difference between L2 and L1 learners was not significant. Also confirmed was that L1 signers use other ways of plural marking significantly less frequently than LL1 learners (β = -9.000, SE = 2.569, z = -3.503, $p < 0.001$) and L2 learners (β = -7.000, SE = 2.569, z = -2.725, p = 0.05). Other between-group effects were not significant.

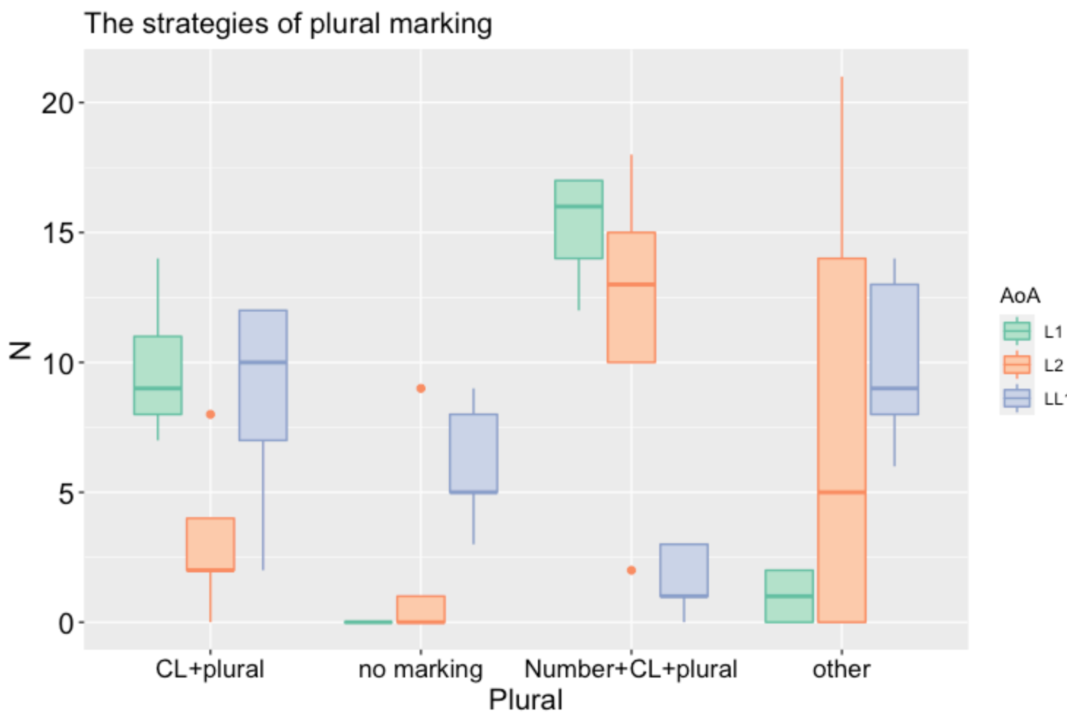


Figure 5.5. The frequency of particular plural marking strategies as a function of AoA group. The Y-axis shows the N of cases where a strategy was used out of a possible 26 pictures showing plural arrangements; the X-axis shows 4 plural marking strategies: Plural Classifier (CL + Pl), no marking, Plural Classifier + Lexical numeral (Number + CL + Pl), and other strategies.

5.6.3. Discussion of Experiment 1 Results.

In this experiment, we investigated the production of plural classifier constructions in ASL by L1, LL1, and L2 learners. The results indicate that despite potential iconicity, plural classifier constructions are difficult for both LL1 and L2 learners to acquire. We found that overall, both LL1 and L2 learners of ASL use classifiers significantly less frequently than the L1 deaf signers, and that the preference towards classifiers does not depend on years of exposure to ASL.

For plural marking, the L1 signers prefer the most explicit construction which is plural classifier combined with the number sign. The next frequent construction is plural marking by classifier alone, and only occasionally do the L1 signers use other strategies of plural marking (such as a quantifier or number with a singular classifier, reduplication, lexical marking or a combination of those). The L2 learners use a plural classifier combined with the number at the same frequency as the L1 learners, but used plural classifiers alone significantly less frequently, instead relying on other strategies. Finally, the LL1 learners use plural classifiers with a frequency similar to the L1 group, but almost never use both a plural classifier and number. Instead, they tend to choose alternative strategies of plural marking, or avoid plural marking altogether.

The qualitative analysis revealed that the absence of plural marking was an error specific to the LL1 learners (all LL1 participants made this error). A possible explanation for such a pattern is that LL1 learners have not acquired the system of morphological plural marking in ASL and therefore avoid it. These results are consistent with the study by Newport (1988), in which LL1 learners used few morphological inflections. The findings are also consistent with those of Galvan (1989), who found that delayed first language exposure negatively influences the morphological complexity of classifier constructions. In a qualitative analysis of the narratives of young children exposed to ASL either from deaf parents or at school, Galvan (1999) mentions that children of hearing parents demonstrate less sensitivity to the subtle number marking on ASL verbs.

However, unlike Newport (1988), we did not identify any “frozen” forms in the production of the LL1 learners. They were able to use classifiers, modify location, orientation, and add movement morphemes appropriately but not in all cases where it was required, that is, with some but not all classifiers (no LL1 participant used the classifier CL:V  bent, or any other classifier, to describe sitting people). Their use of classifiers was characterized by high variation even within individuals. This pattern suggests that LL1 learners of ASL have learned how to use several classifiers with certain entities, but have not generalized the rule to the novel contexts or entities, thus prompting them to avoid the use of classifiers and opt for morphologically simpler strategies. This explanation is conceptually in line with Newport (1988, 1990), and the omissions of plural marking may in fact be functionally similar to the "frozen forms".

An alternative explanation for the choice of less informative number marking by LL1 learners, or of its complete absence, may be that LL1 learners rely more on shared context than on linguistic structure and therefore omitted number marking when a picture was available. It is unlikely that LL1 learners experience conceptual difficulties with number: plural marking was inconsistent, but not absent.

L2 learners did not make such errors. However, their use of classifiers was also not native-like. While they used plural classifiers with number like the L1 signers, their second most frequent strategy was "other", and plural classifiers alone were used rarely.

Additionally, the L2 learners (and no other group) often substituted the semantic classifier handshape with an incorrect one (for example, CL:3 () was used for animal). The handshape substitutions of L2 learners have been previously described for ASL (McKee & McKee, 1992) and BSL (Marshall & Morgan, 2015). Importantly, while the BSL study participants mostly demonstrated handshape errors, location and orientation mismatches were also present, similar to our results. Notably, in our data L2 learners produced errors in response to pictures with non-canonical spatial arrangements than to pictures displaying canonical spatial arrangements.

Several types of errors were common to both types of learners: use of more generic classifiers, articulation errors, incorrect spatial arrangements, and the use of the semantic classifier with one member of the class but not others (ex: cat, but not sheep). A similar pattern has been previously found for deaf children acquiring ASL who used whole entity classifiers only for certain entities inside the semantic domain. For example, the classifier for vehicles was initially used only for cars; by the age of six children expanded it to trains, and only older children started using it for other types of vehicles (Kantor, 1980).

In their study of the use of locative classifier constructions by late learners of TID, Karadöller et al. (2020) did not find an effect of entity in between class comparisons (cat, pen, or apple). Our results show that such effect can be found on the level of the particular entity within the same semantic classifier class. While the early L1 signers demonstrated high consistency in the use of semantic classifiers (such as CL:3 () for vehicle or CL:V () bent for animal), for L2 and LL1 learners of ASL the choice of classifier was affected by entity type. We hypothesized that the effect may be related to frequency of the entity in discourse: cats appear in conversations more often than sheep, so the correct classifier for them may need to be memorized.

The results of Experiment 1 suggest that while L1 and L2 learners acquired some classifier constructions, their use of such constructions differs from the preferences demonstrated by the early L1 signers. Specifically, for plural marking they rely on simpler but precise morphological constructions. Both LL1 and L2 participants demonstrate types of errors specific to their AoA group. These results are in line with the findings reported for locative use of classifiers by late learners of TID (Karadöller et al., 2017, 2020) and L2 learners of BSL (Marshall & Morgan, 2015).

5.7. Experiment 2.

Comprehension of plural classifiers: acceptability judgements.

