Language Deprivation and the American Sign Language Lexicon

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Naomi K. Caselli

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Advisor: Ariel M. Cohen-Goldberg and Ray Jackendoff

Abstract

Our understanding of the mental lexicon, the way meaning is extracted from word forms, is almost entirely built on data from spoken languages. While there is much work demonstrating that in many ways the linguistic structure and psychological mechanisms for processing signed language and spoken language processing are the same, less is known about the signed language mental lexicon. In this dissertation, I examine the structure of the American Sign Language mental lexicon, and the ways meaning can be extracted from the manual/visual signal.

In the third chapter of this dissertation I ask whether a single cognitive architecture might explain diverse behavioral patterns in signed and spoken language. Chen and Mirman (2012) presented a computational model of word processing that unified opposite effects of neighborhood density in speech production, perception, and written word recognition. Carreiras et al. (2008) demonstrate that neighborhood density effects in Spanish Sign Language (LSE) also vary depending on whether the neighbors share the same handshape or location. We present a spreading activation architecture that borrows the principles proposed by Chen and Mirman (2012), and show that if this architecture is elaborated to incorporate relatively minor facts about either 1) the time course of sign perception or 2) the frequency of sub-lexical units in sign languages, it produces data that match the experimental findings from sign languages. This work serves as a proof of concept that a single cognitive architecture could underlie both sign and word recognition.

In the second chapter I present ASL-LEX, a lexical database for ASL that catalogues more than forty properties about almost 1,000 signs. The database includes, for example, information about each sign's iconicity, phonological make-up, and neighborhood density. I use this information to better understand the structure of the ASL lexicon, the distribution of each of these properties, and the relationships between these properties. This lexical database is the largest and most comprehensive database of ASL, and can be used by researchers to develop experiments and by educators to identify and support vocabulary development.

In the fourth chapter, I use ASL-LEX to develop a tightly-controlled study of sign perception. I ask whether neighborhood density and sub-lexical frequency play a role in sign perception, and if the mechanisms of sign perception are affected by early language experience. Eighty deaf participants with varying early language backgrounds completed a lexical decision task. I find that neighborhood density inhibits sign perception in people with low early ASL exposure, but has no effect in people with high early ASL exposure. Location frequency inhibits sign perception in all people, but the effect is stronger in people with low early ASL exposure. This suggests that impoverished access to ASL early in life has lasting consequences for sign perception.

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Chapter 1 Introduction

Human language use is extremely homogenous. People in every region and culture of the world learn it effortlessly, and adults use it with remarkable proficiency and automaticity. The homogeneity in language is at once what makes it so interesting and so difficult to study. What are the ingredients, learned and innate, that enable humans to use and learn language with such facility? It is difficult to answer this question because of the moral implications of manipulating the quality or quantity of language children experience experimentally. Because Deaf people often use and acquire language differently than hearing people they offer a unique way to learn about the human language capacity. The first insight stems from the fact that many deaf people use a signed language as their native language. Studying differences in language processing in the signed and spoken modalities makes it possible to separate the role of language from that of modality—which aspects of language use are particular to the modality, and which reflect language in general? The second insight arises because, unlike nearly every other human on this planet, a subset of the deaf population is not exposed to language from birth. Comparing language processing in deaf people who had impoverished linguistic input to those who had plentiful linguistic input in childhood makes it possible to better understand the consequences of language deprivation, and to ask: What is the role of early language experience in the development and use of the adult language processing system?

One of the most important discoveries about language in the past half-century is arguably the fact that signed and spoken languages share fundamental aspects of their linguistic structure (Klima & Bellugi, 1979; Wilbur, 1979; Poizner, Klima & Bellugi, 1987; Valli & Lucas, 1992; Sandler & Lillo-Martin, 2006; Emmorey, 2002). The fact that all natural languages have common grammatical principles despite vast differences in modality has had critical implications for theories of the human language faculty and its evolution (e.g., Pinker, 1994; Jackendoff, 2002). Though a parallel line of research exists comparing the psycholinguistic mechanisms of signed and spoken language (Berent, Dupuis, & Brentari, 2013; Corina & Emmorey, 1990; Corina & Emmorey, 2993; Emmorey, 1993; Emmorey, Mehta, & Grabowski, 2007; MacSweeney, Waters, Brammer, Woll, & Goswami, 2008; McCullough, Brentar, & Emmorey, 2000; Petitto et al., 2000; Sandler & Lillo Martin, 2006), much work remains. Far less is known, for example, about whether the mental lexicon is organized similarly across modalities and whether words and signs are activated and selected in similar ways. In the same way that the discovery of a common set of grammatical principles influenced theories of universal grammar, discovering similarities (or differences) in processing can profoundly advance our knowledge about psycholinguistic systems.

The perception of words is one of the most fundamental aspects of language processing. At the most basic level, we must store words or signs in our minds—our mental lexicons—that we can use as a kind of dictionary to parse the incoming signal. These words and signs are organized to facilitate this process. The organizing principle might arise at different levels of structure: words that are related in sound or spelling might be grouped together, words that share morphology might also be grouped together, words that are related in meaning might be grouped together. The ways words are organized might vary across languages and modalities. Languages that have more words might be organized differently than those that have few words. Languages that have a high morpheme-to-word ratio might be organized differently than those that have a low morpheme-to word ratio. Languages with many speech sounds might be organized differently than those with few speech sounds. Languages with no written system will not be organized with respect to spelling. How might the signed lexicon be organized?

Beyond this static organization, how is it that we extract meaning from speech, writing and signing? At the broadest level, we must map information from the visual or acoustic signal onto words from the mental lexicon, selecting a single word from all of the words in the lexicon. The candidate words that are entertained will be constrained in part by the modality. In speech perception the signal is ephemeral and unfolds over time. Sequences of sounds can be processed incrementally, narrowing the collection of candidate words with each additional sound. In reading, the image of the entire word persists and is available at once allowing the reader a parafoveal preview of upcoming information. How are signs perceived with respect to the properties of sign language?

In this dissertation, I explore the organizing principles of sign language. Rather than sounds, are sign languages organized based on formal properties (e.g., handshapes, locations, movements)? Are there other factors that shape the signed lexicon? The formal properties of signs (handshapes, locations, and movements) are all produced simultaneously—it is not possible to produce a handshape without producing it in some location or vice versa. In this way, signs are like printed words in that the discrete elements are produced somewhat simultaneously. Signs are also like spoken words in that the signal is ephemeral and is unveiled over time—the hands require time to assume their handshapes and arrive in their locations. Given these facts, how does a perceiver narrow down the candidate signs to a single item during sign perception?

Modality Differences in Lexical Access

Within the psycholinguistic framework, the comprehension of a single word, *lexical access*, ultimately involves mapping a physical signal onto its meaning. Focusing first on spoken and written comprehension, multiple stages of processing have been posited to take place in between these two endpoints, most generally the identification of sub-lexical and lexical units (e.g., McClelland & Ellman, 1986). As sub-lexical units are identified, they pass activation on to associated lexical items. During the process of lexical identification, not only is the target activated so are words that are related to the target (neighbors). In reading neighbors are typically defined as words that differ from the target by one letter (Coltheart et al., 1977), and in speech perception neighbors are defined as words that differ from the target by one phoneme (Luce & Pisoni, 1998). These neighbors are thought to compete. The density of the phonological neighborhood, the number of words that differ from the target word by one grapheme or phoneme, affects how quickly the target can be recognized. Words with many neighbors are more difficult to identify (e.g., Goldinger et al., 1989; Dufour and Peereman, 2003).

There are a number of ways the language processing architecture could be organized with respect to facts about the signed and spoken modalities. On the one hand, it's possible that signed and spoken languages utilize different cognitive mechanisms for all but the most central (i.e., semantic) stages of processing. It is also reasonable that a continuum of processing similarity could exist, where signed and spoken languages rely on different mechanisms to access the lexicon and process sub-lexical elements, but utilize similar cognitive mechanisms to achieve semantic processing. Finally, it is also possible that identical psycholinguistic mechanisms underlie all stages of processing, with only the specific content differing across modalities (e.g., manual sign location vs. oral place of articulation).

Sign processing in many ways is like word processing. Phonological structure is one of the core organizing properties of all languages, including sign languages (Brentari, 2008; Sandler & Lillo Martin, 2006). Like the sounds in words, signs are composed of discrete meaningless formal units such as hand configurations or locations. As in spoken language, lexical access in signed language is thought to entail a two-step procedure involving sub-lexical and lexical levels of processing in production (Thompson, Emmorey, & Gollan, 2005; Corina & Knapp, 2006; Baus, Gutiérrez-Sigut, Quer, & Carreiras, 2008) and perception (Carreiras, 2010; Carreiras Gutiérrez -Sigut, Baquero, & Corina, 2008; Corina & Hildebrandt, 2002; Corina & Emmorey, 1993; Dye & Shih, 2006, Mayberry & Witcher, 2006). For example, signers experiencing a “tip of the tongue” state can recall sub-lexical information (e.g., the handshape or location) about signs while failing to recall the lexical item itself (Thompson, Emmorey, & Gollan, 2005).

Though the structure of sign language is in many ways parallel to that of spoken language, it is yet unknown whether signs compete for recognition as words in spoken language do. In Chapters 3 and 4, I will ask whether the organization of the signed mental lexicon is similar to that of spoken language, and if the mechanisms of lexical access are fundamentally modality dependent or if they are language general.

Language Deprivation and Sign Perception

Though many deaf people acquire a signed language from their deaf parents in much the same way that hearing people acquire a spoken language, a subset of the population has a unique language acquisition trajectory. Some deaf children do not hear speech sounds well enough to easily learn and use spoken language. Among these deaf people, the overwhelming majority (72%) live in homes where family members do not regularly sign (Gallaudet Research Institute, 2013), and thus may of these children are unable to easily learn sign language. Impoverished access to spoken and signed language such that language acquisition is impaired is called *language deprivation* (Glickman, 2007; Humphries, Kushalnagar, Mathur, Napoli & Padden, 2013; Humphries, Kushalnagar, Mathur, Napoli & Padden, 2014; Humphries, Kushalnagar, Mathur, Napoli, Padden, Pollard, Rathmann, & Smith, 2014; Humphries, Kushalnagar, Mathur, Napoli, Padden, Rathmann, & Smith, 2014). We use the term language deprivation here to refer to a continuum of language experience, from slightly limited access to language to complete isolation from language. By studying language deprived deaf people, it is possible to examine the contribution of language experience to language processing.

Even just a few years of language deprivation during childhood can have lasting consequences on a number of aspects of language processing. Deficits can be seen in syntactic (Boudreault & Mayberry, 2006; Mayberry & Eichen, 1991), semantic (Mayberry & Eichen, 1991; Mayberry & Fischer, 1989, Supalla, Hauser, & Bavelier, 2014), morphological (Emmorey, Bellugi, Friederici, & Horn, 1995; Newport, 1988; Newport, 1990), and phonological levels of processing (Mayberry & Fischer, 1989). It is also possible to observe differences in neural organization as a function of language deprivation (Newman, Bavelier, Corina, Jezzard, & Neville, 2001; Ramirez, Leonard, Torres, Hatrak, Halgren, & Mayberry, 2013).

Having identified *that* language deprivation adversely affects deaf people, the question becomes how to mitigate the effects of language deprivation. Prevention is the most straightforward approach to reducing the effects of language deprivation. Both the National Association for the Deaf (NAD) and the American Speech-Language-Hearing Association (ASHA) position statements argue that early access to language is critical. The NAD writes, "it is the position of the National Association of the Deaf that an all-out effort needs to be made to ensure that all deaf and hard of hearing children have full and meaningful access to language from birth and the benefit of visual language and visual learning," and ASHA writes, "...the earlier the hearing loss is identified and intervention begun, the more likely it is that the delays in speech and language development will be diminished." Ensuring that at-risk Deaf children have early, plentiful, and unfettered access to language is critical. Due to limited resources, language deprivation is unfortunately not always prevented. The task then for researchers is to better understand how to reduce the negative impact of language deprivation once it has occurred. The first step toward developing interventions of this kind is to understand the mechanisms of *how* language deprivation affects deaf people, and along the way we can learn more about the psycholinguistic mechanisms of language processing more generally.

In Chapter 2, I will describe the development of ASL-LEX, a lexical database of ASL that describes many properties of the lexicon and lays out several ways the signed lexicon might be organized. I will then work to characterize the effects of language deprivation on lexical access in sign perception. In Chapter 3 I will present a computational model of sign perception that lays out a theory of the mechanisms of sign perception. In Chapter 4 I look at the mechanisms of sign perception in human participants asking how the signed mental lexicon is organized and used: Are the factors that are important for speech perception also important for sign perception? Is sign perception affected by early language experience?

Chapter 2 ASL-LEX: A Lexical Database of ASL

*Before I begin this section, I want to acknowledge that the work described here was a collaboration with Karen Emmorey, Zed Sevcikova, and Ariel Cohen-Goldberg. Karen Emmorey and Zed Sevcikova contributed the videos, frequency ratings, lexical classes, glosses, initialization, and duration information. They also wrote the corresponding methods and results sections, and all three contributed to the writing of the rest of the chapter.

Lexical databases (repositories of information about words in a language) have been crucial to making advances in psycholinguistic research and improving our understanding of language processes. Many lexical databases for spoken languages have been created, compiling an enormous amount of detailed information about spoken and written words. For instance, the English Lexicon Project provides information about lexical frequency, neighborhood density, orthographic and phonological length, morphological structure, and part of speech for more than 40,000 English words (Balota et al., 2007); see also e.g., CELEX for English, Dutch, and German, (Baayen, Piepenbrock, & Van Rijn, 1993) and LEXIQUE for French (New, Pallier, Brysbaert, & Ferrand, 2004). Numerous studies have demonstrated the importance of these properties for spoken and written language processing, making lexical databases critical tools for testing hypotheses and for controlling extraneous aspects of processing. It is not surprising that databases such as these have been collectively cited more than 18,000 times in studies of speech perception and production, literacy, bilingualism, language acquisition, dyslexia, Alzheimer's Disease, autism, aphasia, memory, emotion, and machine learning (cite where this number comes from). Not only have lexical databases been used in scientific research, these resources have also been critical to curriculum and assessment development (e.g., van Bon, Bouwmans, Broeders, 2006; Whitworth, Webster, & Howard, 2014).

Unfortunately, no large corpora or lexical databases are currently available for American Sign Language (ASL). There are a few small scale databases available for other sign languages. For example, Vinson et al. (2008) developed a database for British Sign Language consisting of 300 signs rated by deaf people for frequency, iconicity, and age of acquisition. Gutierrez-Sigut, Costello, Baus, and Carreiras (2015) created a searchable database for Spanish Sign Language consisting of 2,400 signs and 2,700 nonsigns that were coded for phonological and grammatical properties (but frequency data is not available). There are also a number of on-going efforts to develop large annotated corpora for other signed languages (New Zealand Sign Language: McKee & Kennedy, 2006; Australian Sign Language: Johnson, 2012; British Sign Language: Schembri et al., 2011). Currently, only two small-scale lexical resources exist for ASL. Morford and MacFarlane (2003) created a corpus of 4,111 ASL sign tokens as a preliminary study of frequency in ASL, but this corpus is not publically available. Mayberry, Hall, and Zvaigzne (2014) published a list of subjective frequency ratings for 432 ASL signs, but the signs are not coded for lexical or phonological properties. Without a more comprehensive lexical database for ASL, it is difficult to develop well-controlled psycholinguistic studies of ASL language processing.

Ideally a database should have breadth—normative information for many lexical and phonological properties, and depth—many or all of the lexical items in the lexicon. To begin to address this need, we developed ASL-LEX, a broad lexical database of nearly 1,000 ASL signs. The database includes subjective frequency ratings by deaf signers and iconicity ratings by hearing non-signers. Each sign in ASL-LEX has been coded for four lexical properties (initialization, lexical class, compounding, fingerspelling) and for six phonological properties from which sub-lexical frequencies and neighborhood densities have been calculated. The database also includes information about sign length (reported as sign onset and offset times measured from a reference video clip of each sign) and for a subset of signs, information about English translation consistency is available. ASL-LEX is available in Excel spreadsheet and CSV formats in the supplementary materials associated with this article. In addition, a searchable version of ASL-LEX is available online (http://www.preview.asl-lex.org). The online version also provides access to the reference video clip for each sign.

Like speakers, signers are sensitive to lexical frequency; for instance, lexical decision and naming times are longer for low than high frequency signs (e.g., Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008; Emmorey, Petrich, & Gollan, 2013). For spoken languages, lexical frequency is commonly measured by counting the frequency of occurrence in large written and/or spoken corpora (for a discussion of these sources, see Brysbaert & New, 2009). However, because there is no conventional written form for sign languages, corpus-based frequency counts would need to be derived from transcribed conversation. This method requires considerable effort and even the largest corpora currently available for a sign language do not even approach the size of those available for spoken language (i.e., millions of words). As an alternative, most psycholinguistic studies of sign language utilize subjective measures of sign frequency created by asking language users to estimate how frequently they encounter the sign. This is the measure of frequency included in ASL-LEX. Subjective frequency is highly correlated with corpus counts for both signed language (Fenlon, Schembri, Rentelis, Vinson, & Cormier, 2014) and spoken language (Balota, Pilotti, & Cortese, 2001).

Many signs are iconically motivated: there is a direct relationship between form and meaning. Whereas in spoken language iconic motivation is limited to phenomena like onomatopoeia and sound symbolism (e.g., Hinton, Nichols, & Ohala, 2006), the visual modality abounds with opportunities for sign forms to correspond to meaning. The role of iconicity in sign language processing and acquisition has been of great interest for decades (e.g. Emmorey et al., 2004; Frishberg, 1975; Orlansky & Bonvillian, 1984; Taub, 2001; Thompson, Vinson, Vigliocco, 2009). Iconicity has also been of interest to phonologists, as iconicity appears to have a complex relationship with phonological regularity (e.g., Brentari, 2007; Eccarius, 2008; van der Hulst & van der Kooij, 2006; van der Kooij, 2002). Because sign languages offer a unique opportunity to study the role of iconicity in linguistics and psycholinguistics, ratings of iconicity are of particular value in a signed lexical database. As such, ASL-LEX includes a holistic measure of the degree to which a sign is visually similar to its referent. This is similar to the approach used by Vinson et al. (2008) in a corpus of British Sign Language.

Like spoken languages, sub-lexical (phonological) features play an important role in the way sign languages are organized and processed. Many sub-lexical features are distinctive, meaning that minimal pairs of signs exist that differ by only a single property (e.g., in ASL ONION and APPLE differ only in their location). Additionally, psycholinguistic experiments have shown significant priming effects for phonologically related signs, indicating that phonological information is extracted during sign production and comprehension (Baus, Gutiérrez-Sigut, Quer, & Carrieras, 2008; Baus, Gutiérrez & Carreiras, 2014; Corina & Emmorey, 1993; Corina & Hildebrandt, 2002; Corina &

Knapp, 2006a; Dye & Shih, 2006). Unfortunately, the specific direction of phonological priming effects have been decidedly mixed in the literature, possibly an artifact of the different ways in which phonological overlap has been defined across studies (see Caselli & Cohen-Goldberg, 2014). These facts make it important to have an easily searchable, standardized phonological description of signs for use in ASL research.

ASL-LEX provides a linguistically-motivated transcription of six phonological properties for each sign in the database: Sign type (Battison, 1978), Location (Major and Minor Location), Selected Fingers, Flexion, and Movement. First and foremost, these transcriptions make it possible to easily select stimuli with phonological descriptions that are consistent across studies. They may also be useful for linguistic analyses, facilitating the identification of fine-grained phonological patterns among various phonological features and between phonological and lexical properties across the lexicon. Since these transcriptions in effect represent the application of a particular phonological theory to a large swath of the ASL lexicon, ASL-LEX may be useful in assessing how well particular phonological formalisms describe the ASL phonological system. Lastly, consistent phonological transcriptions can serve as a machine-readable resource for ASL-related technology such as automated systems for sign recognition and production.

ASL-LEX also provides several measurements of the distribution of phonological properties in ASL. Research on spoken languages has suggested that sound structure is represented at multiple ‘grains’ (e.g., sub-segmental, segmental, suprasegmental, lexical neighborhoods). Given the relatively fledgling status of sign language research, these distinctions have not been consistently made or investigated in psycholinguistic experiments on sign perception and production. To facilitate research in this area, we provide data about two grains of ASL sign phonology: sub-lexical frequency and neighborhood density. The terms sub-lexical frequency and neighborhood density have also not been consistently used in the literature. We define sub-lexical frequency as the frequency with which each sub-lexical feature value appears in the lexicon. This is straightforwardly calculated as the number of signs containing a particular value (e.g., the sub-lexical frequency of the cheek as a minor location is simply the number of signs that are made on the cheek). ASL-LEX reports the frequency of each value of the six phonological properties described above, plus handshape (unique combinations of flexion and selected fingers). Neighborhood density refers to the number of signs that are phonologically similar to a given target sign. We provide three broad measures of neighborhood density for each sign: Maximal Neighborhood Density, Minimal Neighborhood Density and Parameter-Based Neighborhood Density, defined as the number of signs that share at least 4/5, 1/5, and 4/4 sub-lexical features, respectively, with the target sign (see below). Ideally, phonological distributions should be calculated over all of the signs of a language. As a first step to this goal, ASL-LEX provides sub-lexical frequency and neighborhood density counts calculated over all of the nearly 1,000 signs contained in the database.

In the following sections we describe the procedures we used to create ASL-LEX. We also report descriptive statistics for a number of sign properties. These data are useful in that they provide a characterization of the ASL-LEX database and constitute a first-order description of much of the lexicalized ASL lexicon. Which phonological properties appear more or less commonly in ASL signs? How widely do signs vary in their frequency of use? We then report a number of analyses designed to more deeply understand how phonological, lexical, and semantic factors interact in the ASL lexicon. For example, how are iconity and lexical frequency related to each other? Are certain types of phonological frequency correlated with lexical frequency or iconicity? The answers to these questions may provide important information for researchers interested in how signs are acquired and processed and how the lexicon evolves over time.

METHODS

Deaf Participants: Subjective Frequency Ratings

Each ASL sign was rated for subjective frequency by 25-31 deaf signers, and a total of 69 deaf adults (45 female; *M* age = 34 years, *SD* = 11 years) were included in the frequency rating study. An additional 22 participants were recruited, but were excluded because a) they did not complete at least one section of the ratings survey (*N* = 7), b) they did not use the rating scale appropriately (i.e., their ratings had a standard deviation of only 1 or less; *N* = 8), or c) they had acquired ASL after age six (*N* = 8). Nearly all participants were either congenitally deaf (*N* = 60) or became deaf before age three (*N* = 8); one participant (who acquired ASL from birth) became deaf at age 10. Sixty-seven participants reported severe to profound and two reported moderate hearing loss. All participants reported using ASL as their preferred and primary language, and all rated their ASL fluency as high on a 1-7 self-evaluation scale (7 = fluent; M = 6.78, SD = 0.51). Thirty-nine participants were native signers (25 female; M age = 33 years, SD = 11) who acquired ASL from birth, and 30 participants (20 female; M age = 34 years, SD = 11) were "early signers" who acquired ASL before age six. Subjective frequency ratings were highly correlated for the native and early signers, $r = .94$, $p < .001$ (standardized z-scores), and the mean ratings did not differ between these two groups, Kruskal-Wallis χ^2 (1, 69) = .80, $p = .37$). These findings replicate those of Mayberry et al. (2014) who found that subjective frequency ratings did not differ for early and native signers. All analyses reported here are with the full participant group but we also present the subjective frequency ratings for native signers separately in ASL-LEX for the convenience of researchers who wish to utilize native-only ratings.

The participants were recruited from across the US and were compensated for their time. Forty percent of the participants were born in the West of the US (primarily California), 29% in the North-East, 13% in the Mid-West, 6% in the South, 12% did not report information about their birth place. Fifty-nine percent of the participants currently reside in the West of the US (primarily California), 16% in the North-East, 10% in the South, 8% in the Mid-West, 7% did not report this information, and one participant resided abroad.

Hearing participants: Iconicity Ratings

Each ASL sign was rated for iconicity by 21-37[1] hearing English speakers on Mechanical Turk (www.mturk.com). All participants reported normal or corrected-to-normal vision. None of the participants knew more than ten signs in any signed language. Non-signing participants were chosen partly because Vinson et al. (2008) previously reported that some signers rated initialized signs as highly iconic because the handshape was the fingerspelled counterpart to the first letter of an English translation. We were also concerned that the folk stories about iconic origins of signs might influence iconicity ratings in signers. For example, the sign GIRL is produced with a curved movement of

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[1] Because of technical difficulties, one sign (REMOTE_CONTROL) was rated by only 9 participants.

the thumb on the cheek bearing little resemblance to a girl, but folk etymology suggests that this sign was created to represent the chin strap of a bonnet. By gathering iconicity ratings from non-signers, the ratings cannot be influenced by folk etymology and instead provide a better measure of the visual similarity between the sign form and referent.

Mechanical Turk workers and laboratory participants have been shown to perform similarly on a number of cognitive and perceptual experimental paradigms (e.g., Germine, Nakayama, Duchaine, Chabris, Chatterjee, Wilmer, 2012). Two steps were taken to ensure that participants were human (e.g., not automated scripts) and were making genuine ratings. Participants had to complete a CAPTCHA (Completely Automated Public Turing test to tell Computers and Humans Apart) in order to begin the survey. Additionally, each survey section included one question that was visually similar to the other questions (included a video and a rating scale), but asked participants to enter the number ‘5’ rather than to rate the iconicity of the video. Participants who did not enter a 5 were excluded.