The picture description results revealed that early L1 signers of ASL have a preference towards the most explicit plural marking, plural classifier combined with number. However, this preference could be explained by the nature of particular stimuli or individual idiolects of the participants. To test whether this strategy of plural marking is indeed preferred over others, we performed an online acceptability judgment.

5.7.1. Methods.

5.7.1.1. Participants.

Twelve deaf signers (7 female, 1 non-binary, 4 male) participated in the experiment. Mean age of the group was 36.8 (SD = 8.02), they started acquiring ASL from birth (n = 10) or during the first three years of life (n = 2) from deaf (n = 7) or hearing (n = 6) signing parents, all graduated from deaf high schools, and none participated in the Experiment 1. All the participants use ASL on a regular basis. All participants rated their level of understanding and use of ASL as 7 out of 7. One participant was excluded from the analysis due to incomplete data (technical error).

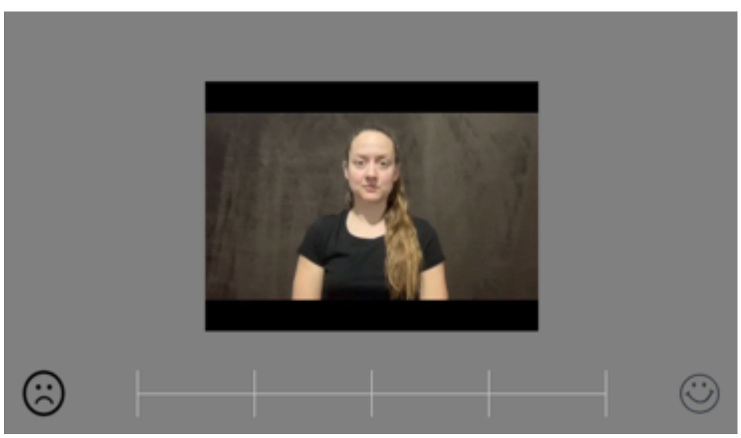
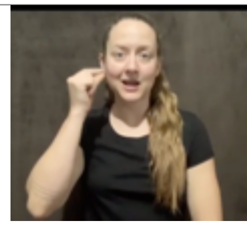
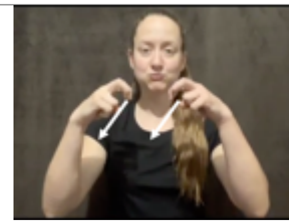
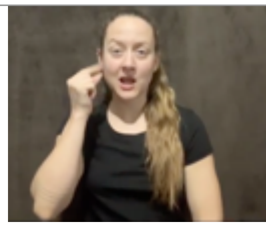
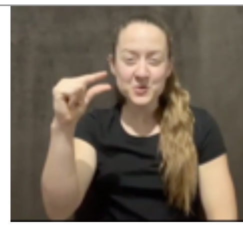
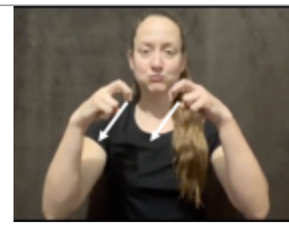
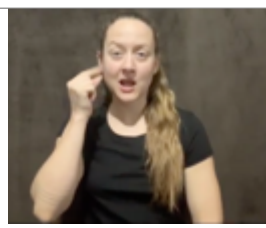
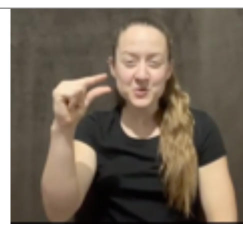
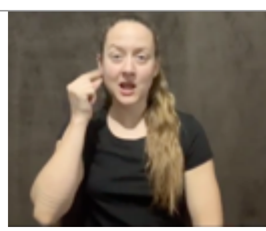
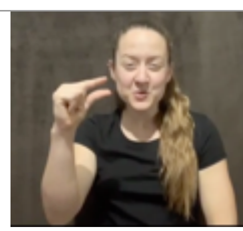
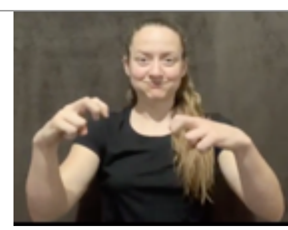


Figure 5.6. The trial for acceptability judgment task

5.7.1.2. Stimuli

Based on the production results, 78 ASL sentences with descriptions of the pictured toy arrangements were signed and recorded by the research assistant (an L1 signer of ASL from a deaf family) and presented to the participants on the computer screen. The stimuli were of four plural marking categories: 1) sentences with number and plural classifier; 2) sentences with plural marking by classifier alone (number of objects more than two); 3) sentences with singular or dual classifiers; 4) and sentences with incorrect classifier handshapes (n for each group = 15). Besides that, there were fillers: grammatical sentences describing multiple toy objects without classifiers (n = 18). The stimuli included descriptions of toy cats (CL:V () bent), toy cars (CL:3 ), toy cups (CL:C ), and toy lego-like people (CL:1 ; CL:4 ). The fillers additionally included descriptions of toy apples. The length of the sentences with classifiers was three signs (plural CL form was counted as one sign independently of the number of hand stamps), while the length of fillers varied from three to five signs. This increased length was necessary to describe plural arrangements without using the classifier. The same stimuli, but combined with pictures, were used in Experiment 3 (examples can be found in Table 5.5).

Table 5.5. Examples of the stimuli sentences in Experiments 2 and 3, describing 6 cats sitting in two rows facing each other[8].

Number + CL+ plural	 SIX	 CAT	 CL:V $_{\text{BENT}}$ PLURAL
CL+ plural	 CAT	 TINY	 CL:V $_{\text{BENT}}$ PLURAL
CL HS Incorrect + plural	 CAT	 TINY	 *CL:3 PLURAL
CL + dual/Sg (in Experiment 3, these were CL + incorrect plural)	 CAT	 TINY	 CL:V $_{\text{BENT}}$ DUAL

[8] - the same stimuli were used in two experiments, but in Experiment 3 they were combined with pictures. Additionally, in Experiment 3, sentences with singular and dual classifier forms were used as number mismatch stimuli.

Table 5.5. Examples of the stimuli sentences in Experiments 2 and 3, describing 6 cats sitting in two rows facing each other (continued)

Picture (only appeared in Experiment 3)	

5.7.1.3. Procedure.

The participants were asked to rate the stimulus sentences using a cursor on a slider with a sad face on the left (really bad sentence) and a happy face on the right end (really good sentence) with no numbers on the scale (Fig.6). Each video was preceded by the fixation point (500 ms). The experiment was preceded by the consent form, video demonstration of the use of slider, and two practice trials. The experiment was designed and created using the experiment building software PsychoPy (Peirce et al., 2019), hosted and run at the Pavlovia, an online platform for behavioral experiments.

5.7.2. Results.

5.7.2.1. Descriptive statistics.

The results the slider responses were converted into a scale from 1 to 5, where 1 was the left edge of the scale (near the sad face), 5 was the right edge of the scale (near the happy face), and the lines on the grid corresponded to 2, 3, and 4. We then calculated the mean ratings for each sentence and then for each category of stimuli using *R*. Sentences with Plural CL forms and numbers were rated the highest (M = 4.44 , SD = 0.82), followed by singular and dual CL forms

(M = 4.12, SD =1.05), fillers (M = 3.98, SD =1.09) and Plural CLs (M = 3.80, SD =1.21). Sentences with incorrect classifiers were rated the lowest (M =1.95, SD =1.21).

We then transformed the mean ratings given by each participant into z-scores to control for individual variation in the use of scale. Figure 5.7 presents the mean ratings (z-scores) for each construction.

Statistical analysis.