Materials

Stimuli selection and preparation

ASL signs were drawn from several sources: previous in-house psycholinguistic experiments, the Appendix from Mayberry et al. (2014), ASL translations of BSL signs from Vinson et al., (2008), and ASL translations of low and high frequency English words from SUBTLEX$_{US}$ (http://expsy.ugent.be/subtlexus/). The later were selected in order to create frequency-balanced survey sections (see below). “Neutral” fingerspelled words (Haptonstall-Nykaza & Schick, 2007) were not included, although a few lexicalized fingerspelled signs were included (#BACK, #FEB). Classifier constructions (also known as depicting constructions or polycomponential signs) were not included.

All ASL signs were produced by the same deaf native signer (female, middle-aged, White, born in the North-East US, resides in California). Signs were produced with appropriate mouth gestures or spontaneous mouthings of the corresponding English word. Mouthing was not prevented because mouthing is a common feature of ASL signs (Nadolske & Brentari, 2013), and isolated signs produced with no mouth movements are perceived as unnatural.

A total of 1,011 ASL signs (unique entries, this number does not include repeated entries) were rated for frequency by the deaf participants and for iconicity by the hearing participants, of these, 5 signs were excluded because at least 50% of participants indicated they did not know the sign and further 13 signs were discovered to be duplicates once the phonological transcriptions were obtained. Thus 993 signs were ultimately included in the database (see below). The signs were divided into four batches (labeled A, B, C, and D). There were 270 signs to be rated in each batch, with the exception of the last batch (D) which contained 282 signs. For ease of rating and to create breaks, the batches were administered in three sub-sections (with 90 items each). In batch A, each deaf participant rated at least one sub-section, in batches B, C and D, each participant rated all three sub-sections. Thirty-four participants rated two or more batches. The order of presentation of signs within a sub-section was constant. For iconicity ratings, each hearing participant rated only one sub-section of 90 items, and the order of the signs within a sub-section was randomized. A second set of iconicity ratings were collected from hearing participants for 54 signs because the dominant translation provided by the deaf signers turned out to be different for these signs (see below). Only the revised ratings appear in the database.

In an attempt to ensure that high and low frequency signs were evenly distributed across batches and within each sub-section of the batch, we used the frequency of English translations as a proxy for ASL frequency. We obtained the log10 word frequency score per million for each sign's English translation from SUBTLEX$_{US}$ and used this data to create sub-sections with similar frequency distributions. The sub-sections did not differ significantly in mean log10 word frequency scores, F (2, 971) = .38, p = .68.

Procedure

The sign recordings were exported at a frame rate of 29.93 frames per second, and signs were edited into individual video clips (there was no carrier phrase). The video clips (video dimensions 640 x 480 pixels) were uploaded to YouTube and incorporated into an online survey tool, Survey Monkey (www.surveymonkey.com) for the frequency ratings by deaf participants. For the iconicity ratings, the same video clips (315 x 420 pixels) were accessed and rated through Mechanical Turk by hearing participants.

Frequency Rating Procedure

Participants completed the rating studies remotely via an online survey tool. At the beginning of each sub-section, participants viewed instructions recorded in ASL and written English (see Appendix for English instructions). Each video clip was presented individually with the rating scale below, and participants rated the video on a 7-point scale based on how often they felt the sign appears in everyday conversation (1 = very infrequently, 7 = very frequently). Participants were asked to rate the model's sign rather than their own sign, if their sign happened to be different. If participants were unfamiliar with a sign, they were asked to check a box labeled *cannot rate because do not know the sign*. We excluded signs that unfamiliar to more than half of the participants who rated the item (1.5% of total responses) and this resulted in removal of 5 signs. If participants encountered a technical difficulty (e.g., a video failed to load), they were asked to check a box labeled *cannot rate because of technical difficulties.* Technical difficulties were rare (only 0.5% of video clips). Participants were permitted to take breaks within sections of the survey, as well as between the survey sections. However, participants were required to the complete each batch within two weeks.

To obtain a measure of the internal validity of the participants' frequency ratings across survey sections (4 surveys, each divided into 3 sections), we included a small number of repeated signs in each survey section. The same 10 signs were repeated for batch A and B, and 5 of these signs were repeated in batches C and D. Ratings for the 5 repeated signs were consistent (did not differ statistically) across sections (F (11, 216) = 1.8, $p = .053$, $\eta_p^2 = .06$). Participants' first rating and subsequent rating for the 5 repeated signs also did not statistically differ (F (1, 427) = 3.7, $p = .06$, $\eta_p^2 = .01$), indicating that participants rated repeated signs consistently across the survey. Only first-time ratings for repeated signs were included in ASL-LEX.

In addition to providing frequency judgments, participants were asked to provide an English translation for a subset of signs ($N = 211$). Signs were included in this subset when either pilot testing or native signer intuition suggested that a) the sign might be misperceived as another similar sign, b) the sign may have more than one English translation, or c) the expected English translation had a very low log10 word frequency score (< 2.0). The signs for which English translations were requested were evenly distributed across the survey sections (roughly 20% of signs in each section). For each sign in this subset, participants provided the English translations by typing into a response box provided on the screen below the rating scale, immediately after rating each sign for frequency. Participants were instructed to indicate if they did not know the sign (1.5 % of data), and if they did so, their translation was not counted.

For signs in this subset, the most frequent English translation (dominant translation) provided by participants was used to determine the Entry Identifier used in the database (see below). The percent agreement for the English translation for these signs is given in ASL-LEX for all participants and separately for native signers. If a participant provided more than one translation of a sign, only their initial response was used to calculate the percentage of dominant and non-dominant translations. All additional translations other than the initial translations and their counts are listed in the tab in ASL-LEX labeled "English translations".

In some cases, participants provided English translations that were inflectionally related. Morphological inflections for aspect (e.g. SURF and SURFING), number (FLOWER and FLOWERS), or gender inflections (WAITER and WAITRESS) were collapsed together for estimating the English translations. Following Bates et al. (2002), we defined morphological alteration as "variation that shares the word root or a key portion of the word without changing the word's core meaning" (p. 7). The breakdown of percentages for the translation variants is listed in the English Translations tab. For example, percentage agreement for the sign SURF (verb) is listed as 83.9%, and this percentage reflects the combination of inflectional variants SURF (54.8%) and SURFING (29.0%). This breakdown of percentages is listed in the English Translations tab, along with a list of the non-dominant glosses, which for SURF were SKATEBOARD (9.7%), RIDE (3.2%), and SURFER (3.2%). If a participant provided more than one translation for a sign, the additional translation (N) are also provided in the English Translations tab.

Iconicity Rating Procedure

Instructions were adapted from Vinson et al. (2008) and customized for use with non-signing participants (see Appendix). Instructions were presented in spoken English in a video with examples of ASL signs across the iconicity spectrum, and the instructions were also available in written English. Each clip was presented individually with the English translation and rating scale below, and participants rated the video on a 7-point scale based on how much the sign "looks like what it means" based on its English translation (1 = not iconic at all, 7 = very iconic). If participants encountered a technical difficulty (e.g., a video failed to load), they were asked to check a box labeled *technical issues (could not rate).* Participants were also able to check a box labeled *prefer not to respond.* Technical difficulties and abstaining responses were rare (only 0.2 % of video clips).

Because a different set of participants rated each survey section, all participants rated a set of 5 or 10 "catch" signs in order to ensure that ratings were consistent across groups of participants. Ratings for these catch signs were consistent (did not differ statistically) across sections ($F(12, 1947) = 1.36$ p = 0.18) and participants ($F(1, 1947) = 0.02$ p = 0.90). An additional 10 signs were added to each survey that were mislabeled (e.g., participants were asked to rate the iconicity of the sign GUESS when given "screwdriver" as its English translation). A Wilcoxon Rank Sum test revealed that the mislabeled signs were rated as less iconic ($M_{mislabeled} = 1.50$ $SD_{mislabeled} = 0.69$) than properly labeled signs ($M_{correctlabel} = 3.16$, $SD_{correctlabel} = 1.69$, $W = 18482.5$, $p < 0.0001$). There was also no interaction between labeling and survey section ($F(11) = 0.52$ p = 0.89), meaning the difference between mislabeled and correctly labeled signs was similar across all survey sections . This result indicates that participants made rational judgements about the relationship between sign forms and meanings, and did not rate all videos as highly iconic.

Phonological Transcription Procedure

Two ASL students independently coded the Major Location, Selected Fingers, and Sign Type for each sign. A hearing native signer (NC) checked all of these codes and arbitrated any disagreements. The hearing native signer coded all of the signs for Minor Location, Flexion, and Movement. To check for reliability once all of the signs were coded, a randomly selected subset of roughly 20% of the signs (200 items) were also coded by a different hearing ASL (non-native) signer. Cohen's Kappa tests showed that all properties were rated reliably ($\varkappa_{signtype} = 0.82$, $\varkappa_{majorlocation} = 0.83$, $\varkappa_{minorlocation} = 0.71$, $\varkappa_{selectedfingers} = 0.90$, $\varkappa_{flexion} = 0.75$, $\varkappa_{movement} = 0.65$; all p's < 0.01).

ASL-LEX properties

Sign Identification

Two kinds of glosses were generated for each sign: *Entry Identifiers* (EntryID, Column A) were designed to uniquely identify every video in the database, and *Lemma Identifiers* (LemmaID, Column B) were designed to identify each lemma in the database grouping together phonological and inflectional variants. The purpose of these glosses is to make ASL-LEX compatible with a machine-readable corpus of ASL, and allow for comparisons between the items in ASL-LEX and corpora. First, EntryIDs were single English words that were evocative of the canonical meaning of the target sign. Where participants provided an English translation, the dominant translation was used as the Entry ID. For four pairs of signs, one English word was deemed the best gloss for both members of the pair (e.g., 'fall' was used to identify a sign referring to the event of losing balance, and the autumn season). In these cases, a number was appended to the gloss (e.g., fall_1 and fall_2). LemmaIDs, also referred to as ID Glosses, were selected according to Johnson (2014) and Fenlon, Cormier, and Schembri (2015). Each LemmaID is an English word that is used to refer to all phonological and inflectional variants of a single lemma. ASL-LEX currently includes only 14 lemmas that have more than one entry, but will become increasingly important as ASL-LEX expands and as corpora are developed. The primary purpose of EntryIDs and LemmaIds is to uniquely identify each video and lemma in the database, and they may *not* be accurate translations, particularly because meanings can change with context. Furthermore these identifiers cannot be reliably used to ascertain the lexical class of the sign.

Frequency

For each sign entry, ASL-LEX provides the mean, standard deviation, and the Z score for ASL frequency ratings from all participants, along with the number of raters and the percentage of participants who did not know the sign (columns C–G). Z scores were calculated over each participant. The data for native signers only are given in columns H-L of the database. The percent agreement with the English translations (EntryIDs) for all participants and for native signers (see above) is provided in columns N and O, respectively. Signs that were not selected for glossing were left blank. The log10 word frequency of the English translation (from $\mathrm{SUBTLEX}_{\mathrm{US}}$) for each sign is provided in column T.

Iconicity

For each sign, ASL-LEX provides the mean iconicity rating, standard deviation, and the Z-score for ratings from hearing participants, along with the number of raters for each sign (columns P-S). Z-scores were calculated over each participant, normalizing for differences in how individuals utilized the rating scale.

Lexical Information

The lexical class is listed for each ASL sign in the database (column U). There are 605 nouns, 186 verbs, 108 adjectives, 23 adverbs, and 78 closed-class items (conjunctions, prepositions, interjections, pronouns). Lexical class was coded by two native signers trained in linguistics who judged the most common use of each sign. This information should be interpreted with caution because in many cases, the lexical class of a sign depends on the context in which it is used. Whether a sign is a compound, an animalized sign, or a fingerspelled loan sign is indicated in columns V-X respectively. Fingerspelled loan signs are those that include more than one letter of the manual alphabet (#STAFF includes the manual letters S and F, #BACK includes all four manual letters). An initialized ASL sign contains a single handshape that represents the first letter of the corresponding English word for that sign. For example, the ASL sign WATER is signed with a ‘W’ handshape touching the chin. Lexicalized fingerspelled signs are not included in the initialized signs subset. There are 60 compounds, 126 initialized signs, and six fingerspelled loan signs in ASL-LEX.

Sign length (onset and offset) and clip length

As the video clips were created to elicit frequency and iconicity judgments and were not designed for use as stimuli in psycholinguistic experiments, the onsets and offsets of the clips vary due to differences in editing procedures. Therefore, we have included timing information for the sign onset and offset within each video clip, along with the sign and clip lengths in milliseconds (columns Y - AB). Sign onset was defined as the first video frame in which the fully formed handshape contacted the body for body-anchored or two-handed signs (e.g. ACCOUNTANT, BUTTERFLY). If the sign did not have contact (e.g. DRINK), sign onset was defined as the first video frame in which the fully formed handshape arrived at the target location near the body or in neutral space before starting the sign movement. Sign offset was defined as the last video frame in which the hand contacted the body for body-anchored or two-handed signs (e.g. BRACELET). If the sign did not end with contact (e.g. BOOK), the offset was defined as the last video frame before the hand(s) began to transition to the rest position. When no clear onset frame was present in the video clip because there was no initial hold (e.g., FIND), sign onset was coded from the first frame in which the fully formed handshape appeared. These criteria for determining sign onset and offset are very similar to those used by Johnson and Liddell (2011) and by Crasborn and Zwitserlood (2008). Agreement for sign onset coding among three independent coders for 205 signs (20% of the data) was 91.2%. Agreement for sign offset between two independent coders for these same signs was 87.3%. All coders were hearing ASL signers.

Phonological Coding

The goal of the phonological coding was to identify the major formal properties of the signs using a theory of sign language phonology that allowed us to generate discrete values and to capture dependencies among properties (columns AC – AH). To this end, phonological coding was guided by Brentari’s Prosodic Model (Brentari, 1998), with some additions and exceptions outlined below. The advantage of using a phonological rather than phonetic description (Gutierrez-Sigut et al., 2015) is that the descriptions can be more easily generalized to other productions and to other signers.

Additionally, using Brentari's model made it possible to capture a large amount of information by coding only a few properties. The Prosodic Model perhaps mores than other models (e.g., Liddell & Johnson, 1989) can be used to reduce redundancy because it describes sub-lexical properties that are predicted by other sub-lexical properties (e.g., it is not necessary to describe the specifications of the non-dominant hand if the sign is symmetrical; and it is not necessary to describe the flexion of the unselected fingers because this is predicted by the flexion of the selected fingers). The following six properties were coded because each has substantial discriminatory power. Though these six properties do not fully describe each sign and alone are not sufficient to uniquely identify all 993 signs, with only these properties it was possible to uniquely identify about half of the signs (52% of signs were uniquely identified, and 32% shared a phonological transcription with fewer than three other signs). These six sub-lexical properties do not uniquely identify each sign because the phonological descriptions exclude properties like thumb position, abduction, contact with the major location, non-manual markers, configuration of the non-dominant hand, and internal movements. See Figure 2 for values and distributions of each property.

Sign Type

Signs were coded using the four Sign Types described by Battison (1978): one-handed, two-handed and symmetrical or alternating, two-handed asymmetrical with the same hand configuration, and two-handed asymmetrical with different hand configurations (column AC). An additional category ('other') was used to identify signs that violate either the Symmetry or Dominance Condition (Battison, 1979). The Symmetry Condition states that if both hands in a sign move, the other specifications of both hands (location, hand configuration etc.) must be identical, and the movement must be synchronous or in 180^{o} asynchrony. The Dominance condition states that in two-handed sign, if only one hand moves, the inventory of non-dominant handshapes is limited to one of seven handshapes (B A S 1 C O 5). In total, 16 signs violated either the Symmetry or Dominance conditions.

Location

Location was divided into two categories (major and minor), and coded according to the concepts of Major Location and Minor Location proposed by Brentari's Prosodic Model (Brentari, 1998). The Major Location of the dominant hand relative to the body comprised five possible values including the head, arm, trunk, non-dominant hand, and neutral space (column AD). Though some signs—primarily compounds—are produced in multiple Major Locations, our coding reflects only the location at sign onset. Signs may or may not make contact with the Major Location (e.g., RADIO is produced near, but not touching, the head, and is coded as having a "head" location). The non-dominant hand was only considered the Major Location if the Sign Type was asymmetrical (i.e., if the non-dominant hand was stationary). The Prosodic Model suggests that for symmetrical/alternating signs the features of the non-dominant hand are the same as those of the dominant hand. The non-dominant hand was only considered the Major Location if the Sign Type was asymmetrical (i.e., if the non-dominant hand was stationary).

There are five Major Locations and each Major Location, except neutral space, was divided into eight Minor Locations (column AE). All 25 locations are listed in the Key section of ASL-LEX. Though many signs are produced in multiple Minor Locations, the coding only includes the Minor Location at sign onset.

Selected Fingers

In keeping with Brentari (1998), Selected Fingers (column AF) was defined as the group of fingers that move. The Selected Fingers are coded only for the first free morpheme in compounds, and the first letter of fingerspelled loan signs. If none of the fingers moved, the distinction between selected fingers and non-selected fingers was ambiguous. In these cases, it was assumed that the non-selected fingers must either be fully open or fully closed (Brentari, 1998). If one set of fingers was neither fully extended nor fully flexed, this group of fingers were considered selected. If the ambiguity was still not resolved, the Selected Fingers were those that appeared foregrounded. The thumb was never coded as a selected finger unless it was the only selected finger in the sign.

Flexion

The selected fingers were assigned one of nine degrees of flexion from The Prosodic Model (Brentari, 1998). Flexion of the selected fingers was only coded at sign onset (column AG). The first seven degrees of flexion (coded as 1-7) roughly map on to an ordinal scale of increasing flexion, and the last two degrees of flexion are ‘stacked’ (flexion of the selected fingers differs as in the letter ‘K’) and ‘crossed’ (the fingers overlap as in the letter ‘R’).

Movement

The path of movement of the dominant hand through x-y-z space was coded for only one type of movement out of six categories (column AH). Three categories (arc, circular, and straight) corresponded to the “path feature” from Brentari (1998). A fourth category, zigzag, was taken from the HamNoSys system (Hanke, 2004) and was used to code signs that have a repeated back and forth movements (BREATHE). Signs without a path movement were coded as “none” (e.g., APPLE has a wrist-twisting motion, but no path movement). Because path movements were restricted to those in which hand changes position in x-y-z space, hand rotation and internal movements were not coded as movement. Signs that did not fit any of these categories or that included more than one path movement were coded as “other” (e.g., CANCELLATION has two distinct straight path movements). The length of the movement was ignored (i.e., a straight movement could be short (e.g., ZERO) or long (e.g., NORTH). The values presented here represent the movement of the first free morpheme of the sign.

Neighborhood Density

We provide three neighborhood density measures based on various definitions of neighbors.

Neighborhood Density

Neighborhood density for spoken language is typically defined as the number of words that differ from the target word by the substitution, insertion, or deletion of one grapheme or phoneme (Coltheart, Davelaar, Jonasson, & Besner, 1977; Luce & Pisoni, 1998). ASL-

LEX includes two measurements of neighborhood density that are roughly parallel to this definition. The first (Maximal Neighborhood Density, column AI) defines neighbors as signs that share any five or six of the six sub-lexical properties described above. Because the six sub-lexical properties offered in ASL-LEX do not uniquely identify each sign, the neighborhood density definitions offered here differ from the traditional definitions of neighborhood density used for spoken language in that here neighbors are not necessarily true minimal pairs. The distribution for Maximal Neighborhood Density values was extremely skewed (Mdn = 9; see Figure 3a). Signed languages are thought to have unusually small numbers of neighbors relative to spoken languages (minimal pairs are extremely rare; van der Kooij, 2002), so Maximal Neighborhood Density may not be the best measure of phonological structure in the lexicon. For this reason, an additional neighborhood density measure (Minimal Neighborhood Density, column AJ) was added that defines neighbors as signs that overlap in at least one feature of any kind with the target. The range of Minimal Neighborhood Density is (Mdn =781; see Figure 3b). A third neighborhood density measure (Parameter-Based Neighborhood Density) was included because it most closely reflects tendencies in the signed language literature to focus on three phonological parameters (movement, handshape, and location). Parameter-Based Neighborhood Density defines neighbors as those that share all four of these phonological properties: Movement, Major Location, Selected Fingers, and Flexion (Mdn = 3; see Figure 3c).

Sub-Lexical Frequency

The neighborhood density measures described above calculate the number of shared sub-lexical properties irrespective of the type of property (i.e., location, movement, handshape). However, much of the linguistic work on sign languages has focused on the relationship between signs that share a particular sub-lexical feature (e.g., location) and the "neighborhood density" for that sub-lexical feature (e.g., location neighborhood density, handshape neighborhood density; Baus, Gutiérrez-Sigut, Quer, & Carrieras, 2008; Baus, Gutiérrez & Carreiras, 2014; Corina & Emmorey, 1993; Corina & Hildebrandt, 2002; Corina & Knapp, 2006a; Dye & Shih, 2006). ASL-LEX offers several measures that are akin to these "one shared feature" neighborhood density measures.

However, when neighbors are defined as signs that share only one sub-lexical property, neighborhood density is actually the same as the frequency of that sub-lexical property in the language. For this reason, we will refer to these types of measurements as sub-lexical frequency (e.g., major location frequency) rather than neighborhood density (e.g., major location neighborhood density).

For each of the six sub-lexical properties, ASL-LEX includes a sub-lexical frequency measurement that is a count of the number of signs in which that property appears. Because previous research has looked at relationships among signs that share the same handshape, one additional measurement was created for handshape frequency in which handshapes were defined as unique combinations of selected fingers and flexion. ASL-LEX includes 26 unique handshapes.

RESULTS AND DISCUSSION

In order to examine the structure of the ASL lexicon, we conducted a number of analyses. First, we describe the distribution of sign frequency, and compare the frequency ratings in ASL-LEX to frequency ratings in other databases (one of ASL and one of BSL). We then describe the distribution of iconicity, phonological properties, and neighborhood density. Because in spoken language may lexical properties are correlated with one another, we ask how the lexical properties in ASL-LEX are related to one another (e.g., are sign frequency and neighborhood density correlated)? Lastly, we asked whether the lexical properties in ASL-LEX influence sign production.

Frequency

Frequency ratings were distributed evenly across the scale (Figure 1a). PEG (M = 1.192) and STETHOSCOPE (M = 1.333) were rated as the least frequent signs, and WATER (M = 6.963) and YOU (M = 6.889) were rated as the most frequent signs.

We conducted a comparison of subjective frequency estimates from ASL-LEX and another independent dataset (Mayberrry et al., 2013). A total of 415 items shared the same English translation in both datasets. Frequency ratings in the two datasets were moderately correlated ($r_s = .65$, $p < .001$), suggesting good external validity.

We conducted a cross-linguistic comparison between raw subjective frequency estimates for a subset of 226 ASL and BSL signs from Vinson et al. (2008) that had translation equivalents in English. The results revealed a moderate correlation ($r_s = .52$, $p < .001$), suggesting that signs expressing similar concepts in two different sign languages (evidenced by the same English translation) tend to receive similar frequency estimates. In addition, raw frequency ratings were also moderately correlated with log10 word frequencies of their English translations from $\mathrm{SUBTLEX}_{\mathrm{US}}$ ($r_s = .58$, $p < .001$), suggesting that the subjective frequency estimate and the objective frequency of its English proxy are only moderately related.

Iconicity

Iconicity ratings were skewed towards the lower end of the scale (Figure 1b), indicating that signs contained in ASL-LEX were generally considered to be less iconic. Although we selected the signs with the intention of achieving a normal frequency distribution, contra Vinson et al. (2008), we did not select signs with a target iconicity distribution. The distribution of the iconicity ratings are skewed toward low iconicity when frequency is normally distributed. BOOK ($M = 6.647$) and ZIPPER ($M = 6.394$) are among the most iconic signs, and YESTERDAY ($M = 1.086$) and LAZY ($M = 1.567$) are among the least iconic signs.

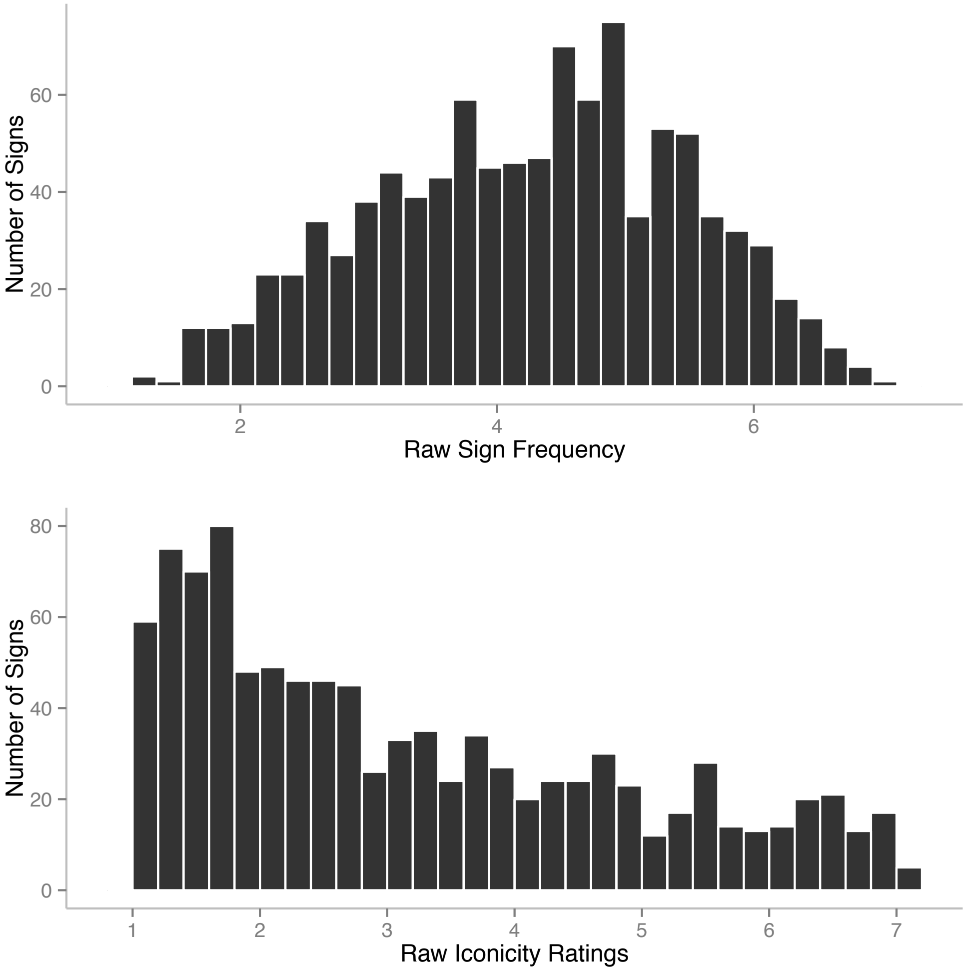


Figure 1. Frequency histograms showing the distribution of raw frequency ratings and raw iconicity ratings of signs in ASL-LEX.

Phonological Properties

The distribution of phonological properties can be seen in Figure 2.

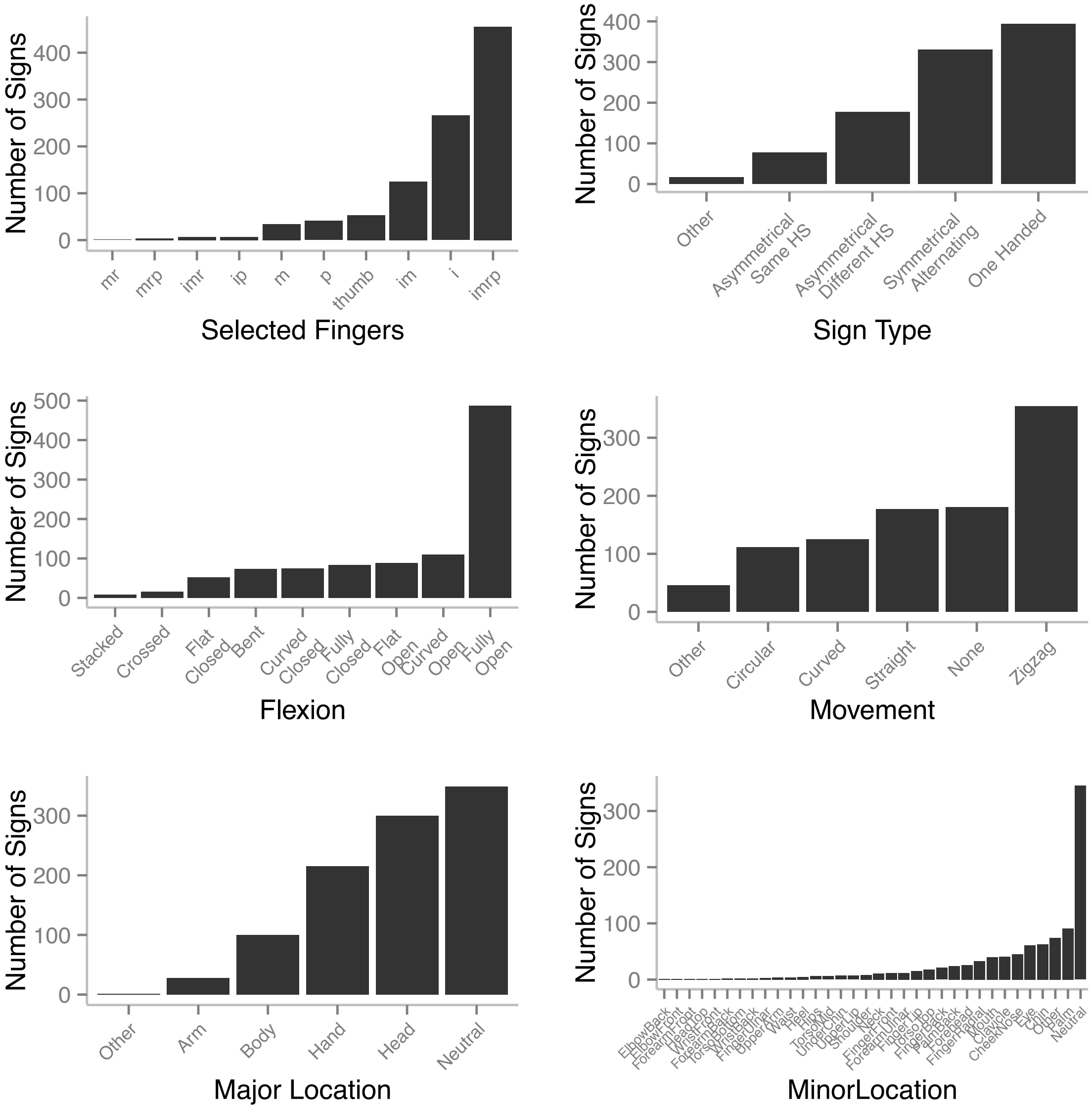


Figure 2. Frequency distribution of phonological properties.

Neighborhood Density

Maximal- and Parameter-Based Neighborhood Density are both skewed toward few neighbors (Figure 3a and 3c). Because Minimal Neighborhood Density includes quite distant neighbors, the distribution is skewed toward more neighbors (Figure 3b). There is also a ceiling on the Minimal Neighborhood Density (all the signs in the lexicon).

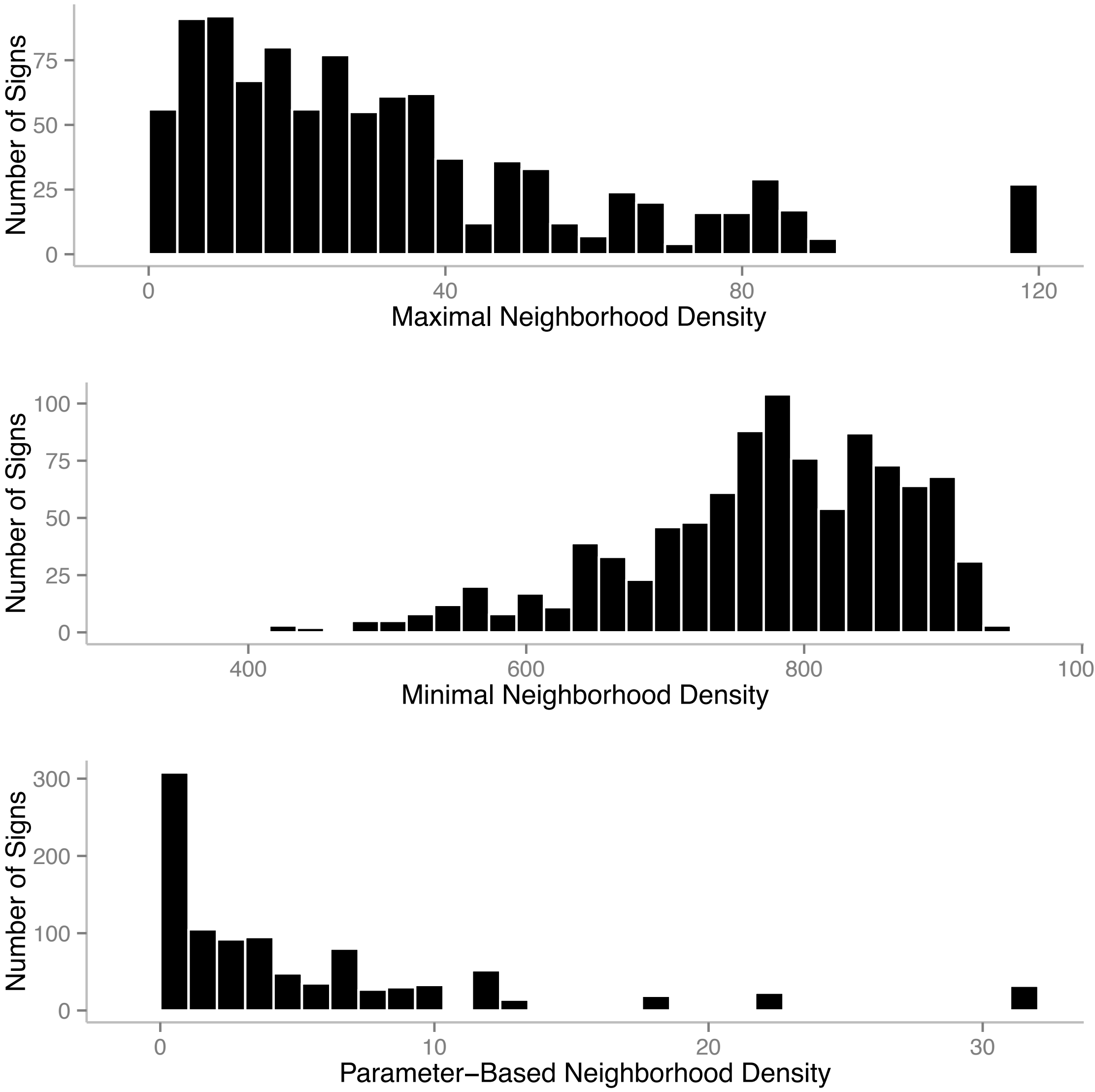


Figure 3. Frequency distribution of Neighborhood Density measurements. Note that the x-axes are not similar.

Relationships Among Lexical and Phonological Variables

Next we examined the relationships among the lexical and phonological variables to more deeply understand how phonological, lexical, and semantic factors interact in the ASL lexicon.

Frequency and iconicity raw scores were negatively correlated (see Table 1), with more frequent signs rated as less iconic, however, this relationship was weak. Though it is possible that this inverse correlation arises because the most frequent signs are closed-class words which may be lower in iconicity than other signs, the correlation remains when function words (words with a "minor" Lexical Class) are excluded (r_s = -0.17, $p <$ 0.001). This correlation may suggest that with frequent use, signs may become better integrated into the phonological system and move away from their iconic origins. Further, the direction of this relationship is opposite that found in British Sign Language (r = .146, $p < .05$; Vinson et al., 2008). This may either be due to cross-linguistic differences in the properties of the BSL and ASL lexicons, or it could be because Vinson et al. (2008) intentionally selected stimuli that were normally distributed with respect to iconicity where we did not attempt to control the distribution of iconicity ratings.

All three measures of Neighborhood Density are highly correlated with one another (see Table 1). This is unsurprising as all three measures are also related by definition (i.e., neighbors that share four of the five sub-lexical properties will also share one of five sub-lexical properties). All three Neighborhood Density measures are also correlated with all of the Sub-Lexical Frequency measures (see Table 1), which is again unsurprising because they are related by definition (signs that include common sub-lexical properties will also have many neighbors).

Signs with many neighbors tend to be more iconic (see Table 1). One explanation for this finding is that signs with many neighbors are constructed from more typical sub-lexical properties (e.g., all four fingers, in neutral space), and these typical sub-lexical properties may be more amenable to iconicity. For example, one of the ways that lexical items can be iconically motivated is by demonstrating the way something is handled (Padden et al., 2013), and these handling configurations may be most compatible with more typical sub-lexical properties (e.g., a grasping action like the signs DRINK and PUSH recruit the most common of the sub-lexical properties: all four fingers, in the neutral location). More research is needed to better understand this relationship.

As in spoken language, there is a small correlation between frequency and neighborhood density: high frequency signs tend also to have many neighbors (Frauenfelder, Baayen, Hellwig & Schreuder, 1993; Landauer & Streeter, 1973). This suggests that words that occur frequently are also those that are more phonologically confusable with other items in the lexicon.

Table 1. Spearman correlations among continuous Lexical variables

		1	2	3	4	5	6	7	8	9	10	11
1	Minimal Neighborhood Density											
2	Maximal Neighborhood Density	0.60***										
3	Parameter Neighborhood Density	0.61***	0.76***									
4	Sign Type Frequency	0.29***	0.14***	-0.03								
5	Movement Frequency	0.26***	0.31***	0.35***	-0.04							
6	Major Location Frequency	0.29***	0.33***	0.29***	0.27***	0.04						
7	Minor Location Frequency	0.18***	0.24***	0.24***	0.04	0.01	0.81***					
8	Selected Fingers Frequency	0.39***	0.38***	0.36***	-0.09**	-0.01	0.04	0.09**				
9	Flexion Frequency	0.59***	0.48***	0.45***	-0.03	-0.05	-0.02	-0.04	-0.05			
10	Handshape Frequency	0.68***	0.64***	0.69***	-0.09**	-0.04	0.02	0.04	0.53***	0.70***		
11	Iconicity	0.10**	0.09**	0.11***	-0.02	0.01	0.02	0.04	0.19***	-0.01	0.12***	
12	Frequency	0.11***	0.14***	0.12***	0.03	-0.02	0.06*	0.05	0.05	0.12***	0.11***	-0.15***

Note *p < .05, **p < .01, ***p < .001. Non-parametric correlations were used because many of the variables were not normally distributed, and some of the data was ordinal.

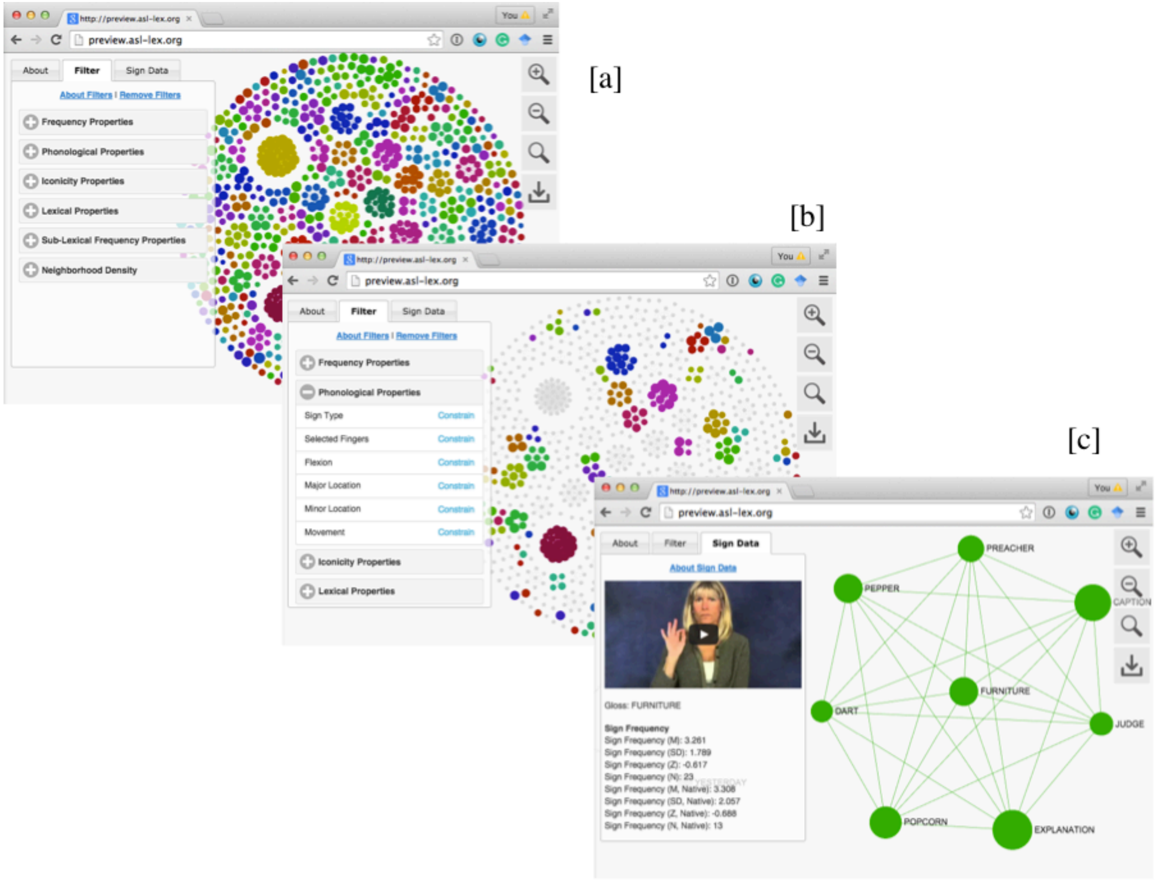
Duration

We conducted exploratory analyses of the production of the signs. These data were derived from a single signer who articulated the signs at a natural signing rate as consistently as possible across all signs. However, because the productions were not controlled with the intention to measure articulatory length, these preliminary analyses should be interpreted with caution. We found a weak negative correlation between raw sign frequency and sign duration (as determined by sign onset and offset, see above), indicating that more frequent signs take less time to articulate ($r_s = -.252$; $p < .001$). This trend is consistent with work on spoken languages showing that word frequency is inversely related to phonetic duration (Aylett & Turk, 2006; Bell, Jurafsky, Fosler-Lussier, Girand, Gregory, & Gildea, 2003; Bell, Brenier, Gregory, Girand, & Jurafsky, 2009; Caselli, Caselli & Cohen-Goldberg, 2015; Gahl, 2008; Gahl et al., 2012; Pluymakers et al., 2005). This correlation adds to the literature suggesting that length plays a role in sign language processing (Wilson & Emmorey, 1998).

Though a number of studies have found that neighborhood density predicts word duration in spoken language (Caselli, Caselli & Cohen-Goldberg, 2015; Gahl, 2008; Gahl et al., 2012), we find no such relationship here between any of the neighborhood density measures and sign duration ($r_{sMaximalNeighborhoodDensity} = -.04$; $p = .20$; $r_{sMinimalNeighborhoodDensity} = -.04$; $p = .22$; $r_{sParameterBasedNeighborhoodDensity} = -.01$; $p = .84$). While this may reflect differences in lexical access in the signed and spoken modalities, the duration data come from a single signer and may not be generalizable. More work is needed to more thoroughly investigate this as a possible modality difference.

ASL-LEX WEBSITE

The entire database is available for browsing, searching, and downloading from http://www.preview.asl-lex.org. As depicted in Figure 4a, signs are represented visually by nodes. Larger nodes indicate signs with higher subjective frequency. Signs are organized into parameter-based neighborhoods by connecting signs that are neighbors (those that share selected fingers, flexion, movement, and major location). This organization was chosen because it the parameters are commonly used in the literature on sign languages, and are more likely to be useful to researchers and educators. Additionally, under this definition neighborhoods are fully-connected (signs in a given neighborhood are all neighbors with one another) making the organization more visually intelligible. Users can filter the visualization to only view signs with particular properties (a filter showing only signs that select the index finger is applied in Figure 4b). By selecting a specific node, it is possible to view all of the information about that sign (see Figure 4c). Users can also download all of the data for either the entire database, or for the database as filtered (excluding the videos).



Gloss: FURNITURE

Sign Frequency
Sign Frequency (M): 3.261
Sign Frequency (SD): 1.789
Sign Frequency (Z): -0.617
Sign Frequency (N): 23
Sign Frequency (M, Native): 3.308
Sign Frequency (SD, Native): 2.057
Sign Frequency (Z, Native): -0.688
Sign Frequency (N, Native): 13

Figure 4. Screenshots of http://www.preview.asl-lex.org. The entire lexicon can be seen in (A), the lexicon filtered so that only the signs that select the index finger can be seen in (B), and the information for the sign FURNITURE can be seen in (C).

CONCLUSION

With 45 properties of 993 signs, ASL-LEX is the largest and most complete publicly available repository of information about the ASL lexicon to date. It enables psycholinguistic researchers to better select stimuli, tightly control studies, and ask questions that would otherwise be difficult to answer. ASL-LEX can also be used by educators and early intervention specialists to identify and support children struggling with vocabulary. It can be used in much the same way that the Dolch (Dolch, 1936) and FRY (Fry, 1957) lists of high frequency English words have been used to identify children who are unable to recognize the most common words (i.e., sight words), and to track progress toward vocabulary milestones. ASL-LEX can also be used to promote *signed* phonological awareness of the formal properties of signs. For example, an educator who whishes to develop an ASL poetry lesson could use ASL-LEX to identify signs that rhyme with one another (i.e., phonological neighbors). This is important, as phonological awareness of the structure of signs has been shown to predict English reading proficiency (McQuarrie & Abbott, 2013).

Though no ASL corpora currently exist, ASL-LEX has been designed so that it could be a complementary tool, should one be developed. As a lexical database, there are several important differences between ASL-LEX and a true sign language corpus. Whereas a corpus would have many tokens of each sign type, each entry in ASL-LEX is unique. The LemmaIDs have been included so that data from a corpus could easily be mapped on to the entries in ASL-LEX. Though we have made some effort to include a diverse set of lexical signs, the signs were selected and not generated from spontaneous language use. As such, without a corpus there is no way to ensure that the items in ASL-LEX are representative of ASL. Indeed, we have intentionally excluded or minimized some classes of signs (e.g., classifier constructions, modified verbs, lexicalized fingerspellings). Neighborhood density estimates and the frequency distributions may differ if calculated over a corpus of spontaneous signing. Nevertheless, robust frequency counts require relatively large corpora (i.e., millions of tokens), much larger than those currently available for sign languages. Until large-scale sign language corpora are available, subjective frequency may be preferable to corpus counts

Finally, we are working to expand ASL-LEX to include additional signs and properties. In the immediate future, we plan to add 2,000 signs and additional properties including more detailed iconicity measures and phonological descriptions. ASL-LEX will also benefit from more fine-grained phonological descriptions including properties such as internal movements, contact with the major location, and abduction.

Chapter 3 Simulation of Lexical Access in LSE

*Note that the work here is published with co-author Ariel M. Cohen Goldberg in Frontiers in Psychology.
Caselli, N. K., & Cohen-Goldberg, A. M. (2014). Lexical access in sign language: a computational model. *Frontiers in psychology*, *5*.

Psycholinguistic research has demonstrated that neighborhood density influences speech perception, speech production, and written word perception, but the effect differs by task and modality. In spoken production neighborhood density is facilitatory (Mirman, Kittredge, & Dell, 2010; Vitevitch, 1997, 2002; though recent studies have suggested a more complicated picture: Mirman & Graziano, 2013; Sadat, Martin, Costa & Alario, 2014) while in spoken perception neighborhood density is inhibitory (e.g., Dufour & Peereman, 2003; Goldinger, Luce & Pisoni, 1989). In visual word recognition neighborhood density is facilitatory (Andrews, 1992), except for high frequency words in which case neighborhood density is inhibitory (e.g., Grainger, O'Regan, Jacobs & Segui, 1989; Davis, Perea, & Acha, 2009)[2].

Until recently, the theoretical accounts of these neighborhood density effects in spoken and written language have differed depending on the modality. For example, in speech perception neighbors were posited to be inhibitory because multiple candidate words compete for selection (McClelland & Ellman, 1986), while in speech production neighbors were thought to be facilitatory because of the dominant influence of feedback connections (Dell & Gordon, 2003). Chen and Mirman (2012) proposed a single

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[2] A related reversal has been shown for semantic neighbors (words that are semantically but not phonologically related to the target). Neighbors that share many semantic features with the target inhibit processing while neighbors that share few features facilitate target processing (Mirman & Magnuson, 2008). As the simulations presented here model form ('phonological') neighbors in sign language processing, we focus the remainder of the review on the literature in spoken word and sign language processing rather than reading or semantics.

architecture that attempts to unify the pattern of reversals in *spoken and written language*. At the heart of their architecture is a spreading activation system with two kinds of connections between linguistic units: inhibitory lateral connections between lexical items and facilitatory ‘vertical’ connections between lexical items and phonemes/graphemes and between lexical items and semantic units (see Figure 5a). Vertical connections are bidirectional, allowing for the feedforward as well as feedback flow of activation, while lateral connections are unidirectional, meaning that two lexical items can inhibit each other with different strengths. The system differs from a standard spreading activation architecture in that the strength of a lexical unit’s inhibitory connections to other units varies as a function of the unit’s activation. Rather than being fixed, inhibitory weights vary according to a sigmoid function: if the unit’s activation is low the weight on the inhibitory connection is small; if the unit’s activation is high the weight is large (see

Figure 5b).