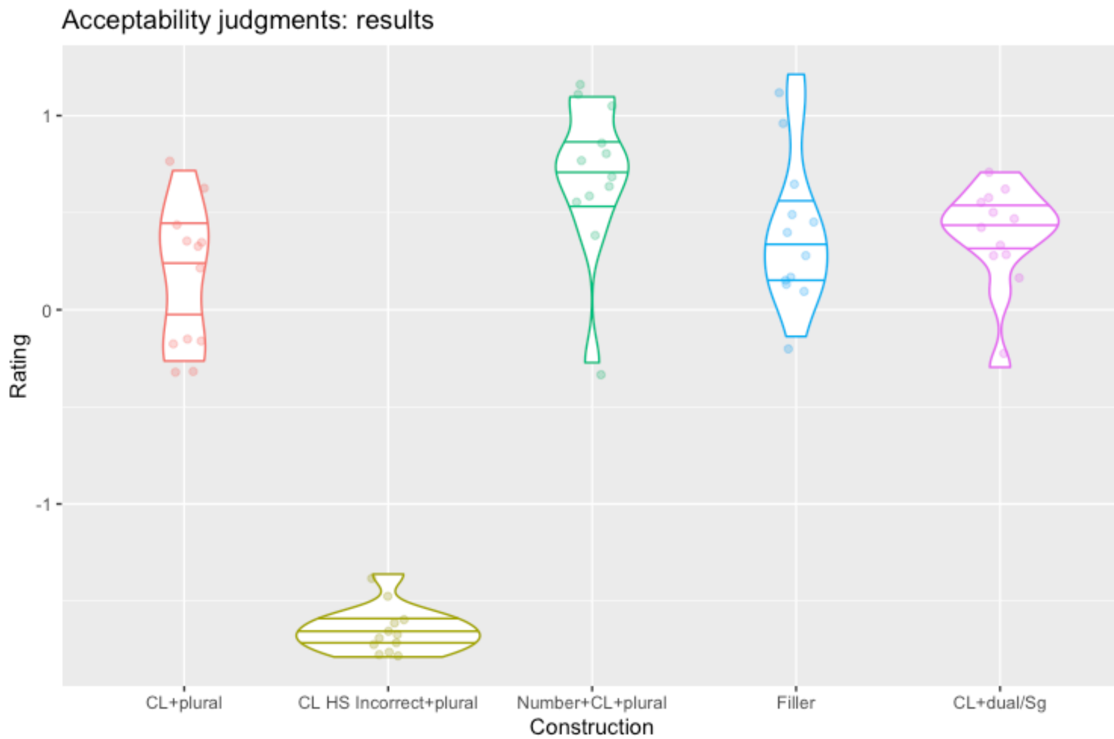


Figure 5.7. The z-scores of the mean rating of particular plural marking strategies as a function of AoA group. The Y-axis shows the rating; the X-axis shows the 5 types of number marking. Each dot represents the z-score of the mean rating by one participant. The lines on each violin plot represent 0.25, 0.5, 0.75 quantiles.

We then fitted a linear regression model using the mean rating (z-scores) of each participant as the dependent continuous variable, and the plural marking strategy (CL + Number, CL Pl, CL Sg or Dual, Filler, Incorrect CL) as the predictor categorical variable. For the plural making strategy, sentences with plural classifiers (CL Pl) were set as the base level. The results indicate that sentences with plural CLs and numbers were rated significantly better than sentences with plural CLs alone ($\beta = 0.52$, CI = 0.26 – 0.78, SE = 0.129, $t = 4.04$, $p < 0.001$). Sentences with incorrect CL handshapes were rated significantly lower than sentences with plural CLs ($\beta = -1.81$, CI = -2.07 – -1.56, SE = 0.129, $t = -14.009$, $p < 0.001$). The difference between sentences with plural CLs and sentences with singular/dual CLs was not significant, as well as the difference between plural CL sentences and fillers.

Additionally, it was important to compare the fillers (which were sentences without classifiers, as used by the LL1 and L2 participants in Experiment 1) to both ungrammatical sentences and sentences with plural classifiers. The post-hoc Tukey HSD test was performed using the package *emmeans* (Lenth, Singmann, Love, Buerkner, & Herve, 2020). It showed that sentences with incorrect CLs were rated significantly lower than all other sentence types, including fillers (all $p < 0.001$). The ratings for the fillers and sentences with classifiers were not statistically significant.

5.7.3. Discussion of Experiment 2 Results.

In Experiment 2, we asked whether the preference towards plural marking by plural classifier and number used by the deaf, early L1 signers of ASL in language production would be observed in acceptability judgments by an independent sample of early L1 ASL signers, and how sentences with the incorrect classifier handshapes but correct plural morpheme would be rated. To do that, we asked early L1 deaf signers of ASL to participate in an online acceptability judgment task where they rated sentences with plural CL and number, plural CLs only, singular or dual CLs only, incorrect CLs, and fillers on a scale of 1 to 5 with a slider.

The results confirmed the preference for plural marking with both number and plural classifier constructions: sentences of this type were rated the highest. The analyses showed that other types of sentences (plural classifiers, dual/singular classifiers, and fillers that also described plural arrangements of objects but without using classifiers) were rated similarly to one another. Sentences with incorrect number and CLs (ex: *FIVE CUP CL:3-PL) were rated significantly lower than all other types of sentences demonstrating the number plus classifier construction is a preferred means of marking plurality in ASL.

The results also suggest that while the L1 signers all used sentences with CL in picture descriptions, sentences without CL are acceptable, as would be expected. The fillers, which were based on the strategies that LL1 and L2 learners used in production were rated no worse than sentences with classifiers.

5.8. Experiment 3: Sentence-to-picture matching task

The previous expeirment showed that LL1 and L2 learners make multipe errors in their ASL productions of pictures designed to elicit ASL classifier constructions with plural morphology. The question we ask in Experiment 3 is whether the classifier plural morphological errors made by LL1 and L2 learners can be interpreted in the context of a picture. To do so, we created a sentence-to-picture matching expeirment with two conditions, accurate and inaccruate plural classifier constructions. For the accurate classifier plural constructions we used the ASL sentence types the L1 signers produced in Experiment 1 and rated as highly acceptable by an independent sample of L1 signers in Experiment 2. For the inaccruate plural classifier constructions, we used the errors made by the LL1 and L2 learners in Experiment 1. This yielded four sets of plural classifier stimuli: 1) accurate plural classifier constructions, 2) accurate plural classifier constructions + number, and 3) inaccurate number marking as produced by the LL1 learners, and 4) errors in classifier handshape as produced by L2 learners. The stimulus sentences with plural classifier errors containsed only one error type in the following way. Stimulus sentences with incorrect classifier handshape have the correct plural marking, and sentences with incorrect plural marker have the correct classifier handshape.

There are three possible outcomes for this study desing. First, signers can reject both sentences with both types of errors, indicating that they detect and do not accept any erroneus descriptions as matching the picture. Second, they can rely on the plural morpheme and thus accept sentences with incorrect classifier handshapes as matching the picture despite the error. Such a finding would indicate that the plural morpheme marking and spatial arrangement are used for interpreting ASL plural classifier constructions. Finally, there is a possibility that the participants would primarily rely on classifier handshape, and accept sentences with an incorrect number morpheme but correct classifier handshape and correct spatial arrangement (for example, entites facing each other, or following each other) as matching the picture.

5.8.1. Methods

5.8.1.1. Participants

Fourteen participants were recruited for Experiment 3 representing two kinds of ASL learning, deaf, early L1 and hearing, L2 signers[9]. Seven early L1 deaf signers of ASL participated in this experiment (6 female, 1 male); they learned ASL from their signing parents, either deaf (n=5) or hearing (n=2). Mean age of the group was 40.71 (SD = 12.81). All participants also took part in Experiment 2 but not Experiment 1. Seven L2 learners of ASL also participated (4 female, 1 non-binary, 2 male). Mean age (SD) of the group was 21.83 (3.15), mean AoA (SD) was 17 (2.16), mean YoE (SD) was 4.57 (4.03). All participants learned ASL in a school/university setting. At the time of experiment, they reported using ASL at least once a week. All listed English as their first language, but 5 participants were bilingual in other spoken languages. Six of the L2 learners rated their level of understanding and using ASL as 5 out of 7, and one as 6 out of 7.

[9] - Due to the global COVID-19 pandemic, we were not able to test LL1 participants, but we hope to do it in the future.

5.8.1.2. Stimuli

The same 78 ASL stimulus sentences used in Experiment 2 were used for Experiment 3 and combined with pictures. For each target picture there were four descriptions: two matching (Number + CL + plural; CL + plural) and two not matching: one with a classifier handshape mismatch (CL HS incorrect + plural) and one with a number mismatch (CL + incorrect plural), as shown in Table 5.5 (note that category "CL + dual/Sg" in this experiment was the number mismatch to the picture. Additionally, there were 18 fillers, 9 with sentences matching the picture, and 9 with a mismatch. Hence, for all sentences with Number + CL and Plural CL, the target response was a match; for all sentences with classifier or number errors the target response was mismatch; and for the fillers, for 9 sentences the target response were a match, and for 9 a mismatch.