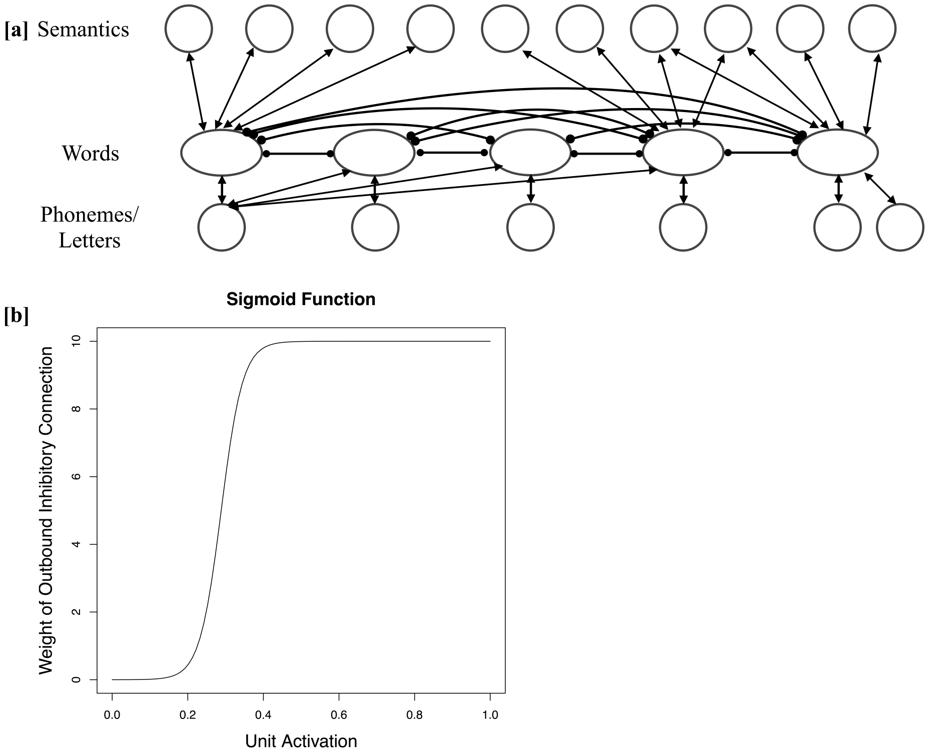

Figure 5 Chen and Mirman (2012) Architecture. Panel **(A)** illustrates the spreading activation architecture used by Chen and Mirman (2012) to account for the pattern of reversals of neighborhood density effects in spoken and written language. Facilitatory connections are drawn with arrows, and inhibitory connections are drawn with circle endpoints. In this architecture, as demonstrated in panel **(B)**, the amount of inhibition a given lexical item exerts if scaled by a sigmoid function of its activation.

Lexical items thus send both facilitatory *and* inhibitory activation to other lexical items. For example, imagine an individual hears the word *cat*. As phonetic information is translated to phonological information, the matching sub-lexical units /k/, /æ/, and /t/ become active. As sub-lexical units receive activation, they each send activation through feedforward connections to the target word and its neighbors (*cap*, *sat, cot* etc.). As the lexical items become active, they feed activation back to the sub-lexical units, which in turn feed activation forward, facilitating the target and its neighbors. At the same time, as the target and neighbors become active they inhibit each other through lateral (lexical-lexical) connections. Neighbors thus simultaneously activate and inhibit the target word.

Chen and Mirman suggest that the reversals in the direction of neighborhood density effects observed in spoken and written language result not from architectural differences across modalities but from delicate shifts in the balance between the facilitation and inhibition sent by a word's neighbors. When a neighbor is strongly activated, the amount of inhibition it sends outweighs the amount of facilitation it sends, due to the activation-dependent weighting of the inhibitory connections (high activation results in a large inhibitory weight). The net effect on the target item is inhibition. Conversely, when a lexical item is weakly activated, the amount of facilitation it sends outweighs the inhibition, resulting in facilitation of the target word. To generalize, strong neighbors inhibit while weak neighbors facilitate. According to their argument, differences in the task being performed lead to shifts in net facilitation or inhibition, causing neighbors to inhibit spoken recognition but facilitate spoken production. Specifically, neighbors become highly activated during speech perception (and thus have an inhibitory influence) since they are directly activated by sub-lexical units (/k/ /æ/ activate both *cat* and *cap*). By contrast, neighbors are relatively weak in production since the only activation they receive is through feedback from sub-lexical units (*cat* sends feedback activation to /k/ and /æ/, which in turn activate *cap*).

Far fewer studies have examined the role of 'phonological' (formal) neighbors in sign language, though the emerging pattern is that neighbors also influence sign processing. To date, neighbors in sign language have generally been defined differently than they have been defined in spoken language. Rather than defining neighbors as signs that *differ* by one sub-lexical unit (minimal pair neighbors), neighbors have been defined as signs that *share* one sub-lexical unit (though other definitions have also been used: Corina & Knapp, 2006; Dye & Shih, 2006; Mayberry & Witcher, 2005). Signs that share the same handshape are typically referred to as 'handshape neighbors', signs that share the same location are called 'location neighbors', and so on. Though this approach makes comparison between signed and spoken language somewhat difficult, it has been used in part because there are far fewer minimal pairs in sign languages relative to spoken languages (van der Kooij, 2002).

This approach has revealed that the effect of neighborhood density in sign perception differs depending on the *specific type* of neighbor. In a study of Spanish Sign Language (LSE) processing, Carreiras et al. (2008) found that signs with many *handshape* neighbors (having 'dense handshape neighborhoods') are easier to identify in a lexical decision task than signs with few handshape neighbors. Meanwhile, signs with dense *location* neighborhoods are harder to identify than signs with few location neighbors. Inhibitory effects have also been observed in primed lexical decision tasks in American Sign Language (ASL), where location primes inhibit target processing (Corina & Emmorey, 1993; Corina & Hildebrandt, 2002).[3] Finally, a similar pattern has been observed in production. In a picture-sign interference task, Catalan Sign Language (LSC) signers named pictures more slowly when the to-be-named picture was presented alongside a distracter sign that used the same location and more quickly when the distracter shared the same handshape or movement (Baus et al., 2008).

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[3] Corina and Hildebrandt (2002) found marginally significant inhibitory effects of location primes.

It is important to note that these effects have not been universally found. Some studies have failed to find priming effects with either handshape neighbors (Corina & Emmorey, 1993; Dye & Shih, 2006) or location neighbors (Dye & Shih, 2006)[4] though there is some suggestion that these null effects may be due to varying ISI and insufficient power (see Carreiras, 2010). Similar null effects of location neighbors and handshape neighbors have been documented in production as well (Corina & Knapp, 2006). There is also some evidence that the effects of neighbors may be modulated by language experience. In the only known study to define neighbors in the same way as spoken language, Mayberry and Witcher (2005) found facilitatory neighborhood effects for signers who started learning ASL between ages 4 and 8, inhibitory effects for signers who started learning ASL between the ages of 9 and 13, and no effects for signers who learned ASL from birth. Clearly more research is needed but to summarize, when neighbors have been defined as signs that share one feature with the target, the studies that have found significant effects have consistently indicated that location neighbors inhibit lexical access while handshape neighbors facilitate access.

Putting these findings together, we see that in spoken language it is the specific task (perception vs. production), while in signed language it is the specific type of neighbor (location vs. handshape) that determines facilitation and inhibition. How might we account for these differences? One possibility is to assume that there are different computational principles at work in signed and spoken language, leading to fundamental differences in the way words and signs are activated during language processing (e.g., Baus et al., 2008; Corina & Knapp, 2006). The fact that it matters in sign language

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[4] Note that Dye and Shih (2006) found a facilitatory effect of primes that shared both movement and location. However, because targets and primes shared two sub-lexical units, it is difficult to know whether the source of the effect was location, movement, or an interaction of the two.

whether a neighbor shares its location or its handshape with the target suggests that there are sign language-specific retrieval mechanisms since there is no exact corollary of these parameters in spoken language. These different mechanisms could have their origins in the different neural substrates that may underlie signed and spoken word processing. For example, the difference between location and handshape in sign processing may be due to the fact that spatial location and object recognition are carried out via different neural "streams" in the visual system (e.g., Mishkin, Ungerleider, & Macko, 1983). The different mechanisms could also arise because handshapes are compositionally more complex than locations since they comprise many features (selected fingers, abduction, etc.) while locations can be specified by a single feature (e.g., *shoulder*; Corina & Knapp, 2006). Another difference is that handshape is perceived categorically, while location is not (Emmorey, McCullough & Brentari, 2010). These sorts of explanations imply that the language architecture differs across the modalities.

Another possibility is that spoken and signed languages make use of the same core mechanisms to access the mental lexicon and it is a handful of relatively peripheral differences between modalities that accounts for the differences in the way neighbors affect processing. Chen and Mirman's theory of lexical access accounts for the pattern of reversals observed in spoken (and written) language with a single core lexical access mechanism, varying only the most peripheral elements across modality (the sequence of activation of sub-lexical units in speech perception and word recognition). In the same way, it could be the case that the same computational mechanism underlies sign and word processing and the pattern of reversals apparent in sign language is a result of variation in the peripheral facts about location and handshape in signs. To the point, location neighbors may be inhibitory and handshape neighbors facilitatory because facts about sign locations and handshapes may make location neighbors stronger competitors than handshape neighbors.

In the present investigation, I explore three reasons that location neighbors might generally be stronger competitors than handshape neighbors. The first possibility relates to the temporal order of a sign's perception. As a sign unfolds over time, location is identified approximately 30 ms earlier in perception than handshape (Emmorey & Corina, 1990; Grosjean, 1981, though see Morford & Carlson, 2011). This might mean that location sub-lexical units send activation to neighbors for a relatively long time, enabling location neighbors to become strong competitors. By the same token, the later recognition of handshape might mean that handshape sub-lexical units become activated later in time and send activation to neighbors for only a relatively short amount of time, leading handshape neighbors to become only weakly activated. It is thus possible that the timing of sub-lexical feature activation in perception is what causes location neighbors to be inhibitory and handshape neighbors to be facilitatory in recognition.

The second possibility relates to the absolute number of neighbors a target sign has. Although Carreiras et al.'s (2008) design crossed neighbor type (location/handshape) with density (high/low), the number of neighbors in the high and low density conditions varied across neighbor type. Specifically, the high density location neighborhoods were almost seven times larger on average than the high density handshape neighborhoods. It could be simply that the purported difference between location and handshape neighborhoods was actually due to the difference in neighborhood size across the location and handshape conditions. That is, it is possible that a large number of neighbors (e.g., the number of neighbors in the location condition) inhibits perception, but a ‘medium’ amount of neighbors (e.g., the number of neighbors in the handshape condition) facilitates perception. According to this hypothesis, it is the absolute number of neighbors that causes location neighbors to be inhibitory and handshape neighbors to be facilitatory in recognition

The last possibility is that location is more robustly represented than handshape. There is a wealth of evidence that this may be the case. Location is misperceived less frequently than other features (Orfanidou, Adam, McQueen, & Morgan, 2009), and is easier to remember than movement and orientation (Thompson, Emmorey, & Gollan, 2005). Location errors are less frequent than handshape errors (Corina, 2000; Klima & Bellugi, 1979; Hohenberger, Happ, & Leuninger, 2002), and location is learned sooner (e.g., Marentette & Mayberry, 2000). If location representations are more robust than handshape representations, location *neighbors* will become strongly activated during sign recognition while handshape neighbors will be relatively weakly activated. Within the Chen and Mirman architecture, this would cause location neighbors to have a net inhibitory effect and handshape neighbors to have a net facilitatory effect on target recognition.

There are several reasons that location may be more robustly encoded than handshape, for example, locations might be more salient, draw more attention, or be attended to at an earlier age than other sign parameters. For the purposes of this investigation, I focus on a possibility that arises because of the particular way that neighbors have been defined in sign language research. When neighbors are defined as signs that share one sub-lexical unit rather than signs that share all but one sub-lexical unit (as in spoken and written language research), neighborhood density is actually the same as *sub-lexical frequency*. What Carreiras et al. (2008) called an effect of neighborhood density—a lexical property—could actually be an effect of sub-lexical frequency. In their stimuli, the average location was seven times more frequent in the language than the average handshape. I consider the possibility that sub-lexical frequency (or other factors, such as salience/attention) influences how robustly sub-lexical units are encoded, which I instantiate as different levels of resting activation. According to this proposal, high frequency sub-lexical units (locations) could have high resting levels of activation leading location neighbors to become strong (inhibitory) competitors. Low frequency sub-lexical units (handshapes) could have low resting levels of activation, leading handshape neighbors to become weak competitors and result in net facilitation.

I report the results of 3 simulations of sign recognition using a lexical network that utilizes the activation principles proposed by Chen and Mirman (2012) and that incorporates differences in sub-lexical activation and timing and neighborhood density, as described above. The use of computer simulations allows me to test how sign perception could function in a system that has no intrinsic location or handshape, or any other sign-specific features. I can test whether the factors that influence the strength of a neighbor's activation described above are sufficient for obtaining the observed pattern of facilitation and inhibition. If the simulations are capable of reproducing the observed effects, they will serve as a proof of concept that language-general principles are sufficient to account for lexical access in sign language. If the simulation is incapable of reproducing the empirical results, I conclude that sign access involves different—i.e., sign language-specific—retrieval mechanisms than spoken language (though null results are always difficult to interpret).

Model Architecture

Like Chen and Mirman (2012), the structure of the architecture comprised two layers of units: a sub-lexical level and lexical level (see Figure 6). Bidirectional facilitatory weights connected the lexical and phonological levels, and unidirectional lateral inhibitory weights connected lexical items (see Table 2 for parameter values). As in Chen and Mirman (2012) lateral inhibitory connections were scaled by a sigmoid function of word activation that forces rapid selection of only one lexical item (in all models $\beta = 35$ and $x_0 = 0.3$, following Chen and Mirman):

$$y = \frac{15}{1.5 + e^{-\beta(x - x_0)}}$$

In order to simulate the recognition of a single target sign, the sub-lexical units associated with the target were activated through external input, and the activation of the target sign was taken as a measure of lexical access. The simulations reported here orthogonally varied the timing (Study 3a) and amount of activation given to the sub-lexical units (Study 3b) as well as the number of neighbors shared by the target (Study 3b). I provide the details of these manipulations in the simulations below. Note that I modeled average reaction times for each cell (density: high and low; neighbor type: handshape and location) rather than reaction times for particular items. The assumptions regarding timing, sub-lexical frequency, and neighborhood density were also derived from averages rather than particular lexical items. The net effect of a neighbor on the target was calculated by subtracting the activation of a target no neighbors from the activation of the target with a neighbor (or neighbors). The simulations presented here were implemented using PDPtool in MATLAB (McClelland, 2009).

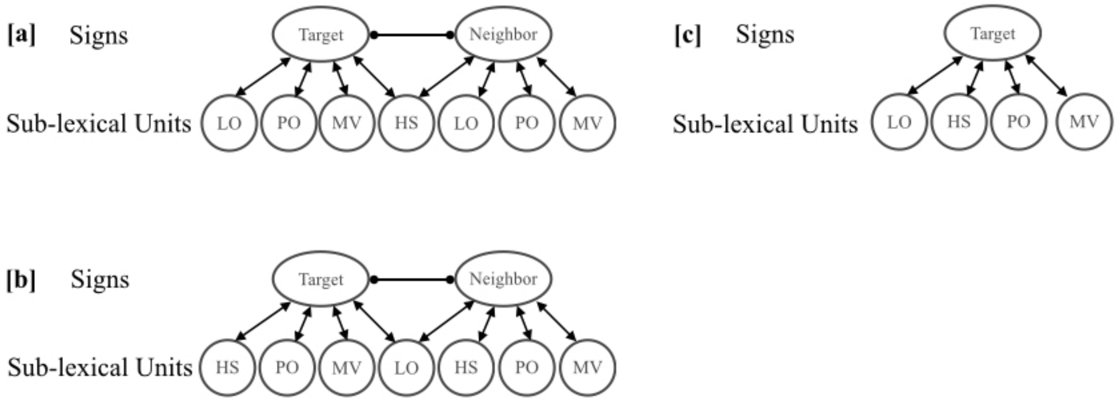

Figure 6 Model Architecture. Activation of the target with a handshape neighbor **(A)** or location neighbor **(B)** was compared to activation of the target without a neighbor **(C)**. Neighbors were considered to have a facilitatory effect on sign recognition if the target item with a neighbor **(A** and **B)** became active more quickly than the target item without a neighbor **(C)**. Neighbors were considered to have an inhibitory effect if the target item with a neighbor became active more slowly than the target item without a neighbor.

Table 2. Values Used in All Simulations

Parameter	Value
Sub-lexical unit to sign excitation	0.2
Sign to sub-lexical unit excitation	0.2
Sign to sign inhibition	see formula
Resting activation	0 unless otherwise specified
Sub-lexical unit Decay	0
Word Decay	0

Study 1: Timing Simulation

In Study 1, I tested the hypothesis that the effects of location and handshape can actually be attributed to the sequence with which sub-lexical units become active in perception. To do this, I manipulated the timing of the activation of the sub-lexical units in accordance with the average time of sub-lexical unit identification from behavioral data. Emmorey and Corina (1990) report that location and orientation are identified first (146 ms on average), followed by handshape (172 ms), and then movement (238 ms). To simulate timing, two of the target sub-lexical units (‘location’ and ‘orientation’) received input for 3 cycles (equivalent to ~30 ms) before the ‘handshape’ sub-lexical unit was activated for 7 cycles (equivalent to ~70 ms). Finally, the ‘movement’ sub-lexical unit was activated for the remaining cycles. The effect of having a location neighbor was simulated by creating an additional lexical unit that shared the location unit with the target but had three distinct other features (e.g., orientation, handshape, and movement; see Figure 6a). The effect of having a handshape neighbor was simulated the same way, except that the neighbor shared the handshape unit with the target (see Figure 6b). Since I am simulating the recognition of the target item, only the target’s sub-lexical units received activation—none of the neighbor’s sub-lexical units were activated except for the shared unit. The amount of external input applied to the sub-lexical units was set to 2, though I explored other levels of activation and the results were qualitatively the same throughout.

Study 1 Results

The results of Study 1 are presented in Figure 7. As predicted, when the shared sub-lexical unit became active early in processing (as is empirically the case with location), the neighbor contributed net inhibition to the target sign. When it became active late in processing (as has been demonstrated for handshape), the neighbor contributed net facilitation to the target sign. The fact that the network tested in Study 1 produced the correct pattern of behavior suggests that the inhibition and facilitation observed for location and handshape neighbors in sign recognition may be due to differences in when different sub-lexical units are activated in perception.

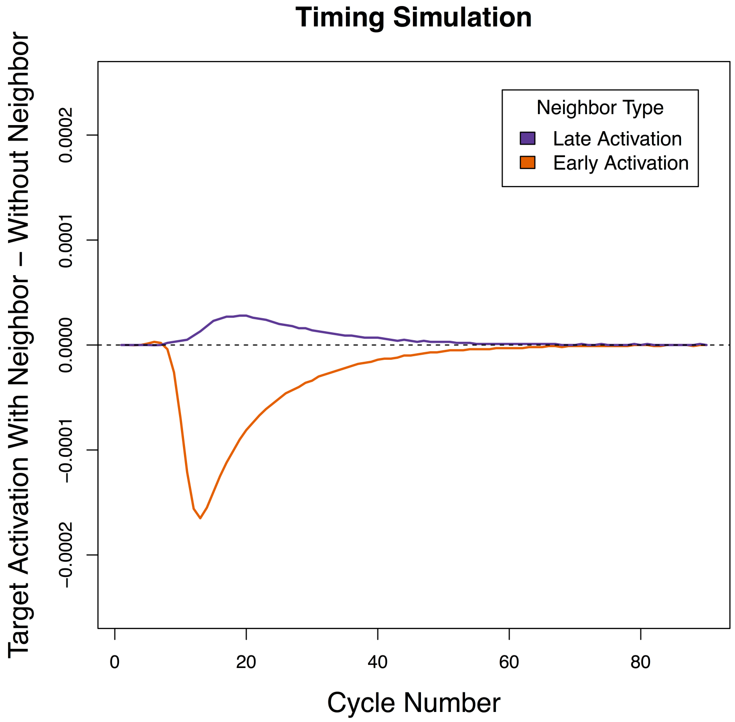

Figure 7 Net contribution of a handshape neighbor and a location neighbor when the timing of sub-lexical unit activation was manipulated. Handshape neighbors had a net facilitatory effect on the target, while location neighbors had a net inhibitory effect on the target.

Study 2: Sub-lexical Frequency Simulation

In Study 2, I tested the hypothesis that the effects of location and handshape could actually be due to differences in how robustly encoded the sub-lexical units are. I simulated this possibility by manipulating the resting level of activation of the sub-lexical units in accordance with the average sub-lexical frequencies of the location and handshape parameters. As described above, in the existing behavioral research the high density location neighborhoods (*M* = 203, range = 203-203) were almost seven times larger than the high density handshape neighborhoods (*M* = 28*,* range = 21-35; Carreiras et al., 2008). To model this difference, the resting activation of one sub-lexical unit (the ‘location’ unit) was set to 0.7 while the resting level of the other units was set to 0.1. The amount of external activation applied as input to the sub-lexical units was set to 1, though the results are qualitatively the same with other levels of input. All sub-lexical units received external activation simultaneously, rather than sequentially as in Study 3a. Note that resting level of activation is only one way of modeling frequency (Dahan, Magnuson, & Tanenhaus, 2001; Knobel, Finkbeiner, & Caramazza, 2008), and resting activation could also be thought to correspond to attention or salience (e.g., Mirman et al. 2008).

Study 2 Results

As in Study 1, Study 2 revealed that a when the shared feature had high resting activation the neighbor contributed net inhibition to the target sign, and when the shared feature had low resting activation (which corresponded to handshape) the neighbor contributed net facilitation to the target sign (see Figure 8). The results were qualitatively the same within +/- .2 units of resting activation. This suggests that facts about sub-lexical frequency could be responsible for the patterns of facilitation and inhibition in sign recognition.

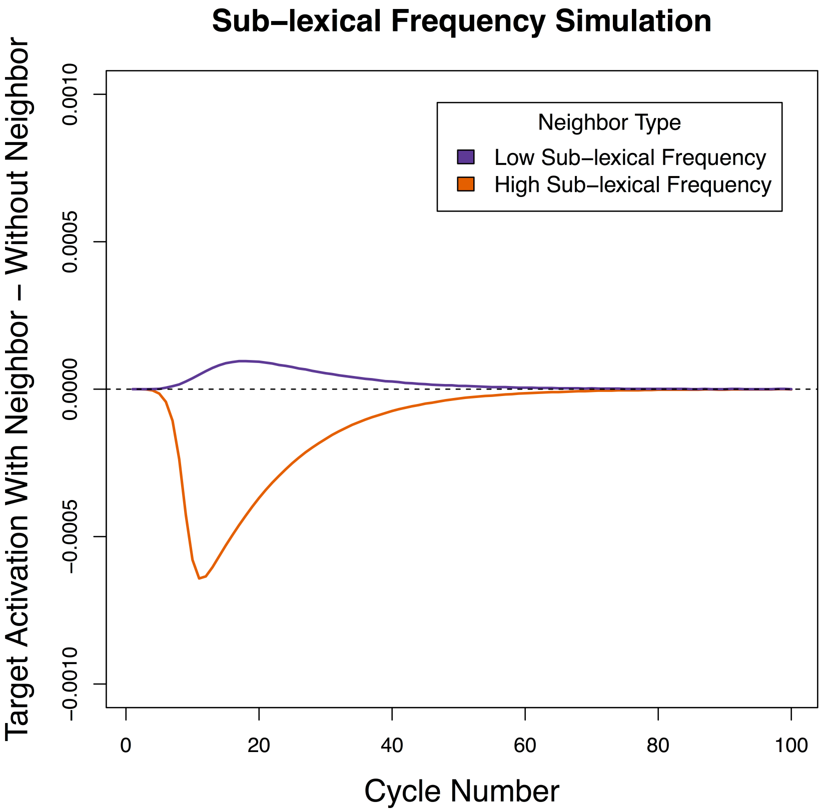

Figure 8 Net contribution of a handshape neighbor and a location neighbor when the resting level of activation of sub-lexical units was manipulated. Handshape neighbors had a net facilitatory effect on the target, while location neighbors had a net inhibitory effect on the target.

Interim Discussion

Both simulations demonstrated that it is possible to model the pattern of reversals seen in behavioral studies of sign perception with minimal modifications to the architecture thought to underlie spoken language. At the sub-lexical level, varying either the timing of activation or the amount of resting activation is sufficient to produce quantitatively similar patterns to what has been observed with humans performing sign recognition. These results demonstrate that differences in the timing with which location and handshape targets are perceived and differences in the robustness with which these parameters are encoded (as modeled using sub-lexical frequency) are computationally tractable explanations for the pattern of reversals in sign language.

Study 3: Number of Neighbors Simulation

The first two simulations evaluated whether manipulations of sub-lexical properties can produce the observed pattern of facilitation and inhibition. In Study 3b I consider whether the pattern of reversals is due to activity at the lexical level, in particular the number of neighbors that are active during processing.

Two conditions were simulated: having a high neighborhood density and having a low neighborhood density. In the high neighborhood density (HND) condition, which simulated the size of the location neighborhoods in Carreiras et al. (2008), there were four neighbors and in the low neighborhood density condition (LND; simulating the handshape neighborhoods), there was only one neighbor (see Figure 9). To determine the net contribution of the neighbor(s), the activation of the target in the LND condition (Figure 9b) and the HND condition (Figure 9a) was compared to the activation of the target without a neighbor (Figure 9c). To test the generality of the density effects, I tested LND and HND conditions using different amounts of external activation to the target sub-lexical units. I report data for external activation levels of 1 and 9 but the results are qualitatively the same at other input levels. In order to isolate the effect of lexical neighborhood density, all sub-lexical units simultaneously received the same amount of external activation.