5.8.1.3. Procedure

The participants were asked to complete an online sentence-to-picture matching task. The experiment was preceded by the consent form, instructions, and two practice trials. The instructions were as follows: "You will see a video of an ASL sentence followed by a picture. You have to decide whether the sentence matches the picture. If it does match, press the "right" key. If it does not, press the "left" key."

Participants saw a fixation point for 500 ms, followed by a video of an ASL sentence. After the sentence was finished, a picture appeared on the screen. It remained on the screen until the participants pressed the right or left key. The experiment was designed and created using the experiment building software PsychoPy (Peirce et al., 2019), hosted and run at the Pavlovia, an online platform for behavioral experiments.

5.8.2. Results.

5.8.2.1. Descriptive statistics.

Table 5.6 shows the mean accuracy for both groups of participants on each type of plural marking, as well as the fillers. The results showed that both early L1 and L2 learners of ASL performed with high accuracy in all conditions, except for the incorrect classifier handshape. L2 learners were at chance (i.e., they accept 50% of the sentences with the wrong classifier handshapes as matching the picture), but the early L1 signers also demonstrated low accuracy, accepting on average 30% of sentences with wrong classifier handshapes. Notably, variation in both groups was very high. On the other hand, both groups detected number mismatches with high accuracy. Both groups demonstrated slightly lower accuracy on fillers, many of which were more ambiguous. Figure 5.8 illustrates the performance of both groups.

Table 5.6. Mean accuracy (SD) in the sentence-to-picture matching task

	L1	**L2**
CL + Pl	0.90 (0.06)	0.85 (0.06)
Number + CL + Pl	0.91 (0.09)	0.87 (0.10)
CL HS incorrect + Pl	0.72 (0.17)	0.56 (0.20)
CL + incorrect Pl	0.95 (0.06)	0.90 (0.07)
Fillers	0.88 (0.09)	0.86 (0.07)

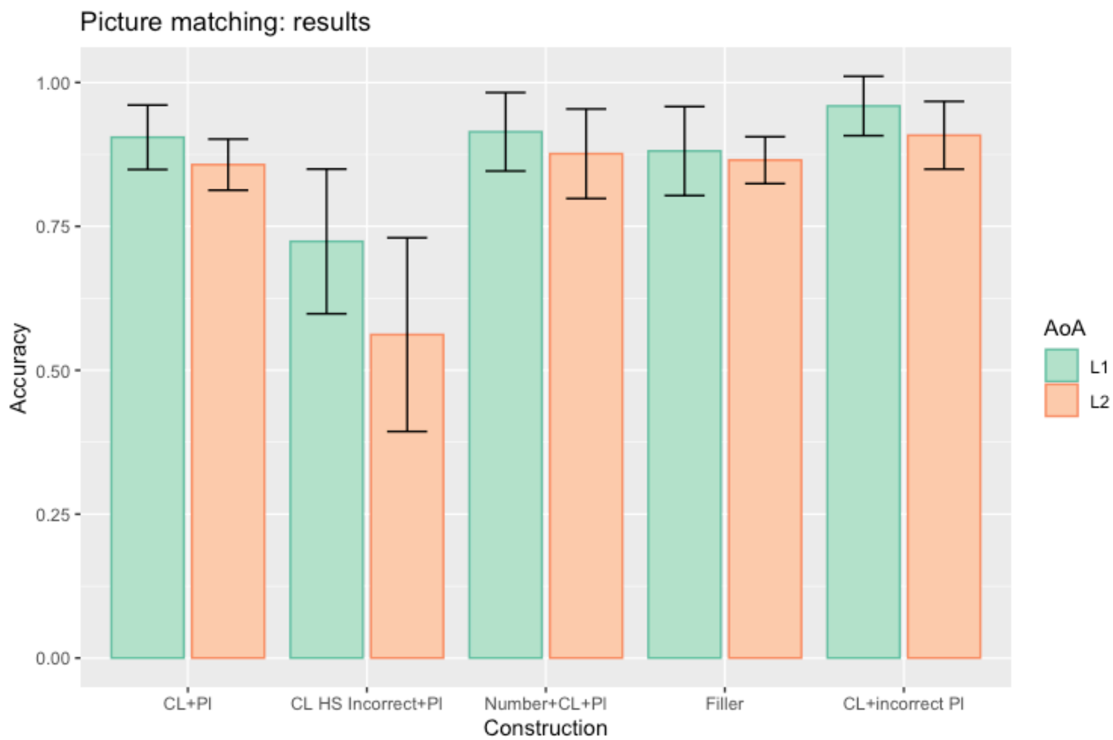


Figure 5.8. The accuracy on plural marking strategies as a function of AoA group. The mean accuracy for each participant was used. The Y-axis shows the accuracy; the X-axis shows the 5 types stimuli sentences. Error bars represent standard error.

5.8.2.2. Statistical analysis

We performed a binomial generalized mixed model using the R package lme4 (Bates et al., 2016) with bound optimization by quadratic approximation (BOBYQA), to estimate whether the type of plural marking and the AoA of the participants affected whether the stimulus sentence would be accepted as a good picture description. We used the accuracy of each individual response as the categorical dependent variable, and included type of plural marking (Classifiers + Pl, Number + Classifiers + Pl, CL HS incorrect + Pl, CL + incorrect Pl), AoA group (L1 vs L2), target response (match or mismatch) and their interactions, with participants and stimulus trials as random variables. For AoA, the L1 group was set as the base level, and for the plural strategy, the base level was Plural Classifiers strategy.

The main effects of AoA and target response were not significant. The main effect of plural strategy was significant, with significantly lower accuracy on incorrect classifier handshape (CL incorrect) compared to sentences with plural classifiers (Cl Pl): Odds Ratio = 0.11, z = -2.014, CI = 0.01 – 0.94, $p < 0.05$. None of the interactions were significant. A post-hoc Tukey HSD test was performed using the package *emmeans* (Lenth et al., 2020). It showed that accuracy on sentences with incorrect CLs was significantly lower than accuracy on sentences with classifier and number ($p = 0.001$), sentences with number mismatch ($p < 0.001$), and fillers ($p = 0.002$). No other stimulus type contrasts were significant.

5.8.3. Discussion of Experiment 3 Results

In this experiment, we asked two questions. Can signers detect picture descriptions containing classifier plurality errors, and does AoA affect this ability.

Sentences with plural classifier and number, plural classifiers, fillers, and sentences with number mismatch were all successfully matched to pictures by both the L1 signers and the L2 learners. L2 learners were successfully able to detect number mismatches, including errors they both did and did not make themselves in Experiment 1. Examination of the sentence types using plural marking showed that, when provided with a picture a sentence, the L1 and L2 signers relied on the plural marking more than they relied on the classifier handshape, underscoring the importance of the acquisition of non-concatenative plural morphology for ASL proficiency.

However, the L1 signers and L2 learners showed high variation on the sentences with incorrect classifier handshapes. Both groups showed the same pattern of accepting some stimulus sentences with incorrect classifier handshapes as good picture descriptions but not others. Although the performance of the groups was not statistically different, the early L1 signers were numerically more accurate (i.e., gave the target “mismatch” response more often than the L2 participants.)

Although plural marking was not a factor in the study, these results for classifier handshape mismatch are consistent with those of a previous study of L2 learners of BSL who were more accurate in classifier handshape comprehension than in production (Marshall & Morgan, 2015). Comparing the results of Experiment 1 above with the present experiment shows a similar pattern for L2 learners of ASL. They tended to reject sentences with incorrect classifier handshapes as not matching the picture even though they produced such errors in their own picture descriptions.

Finally, although all the L1 signers gave low acceptability ratings to the stimuli with incorrect classifier handshapes in Experiment 2, they did not reject the same stimuli as mismatches in the Experiment 3. In other words, when matched with a picture, some of the erroneous sentences rated as unacceptable were nonetheless judged by the L1 signers as matching the picture. This result is consistent with studies of spoken languages showing that proficient L1 users are highly sensitive to ungrammaticalities, but at the same time are good at comprehending such structures. So “understandable” does not mean “acceptable” (Chastain, 1980; Guntermann, 1978; Piazza, 1980).