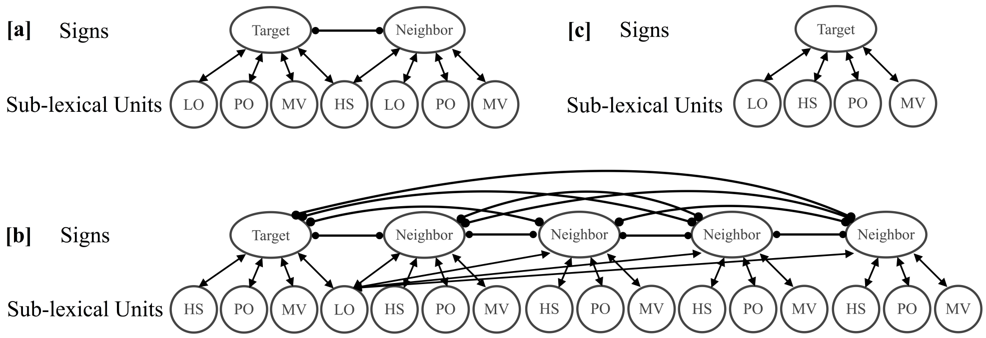

Figure 9 Architecture of sign perception when Neighbor Type was manipulated by varying the number of neighbors. Activation of the target with a handshape neighbor **(A)** or location neighbor **(B)** was compared to activation of the target without a neighbor **(C)**. Neighbors were considered facilitatory if the target item with a neighbor **(A** and **B)** became active more quickly than the target item without a neighbor **(C)**.

Study 3 Results

A very different pattern emerged in Study 2 than the previous 2 simulations. Here, neighborhood density did not determine the direction of the effect (the HND and LND conditions patterned together) and what determined whether the effect was facilitatory or inhibitory was the amount of activation applied to the input units (Figure 10). Specifically, when a low amount of activation was applied, both HND and LND were facilitatory and when a high amount of activation was applied, both HND and LND inhibitory. In all cases, having four neighbors magnified the effect of having a single neighbor—when a single neighbor was facilitatory, four neighbors were more facilitatory, and when a single neighbor was inhibitory, four neighbors were more inhibitory. These results suggest that the pattern of reversals linked to location and handshape in sign recognition cannot be reduced to differences in neighborhood density, a lexical property.

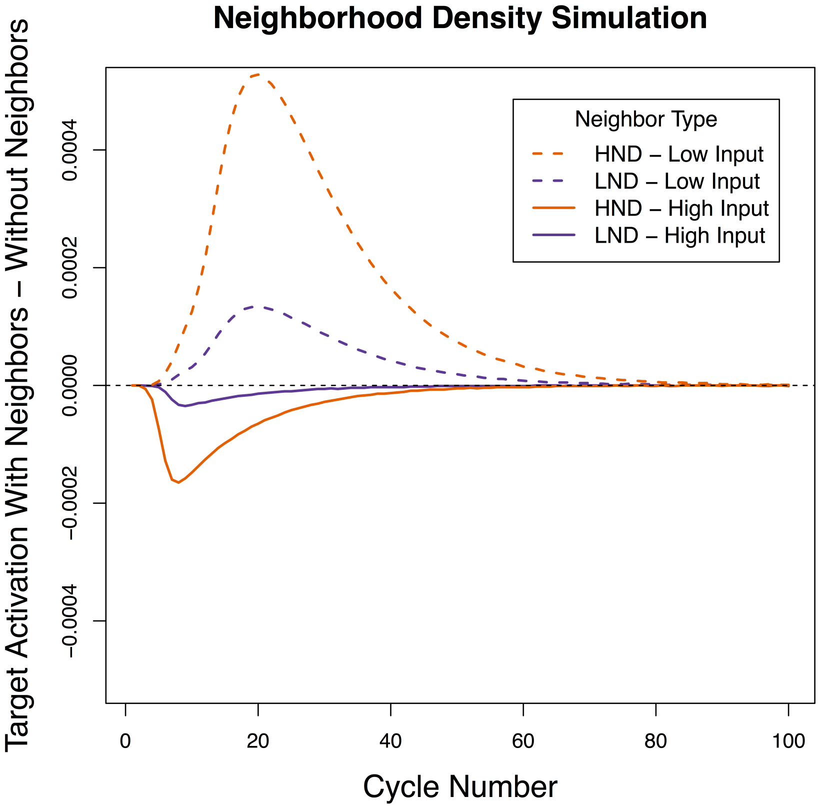

Figure 10 Net contribution of a handshape neighbor and a location neighbor when the number of neighbors was manipulated. Both high and low levels of external input are presented. Both handshape and location neighbors had a net facilitatory effect on the target when the external input was low, and both handshape and location neighbors had a net inhibitory effect on the target when the external input was high.

Discussion

The aim of Studies 1-3 was to computationally test the hypothesis that behavioral patterns in sign recognition can be accounted for using the same lexical access mechanisms that have been proposed for spoken language. Specifically, I investigated whether the opposing effects observed for location and handshape can be obtained in a lexical network that employs universal (language-general) activation principles mediated by language-specific facts about activation levels and neighborhoods.

To do so, I created a spreading activation network with two levels of representation (sub-lexical and lexical) and two types of activation: facilitatory, bidirectional connections between sub-lexical and lexical units; and inhibitory, activation-scaled, unidirectional connections between lexical units (Chen & Mirman, 2012). I then systematically varied three relatively peripheral facts about this network: 1) the timing with which sub-lexical units become active during perception, 2) the resting activation of the sub-lexical units, and 3) the number of lexical neighbors of a target sign. These factors were orthogonally tested in a simulated recognition task with parameters drawn from empirical data about sign languages (specifically: 1) the timing of the perception of location vs. handshape, 2) the sub-lexical frequency of locations vs. handshapes, and 3) the number of a target's location neighbors vs. handshape neighbors).

I found that the specific pattern of facilitation and inhibition reported in sign recognition was obtained when the timing of sub-lexical activation (Study 1) and the level of sub-lexical resting activation (Study 2) were varied in a manner consistent with real-world facts about location and handshape. I was not able obtain the observed pattern of results when the number of lexical neighbors was similarly varied (Study 3). Before drawing conclusions from these results, I will address why the network presented a different pattern of results depending on whether sub-lexical or lexical properties were manipulated.

To understand why variations in properties of the shared sub-lexical unit (timing/resting activation) determined whether the net contribution of the neighbor was facilitatory or inhibitory but variations in the size of the lexical neighborhood did not, it is useful to return to the basic principle at the heart of Chen and Mirman (2012)'s architecture: strong neighbors inhibit target processing while weak neighbors facilitate processing. Differences in the timing and resting activation of a shared sub-lexical unit directly influence how active the neighbor becomes, which in the Chen & Mirman architecture determines whether its net contribution to the target will be negative or positive. In other words, variation in the sub-lexical properties can change the *polarity* of the activation flowing to the target from net positive to net negative. This is why the sub-lexical variations I explored in Studies 1 and 2 led to differing patterns of facilitation and inhibition. What, then, is the effect of giving a target sign fewer or more neighbors, as in Study 3? The crucial fact in this case is that varying the number of neighbors a target has does not influence whether the neighbors themselves are strongly or weakly activated. Because all the neighbors in this model are activated by the same sub-lexical unit, the amount of activation they receive is the same. Therefore, whatever the effect of a single neighbor is in this model, the effect of multiple neighbors will be the same. While the neighbors will become more strongly or less strongly active based on the properties of the sub-lexical units, all of the target item's neighbors will either be net facilitatory or net inhibitory but not both. In other words, the number of neighbors thus does not change the *polarity* of the activation flowing to the target but it does influence the *magnitude*.

The success in modeling the effects of location and handshape in Studies 1 and 2 provides evidence that there may be universal principles governing the way the mental lexicon is accessed. Even though location and handshape are elements that are unique to sign languages, it appears that their influence on recognition can be modeled using the same principles that have been used to explain lexical access across tasks in spoken and written language. Note that our results do not rule out the possibility that there are sign language-specific factors that influence lexical processing (e.g., distinct ‘what’ vs. ‘where’ processing streams in visual perception). They do, however, indicate that such factors are not necessary to account for the empirical data on reversals. Our investigation suggests that—like the commonalities observed in the grammars of signed and spoken languages—the mind stores and accesses words in the same manner, no matter the modality (spoken, print, or signed).

Though this computational work serves as a proof of concept that the mechanisms of signed and spoken perception are largely shared, there are a number of limitations that are addressed in Chapter 4. Most notably, the behavioral data on which these models rest (Carreiras et al., 2008) consist of only four data points (average response times for signs with high and low location and handshape neighborhood densities), and the high location and handshape neighborhood density conditions are not matched for the number of neighbors. In the next chapter, I will use the full continuum of neighborhood density values from ASL-LEX to examine a range of location and handshape densities. Also, the definition of ‘neighborhood density’ used in the existing behavioral work is markedly different from that used in most psycholinguistic research on spoken and written language—one shared sub-lexical feature rather than all but one shared sub-lexical feature. In Chapter 4, I will examine the effects of neighborhood density defined in a number of different ways.

Chapter 4 Behavioral Study of Lexical Access in ASL

With ASL-LEX in hand, it is possible to take an in depth look at the mechanisms of sign perception while testing and controlling for more lexical variables than previously possible. Just as ASL-LEX was designed to characterize the ASL lexicon, the goal of this chapter is to characterize the *mental* lexicon of ASL users. Of particular interest is the way the signed mental lexicon is organized, whether and how this organization affects sign perception, and if the organization and use of the mental lexicon is affected by early language experiences.

Though there is a fair amount of evidence suggesting that neighbors are important in sign perception (Baus, Gutiérrez-Sigut, & Carreiras, 2014; Carreiras et al., 2008; Corina & Emmorey, 1993; Corina & Knapp, 2006; Dye & Shih, 2006; Hildebrandt & Corina, 2002; Mayberry & Witcher, 2005), the pattern of effects is somewhat difficult to interpret due to variation in methodology across studies. All of these studies have defined phonological overlap in terms of shared formational parameters, but few mention a guiding phonological theory defining those parameters (Carreiras et al. 2008 is an exception in that they used the HamNoSys system to assess handshape similarity, but did not refer to a theory for assessing other features). This makes it difficult to assess whether these studies use the same inventory of locations, handshapes and movements (e.g., Which signs are considered to have a “neutral” location? Do signs with different palm orientations count as having the same handshape?). Lack of a consistent phonological theory is particularly problematic for the study of neighborhood density, because the average neighborhood density is inversely proportional to the number of sub-lexical units in the inventory.[5] These studies also vary in their definitions of phonological neighbors. Definitions include signs that share the same location (Carreiras et al. 2008; Corina & Emmorey, 1993; Dye & Shih, 2006; Hildebrandt & Corina, 2002), movement (Corina & Emmorey, 1993; Dye & Shih, 2006; Hildebrandt & Corina, 2002), or handshape (Carreiras et al. 2008; Corina & Emmorey, 1993), signs that share various permutations of two parameters (Baus, Gutiérrez-Sigut, & Carreiras, 2014; Dye & Shih, 2006), and signs that share all but one parameter (Mayberry & Witcher, 2005).

The results of these studies are as diverse as the methodologies employed. Some studies have failed to find priming effects with handshape neighbors (Corina & Emmorey, 1993; Dye & Shih, 2006) or location neighbors (Dye & Shih, 2006)[6]. Dye and Shih (2006) found only facilitation for signs that share the same location *and* movement in a primed lexical decision task. This variation may be because of inconsistent definitions of phonological properties and phonological overlap. It has also been suggested that these null effects are due to varying amounts of time between prime and target or insufficient power (see Carreiras, 2010 for a discussion).

It is difficult to know whether effects of neighbors arise because of the neighbors themselves or because of other facts about the lexicon. In most of the existing studies, the neighbor and target are both present in the experimental context (e.g., the neighbor is a prime that precedes the target (Corina & Emmorey, 1993; Dye & Shih, 2006; Hildebrandt & Corina, 2002; Mayberry & Witcher, 2005), or the neighbor is a distractor in a visual

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[5] Assuming that a language has a lexicon of size Y and that all sub-lexical units appear with equal frequency, if there is only 1 sub-lexical unit the average neighborhood density be Y, and if there are 100 sub-lexical units the average neighborhood density will be Y/100.

[6] Dye and Shih (2006) found a facilitatory effect of primes that shared both movement and location. However, because targets and primes shared two sub-lexical units, it is difficult to know whether the source of the effect was location, movement, or an interaction of the two.

world paradigm (Lieberman, Borovsky, Hatrak, & Mayberry, 2014)). While effects of neighbors in these cases might indicate that the neighbor directly affects the target, it is equally possible that the neighbor has an effect simply because the sub-lexical units have been pre-activated which in turn affect the target. Carreiras et al. (2008) illustrate that the number of signs in which a target's location and handshape appear affects the speed with which the target is recognized, but as described in Chapter 3 this definition of neighborhood density is the same as sub-lexical frequency. More evidence is needed to determine whether neighbors are active during sign perception.

The Effects of Early Language Experience on Lexical Access

Phonological neighborhoods are a way of organizing the lexicon, and this organization not only affects how lexical items are perceived and produced but also how they are acquired. As children acquire spoken language, they learn words from dense neighborhoods more rapidly than those from sparse neighborhoods (Hollich, Jusczyk & Luce, 2002; Storkel, 2004; Storkel & Rogers, 2000). This suggests that children's lexical acquisition is dependent upon the phonological organization of the emerging lexicon. The organization of the lexicon may be shaped partially by linguistic input a child receives, and partially by innate maturational factors. Though it is not possible to experimentally tease these two influences apart by manipulating the amount of linguistic exposure, there is a natural version of this experiment that may provide insight.

While some deaf children learn sign language from their parents and peers just as hearing children learn spoken language, this is not the case for many deaf children. Deaf children who do not hear the sounds of speech, and have limited or no access to sign language during the critical early years of life are at great risk for language deprivation. (Glickman, 2007; Humphries, Kushalnagar, Mathur, Napoli & Padden, 2013; Humphries, Kushalnagar, Mathur, Napoli & Padden, 2014; Humphries, Kushalnagar, Mathur, Napoli, Padden, Pollard, Rathmann, & Smith, 2014; Humphries, Kushalnagar, Mathur, Napoli, Padden, Rathmann, & Smith, 2014). By comparing these two populations of deaf people, language exposed and language deprived, it is possible to examine the contribution of language experience to language acquisition.

Language deprivation affects many aspects of linguistic and cognitive functioning, including lexical access. One of the effects of language deprivation on lexical access is referred to as the *phonological bottleneck* (Mayberry & Fischer, 1989). In sign perception, late signers are thought to process phonological information less efficiently than early signers to the detriment of semantic processing. This phenomenon was first revealed in a sentence repetition task (Mayberry & Fischer, 1989). Adults who were exposed to sign language late in development are more likely to reproduce sentences with phonological errors even if the sentences are rendered nonsensical. For example, a late signer might inadvertently substitute the sign SLEEP for AND because the two signs are phonologically related in ASL. In contrast, the errors native signers typically produced were equivalent in meaning to the target. For example, a native signer might substitute the sign FRIENDS for CHILDREN because the two signs are semantically related. Evidence for the phonological bottleneck has also been found in a primed lexical decision task, which more clearly demonstrates that the phonological bottleneck arises in sign perception, not production. Mayberry and Witcher (2005) found that primes that were phonological neighbors (shared two out of three major parameters:

movement, location, and handshape) with a target facilitated sign perception for early exposed signers, but inhibited sign perception for late exposed signers. They found no effect of phonological neighbors in native signers.

The phonological bottleneck might indicate that people with language deprivation have some disruption at the lexical level, sub-lexical level, or the interface between the two. Mayberry and Witcher (2005) suggest that late learners make fewer distinctions between sub-lexical features (i.e., have fewer phonemes), which means they may have relatively larger neighborhoods on average than early learners. In this case, in the primed lexical decision task the neighbor prime activates lexical items in the target's neighborhood, presumably making these lexical items stronger competitors. Because this research has primarily been done using paradigms in which both the neighbor and target are presented such as the primed lexical decision (Mayberry & Witcher, 2005) and the visual world paradigm (Lieberman, Borovsky, Hatrak, & Mayberry, 2014), it is also possible that late and early signers differ in their sub-lexical representations. In this case, the prime would pre-activate the sub-lexical units of the target, and late signers might have a longer refractory period requiring more time to re-activate the sub-lexical. This would in turn make late signers slower to identify the target. More work is needed to identify the locus of the phonological bottleneck.

Present Investigation

The goal of this investigation is twofold. Because ASL-LEX includes measures of both neighborhood density and sub-lexical frequency, it is possible for the first time to examine the effects of entire neighborhoods rather than neighbor-target pairs, and to disentangle the effects of sub-lexical frequency and neighborhood density in sign perception. In this study, we ask whether signed neighborhoods affect sign perception, and if so does the effect of signed neighborhoods differ as a function of early language exposure. We address these questions with a lexical decision task in which the effect of neighbors is measured through neighborhood density rather than neighbor priming. The advantage of this task is that neighbors are not presented together as they are in a primed lexical decision task, so any effects of neighbors have must reflect the role of the neighbors themselves in sign perception and not an artifact of the experimental context.

The second goal of this study is to characterize the mechanisms of sign perception in people who are language deprived, with an eye toward the phonological bottleneck. If neighborhood density has a different effect in people who are and are not language deprived, this would suggest that the phonological bottleneck has a lexical locus. In addition, ASL-LEX makes it possible to look for differences in the effects of frequency, sub-lexical frequency, and iconicity as a function of language deprivation.

In Study 1 Analysis 1, we examine both questions about the mechanisms or sign perception and the effects of language deprivation together in a single mixed-effects linear regression. Analysis 2 is a replication of the work looking at sub-lexical frequency by Carreiras et al. (2008), and Analysis 3 is an extension of work looking at the phonological bottleneck by Mayberry and Witcher (2005).

STUDY 1

Methods

Participants

Eighty deaf participants who consider themselves to be fluent signers were recruited (*M* = 39 years, *SD* = 13 years). Most participants were deaf at birth (n = 55), and the rest became deaf before age three. All participants rated their ASL fluency as high on a scale of 1-7 (*M* = 6.6, *SD* = .76). Age of first exposure to ASL ranged from birth (n=32) to age 22. Twenty-five participants had at least one deaf parent. Participants were distributed geographically at the time of testing: 15% from the Midwest, 36% from the Northeast, 18.75% from the Southeast, 18.75% from the Southwest, one person not reporting, two living in Canada, and two living elsewhere abroad. The Tufts University IRB approved this protocol. Informed consent was collected in written English, ASL or both.

Demographic Variables

Participants completed a survey with 130 questions about language background and other demographic information. English and ASL versions of the survey were available. Thirty questions regarding ease of communication were added mid-way through data collection, and only 33 of the participants completed that portion of the demographics survey. There is no available objective measure of language deprivation. We measured ASL and spoken English exposure, but worried that these measures may not adequately capture the ability to use either language. It is possible that a person could be exposed to language without actually being able to effectively learn or use it. We also added a measure of the degree of difficulty communicating each person had. Using the survey, composite measures of CommunicationEase, ASLExposure, and SpeechExposure were created. The composite measures were helpful in reducing the number of variables and collinearity among related variables in the analyses. The composite scores were calculated by selecting a subset of questions pertaining to ease of communication (Appendix B) experiences with ASL (Appendix C), and experiences with spoken English (Appendix D) respectively. Some of the responses were on Likert scales (maximum of 4, 5, or 6 depending on the question), and some responses were binary (0 or 1). All responses were converted to a 0-1 scale (response given / maximum possible response). Some responses were inverted so that the maximum values were congruent with the spirit of the measurement (e.g., responses to the question “How frequently did you encounter communication difficulties?” were recoded so that high numbers indicated high CommunicationEase). The three composite scores (CommunicationEase, ASLExposure, and SpeechExposure) were created by averaging the scores on the relevant questions. Due to missing values, Communication Ease scores were only computed for 33 participants.

There were a few notable relationships among the demographic variables (see Table 3). People who were exposed to ASL earlier tended to have more ASLExposure, report greater ASLFluency, higher CommunicationEase scores (i.e., had less frustrated communication), and report lower spoken English fluency (SpeechFluency). People who got a cochlear implant or hearing aid early in life reported more sources of spoken English input (SpeechExposure), greater SpeechFluency, lower ASLFluency (though all of the participants reported having high ASL fluency). Younger people were more likely to have learned ASL earlier.

While a number of things could influence these patterns, one possibility is that there are generally two groups of people in this sample: people who were ASL dominant in terms of early exposure and fluency, and people who were speech dominant in terms of early exposure and fluency. While certainly it is possible that one could be balanced with respect to speech and ASL, it is noteworthy that the division seems quite dichotomous even in this sample of highly fluent ASL users. That those who were more ASL dominant also experienced fewer communication difficulties is worthy of further consideration and research. One reason for this may be that people with early and rich exposure to ASL tended to be exposed to more people who used ASL (part of the definition of ASL exposure in this study), meaning that these people had more people with whom they could communicate effortlessly. Exposure to rich and varied sources of ASL might be a protective factor for language deprivation.

Table 3. Correlations among demographic variables

		1	2	3	4	5	6	7
1	ASLExposure							
2	AgeOfCI	0.74*						
3	SpeechExposure	-0.64	-0.90**					
4	CommunicationEase	0.95***	0.64	-0.57				
5	Age	-0.90**	-0.64	0.55	-0.93***			
6	ASLAge	-0.90**	-0.88**	0.74*	-0.81*	0.86**		
7	ASLFluency	0.67	0.88**	-0.98***	0.62	-0.57	-0.76*	
8	SpeechFluency	-0.71*	-0.95***	0.90**	-0.6	0.67	0.86**	-0.86**

Materials

Procedure

Participants completed a lexical decision task, in which they watched videos of real signs and non-signs and decided whether the signs were real or not by selecting one of two keys on a keyboard. The key on the left was marked with yellow and was used to indicate that the sign was real, and the key on the right was marked with blue and was used to indicate that the sign was not real. Participants could make their decisions at any point during or after the presentation of the video, and a fixation point appeared on the screen once a decision was made and lasted 1,000ms.

Instructions were given in ASL on a computer screen. Participants were asked to make decisions as quickly and as accurately as possible. They were asked to consider all signs that they would recognize to be real even if they might personally prefer to use a different lexical item (e.g., there are two variants of the signs HOSPITAL that are widely known, but there is dialectal variation and some people prefer to use one over the other). They were also told that all of the real signs would be generic frozen signs, and not creative modifications of signs (e.g., the generic sign SURGERY is typically produced on the palm of hand, though it might be produced on a different body part like the forehead to describe a particular surgery like forehead surgery). They were told that some signs might not be variants that they personally use (i.e., the sign might have two alternate forms that are used in different dialects), and were asked to consider any sign that they would recognize as real. After the instructions, they completed 20 practice trials (ten real and ten non-signs). There were eight built-in breaks, and a notice was given that the experiment was halfway complete. A demographic questionnaire was completed after the lexical decision task.

Stimuli

A subset of 302 signs, all of which appear in ASL-LEX, were selected in part because they were picturable. Pictures representing the meaning of each sign were shown to a native signer who was filmed producing the sign. Of the 302 signs, 51 were ultimately removed because of the articulation of these signs differed from the productions in ASL-LEX. This is important because the neighborhood density estimates were based on the productions used in ASL-LEX, and would not match signs that had different structure. An additional 297 non-signs were created by modifying one phonological parameter of the real signs. The replacement parameters were selected from a list of the parameters that occurred in the real signs, and the distribution of these replacement parameters roughly matched the distribution in the real signs. If the modified sign happened to also be an existing sign, a second parameter was changed. Two native signers (the author and the model) agreed that all of the non-signs were indeed non-signs and were phonologically plausible in ASL.

Modeling Procedure

A series of mixed-effects linear regressions were constructed using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2014) of the statistical program R. The dependent variable in all models was reaction time to the real signs, and all models include participants and items as random factors. Because the investigation was exploratory in nature, random slopes were not included.

Responses faster than one standard deviation below the mean response time for the group (302ms; N = 55), and slower than 3,500ms (N = 436), as well as incorrect responses (N = 1,371) were removed. As illustrated in Figure 11, the time course of sign perception is such that participants generally responded after the SignOffset but before the end of the video. Response times were log transformed, and all continuous predictors were centered and scaled.