5.9. General discussion

5.9.1. Summary

In the current study, we sought to investigate the learning of plural classifier constructions in ASL. In three experiments we asked what plural marking strategies early deaf L1 signers of ASL use, whether LL1 and L2 learners use plural classifiers in the same way as early L1 learners, and whether there is an asymmetry between production and comprehension in terms of errors that LL1 and L2 learners make.

First, we compared the production of plural classifier constructions of early L1, LL1 and L2 learners (Experiment 1). The early L1 signers used classifiers in all picture descriptions and preferred to use sentences with both plural classifier constructions and lexical number, although they used sentences with plural classifiers alone as well. The LL1 learners of ASL used classifiers, but differently from the early L1 signers: they almost never used both classifier and lexical number, and tended to choose alternative strategies of plural marking (such as number, quantifier, lexical marking), not used by the early L1 signers, or entirely omitted plural marking. Overall, LL1 signers did not demonstrate a preference towards classifiers, in line with studies investigating the use of locative constructions in LL1 learners of TID (Karadöller et al., 2017, 2020). Additionally, LL1 learners exhibited several characteristics found in child but not adult ASL signers.

L2 learners also did not demonstrate native-like use of classifiers. While both L2 and LL1 learners of ASL produced some common errors, each group also demonstrated a kind of error specific to them.

In Experiment 2 we further investigated the choice of plural marking strategies by early L1 signers of ASL using an acceptability judgement task. We asked if the preferences shown in picture descriptions would be the same without context, and how the typical errors that L2 and LL1 learners produced would be rated. The results confirmed the preference towards plural marking with both number and plural classifier constructions: sentences of this type were rated the highest. Sentences with incorrect CLs were rated the lowest. The study also confirmed that the strategies without classifiers that LL1 and L2 participants used in the production study are also acceptable in ASL.

In Experiment 3, we asked, how do signers (both early L1 and L2 learners) interpret picture descriptions paried with ASL sentences containg errors and whether the ability to detect errors is affected in L2 learning. We compared stimulus sentences with incorrect classifiers and incorrect number marking to stimulus sentences with correct plural marking to see which were more interpretable. Additionally, we asked whether L2 learners would be sensitive to the types of errors that they do and do not produce themselves.

Both early L1 signers and L2 learners detected number mismatches and did not accept such stimuli as matching the pictures. On the other hand, stimulus sentences with incorrect classifier handshapes were often accepted as matching the pictures by both early L1 and L2 signers. In the following discussion, we focused on the key finding of the Experiments, grouping them by research question rather than particular experiment.

5.9.2. Plural marking by the early L1 signers

In the introduction, we cited a deaf teacher who defined classifiers as the heart of an expressive ASL (McKee & McKee, 1992). Indeed, the results of the study suggest that the early L1 signers of ASL actively use classifiers when they describe pictures. However, they don't rely on classifiers exclusively and prefer to mark exact plural with both plural classifier constructions and the lexical number sign. These sentences were both more frequent in L1 production and were rated the highest in the acceptability judgment task.

When presented with a stimulus sentence with an incorrect classifier handshape but correct plural morpheme the early L1 signers accepted such sentences as matching the picture. On the other hand, the stimulus sentences with correct classifier handshape and spatial positioning but incorrect plural morpheme were rejected with high accuracy. This result suggests that the signers heavily rely on non-concatenative plural morphology in comprehension. Both handshape and plural morphemes are iconic, yet conventional, and the ambiguous context might modulate which component of the construction the signers rely most. This result indicates that early L1 signers are tolerant to the grammatically of imperfect productions. The difference between the results of Experiments 2 and 3 (i.e., that sentences with low ratings were accepted as matching the picture), suggest that "comprehensible" and "acceptable" are different and separable categories for the proficient early L1 signers, exposed to the typical errors of L2 learners. This phenomenon has been described for spoken languages as well.

5.9.3. Plural marking by LL1 and L2 learners: how are they similar and different?

Both LL1 and L2 learners used classifiers less frequently and less consistently than the early L1 learners, and used a large number of morphologically simpler constructions for number marking (reduplication, quantifier, lexical number marking). Such constructions are acceptable in ASL, as Experiment 2 showed, but can be more ambiguous, since they do not contain explicit information about spatial arrangement.

For plural marking, LL1 learners almost never used both plural classifier and number (the strategy preferred by L1 signers). While LL1 signers used plural marking by classifiers in some contexts, they also often used less morphologically complex strategies of plural marking, or avoided plural marking altogether.

L2 participants, in a sense, resembled both L1 and LL1 signers. Like L1 signers they preferred to use both plural classifier and number (the strategy which they might have been explicitly taught in ASL classes). However, similarly to the LL1 signers, their second choice was a sentence without classifiers.

In their use of classifiers, both LL1 and L2 groups demonstrated error types typical of young children in the effect of the individual entity, as shown by Kantor (1980), and substitution of more specific classifier with the more generic one (Supalla, 1983). They also showed similar articulation and spatial arrangement errors in the non-canonical pictures. The last type of error can indicate reduced spatial depiction skills. Comparison of the use of particular classifier handshapes in these two groups showed the same pattern: both LL1 and L2 groups were least likely to use CL:V  bent to describe sitting people and plural CL:5  bent to describe crowds and flocks of animals. Also, both groups were most likely to use CL:3  for vehicles and plural CL:4  to describe people in line.

However, there were different types of errors as well: L2 learners systematically used the incorrect entity classifier handshapes, while LL1 learners made errors, omitting the plural marking.

Based on the results of this study, it is possible that L2 learners had difficulty not with simultaneous morphology per se, but with internalizing the constraints on classifier handshape choice. However, perhaps due to the extensive focus on classifier constructions in ASL curricula, L2 learners persisted and used the classifiers in new contexts or with entities that occur in discourse less frequently. Unlike the L2 learners of BSL (Marshall & Morgan, 2015), in our sentence-to-picture matching experiment the L2 learners of ASL did not improve their accuracy on the choice of handshape. We hypothesize that this relates not only to difficulties of handshape choice, but also to a tendency to primarily rely on plural movement morpheme and location.

In production, L2 learners were also more accurate (although not perfectly accurate) with location and movement, which is similar to the pattern observed in children. In a study by Kantor (1980), young deaf L1 learners (age 3.0 – 11.0 y.o.) first acquired location, which was followed by movement patterns, and finally the handshape.

It has been shown that hearing L2 learners of ASL have a tendency to overestimate their performance on certain grammatical constructions (Beal, 2020; Beal, Scheetz, Trussell, McAllister, & Listman, 2018; McKee & McKee, 1992) and, according to Horwitz (1987), 21% of

ASL learners believe that this language is easier to learn than other languages. In particular, McKee & McKee, (1992) showed a high mismatch between self-ratings and the rating given by instructors, when students estimated their proficiency with ASL classifiers. The students overestimated their skills, but also acknowledged that using a correct classifier is challenging. We hypothesize that overestimation of the L2 classifier skills might be partially explained by the ability of deaf signers of ASL to correctly interpret the ungrammatical classifier sentences, which we demonstrated in Experiment 3, and by the fact that both L2 and the early L1 signers rely heavily on plural morphemes, which second language learners have less difficulties with.

LL1 learners, on the other hand, never used the wrong classifier handshapes: when the classifier was used, it was the correct one. However, both handshapes and movement morphemes were used inconsistently, which might indicate that the rule was not internalized. Instead, certain classifier handshapes, plural morphemes, or combinations of those were learned (or memorized) separately and applied correctly when the context was frequent. But when describing a less frequent member of the class or a new plural arrangement, LL1 learners could not use a classifier. Hence, they used morphologically simpler strategy and still managed to describe picture in most cases.

An alternative explanation for the choice of less informative number marking by the LL1 learners, or of its complete absence, may be that they rely more on an assumed shared context than linguistic structure and therefore omitted number marking when picture was available. This interpretation is underscored by the fact that LL1 learners also omitted describing other important parts of the scene. While the nature of our task was not interactive, the experimenter was physically present when filming the picture descriptions by early L1 signers and LL1 learners of ASL, and participants from both groups occasionally engaged in communication with the experimenter, providing comments or asking questions ("Weird car; where is it from?"), which suggests that they might have perceived the experimenter as the interlocutor. Several studies investigating referential communication showed that adult interlocutors formulate their descriptions in such a way that facilitates object identification by their communication partners and adjust descriptions based on the properties of stimuli or shared knowledge (Gorman, Gegg-Harrison, Marsh, & Tanenhaus, 2013; Mangold & Pobel, 1988). But it has been shown that children may fail to provide the information that their interlocutor needs in their descriptions by being under-informative (Davies & Katsos, 2010; Deutsch & Pechmann, 1982). Crucially, children produced under-informative, abbreviated and ambiguous descriptions when communicating to an imaginary interlocutor (Girbau, 2001). This is similar to picture descriptions produced by the late first language learners of ASL. Whether this similarity arises from incomplete linguistic ability or weak pragmatic skills is an important question requiring further research.

Overall, the results of our study showed that both LL1 and L2 learners of ASL can use plural classifier constructions, but their use of such constructions in picture description differs from the preferences demonstrated by early L1 signers. While adult L2 learners might benefit from the iconicity of location and movement in plural classifier predicates, it did not appear to facilitate the acquisition of CL handshapes.

Previous studies have found that use of some aspects of locative constructions are not affected by language deprivation (Karadöller et al., 2020), but plural marking adds more complexity to the predicate of location and therefore appears to be more affected. While LL1 learners used plural classifier constructions, they did so to a limited extent and did not demonstrate systematic use of plural morphology, which appears to be crucial for the interpretation of correct and even erroneous sentences by L1 signers. Despite the iconicity of plural classifiers, LL1 learners tended to use morphologically simpler constructions, suggesting that even iconic constructions need early language input to be fully acquired.

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Chapter 5, in full, is being prepared for publication and may appear as Semushina, N., Keller, M.A., Mayberry, R. I. Age of acquisition effects on the use of plural classifier constructions in ASL. The dissertation author was the primary investigator and author of this paper.

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Chapter 6. Conclusion

In this dissertation, I approached the question of quantification by users of natural sign languages and the impact of early language deprivation on magnitude processing and acquisition of linguistic number use. Each study approached different aspect of quantification: Chapters 2 and 3 investigated the properties of numeral systems in sign languages by putting them in context of numeral systems of spoken languages as well as the number gestures of hearing cultures. The results show that such systems rely on iconicity in a limited way, and even when they do, such systems are constrained by language-internal phonological rules of non-concatenative morphology. Chapter 4 used the Number Stroop Test to investigate magnitude activation by both Arabic digits and a partially iconic sign language numeral system of ASL by three groups of language users: deaf signers exposed to ASL from birth, deaf signers who experienced early language deprivation and hearing second language learners of ASL. The results showed that, first, ASL number signs do not elicit a Number Stroop Effect (similarly studies of spoken languages), and second, automatic magnitude activation can be acquired despite language deprivation, even though early language deprivation affects speed activation in terms. Chapter 5 investigated how the same three groups of language users use plural classifier constructions – another example of plural marking through non-concatenative morphology. Three experiments showed that, first, signers exposed to ASL early in life, prefer plural marking by both plural classifier construction and number sign (unlike the late and second language learners). Late learners and second language learners, on the other hand, demonstrate distinct kinds of errors: late learners use grammatically correct sentences (as tested by acceptability judgment task) with no plural marking, while second language learners make errors in the choice of classifier, resulting in ungrammatical sentences (tested with acceptability judgments). However, these errors have different implications for communication: when paired with the picture in picture-matching task, the sentences with incorrect plural marking are not accepted as correct, while sentences with wrong classifiers are often still understood correctly and accepted.

Together, the studies of this dissertation make contribution to two areas of linguistics: the typology of number systems, and the study of critical period for language acquisition. Each paper contributes new knowledge to each domain, but here I discuss the contributions to each separately, using material from all studies.

6.1. Number signs in sign languages and the typology of number

One of the goals of this work was to put sign language numeral systems in context of larger study of exact quantification in languages. Sign language numerals remain largely ignored by the typology of numeral systems – while numerous works investigated exact quantification in a number of deaf community and shared sign languages (Sagara, 2014; Sagara & Zeshan, n.d.; Yang, 2016; Yano & Matsuoka, 2018; U Zeshan, Escobedo Delgado, Dikyuva, Sibaji, & De Vos, 2013), this work remains overlooked by the broader number typology literature. While it has to be acknowledged that typological works often focus on a subset of languages or particular language (Bowern & Zentz, 2012; Calude & Verkerk, 2016; Evans, 2009), sign language numeral systems are not mentioned in works investigating broad issues of numeral typology or number evolution (such as Chrisomalis, 2021; Comrie, 2011). However, they are included in the large study of number gestures (Bender & Beller, 2012). Although this study acknowledges the high complexity and regularity of such systems, together with the psychological reality of sub-base in two-handed numeral system (Iversen, Nuerk, & Willmes, 2004), it is important to distinguish gesture (even conventionalized and culturally significant number gestures) from linguistic number instantiation, even if it is produced manually.

By analyzing 82 numeral systems in terms of base structure and systematic properties and comparing them to both spoken languages and number gestures, Chapter 2 demonstrates that in terms of base structures sign languages resemble spoken languages a lot: most contemporary sign languages have decimal numeral systems, but a variety of other bases exist. Importantly, it has been reported that shared sign languages with complex and rare bases resemble spoken languages more than they resemble sign languages (U Zeshan et al., 2013), and indeed our study did not find deaf community sign languages with rare vigesimal or additive bases. Similarly, the observation that the change of the morphological rule appears at the level of the base (Calude & Verkerk, 2016) holds for sign languages as well. Similar to spoken languages, phonological changes can happen in numeral systems of sign languages, such as change of handshape for SIX in Australian Sign Language (Johnston, 1989) or the emergence of one-handed variants for two-handed numerals in Russian, Estonian and Catalan Sign Languages (Fuentes, Massone, Fernanez-Viader, Makotrinsky, & Pulgarin, 2010; Hollman, 2016). Similar to spoken languages, sign language numeral systems demonstrate geographic clustering (in this case, two-handed or one-handed numeral systems are found together in the same regions).

Language contact influences sign language numeral systems in various ways: sometimes a rare base of a neighboring spoken language is found in a sign language as well (Safar, Guen, Collí, & Hau, 2018); sometimes the hearing number gestures influenced the number signs (Morgan, 2017); sometimes the impact of the writing system on the structure of a sign language numeral system is visible (such as Arabic Indic numerals influenced the numeral system of Turkish Sign Language), sometimes it is the widespread use of Arabic digits that influenced the form of the numerals (like in Ugandan Sign Language), or the borrowing of a numeral system of a foreign sign language brought by the educators, as in Thailand (Woodward, 1996) or Costa Rica (Woodward, 1991).

Even though partially iconic and resembling the number gestures of hearing people on the surface, two-handed numeral systems are fully integrated in the sign language system and follow language-internal constraints that govern their form and combination with other signs. In Chapter 3, the iconic two-handed numeral system of Russian Sign Language was analyzed in its interaction with non-concatenative morphology in process of numeral incorporation, where the number handshape is combined with the location, orientation, and movement of the lexical time or calendric sign. This is the first study to conduct a phonological analysis of Russian Sign Language and analyze numeral incorporation in this language from the point of view of morphophonology.

While previous accounts suggested that two-handed numerals are not incorporated as a rule (Korolkova, 2013), the results of Chapter 3 suggest that two-handed sign language numerals, just as one-handed numerals, obey the general phonological constraints of the language that prevent them from being incorporated in certain lexical signs, but not others. Constraints that restrict the parameters of asymmetrical two-handed signs operate on every featural level of lexical signs: location, movement, handshape, orientation. The last feature is particularly important for two reasons: first, it underscores the importance of orientation which is sometimes regarded as an inherent feature of handshape. Second, in Chapter 2 it was discovered that most two-handed numeral systems have the same orientation: palms can be turned either away or towards the signer, but the orientation is never lateral to the body (as in clapping gesture). The fieldwork results and phonological analysis in Chapter 3 showed that Russian Sign Language strongly disprefers asymmetrical two-handed signs with such lateral orientation, and if this constraint is found cross-linguistically, it might explain why no two-handed numeral system have such an orientation.