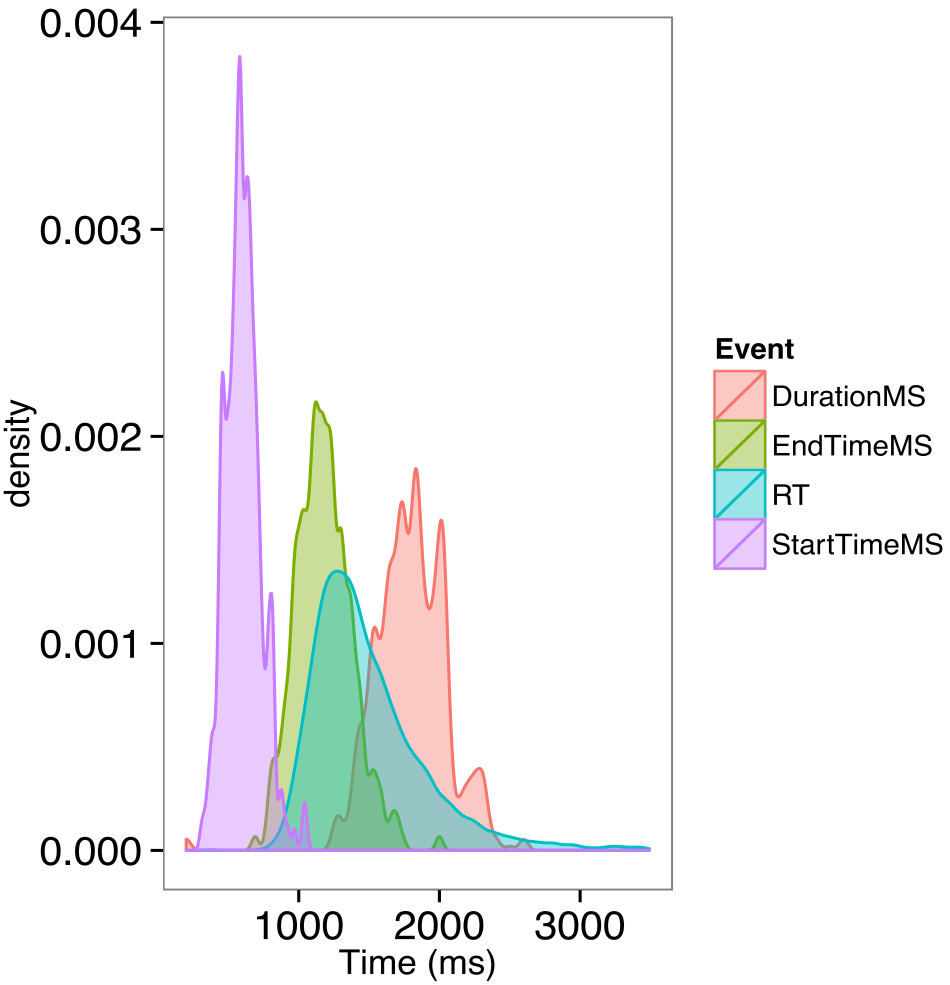

Figure 11. Time course of sign onset and offset, video duration, and reaction time. On the y-axis, density refers to the kernel density estimate using a Gaussian distribution.

A number of nuisance variables were identified that might affect reaction time. These variables comprised: the video duration, the onset of the sign (ms), the offset of the sign (ms), the trial number, the previous trial type (real sign or non-sign), previous trial accuracy (correct or error), the log transformed reaction time to the previous sign, lexical class, compounding (compound or not), and initialization (initialized or not), sign type, selected fingers, flexion, major location, minor location, and movement. All of these variables were entered into a model of log reaction time to see which of these affect reaction time. Because major location and minor location are correlated, a model containing both failed to converge so two separate models were created that were the same except one included major location and the other included minor location. The nuisance variables that significantly predicted reaction time (indicated by a t-value greater than 2[7]) included: onset of the sign (ms), the offset of the sign (ms), the trial number, the previous trial type (real sign or non-sign), the log transformed reaction time to the previous sign, minor location, and movement (see Table 4). The nuisance variables that significantly predicted duration were included in all following models, and the other nuisance variables were not.

Table 4. A mixed-effects linear model of the effect of nuisance variables log reaction times. The baseline variables were: PrevTrialType-Break, PrevTrialAccuracy-Correct, LexicalClass- Adjective, SignType-AsymmetricalDifferentHandshape, MinorLocation-CheekNose

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[7] For categorical variables, if at least one level had a t-value greater than 2 then it was retained in future models).

	Estimate	Std. Error	t value
(Intercept)	6.611	0.060	110.785
DurationMS	0.000	0.000	0.853
EndTimeMS	0.000	0.000	4.316
StartTimeMS	0.000	0.000	6.580
TrialNum	-0.003	0.001	-2.394
PrevTrialType-Nonsign	0.080	0.014	5.850
PrevTrialType-Realsign	0.075	0.014	5.370
PrevTrialAccuracy-Error	0.004	0.005	0.876
PrevTrialLogReactionTime	0.031	0.002	16.869
Age	0.039	0.014	2.730
LexicalClass-name	0.074	0.044	1.680
LexicalClass-noun	0.021	0.026	0.811
LexicalClass-verb	0.026	0.031	0.831
Compound	-0.047	0.035	-1.342
Initialized	-0.030	0.017	-1.793
SignType-AsymmetricalSameHandshape	-0.001	0.022	-0.030
SignType-OneHanded	0.013	0.023	0.572
SignType-Other	-0.009	0.046	-0.199
SignType-SymmetricalOrAlternating	-0.018	0.023	-0.781
MinorLocation-Chin	0.020	0.026	0.793
MinorLocation-Clavicle	0.027	0.030	0.897
MinorLocation-Eye	0.032	0.025	1.282
MinorLocation-FingerBack	-0.006	0.044	-0.127
MinorLocation-FingerFront	0.008	0.059	0.133
MinorLocation-FingerRadial	0.007	0.036	0.195
MinorLocation-FingerTip	0.092	0.051	1.785
MinorLocation-FingerUlnar	-0.058	0.051	-1.125
MinorLocation-ForearmBack	0.023	0.056	0.413
MinorLocation-ForearmFront	-0.045	0.079	-0.565
MinorLocation-ForearmUlnar	0.055	0.059	0.918
MinorLocation-Forehead	0.027	0.033	0.822
MinorLocation-HeadTop	-0.045	0.075	-0.603
MinorLocation-Heel	0.031	0.051	0.619
MinorLocation-Mouth	0.054	0.030	1.822
MinorLocation-Neck	0.108	0.049	2.213
MinorLocation-Neutral	0.062	0.020	3.095
MinorLocation-Other	0.060	0.027	2.238
MinorLocation-Palm	0.008	0.032	0.251
MinorLocation-PalmBack	0.023	0.042	0.555
MinorLocation-TorsoTop	0.065	0.039	1.649
MinorLocation-UnderChin	-0.034	0.037	-0.923
MinorLocation-UpperArm	0.135	0.063	2.140
MinorLocation-UpperLip	0.042	0.057	0.729
MinorLocation-WristBack	0.082	0.081	1.017
SelectedFingers-im	0.005	0.017	0.309
SelectedFingers-imr	0.026	0.055	0.483

Analysis and Results

Analysis 1: Demographic and Task Characteristics

There was a lexicality effect (*t*(42,687) = 12.01, *p* < .0001): real signs (M = 1,638, SD = 1,871) were identified faster than non-signs (M = 1,824, SD = 1,399). Response times were faster on accurate trials (M = 1,506, SD = 439) than inaccurate trials (M = 1,793, SD = 708; *t*(1,522) = 15.08, *p* < .0001). A model was constructed containing the nuisance variables and several language measures including the age of first exposure to ASL (ASLAge), self-reported ASLFluency, ASLExposure, SpeechExposure, and CommunicationEase. There were no significant main effects of any of these language measures (see Table 5).

Table 5. The effect of language measures on log reaction time.

	Estimate	Std. Error	t value
(Intercept	6.616	0.079	83.379
TrialNum	-0.007	0.002	-3.578
PrevTrial-RealSign	0.084	0.021	4.073
PrevTrial-NonSign	0.075	0.021	3.600
SignOnsetMS	0.000	0.000	-1.319
SignOffsetMS	0.000	0.000	3.446
Age	0.075	0.031	2.448
LogPrevRT	0.063	0.006	9.988
Movement-Curved	0.034	0.035	0.992
Movement-None	0.009	0.028	0.304
Movement-Other	0.082	0.037	2.234
Movement-Straight	0.062	0.033	1.890
Movement-Zigzag	0.029	0.026	1.142
MinorLocation-Chin	0.008	0.035	0.241
MinorLocation-Clavicle	0.041	0.039	1.054
MinorLocation-Eye	0.052	0.034	1.544
MinorLocation-FingerBack	-0.019	0.052	-0.368
MinorLocation-FingerFront	-0.003	0.078	-0.043
MinorLocation-FingerRadial	-0.030	0.041	-0.718
MinorLocation-FingerTip	-0.013	0.059	-0.227
MinorLocation-FingerUlnar	0.006	0.065	0.098
MinorLocation-ForearmBack	-0.031	0.078	-0.399

MinorLocation-ForearmFront	-0.146	0.111	-1.310
MinorLocation-ForearmUlnar	-0.007	0.081	-0.086
MinorLocation-Forehead	0.107	0.046	2.316
MinorLocation-HeadTop	0.016	0.107	0.153
MinorLocation-Heel	0.067	0.064	1.035
MinorLocation-Mouth	0.020	0.041	0.494
MinorLocation-Neck	0.015	0.066	0.231
MinorLocation-Neutral	0.011	0.026	0.431
MinorLocation-Other	0.004	0.036	0.103
MinorLocation-Palm	0.021	0.033	0.638
MinorLocation-PalmBack	0.007	0.050	0.146
MinorLocation-TorsoTop	0.006	0.053	0.109
MinorLocation-UnderChin	-0.085	0.052	-1.632
MinorLocation-UpperArm	0.143	0.081	1.751
MinorLocation-UpperLip	-0.033	0.080	-0.408
MinorLocation-WristBack	0.332	0.109	3.047
SpeechExposure	-0.049	0.034	-1.436
ASLExposure	-0.044	0.042	-1.048
ASLAge	-0.010	0.040	-0.240
CommunicationEase	0.018	0.029	0.600
ASLFluency	-0.033	0.025	-1.300

Analysis 2a: Neighborhood Density

The next analysis included the nuisance variables, English exposure, and a three-way interaction between ASLExposure, sign frequency, and maximal neighborhood density. English exposure and ASL exposure were included in order to see how language exposure affects sign processing. The three way interaction was included because previous work has found effects of neighborhood density but only in people with late exposure to ASL and only in low frequency words (Carreiras et al., 2008). ASL experience was measured in several ways, all of which are correlated (see Table 6). In order to avoid issues of multicollinearity and to reduce the number of variables in the model, each measure of ASL exposure was entered into the model separately. ASLExposure was selected from among the five measures of ASL exposure because the model had the best fit, indicated by the lowest Akaike information criterion as low AIC values indicate better model fit ($AIC_{ASLExposure}$ = -11888 AIC_{ASLAge} = -10995, $AIC_{CommunicationEase}$ = -4952, $AIC_{ASLFluency}$ = -11876). The analysis revealed a facilitatory main effect of sign frequency (see Table 6), replicating studies of both spoken (e.g., Hudson & Bergman, 1985; Grainger, 1990; Schilling, Rayner, Chumbley, 1998) and signed language (e.g., Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008; Emmorey, Petrich, & Gollan, 2013). There was also an interaction between sign frequency and ASLExposure whereby the facilitatory effect of sign frequency was stronger in those with less ASLExposure than those with more ASLExposure (see Figure 12). Finally there was a three-way interaction between maximal neighborhood density, sign frequency, and ASLExposure. There was an inhibitory effect of neighborhood density for the people with low ASLExposure, there was always an effect of frequency in low density signs regardless of ASL exposure but there was no effect of sign frequency in the high neighborhood density signs for the people with high ASLExposure (see Figure 13).There was also no main effect of neighborhood density.

Table 6. The effects of sign frequency, neighborhood density, ASLExposure, and the interactions among these variables.

	Estimate	Std. Error	t value
(Intercept)	6.579	0.059	112.223
TrialNum	-0.003	0.001	-2.415
PrevTrialType-Nonsign	0.081	0.014	5.985
PrevTrialType-Realsign	0.076	0.014	5.512
SignOnsetMS	0	0	-1.473
SignOffsetMS	0	0	2.894
Age	0.039	0.017	2.33
PrevTrialLogReactionTime	0.069	0.004	17.322
Movement-Curved	0.023	0.033	0.68
Movement-None	-0.009	0.027	-0.333
Movement-Other	0.074	0.035	2.106
Movement-Straight	0.054	0.032	1.702

Movement-Zigzag	0.018	0.025	0.726
MinorLocation-Chin	0.022	0.033	0.658
MinorLocation-Clavicle	0.044	0.038	1.183
MinorLocation-Eye	0.055	0.032	1.696
MinorLocation-FingerBack	-0.009	0.05	-0.181
MinorLocation-FingerFront	0.027	0.075	0.361
MinorLocation-FingerRadial	-0.002	0.04	-0.062
MinorLocation-FingerTip	-0.043	0.057	-0.745
MinorLocation-FingerUlnar	0.013	0.062	0.216
MinorLocation-ForearmBack	-0.032	0.075	-0.433
MinorLocation-ForearmFront	-0.111	0.107	-1.04
MinorLocation-ForearmUlnar	0.01	0.078	0.126
MinorLocation-Forehead	0.124	0.043	2.862
MinorLocation-HeadTop	0.051	0.102	0.498
MinorLocation-Heel	0.083	0.062	1.342
MinorLocation-Mouth	0.017	0.039	0.431
MinorLocation-Neck	-0.02	0.064	-0.316
MinorLocation-Neutral	0.028	0.025	1.105
MinorLocation-Other	0.031	0.035	0.887
MinorLocation-Palm	0.032	0.032	1.001
MinorLocation-PalmBack	0.034	0.049	0.699
MinorLocation-TorsoTop	0.001	0.051	0.027
MinorLocation-UnderChin	-0.068	0.05	-1.356
MinorLocation-UpperArm	0.152	0.078	1.953
MinorLocation-UpperLip	-0.033	0.076	-0.438
MinorLocation-WristBack	0.29	0.103	2.804
SpeechExposure	0.001	0.015	0.06
ASLExposure	0	0.018	0.02
MaximalNeighborhoodDensity	0.002	0.008	0.203
SignFrequency	-0.026	0.007	-3.576
ASLExposure:MaximalNeighborhoodDensity	-0.002	0.001	-1.533
ASLExposure:SignFrequency	0.004	0.001	3.017
MaximalNeighborhoodDensity:SignFrequency	0.008	0.007	1.114
ASLExposure:MaximalNeighborhoodDensity:SignFrequency	0.003	0.001	2.135

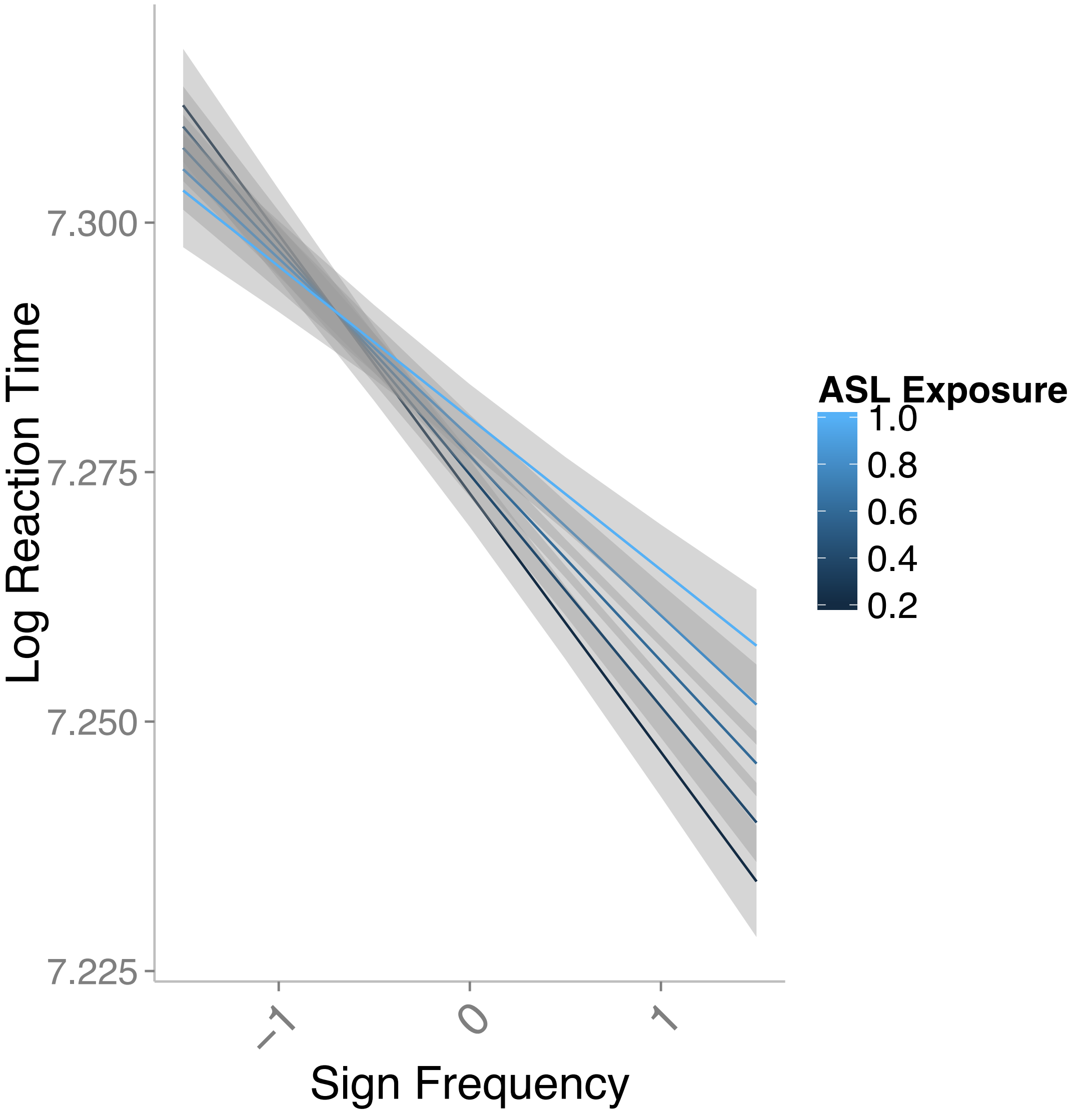

Figure 12. The effect of sign frequency as a function of ASLExposure. The effect of frequency is larger in those with low ASL exposure. Note that this and all following figures are plotted from models without random effects due to limitations in the graphing software.

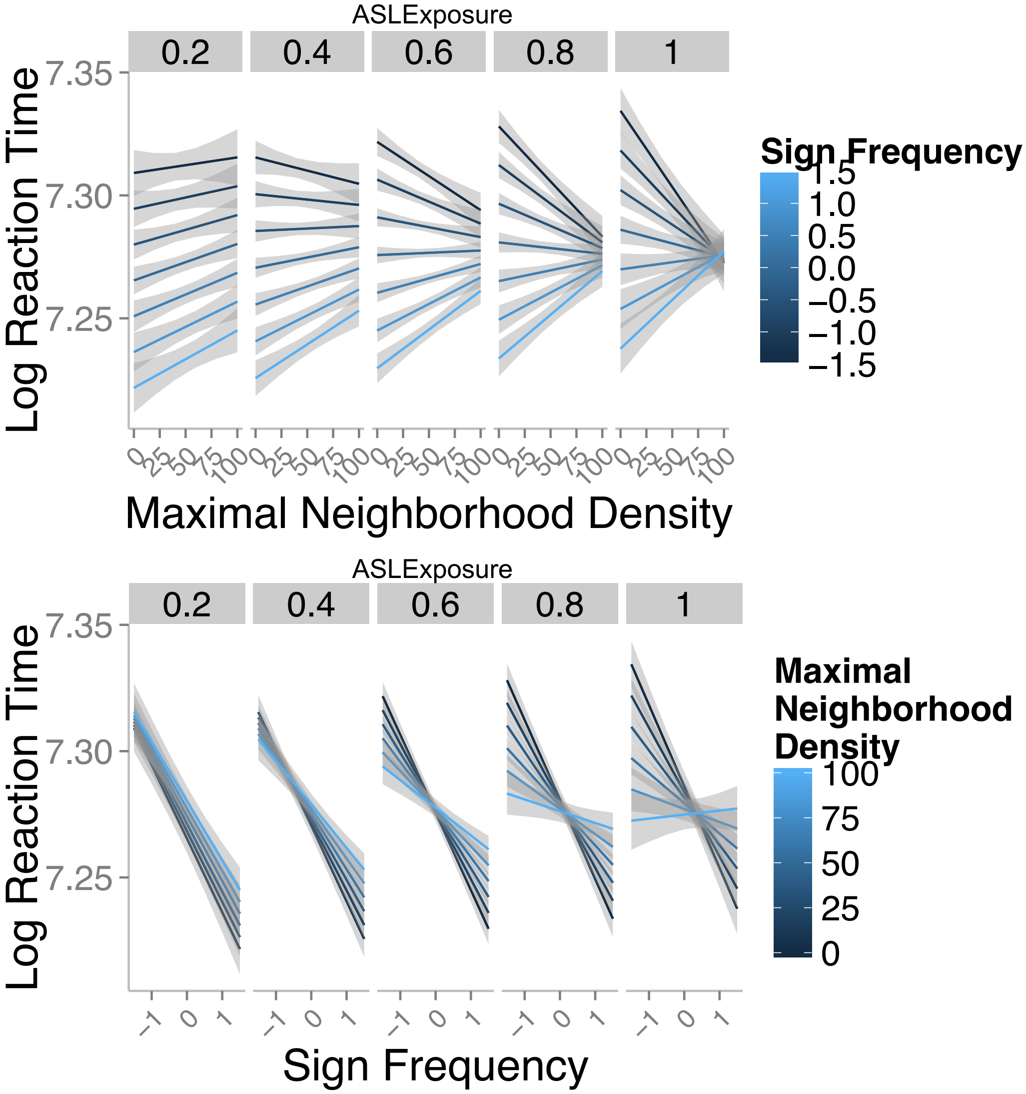

Figure 13. The three-way interaction between maximal neighborhood density, sign frequency, and ASLExposure on reaction time. These graphs represent the same information in different ways: the top graph highlights the effect of sign frequency while the bottom graph highlights the effect of neighborhood density.

Analysis 2b: Mayberry & Witcher (2005) ASL Exposure

A second analysis was done with a different measure of language exposure so as to allow for easier comparison with Mayberry and Witcher (2005). A categorical measure of ASL exposure (MayberryASLExposure) divided participants into three groups: native (primary caregiver is deaf), early (first exposed to ASL before age 3), and late (first exposed to ASL after age 3). MayberryASLExposure corresponds well to the gradient measure, ASLExposure (see Figure 14).

A model was constructed that was identical to Analysis 2a except MayberryASLExposure replaced ASLExposure. The fit of this model (AIC = -11005.3) was poorer than the model using the gradient measure of ASLExposure (AIC = -11887.6), suggesting that the gradient measure is preferred to the categorical one.

In this model, there was a main effect of MayberryASLExposure (see Table 7 and Figure 14). There was again no main effect of neighborhood density, a facilitatory effect of sign frequency, and no interaction between MayberryASLExposure and neighborhood density. As in Analysis 2a, there was an interaction between sign frequency and MayberryASLExposure, though in this case sign frequency had weaker effects in the early than late signers (see Figure 15). There was no difference in the effect of sign frequency for Early and Native (see Table 7), or Native and Late signers ($\beta = -0.005$, s.e. = 0.003, $t = -1.458$). There was a three-way interaction between sign frequency, MayberryASLExposure, and neighborhood density whereby early signers pattern differently from both the late and native signers (see Figure 16).

Table 7. The effects of sign frequency, neighborhood density, ASL exposure as measured by Mayberry & Witcher (2005), and the interactions among these variables. The baseline variable for MayberryASLExposure was Early.