Importantly, the Number Stroop Test of Chapter 4 showed that the partially iconic numeral system of a sign language (ASL in this case) activates magnitude in a similar way to spoken languages with non-ideographic scripts, such as Hebrew, Hindi, and Japanese, when written with syllabic script (Besner & Coltheart, 1979; Kadosh et al., 2008; Kadosh & Walsh, 2009; Takahashi & Green, 1983; Vaid, 1985). The results of Chapter 4 show that when language is learned early in life, number signs are as good and sufficient for forming number representation as spoken language lexemes: when tested on Arabic digits, early signers of ASL performed identically to hearing controls. This result adds another piece of evidence showing that in some tasks (such as number comparison), number representation can be format-specific. However, number processing in both modalities is similarly slowed down by language deprivation.

Compared with number gestures of hearing people (Bender & Beller, 2012), sign languages show much less variation in the use of the articulators. While number gestures have a range of articulators that re not limited to fingers and can include the space between fingers, finger phalanges, toes, and, finally, the whole body, sign languages in the data set analyzed here (except for two) only use the hands (fingers and palms). Moreover, only 36 languages (out of 82) make use of the readily available iconic tool – two hands – to represent numbers. While a rapid change from two-handed numeral system to one-handed was observed in Nicaraguan Sign Language, the data in Chapter 2 do not support the hypothesis of a general trend against asymmetrical two-handed signs with a tendency towards replacing two-handed numeral systems with one-handed ones. In fact, older sign languages do not more frequently have one-handed numeral systems. This result aligns with the argument by Stephen Chrisomalis (2004, 2019). He discusses the diachronic change in number notation in terms of transformation and replacement and concludes that there are a limited number of patterns observed across systems, but no linear trend and no final, best cognitively optimal notation.

Most number systems in the data are one-handed and make use of iconicity, both orthographic and number-to-number iconicity, in a limited way. This may have implications for number acquisition, but so far it is unclear whether iconic numbers are processed differently from non-iconic ones. Iconicity may be confounded with frequency – in most sign languages iconic numerals are the first five numbers, and cross-linguistically these are more frequent than the subsequent ones (Dehaene & Mehler, 1992). The results of the Number Stroop Test in ASL (Chapter 4) show that magnitude comparisons that involved the first five numbers were indeed done faster. But there are two arguments in favor of the frequency and not the iconicity hypothesis. First, these numbers are indeed more frequent in ASL (Sehyr, Caselli, Cohen-Goldberg, & Emmorey, 2021). Second, faster reaction times for smaller numbers was found in Italian Sign Language which has a fully iconic and transparent two-handed numeral system (Chinello, de Hevia, Geraci, & Girelli, 2012). Finally, the stimuli that included comparison of iconic stimuli (smaller frequent numbers) to non-iconic ones (larger, less frequent numbers) were not processed faster, so iconicity did not have a facilitatory effect in magnitude estimation.

Additionally, studying number systems in sign languages can provide unique insights to the structure of number deficits. In a recent case study, Friedmann and colleagues identified a particular form of number deficit – the impaired processing of decimal structure (Friedmann, Haluts, & Levy, 2021). The participant, a deaf proficient signer who performed well in a variety of linguistic and numeral tasks, showed a deficit in reading and producing decimal structures, but not place-value ones. Identifying this deficit only became possible because the numeral system of Israeli Sign Language allows two ways of signing multidigit numbers: one with the use of powers (84 – EIGHT-TENS FOUR), and one relying on place-value (84 – EIGHT FOUR).

Currently, the studies that investigate number processing in sign languages and the effects such as Number Stroop Effect or Spatial Numerical Association of Response Codes (SNARC) often do it from the perspective of education and often attempt to use the results to explain mathematic underachievement of deaf students (R. Bull, Blatto-Vallee, & Fabich, 2006; Rebecca Bull, Marschark, & Blatto-Vallee, 2005). The results of the studies in my dissertation suggest that number systems in sign languages must be included in the larger typology of numeral systems and theories of language and number acquisition without any assumption that their users necessarily have a mathematic underachievement. However, as with studies of number acquisition in various spoken languages, potential cross-linguistic differences are not to be ignored.

The structure of the numeral system might also affect number acquisition or processing. It has been shown that the structure of two-handed numerals influences parity judgments in German and Italian Sign Languages (Chinello et al., 2012; Iversen, Nuerk, Jäger, & Willmes, 2006; Iversen et al., 2004). In similar tasks, the notation effects found in spoken languages with various orthographies: the studies of spatial numerical association of the response codes (SNARC effect) show that users of languages written from left to right response faster on the bigger numbers represented on the right part of the screen and to the smaller numbers on the left side (Dehaene, Bossini, & Giraux, 1993), but the effect differs in languages written from left to right (Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017) and can be modulated by practice or priming (Fischer, Shaki, & Cruise, 2009). Finger counting practices with two hands also were shown to contribute to the SNARC effect (Fischer, 2008). However, in this dissertation the SNARC effect with one-handed ASL numerals was not detected, as in a previous study by Bull et al., (2006). This result might be related to the choice of task (the SNARC effect usually is investigated by parity judgements, not a Stroop paradigm) but also to the difference between two-handed and one-handed numeral systems.

When processing a two-handed numeral sign, there might be a direction of "reading" it, while it is not the case for one-handed numerals.

While these notation or language effects are mild and do not mean that some languages are giving their users a cognitive advantage over others or slowing them down (Chrisomalis, 2021), studying them and controlling for such effects in studies of number acquisition is essential.

6.2. Number acquisition and language deprivation

In an extensive review on critical period in language acquisition, Mayberry & Kluender (2018) systematize the results of behavioral and neuroimaging research with both second language learners (deaf and hearing) and deaf people that acquired their first language late in life, following extreme language deprivation. While initially language acquisition of late learners follows the typical milestones (Berk & Lillo-Martin, 2012; Ferjan Ramirez, Lieberman, & Mayberry, 2013; Morford, 2003), language deprivation affects the language proficiency on all levels. Late first language learners may never reach the native-like full proficiency. They are less sensitive to the phonological structure of signs (Lieberman, Borovsky, Hatrak, & Mayberry, 2015, 2016). While there is evidence that late first language learners use the basic ASL word order (Cheng & Mayberry, 2019), in comprehension they rely on world knowledge more than on linguistic structures (Cheng & Mayberry, 2020). Complex syntactic constructions are not acquired (R.I. Mayberry, Cheng, Hatrak, & Ilkbasaran, 2017). It has been reported that the use of complex morphological predicates of motion was affected as well (Newport, 1988, 1990).

However, various aspects of language may be affected by early language deprivation to a varying degree, and some construction that is intactly used in one context may pose difficulties in another context. Karadöller, Sümer, & Özyürek (2017) showed that late learners of Turkish Sign Language (TID) use complex classifier constructions in locative descriptions, but do not demonstrate a robust preference towards them (unlike the native signers) In their next study, Karadöller, Sümer, & Özyürek (2020) proceeded with even more in-depth analysis of use of locative constructions in Turkish Sign Language (TID) by adults and children who acquired the language with a delay and found that view-dependent (left vs right) and view-independent (on/under) relations were affected differently. In view-dependent construction the late learners (both children and adults) used the simpler constructions (less classifier constructions and more other strategies) than the deaf early signers did, but for view-independent constructions age of acquisition did not have an effect. Crucially, even when the strategies differed, late learners used correct spatial encoding in the same proportion as the early deaf signers did.

The results of picture description study (reported in Chapter 5 of this dissertation) show similar results for another type of complex morphological constructions – plural classifier constructions. While such constructions combine iconic and gestural information, iconicity does not facilitate their use and mastery for children (Kantor, 1980; T. Supalla, 1986; T. R. Supalla, 1983) or for adult late learners, as Chapter 5 shows. Additionally, the use of plural classifier constructions is understudied, and Chapter 5 newly documents the preferences of native signers in their use of such constructions.

The use of complex number morphology was affected by early language deprivation. Late learners were still able to use grammatically correct constructions to describe pictures, but they did so inconsistently and did not demonstrate the same preferences for complex non-concatenative morphology and the most informative way of description as early signers did. They preferred other, morphologically simpler constructions. Similar to the finding in TID, such constructions are not ungrammatical, but the native signers do not use them in the same task.