	Estimate	Std. Error	t value
(Intercept)	6.609	0.063	104.994
TrialNum	-0.002	0.001	-1.798
PrevTrial-NonSign	0.085	0.014	6.087
PrevTrial-RealSign	0.080	0.014	5.632
SignOnsetMS	0.000	0.000	-1.527
SignOffsetMS	0.000	0.000	2.940

Age	0.040	0.015	2.633
LogPrevRT	0.069	0.004	16.936
Movement-Curved	0.025	0.033	0.743
Movement-None	-0.008	0.027	-0.283
Movement-Other	0.076	0.035	2.162
Movement-Straight	0.057	0.032	1.814
Movement-Zigzag	0.020	0.025	0.775
MinorLocation-Chin	0.021	0.033	0.636
MinorLocation-Clavicle	0.047	0.038	1.245
MinorLocation-Eye	0.054	0.032	1.669
MinorLocation-FingerBack	-0.011	0.050	-0.223
MinorLocation-FingerFront	0.028	0.075	0.378
MinorLocation-FingerRadial	-0.002	0.040	-0.055
MinorLocation-FingerTip	-0.038	0.057	-0.657
MinorLocation-FingerUlnar	0.014	0.062	0.222
MinorLocation-ForearmBack	-0.035	0.075	-0.471
MinorLocation-ForearmFront	-0.107	0.107	-1.003
MinorLocation-ForearmUlnar	0.009	0.078	0.120
MinorLocation-Forehead	0.125	0.043	2.883
MinorLocation-HeadTop	0.050	0.102	0.487
MinorLocation-Heel	0.080	0.062	1.286
MinorLocation-Mouth	0.018	0.039	0.459
MinorLocation-Neck	-0.027	0.064	-0.417
MinorLocation-Neutral	0.027	0.025	1.068
MinorLocation-Other	0.029	0.035	0.840
MinorLocation-Palm	0.032	0.032	1.015
MinorLocation-PalmBack	0.034	0.049	0.695
MinorLocation-TorsoTop	0.001	0.051	0.019
MinorLocation-UnderChin	-0.068	0.050	-1.360
MinorLocation-UpperArm	0.153	0.078	1.962
MinorLocation-UpperLip	-0.032	0.076	-0.421
MinorLocation-WristBack	0.290	0.103	2.803
SpeechExposure	-0.016	0.016	-0.998
MayberryASL-Late	-0.023	0.038	-0.596
MayberryASL-Native	-0.109	0.036	-3.028
MaximalNeighborhoodDensity	0.000	0.008	0.042
SignFrequency	-0.022	0.007	-2.958
MayberryASL-Late:MaximalNeighborhoodDensity	0.005	0.003	1.450
MayberryASL-Native:MaximalNeighborhoodDensity	0.000	0.003	-0.121
MayberryASL-Late:SignFrequency	-0.007	0.003	-2.210
MayberryASL-Native:SignFrequency	-0.002	0.003	-0.697
MaximalNeighborhoodDensity:SignFrequency	0.015	0.007	2.136
MayberryASL-Late:MaximalNeighborhoodDensity:SignFrequency	-0.013	0.003	-4.066

MayberryASL-Native:MaximalNeighborhoodDensity:SignFrequency	-0.010	0.003	-2.951

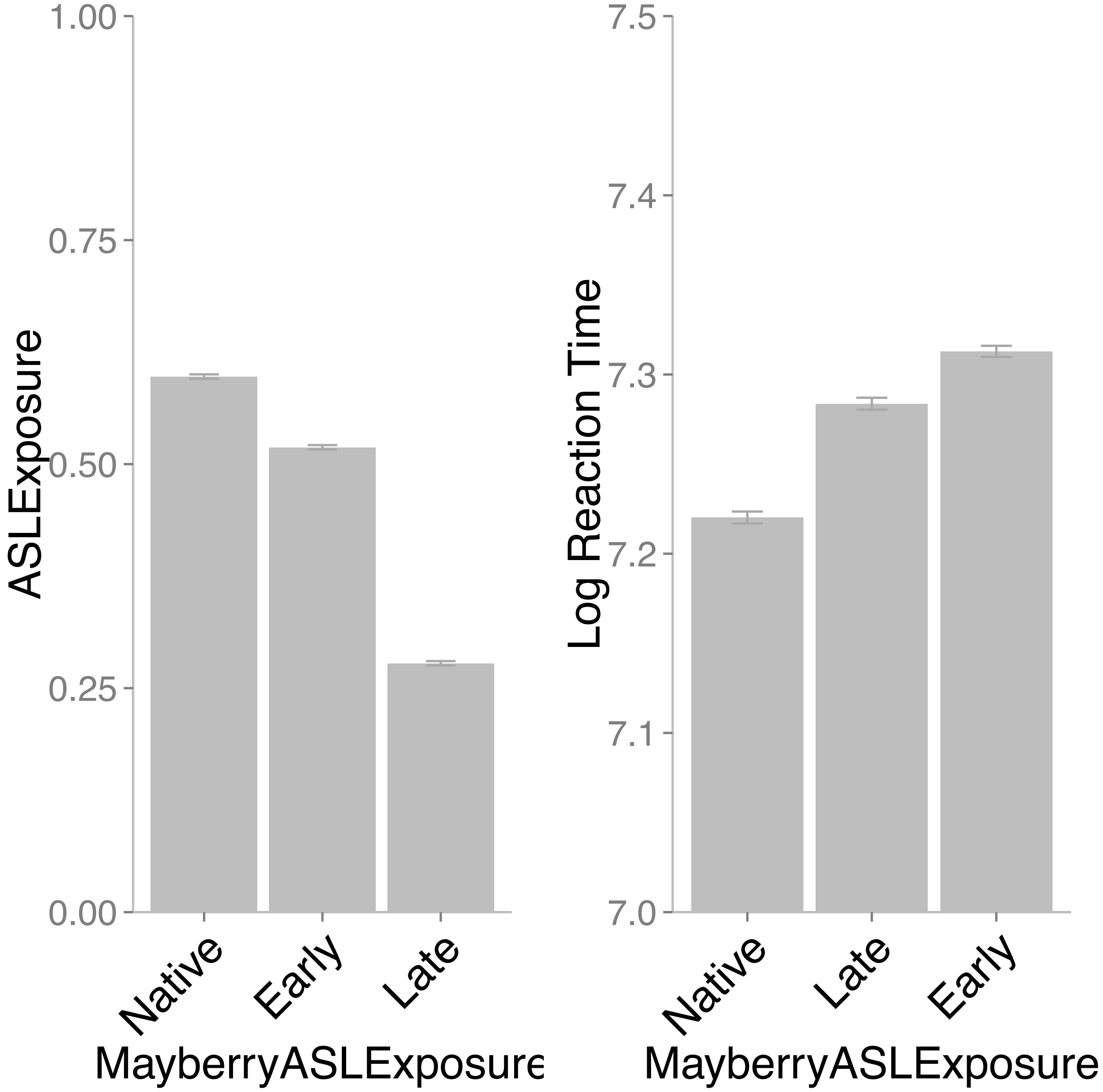

Figure 14. ASLExposure and reaction time as a function of ASL exposure as defined by Mayberry and Witcher (2005).

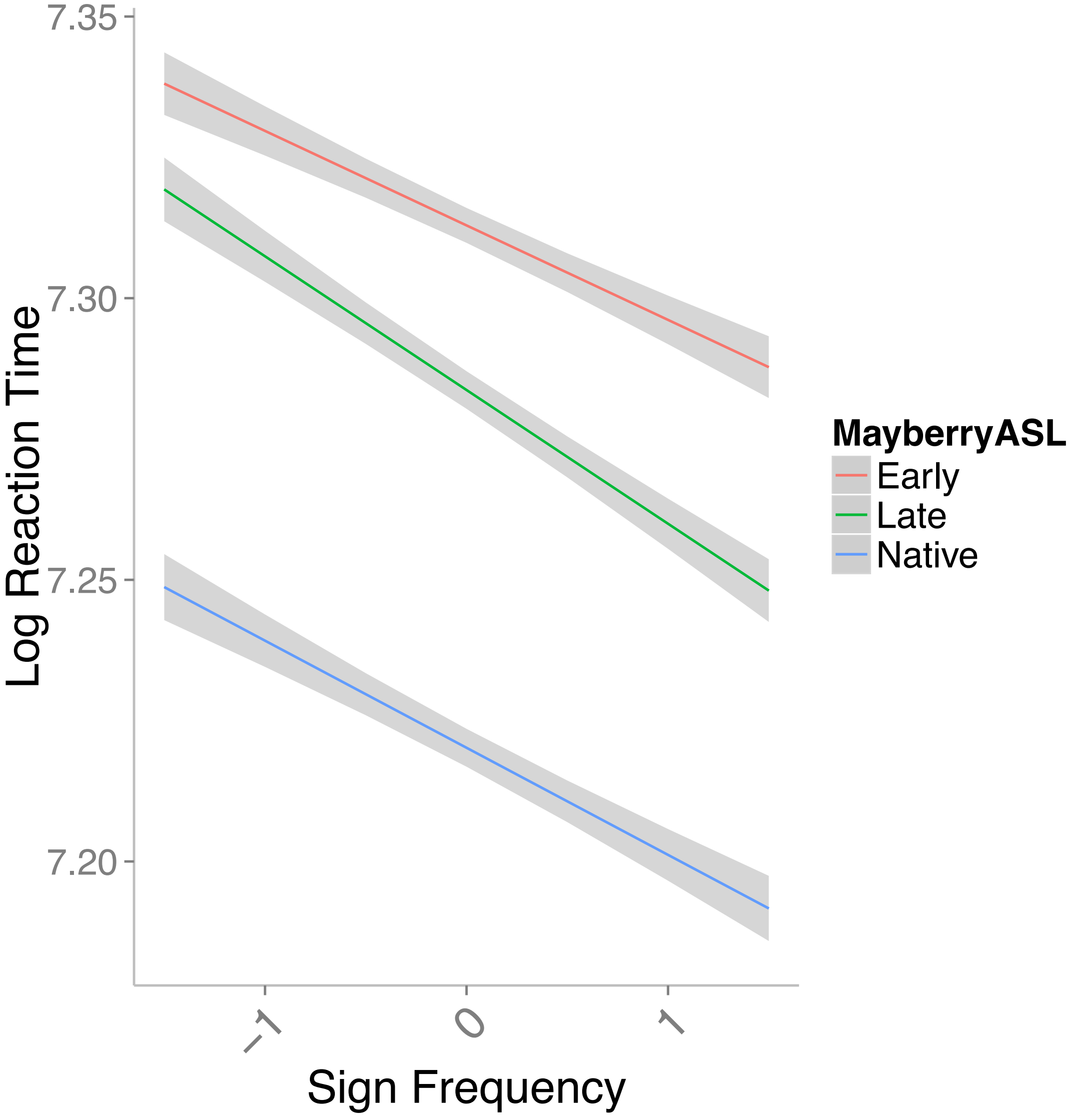

Figure 15. The effect of sign frequency on reaction time as a function of ASL exposure as defined by Mayberry and Witcher (2005).

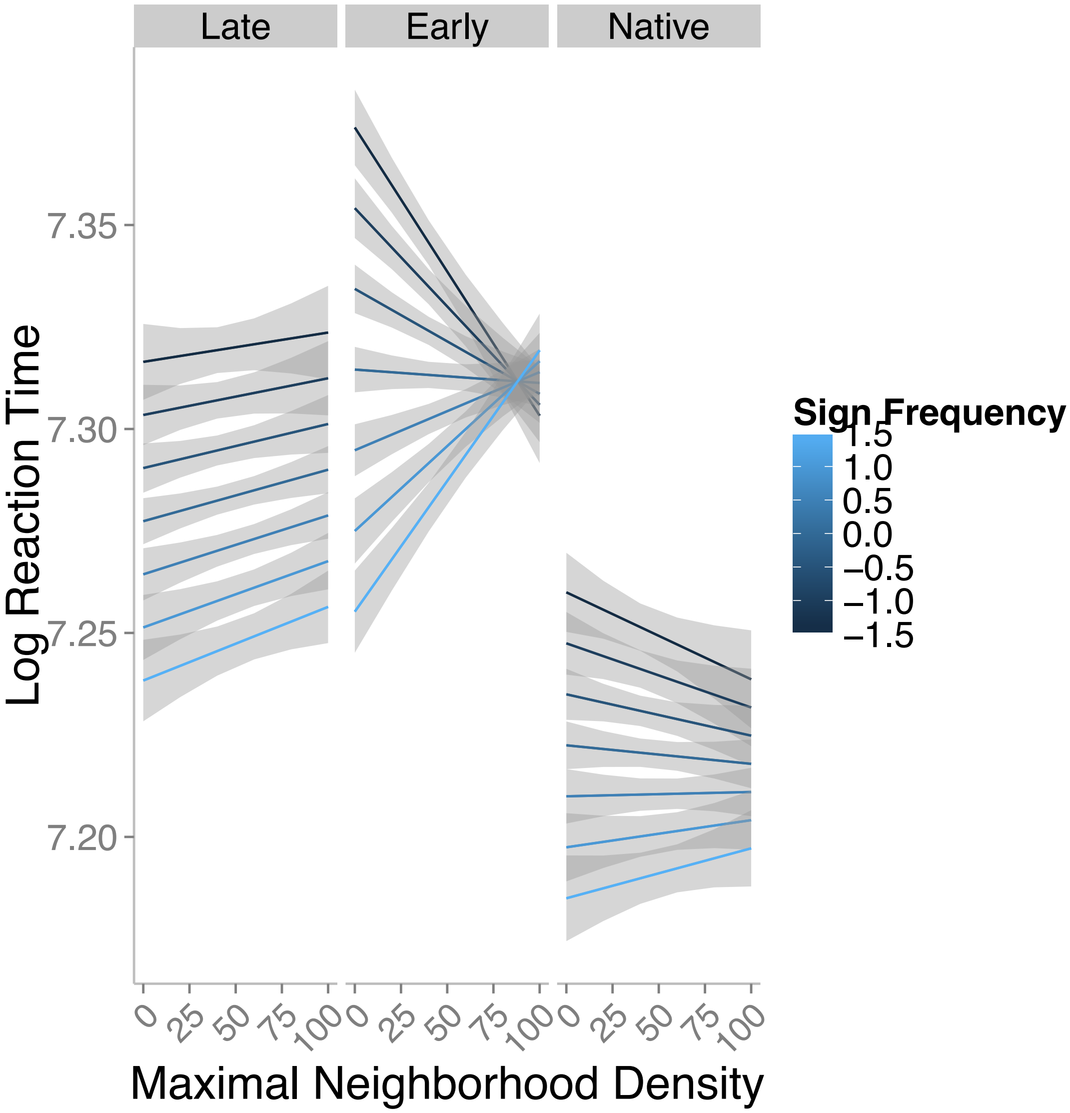

Figure 16. The interaction between neighborhood density, sign frequency, and ASL Exposure as defined by Mayberry and Witcher (2005) on reaction time.

Analysis 3a: Sub-Lexical Frequency

To assess the effects of location and handshape frequency, a model was constructed that included: the nuisance variables; a three-way interaction between ASLExposure, SignFrequency, and HandshapeFrequency; and a three-way interaction between ASLExposure, SignFrequency and MajorLocationFrequency (see Table 8). There were no main effects of either handshape frequency or major location frequency.

There were no significant interactions including handshape frequency. There was a two-way interaction between sign frequency and major location frequency where major location frequency was inhibitory for all participants but more so for people with less ASL exposure (see Figure 17). There were no three-way interactions.

Table 8. The effect of location frequency, handshape frequency, sign frequency, ASLExposure, SpeechExposure, and the interactions among these.

	Estimate	Std. Error	t value
(Intercept)	6.554	0.060	109.206
TrialNum	-0.003	0.001	-2.410
PrevTrial-NonSign	0.081	0.014	5.969
PrevTrial-RealSign	0.076	0.014	5.493
SignOnsetMS	0.000	0.000	-1.601
SignOffsetMS	0.000	0.000	3.010
Age	0.039	0.017	2.330
LogPrevRT	0.069	0.004	17.304
Movement-Curved	0.019	0.033	0.577
Movement-None	-0.008	0.027	-0.314
Movement-Other	0.071	0.035	2.040
Movement-Straight	0.057	0.031	1.818
Movement-Zigzag	0.019	0.024	0.786
MinorLocation-Chin	0.026	0.033	0.784
MinorLocation-Clavicle	0.238	0.103	2.311
MinorLocation-Eye	0.053	0.032	1.639
MinorLocation-FingerBack	0.070	0.063	1.101
MinorLocation-FingerFront	0.086	0.084	1.032
MinorLocation-FingerRadial	0.063	0.056	1.121
MinorLocation-FingerTip	0.056	0.070	0.799
MinorLocation-FingerUlnar	0.085	0.073	1.171
MinorLocation-ForearmBack	0.176	0.147	1.197
MinorLocation-ForearmFront	0.123	0.167	0.734
MinorLocation-ForearmUlnar	0.311	0.156	2.000
MinorLocation-Forehead	0.125	0.043	2.923
MinorLocation-HeadTop	0.053	0.101	0.523
MinorLocation-Heel	0.139	0.073	1.905
MinorLocation-Mouth	0.017	0.039	0.432
MinorLocation-Neck	0.208	0.119	1.751
MinorLocation-Neutral	-0.015	0.034	-0.426
MinorLocation-Other	0.052	0.036	1.440
MinorLocation-Palm	0.101	0.050	2.014

MinorLocation-PalmBack	0.101	0.062	1.640
MinorLocation-TorsoTop	0.198	0.109	1.820
MinorLocation-UnderChin	-0.064	0.049	-1.298
MinorLocation-UpperArm	0.421	0.152	2.776
MinorLocation-UpperLip	-0.037	0.075	-0.494
MinorLocation-WristBack	0.549	0.164	3.339
SpeechExposure	0.001	0.015	0.060
ASLExposure	0.001	0.018	0.035
SignFrequency	-0.023	0.007	-3.200
HandshapeFrequency	0.002	0.007	0.300
MajorLocation-Frequency	0.073	0.039	1.875
ASLExposure:SignFrequency	0.004	0.001	2.856
ASLExposure:HandshapeFrequency	-0.002	0.001	-1.421
SignFrequency:HandshapeFrequency	0.004	0.006	0.585
ASLExposure:MajorLocationFrequency	0.000	0.001	0.138
SignFrequency:MajorLocationFrequency	-0.017	0.008	-2.076
ASLExposure:SignFrequency:HandshapeFrequency	0.002	0.001	1.440
ASLExposure:SignFrequency:MajorLocationFrequency	0.000	0.001	-0.205

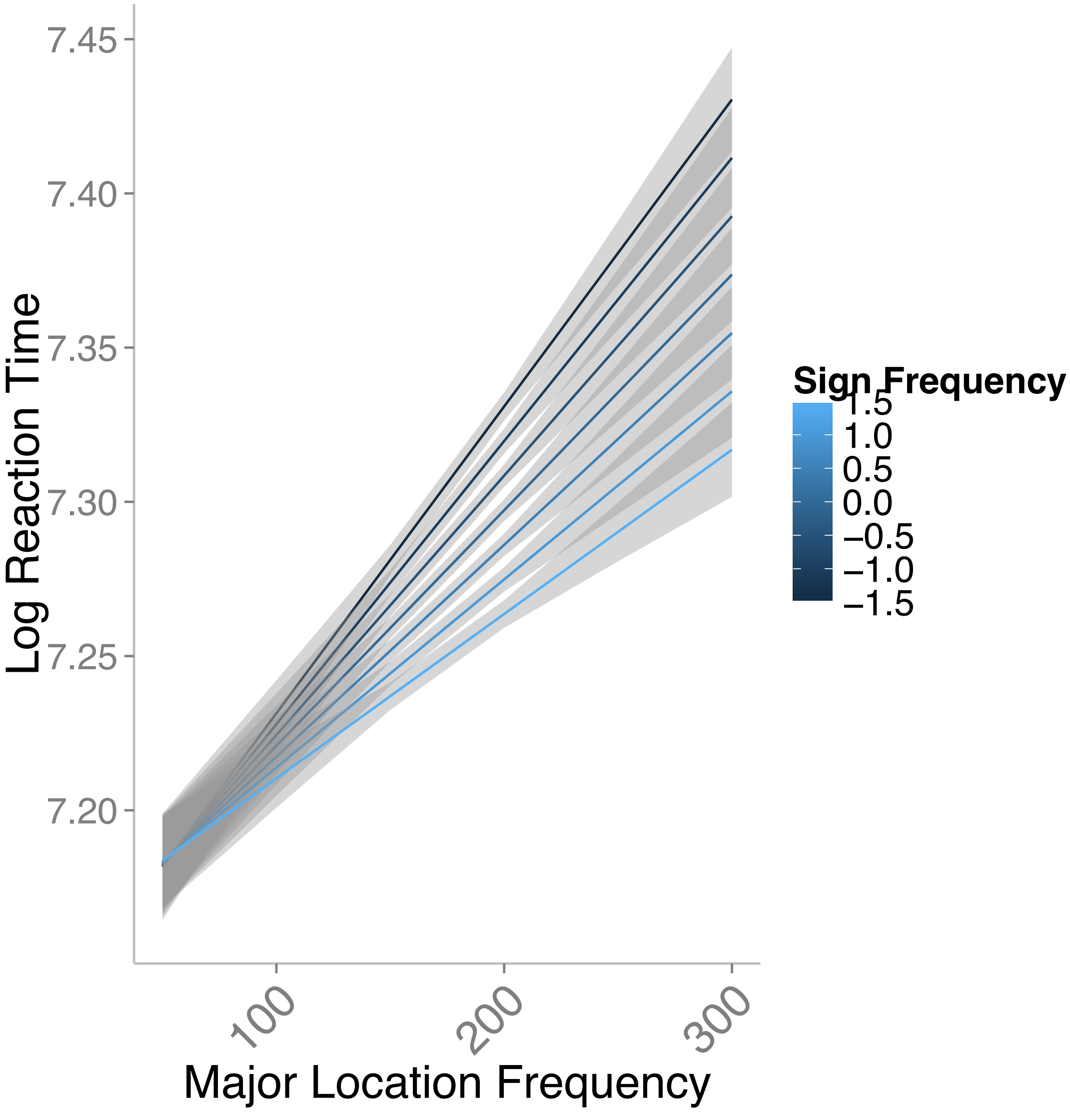

Figure 17. The effect of major location frequency on reaction time as a function of sign frequency.

Analysis 3b: Carreiras et al. (2008) Replication

The third analysis redefined location and handshape frequency to be closer to the definitions used by Carreiras et al., (2008). In this case, signs with high frequency locations (which Carreiras et al. refer to as signs with high location neighborhood density) are exclusively those produced in the neutral location, and all other signs are considered to be low frequency locations. Handshape frequency was redefined categorically as low (below median) and high (above median) handshape frequency. The high frequency handshapes (M = 129.5, SD = 53.62) were 5.65 times more frequent than the low frequency handshapes (M = 22.93, SD = 13.38). This is proportionally similar to the difference between high and low frequency handshapes reported in Carreiras et al. (high frequency handshapes were 5.28 times more frequent than low frequency handshapes; 2008). The model included the nuisance variables; a three-way interaction between ASL exposure, sign frequency, and categorical handshape frequency; and a three-way interaction between ASL exposure, sign frequency and categorical location frequency (see Table 9).

Table 9. The effects of location frequency and handshape frequency (as measured by Carreiras et al. (2008)), sign frequency, ASLExposure, SpeechExposure, and the interactions among these. The baseline variables were: CarreirasHandshapeND-High, and CarreirasLocationND-Neutral.

	Estimate	Std. Error	t value
(Intercept)	6.592	0.059	111.719
TrialNum	-0.003	0.001	-2.398
PrevTrial-NonSign	0.081	0.014	5.964
PrevTrial-RealSign	0.076	0.014	5.489
SignOnsetMS	0.000	0.000	-1.313
SignOffsetMS	0.000	0.000	2.676
Age	0.039	0.017	2.329
LogPrevRT	0.069	0.004	17.296
Movement-Curved	0.020	0.033	0.608
Movement-None	-0.011	0.027	-0.402
Movement-Other	0.071	0.035	2.043
Movement-Straight	0.053	0.032	1.666
Movement-Zigzag	0.018	0.024	0.753
MinorLocation-Chin	0.018	0.033	0.553
MinorLocation-Clavicle	0.047	0.037	1.263
MinorLocation-Eye	0.057	0.032	1.759
MinorLocation-FingerBack	-0.007	0.050	-0.147
MinorLocation-FingerFront	0.016	0.074	0.214
MinorLocation-FingerRadial	-0.008	0.040	-0.198
MinorLocation-FingerTip	-0.022	0.056	-0.388

MinorLocation-FingerUlnar	0.008	0.062	0.133
MinorLocation-ForearmBack	-0.041	0.074	-0.557
MinorLocation-ForearmFront	-0.122	0.107	-1.138
MinorLocation-ForearmUlnar	0.030	0.076	0.393
MinorLocation-Forehead	0.117	0.043	2.731
MinorLocation-HeadTop	0.045	0.101	0.440
MinorLocation-Heel	0.070	0.062	1.136
MinorLocation-Mouth	0.020	0.039	0.514
MinorLocation-Neck	-0.001	0.063	-0.014
MinorLocation-Neutral	0.028	0.025	1.100
MinorLocation-Other	0.029	0.034	0.852
MinorLocation-Palm	0.027	0.031	0.876
MinorLocation-PalmBack	0.029	0.048	0.606
MinorLocation-TorsoTop	0.007	0.050	0.137
MinorLocation-UnderChin	-0.060	0.050	-1.208
MinorLocation-UpperArm	0.159	0.077	2.060
MinorLocation-UpperLip	-0.013	0.076	-0.170
MinorLocation-WristBack	0.296	0.102	2.903
SpeechExposure	0.001	0.015	0.060
ASLExposure	-0.002	0.018	-0.107
SignFrequency	-0.048	0.014	-3.467
CarreirasHandshapeND-Low	-0.010	0.013	-0.731
ASLExposure:SignFrequency	0.006	0.003	2.127
ASLExposure:CarreirasHandshapeND-Low	0.002	0.003	0.847
SignFrequency:CarreirasHandshapeND-Low	-0.002	0.013	-0.123
ASLExposure:CarreirasLocationND-Other	0.002	0.003	0.848
SignFrequency:CarreirasLocationND-Other	0.034	0.014	2.355
ASLExposure:SignFrequency:CarreirasHandshapeND-Low	-0.002	0.003	-0.765
ASLExposure:SignFrequency:CarreirasLocationND-Other	-0.002	0.003	-0.675

There was a two-way interaction between sign frequency and categorical location frequency where the facilitatory effect of sign frequency is stronger in the high frequency locations (neutral space) than in the low frequency locations (all other locations; see Figure 18). Another interpretation of this interaction is that location frequency has a facilitative effect for the high frequency signs and an inhibitory effect for the low frequency signs. There were no main effects or interactions including categorical handshape frequency.