A difference can be seen on the level of plural marking strategy, on the level of individual classifier choice, and on the level of entity described. While the native signers demonstrated high consistency in the use of semantic classifiers (such as CL:3 for vehicle or CL:V bent for animal), for late learners of ASL the choice of classifier was also defined by the frequency of particular entity, as it has been previously shown for children acquiring ASL. Thus, the frequent animal, such as cat, was described with the classifier more often than the less frequent animal, such as sheep. As far as the strategies of plural marking are concerned, the native signers of ASL preferred to use sentences with both plural classifier constructions and lexical number, although they used sentences with plural classifiers alone as well. Late learners of ASL almost never used both number and plural classifier, frequently used other strategies, or did not mark plural altogether. While constructions with omitted plural marking constituted a minority, late learners were the only group who demonstrated such strategy, and all participants in this group produced this type of error.

Late learners were able to use classifiers productively and modify the handshape position appropriately, but not in all cases where it was required: with some but not all classifiers and with high variation even within one person's production. This pattern might suggest that late learners of ASL have memorized several classifier paradigms and remember that some entities require a certain classifier. The rule, however, was not acquired and was not generalized to the new context. Such explanation is conceptually in line with previous studies by Newport (1988, 1990). The omissions of plural marking may be functionally similar to the "frozen forms" that late learners produced in Newport's data instead of productive use: the inconsistency of classifier use might indicate that the rule was not indeed internalized. Rather the instantiations of the rule that occur in certain frequent contexts or with certain classifiers were learned separately and used correctly.

An alternative explanation is not related to morphology, but to pragmatics. Several picture descriptions by late learners omitted important parts of the scene: either the number of entities involved, or the agent/patient. Importantly, one other study with late learners of ASL reported the opposite: the over-informative picture descriptions (Miles, 2021). It is possible that late first language learners fail to identify the common knowledge that is important for efficient communication (Gorman, Gegg-Harrison, Marsh, & Tanenhaus, 2013; Mangold & Pobel, 1988) or violate the maxim of quantity (Grice, 1975). Such violations of the maxim of quantity both in production and comprehension were attested in young children (Davies & Katsos, 2010; Deutsch & Pechmann, 1982; Ford & Olson, 1975; Grigoroglou & Papafragou, 2019; Sonnenschein, 1984).

The sentence-picture matching task in Chapter 5 allowed us to disentangle these two possible explanations. The test items only included the sentences for entities and items that late learners successfully produced in Experiment 1, combined with a variety of plural arrangements. If late learners can reliably interpret new sentences where number is marked only by plural classifiers, this would suggest that plural marking can be understood in variety of contexts. If they also reject the grammatically correct sentences with the number marking not matching the picture, this will show that they can detect under-informative sentences in language comprehension tasks, suggesting that the problem is not related to pragmatics. However, due to the unforeseen circumstances (COVID-19 pandemic) we were not able to test the late learners of ASL on sentence-picture matching task (online data collection was not an option due to various life constraints and the lack of access to technology). The data will be collected as soon as it is safe and convenient for the participants, should they still be willing to participate.

However, the pragmatic competence following language deprivation is still understudied. The only study, by Davidson & Mayberry (2015), investigated the comprehension of scalar implicatures by deaf signers with a variety of language backgrounds and found that participants that learned language later in life demonstrate a nonnative performance on sentences with quantifiers (lexically based scale), but were native-like on ad hoc scales (spatial and coordination). Overall, the participants in their study demonstrated strong Gricean pragmatic competence. However, they experienced a less severe language deprivation than participants of the studies described in this dissertation, and acquisition of pragmatics following extremely severe language deprivation has not been studied to date. Therefore, an important direction of the future work based on the results of the plural classifier study is an in-depth investigation of pragmatic competences of late first language learners.

It should be pointed out, however, that it is unlikely that late learners of ASL have conceptual difficulties with the category of number and quantification, find it irrelevant, or did not acquire the numeral system of ASL. The results of Number Stroop Test (Chapter 4) show that both numeral system of ASL and the numeral notation using Arabic digits were acquired and understood with very high accuracy. When number was expressed by Arabic digits, late first language learners demonstrated a robust Number Stroop pattern, suggesting the automatic magnitude activation, expected in adults from numerate culture with rich number experience. When number was expressed with ASL number signs, there was no Number Stroop Effect, similar to other groups of participants. These results show that people who had early exposure to numerical culture, but no language, can learn a linguistic number system, once the language is finally available to them.

This finding adds to the results of studies of number use in homesigners from Nicaragua, a highly numerate culture. It has been documented that quantity-tracking devices can emerge in homesign systems without language models (Coppola, Spaepen, & Goldin-Meadow, 2013).

Although conventional signs for large exact numbers may not be developed (Spaepen, Coppola, Spelke, Carey, & Goldin-Meadow, 2011) and such constructions function more similarly to indexes of items within sets rather than cardinal representations of sets (Spaepen, Coppola, Flaherty, Spelke, & Goldin-Meadow, 2013), the mere fact that quantity-tracking device develops on its own shows how salient and important the quantity tracking is for people living in numerate cultures. Flaherty & Senghas (2011) show that some deaf homesigners were familiar with a counting sequence using Arabic digits prior to learning it in sign language. At least one of these participants succeeded in number matching tasks with stimuli physically present, but not on ephemeral matching task (when the items that the participants had to match were no longer visible after they were presented). However, other participants who learned the Nicaraguan Sign Language numerals after language deprivation, succeeded in both tasks, allowing the researchers to conclude that number can be acquired later in life. The results of Number Stroop Test in this dissertation asks what happens at the next stage (when language is available) and confirms the results of the Nicaraguan study. Together these studies on language deprivation in numerate cultures adds more evidence against linguistic determinism: when a language to track precise large quantities became available, individuals who previously had no such tool successfully acquired it, contrary to the strong linguistic relativity hypothesis.

Additionally, Number Stroop Study, was the first study to explicitly investigate the processing of number following language deprivation. In comparison to early signers, late learners of ASL demonstrated slower reaction times and sometimes unusual patterns of reaction times. Importantly, the slow speed is not a general property of late learners' performance on linguistic and cognitive tasks: in previous studies they performed on non-verbal tasks on par with control groups (Mayberry et al, 2018), and in ASL tasks, they performed similar to or faster than the second language learners (Ferjan Ramirez, N., Leonard, M.K., Halgren, E., Mayberry, 2013; Ferjan Ramirez et al., 2016; Mayberry, Davenport, Roth, & Halgren, 2018). However, slow speed has been evoked as a general characteristic of magnitude processing by deaf people in some previous studies that did not control for age of first language acquisition (Rebecca Bull et al., 2005; Epstein, Hillegeist, & American, 1994).

Contrary to these observations, the results of Number Stroop Test show that the native signers of ASL who acquired language early in life did not demonstrate any slowdown in comparison to the hearing controls and performed with even higher (although not significantly) accuracy than hearing controls in the Arabic digit condition. This leads us to hypothesize that the slowdown detected in previous studies may in fact be related to language deprivation that is common in deaf community (Humphries et al., 2012; Mitchell & Karchmer, 2004), but can be overlooked if the only characteristic of language background that the study controlled for is the "preferred communication mode". Therefore, another contribution of this dissertation is evidence that control for age and setting of first language acquisition is crucial.

Clearly, language deprivation is not the only reason for school underachievement in mathematics that has been demonstrated in several studies of mathematic development in deaf children. For example, Kritzer (2009) showed that deaf preschool children of deaf signing parents, while outperforming their peers from hearing families, still demonstrate a delay in early mathematics development. Story problems were particularly challenging to all participants: children had a hard time connecting the computational part to the narrative part of the problem. One of the explanations Kritzer proposes is related to the lack of information access and therefore fewer opportunities for incidental learning (even for deaf children from deaf families), and therefore she suggests that extra attention needs to be paid to stimulating early informal mathematic learning. As she puts it, "*what is done with language may be more important*" (Kritzer, 2009).

However, if we compare access to linguistic structures and to numbers for people growing up without accessible language input, the situation is paradoxically reversed. Growing up surrounded by numbers, Arabic digits, watching number gestures of hearing people, using transportation and measurements, late learners of ASL operated quantities and digits prior to the onset of language acquisition. Two of the participants who are siblings shared the homesign number system they used with their mother prior to coming to the USA (importantly, their variants differed). Perhaps, the relatively abundant access to quantification and numerical contexts in highly numerical cultures underlies the fact that the command of basic numbers and automatic magnitude activation in late first language learners is less affected by early language deprivation than other aspects of language.

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