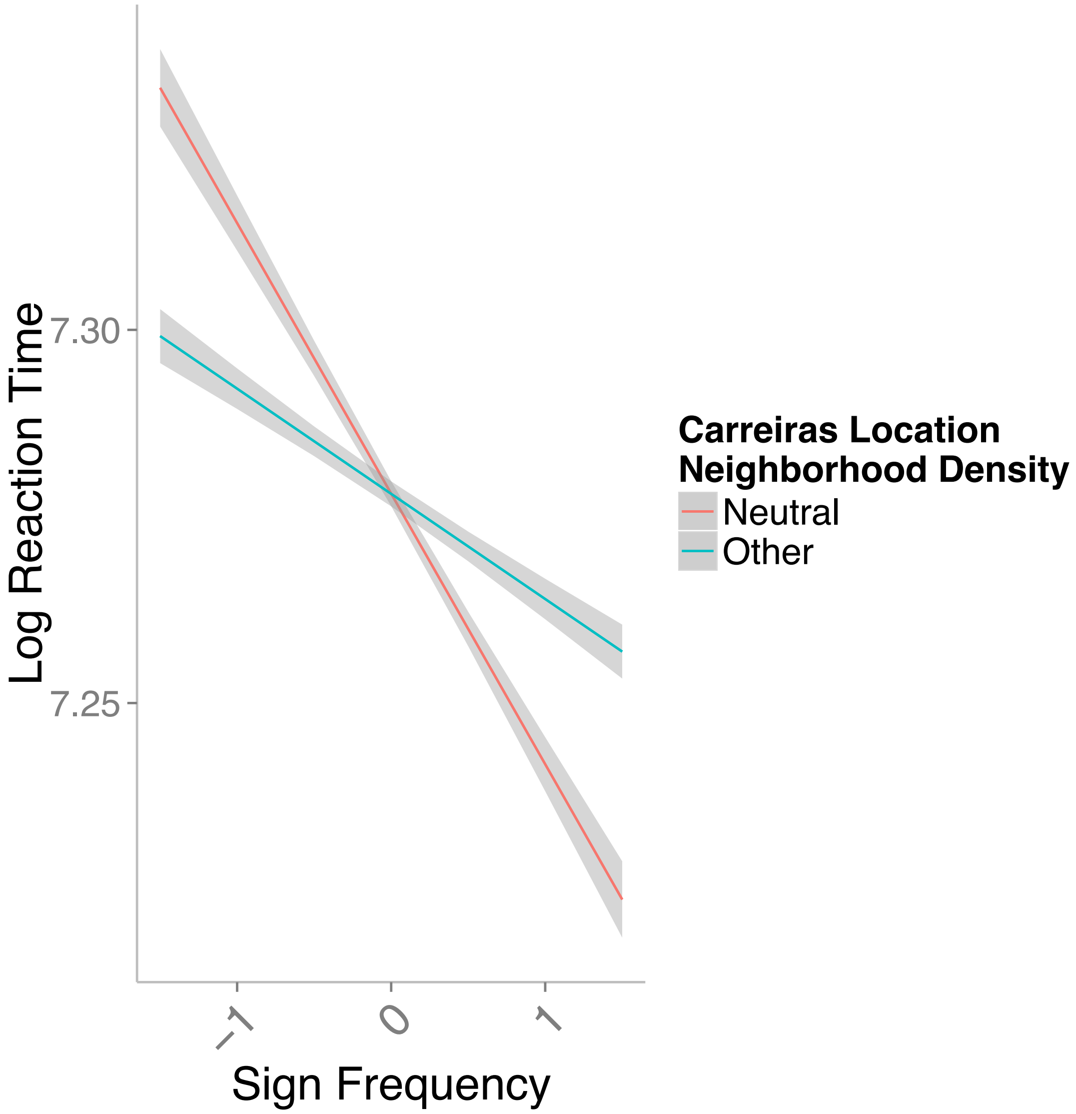

Figure 18. The effect of sign frequency as a function of location neighborhood density (as defined by Carreiras et al., 2008).

Discussion

From these analyses, we can draw three primary conclusions. First, where there are effects of neighborhood density and sub-lexical frequency, they are always inhibitory.

Second, neighborhood density effects appear to only arise in people with low ASL exposure. The lack of neighborhood density effects cannot be explained by differences in overall response time. Rather, people with high ASL exposure are neither inhibited nor facilitated by neighborhood density and sub-lexical frequency. Third, frequency and neighborhood density seem to be at odds, each thereby minimizing the effect of the other. For example, location frequency has a bigger effect in the low sign frequency words; sign frequency has a bigger effect in low location frequency words; and in the people with high ASL exposure, sign frequency has no effect in the high neighborhood density words.

The inhibitory effect of neighborhood density is comparable to that of spoken word perception. Inhibitory effects of phonological neighbors in spoken word perception have been demonstrated across many experimental paradigms including lexical decision (e.g., Dufour & Peereman, 2003; Garlock, Walley, & Metsala, 2001; Goldinger, Luce & Pisoni, 1989; Luce 1986; Luce & Pisoni, 1998; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; though Vitevitch & Rodriguez, 2005 find facilitatory effects in spoken Spanish). Inhibitory effects of phonological neighbors are thought to reflect competition among candidate words in spoken perception. The results presented here suggest that there is also competition among phonologically related candidate signs.

While we found the expected effect of neighborhood density in people with limited ASL exposure, we did not see effects of neighborhood density in the people with the most ASL exposure. Instead, in the people with high levels of ASL exposure, frequency and neighborhood density interact such that there is no effect of frequency in the high-density words. These results suggest that effects of neighborhood density on sign perception are amplified as a result of limited ASL exposure, and are consistent with other studies of sign perception, including Mayberry and Witcher (2005) and Carreiras et al. (2008) who do not find effects of neighbors or sub-lexical frequency in native signers. This may be somewhat surprising given that most of the studies on neighborhood density in spoken and written language find effects in on people without language deprivation. It is however, compatible with the hypothesis that frequency effects become weaker with more use. Bilinguals have stronger frequency effects in their non-dominant languages, which they presumably use less than their dominant languages (e.g., Antón-Méndez & Gollan, 2010; Gollan, Montoya, Cera, & Sandoval, 2008; Diependaele, Kevin, Kristin Lemhöfer, & Brysbaert, 2013; Duyck, Vanderelst, Desmet, & Hartsuiker, 2008), and older people have stronger frequency effects than younger people because their language experience has given them more time to rehearse the words in their lexicons (e.g., Gollan, Montoya, Cera, & Sandoval, 2008). Mayberry and Witcher (2005) suggest that native signers may be extremely efficient at processing signs, and the failure to find effects may be because performance is at ceiling. Emmorey and Corina (1990) also suggest that native signers may be better able to identify signs using very early phonetic cues, rather than later appearing phonological information.

Differences between late and early learners might also be attributed to the measures used in these studies. The frequency measure does not come from corpus counts, and is subjective. Subjective frequency ratings may be a better approximation of the experience with language from native than non-native users (or vice-versa). This seems unlikely as subjective frequency ratings are highly correlated in native and early learners and are correlated with corpus counts (see Chapter 2). It could be the case that subjective frequency ratings are very different for late learners, though it is unclear how this could cause the late learners to have stronger subjective frequency effects. Similarly, the neighborhood density estimates may be better approximations of the language experience of native than non-native users (or vice-versa). It is possible that a person with low ASL exposure may not know some of the signs used to estimate neighborhood density in ASL-LEX, though this would presumably make the effect of neighborhood density weaker not stronger. Alternatively, it is possible that signs that are not in ASL-LEX affect sign perception but disproportionately affect people with high ASL exposure who are familiar with these signs, or that people with high and low ASL exposure use different sub-lexical units to divide the lexicon into neighborhoods. Under both of these explanations, the neighborhood density measure in ASL-LEX would then be a better estimate of neighborhood density for people with low ASL exposure.

Turning to next to sub-lexical frequency, we found inhibitory effects of location frequency. This is similar to the results reported by Carreiras et al. (2008) for LSE, despite differences in definitions—Carreiras et al. defined location frequency categorically (neutral location versus other locations), and here location frequency was a continuous measure. Unlike Carreiras et al., (2008), we do not find a facilitatory effect of handshape frequency, and if anything, the numeric relationship between handshape frequency and reaction time was inhibitory though not signficant. One possibility is that handshape is articulated so late that signers have already identified the sign before the handshape is articulated. It is also possible that cross-linguistic differences may be at play. Differences in the effect of spoken word recognition have been identified cross linguistically (e.g., Vitevitch & Rodriguez, 2005). Unfortunately, at present there is not enough information comparing ASL and LSE to identify a particular mechanism that would lead to cross-linguistic differences. Lastly it is possible that the definitions of handshapes and the inventory used here and in Carreiras et al. (2008) are not the same, leading to very different neighborhood measurements making these two studies incomparable.

Interestingly, when we used a categorical measurement of location frequency (akin to high and low location neighborhood density from Carreiras et al., 2008), location frequency interacted with sign frequency. This interaction is similar numerically to that reported of LSE, and can be thought of in terms of the effect of frequency as a function of location neighborhood density, or in terms of the effect of location neighborhood density as a function of frequency (this is how it was reported in Carreiras et al., 2008). Under the first interpretation, the effect of frequency is larger for the signs with a high location neighborhood density (i.e., signs produced in a neutral location) than in signs with a low location neighborhood density (i.e., signs produced in any other location). In the second approach, the effect of neighborhood density is inhibitory in the low frequency signs (this was significant in Carreiras et al., 2008), and facilitatory in the high frequency signs (this was numerically true but not significant in Carreiras et al., 2008).

We offer that the amount of information in the signed signal may be so dense that late occurring information is of less use during perception. The information density of the signal may also explain why people who learned ASL early did not show effects of neighborhood density Late occurring features like handshape may be of little use to the perceiver.. People who learned ASL early may be able to make better use of early occurring cues, perhaps even phonetic cues, that the late occurring cues are not useful. According to this line of reasoning, the phonological bottleneck experienced by late signers could arise because they do not make good use of these early occurring cues, instead waiting until phonological information available. More work is needed to fully understand how the information density and the time course with which information becomes available affects sign perception.

STUDY 2

People who are bilingual in a spoken/written and signed language (bilingual-bimodals) activate representations of both languages (and modalities) during language processing. Co-activation of a spoken to signed representations has been demonstrated in speech production (Casey & Emmorey, 2009; Emmorey, Borinstein, Thompson, & Gollan, 2008), speech perception (Shook & Marian, 2012), reading (Kubus, Villwock, Morford, & Rathman, 2012; Morford Wilkinson, Villwock, Piñar, & Kroll, 2011; Morford, Kroll, Pinar, & Wilkinson, 2014; Navarrete, Caccaro, Pavani, Mahon & Peressotti, 2015; Ormel, Hermans, Knoors, & Verhoeven, 2012), sign production (Giezen & Emmorey, 2015), and sign perception (Hosemann, Altvater-Mackensen, Hermann & Mani, 2013; Williams & Newman, 2015; Van Hell, Ormbel, Van der Loop & Hermans, 2009; see also Emmorey, Giezen, & Gollan, 2015 for a review). Understanding lexical access in bilingual bimodals is of particular interest because unlike unimodal bilinguals, there are no shared sub-lexical representations for sign-written bilinguals.

In all of the sign and word perception studies, an item that is phonologically related to the translational equivalent of the target was present in the experimental context (e.g., as a prime in a primed lexical decision task, a distractor in a visual world paradigm, picture-word interference task, semantic relatedness task, or word-picture verification task). Cross-modal activation was assessed by comparing performance with a phonologically related prime/distractor to performance without a prime/distractor. These tasks demonstrate that during perception of a word or sign, the lexical and sub-lexical representations of its translational equivalent are active.

In Study 2, we ask whether other lexical items in English, not only the translational equivalent, compete during sign perception. Using the lexical decision data from Study 1, we asked whether the neighborhood density and lexical frequency of the English translational equivalents significantly predicted the speed of identification of lexical items in ASL.

Methods and Results

The methods, participants, and data used in Study 2 are the same as those used in Study 1.

The orthographic neighborhood density (number of words that differ by one letter from the gloss), and lexical frequency of the English translations each sign was extracted from the English Lexicon Project (Balota et al., 2007). Though the ideal English translations for a sign may vary depending on the context in which the sign is used, the English glosses were selected because they were reasonably common translations of the signs. Though these glosses are not perfect translational equivalents, they can offer some insight into the effect of English co-activation during sign perception.

A model was constructed containing the nuisance variables, SpeechExposure, ASLExposure, SignFrequency, MaximalNeighborhoodDensity, the English Gloss Frequency, and English Gloss Orthographic Neighborhood Density. English Gloss Orthographic Neighborhood Density predicted reaction time (β =-0.003, s.e. = 0.008, t = -

2.98). Words in large orthographic neighborhoods were identified faster than words in small orthographic neighborhoods.

Discussion

Orthographic neighborhood density was a negative predictor of reaction time—signs whose English translations have many neighbors were identified faster than signs whose English translations have few neighbors. The direction of this relationship is similar to effects of orthographic neighborhood density on monolingual spoken word recognition in an auditory lexical decision task and a shadowing task (Ziegler, Muneaux, & Grainger, 2003).

The effect of orthographic neighborhood density may also reflect an effect of phonological neighborhood density, because the two are correlated. It was not possible to tease the two measures of neighborhood density apart in this dataset. We are inclined to interpret these results as orthographic in nature because these participants are deaf are may be more likely to have orthographic than phonological representations of English words. Nevertheless, more work is needed in this area.

This confirms that deaf bilinguals co-activate English words during sign comprehension, though this was not a task demand. It also suggests that not only are the lexical and orthographic representations of the English translational equivalents active during sign processing, but other orthographically related lexical items are also active. For this to be true, the lexical representations of the English translations would have to become active either via direct lateral connections with the ASL lexical representations (see Emmorey, Giezen, & Gollan 2015 for a review) or via feedback from shared semantic representations. Then the English lexical representations would activate their orthographic units via feedback, which would then activate other English lexical representations.

Chapter 5 The Signed Lexicon

The goal of this dissertation was to characterize the ASL lexicon, the mechanisms of lexical access in sign perception, and the effects of language deprivation on sign perception. I was also able to begin to explore some questions about bilingualism in sign perception.

Modality Differences in Lexical Access

In Chapter 3, I developed the first known computational model of sign language perception. I simulated a pattern of reversals in sign perception whereby signs that share their location with many other signs are harder to perceive than those that share their location with few other signs, while signs that share their handshape with many other signs are easier to perceive than those that share their handshape with few other signs. This simulation borrowed principles developed in models of spoken language processing, minimally altering the structure of these models. I was able to successfully capture the human pattern of reversals by 1) manipulating the resting activation of the sub-lexical units and by 2) manipulating the timing of activation of the sub-lexical units. I was unable to capture the human pattern of behavior by 3) manipulating the number of competing lexical items (i.e., neighborhood density).

This work serves as a proof of concept that despite vast differences in the surface structure of signs and spoken words (signs are perceived visually, and words auditorily), the mechanisms of sign and word perception may be remarkably similar. It also serves as a framework for understanding the functional architecture of sign perception. More broadly, these simulations suggest that the neighborhood density reversals seen across spoken, written, and signed language arise because of variation at the sub-lexical level and not the lexical level.

While in Chapter 4 I was able to replicate the inhibitory effect of location frequency found in Carreiras et al. (2008), I was unable to replicate the pattern of reversals. In contrast to the facilitatory effects of handshape frequency identified by Carreiras et al. (2008), I found no effect of handshape frequency. While this may reflect unidentified cross-linguistic differences between ASL and LSE, it may also arise for more practical reasons (e.g., different definitions of handshapes). More work using consistent methodologies is needed to make a determination here.

In Chapter 4 I also found effects of neighborhood density in people who had a low levels of ASL exposure, but not in people who had high levels of ASL exposure. This suggests that there may be difference in modality where neighborhood density matters for native users of spoken but not signed language. These native users may be making use of early cues as a signer prepares to articulate a lexical item. This kind of preparatory information is not available in spoken language—a listener cannot perceive the movements of the mouth as the prepare to produce a spoken word, while a signer can glean substantial information about the hand configuration location and movement before any of these has actually been produced.

The Structure of the ASL Lexicon

Research on sign perception has been frustrated by a lack of a lexical database containing information about lexical and phonological properties of signs. In particular, findings about the effects of phonological neighbors have been difficult to interpret due to inconsistencies in definitions of phonological overlap. In Chapter 2, I presented a lexical database of nearly 1,000 ASL signs that contains more than forty lexical and phonological properties including iconicity ratings, phonological transcriptions, and neighborhood density.

This work revealed several things about the structure of the lexicon. First and foremost, it describes the distribution of many lexical and phonological properties in the ASL lexicon. It also demonstrates that iconicity shapes the ASL lexicon. High frequency signs tend to be less iconic; and signs in dense phonological neighborhoods tend to be more iconic. Despite differences in the phonological forms of signs and words (manual/visual versus oral/auditory), the signed and spoken lexicons are both organized into neighborhoods based on phonological overlap. As in spoken language, common signs tend to reside in dense phonological neighborhoods.

For the purposes of this dissertation, ASL-LEX made it possible to conduct a detailed investigation of sign perception controlling for many more factors than ever before. This is the first time neighborhood density and sub-lexical frequency estimates have been available for ASL, and enabled the first investigation of the role of these two factors in sign perception.

Because ASL-LEX is publicly available, it can be used by educators, students, and researchers. ASL teachers can use it to illustrate phonological relationships between signs, to highlight important phonological contrasts, or to select vocabulary items for instruction. ASL students can use it as a supplementary tool to aid vocabulary acquisition. It can also be used with young children to track acquisition of ASL. As it was used in this dissertation, ASL-LEX can be used by researchers to control for or examine the effects of many lexical and phonological properties.

The Effect of Early Language Experience on Sign Perception

In Chapter 4, I explored the mechanisms of sign perception in adults with varying early language experiences. I only found neighborhood density effects in people with low ASL exposure, not in native signers. I found that where there were effects of neighborhood density and sub-lexical frequency, they always predicted slower response times. This may be because people with high ASL exposure are extremely efficient and processing signs, perhaps using early phonetic cues to identify signs. In contrast, people with low ASL exposure are not able to make use of this early phonetic information and may rely more on late occurring phonological information to identify signs.

Lexical Access in Deaf ASL-Written English Bilinguals

Finally, in a post hoc analysis I found that orthographic neighborhood density of the English translations facilitates sign perception. This adds to the literature on bilingualism and suggests that not only do deaf bilinguals activate English translations during sign perception, they also activate orthographically related English words. This suggests that during sign perception, English translations become activated either via lateral connections with the target lexical item or via feedback from shared sematic representations. Then orthographic representations become active through feedback connections, which in turn activate other English lexical items through feedforward connections. In sum, this suggests that competition among lexical items is not limited to items that share sub-lexical units with the incoming signal. Rather, words that are not related in form to the target but are related in form to other simultaneously active words participate in lexical access.

APPENDIX A

English instructions for frequency rating

This is an ASL rating task. Here is an explanation of what you will be doing. You will see movies of different signs. Your job is to decide how often you feel each sign shows up in conversation, chatting, work, family, etc. Just use your gut feeling about how often you see that sign. It's important that you please rate the score based on my sign not yours if your sign is different from mine.

You will see the numbers 1 thru 7. A 7 means you see the sign frequently. A 1 means you see the sign once in a while. For example, for the sign DEAF, if you feel that sign tends to occur very frequently, you would click 7. Another example, the sign for SHY, maybe you feel that sign happens somewhat frequently, so maybe you would click 4. While the sign for Thanksgiving, maybe you feel only happens once in a while, so maybe click 1. There is no right or wrong answer. We just want you to rate them based your gut feeling.

We would like you to take your time and really think. Please don't hurry and just pick any number. Also, please use all the numbers 1, 2, 3, 4, 5, 6, 7; do not just pick the same number over and over. After you've rated the sign and clicked the number, sometimes you will see a white box under the sign that says "English Translation". If you see that box, then you need put down the English word based on sign you just saw.

It's important that you take this test seriously because we need to collect data based on the frequency of signs you see in ASL. So, please do not guess or just pick any number. We really appreciate you doing this task for us.

(The English instructions were translated from the ASL instructions).

Written instructions for iconicity ratings

For this task we want to know how iconic you think some signs in American Sign Language are. First we will explain what we mean by iconic: some signs look like what they mean. For example, the sign for 'drink' is generally thought to be very iconic, because it looks like a person holding a cup and bringing it to their mouth. A person who does not know sign language might be able to guess this sign’s meaning. Other signs are not iconic at all; for example, the sign for 'brother' does not look like a brother.

Signs can be iconic for different reasons. Some signs, like the sign for 'drink', show the way an object is used. Other signs, like the sign for 'ball' show the shape of the object.

For each sign that you will see, rate on a scale of 1 to 7 how iconic you think the sign is, with 1 as not iconic at all and 7 as extremely iconic. For example DRINK is extremely iconic; it looks just like drinking from a cup, so this would be a 7. BROTHER is not at all iconic and would be a 1. Signs that are intermediate in iconicity, of course, should be rated appropriately between the two extremes, for example the sign COOK may have a rating of 3 or 4.

Feel free to use the entire range of numbers, from 1 to 7; at the same time, don’t be concerned about how often you use a particular number as long as you are honest in your ratings. Work fairly quickly but do not be careless in your ratings, the important thing is for you to be as accurate as possible.

APPENDIX B

ASL Exposure
Who did you learn ASL from (check all that apply)?-Parents
Who did you learn ASL from (check all that apply)?-Brothers/Sisters
Who did you learn ASL from (check all that apply)?-Friends
Who did you learn ASL from (check all that apply)?-Teachers
What kind of language did you use in school (check all that apply)?-Preschool-ASL
What kind of language did you use in school (check all that apply)?-Preschool-PSE
What kind of language did you use in school (check all that apply)?-Elementary School-ASL
What kind of language did you use in school (check all that apply)?-Elementary School-PSE
What kind of language did you use in school (check all that apply)?-Junior High School-ASL
What kind of language did you use in school (check all that apply)?-Junior High School-PSE
What kind of language did you use in school (check all that apply)?-Hgh School-ASL
What kind of language did you use in school (check all that apply)?-Hgh School-PSE

APPENDIX C

Spoken English Exposure
What kind of language did you use in school (check all that apply)?-Preschool-Cued Speech
What kind of language did you use in school (check all that apply)?-Preschool-Spoken English
What kind of language did you use in school (check all that apply)?-Elementary School-Cued Speech
What kind of language did you use in school (check all that apply)?-Elementary School-Spoken English
What kind of language did you use in school (check all that apply)?-Junior High School-Cued Speech
What kind of language did you use in school (check all that apply)?-Junior High School-Spoken English
What kind of language did you use in school (check all that apply)?-Hgh School-Cued Speech
What kind of language did you use in school (check all that apply)?-Hgh School-Spoken English
How frequently did you use your hearing aids or cochlear implant / while awake?-Before you were 5 years old
How frequently did you use your hearing aids or cochlear implant / while awake?-When you were 5-10 years old
How frequently did you use your hearing aids or cochlear implant / while awake?-When you were 10-15 years old
How frequently did you use your hearing aids or cochlear implant / while awake?-When you were 15-20 years old
How frequently did you use your hearing aids or cochlear implant / while awake?-As an adult
If you were in a quiet room, how well could you understand a person / speaking if you had your eyes...-Before you were 5 years old
If you were in a quiet room, how well could you understand a person / speaking if you had your eyes...-When you were 5-10 years old
If you were in a quiet room, how well could you understand a person / speaking if you had your eyes...-When you were 10-15 years old
If you were in a quiet room, how well could you understand a person / speaking if you had your eyes...-When you were 15-20 years old
If you were in a quiet room, how well could you understand a person / speaking if you had your eyes...-As an adult
If you were in a quiet room, how well could you understand a person / speaking if you were looking...-Before you were 5 years old
If you were in a quiet room, how well could you understand a person / speaking if you were looking...-When you were 5-10 years old
If you were in a quiet room, how well could you understand a person / speaking if you were looking...-When you were 10-15 years old
If you were in a quiet room, how well could you understand a person / speaking if you were looking...-When you were 15-20 years old
If you were in a quiet room, how well could you understand a person / speaking if you were looking...-As an adult
How easily could you use spoken English to express yourself?-Before you were 5 years old
How easily could you use spoken English to express yourself?-When you were 5-10 years old
How easily could you use spoken English to express yourself?-When you were10-15 years old
How easily could you use spoken English to express yourself?-When you were between 15 and 20 years old
How easily could you use spoken English to express yourself?-As an adult
How easily could you understand people who used spoken English with / you?-Before you were 5 years old
How easily could you understand people who used spoken English with / you?-When you were 5-10 years old
How easily could you understand people who used spoken English with / you?-When you were10-15 years old
How easily could you understand people who used spoken English with / you?-When you were between 15 and 20 years old
How easily could you understand people who used spoken English with / you?-As an adult

APPENDIX D

Communication Ease
How easily could you communicate with your friends?-Before you were 5 years old
How easily could you communicate with your friends?-When you were 5-10 years old
How easily could you communicate with your friends?-When you were10-15 years old
How easily could you communicate with your friends?-When you were between 15 and 20 years old
How easily could you communicate with your friends?-As an adult
How many friends did you have?-Before you were 5 years old
How many friends did you have?-When you were 5-10 years old
How many friends did you have?-When you were10-15 years old
How many friends did you have?-When you were between 15 and 20 years old
How many friends did you have?-As an adult
How frequently did you encounter difficulties in communicating with / friends?-Before you were 5 years old
How frequently did you encounter difficulties in communicating with / friends?-When you were 5-10 years old
How frequently did you encounter difficulties in communicating with / friends?-When you were10-15 years old
How frequently did you encounter difficulties in communicating with / friends?-When you were between 15 and 20 years old
How frequently did you encounter difficulties in communicating with / friends?-As an adult
How frequently did you encounter difficulties in communicating with / family members?-Before you were 5 years old
How frequently did you encounter difficulties in communicating with / family members?-When you were 5-10 years old
How frequently did you encounter difficulties in communicating with / family members?-When you were10-15 years old
How frequently did you encounter difficulties in communicating with / family members?-When you were between 15 and 20 years old
How frequently did you encounter difficulties in communicating with / family members?-As an adult
How socially isolated did you feel?-Before you were 5 years old
How socially isolated did you feel?-When you were 5-10 years old
How socially isolated did you feel?-When you were10-15 years old
How socially isolated did you feel?-When you were between 15 and 20 years old
How socially isolated did you feel?-As an adult
How socially connected did you feel-Before you were 5 years old
How socially connected did you feel-When you were 5-10 years old
How socially connected did you feel-When you were10-15 years old
How socially connected did you feel-When you were between 15 and 20 years old
How socially connected did you feel-As an adult

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