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The signed mental lexicon: Effects of phonological neighborhood density, iconicity, and childhood language experience

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ABSTRACT

Most of what is known about the mental lexicon comes from studies of spoken language and their written forms. Signs differ from spoken/written words in two important ways that may affect lexical recognition: their phonological composition is unique (e.g., more simultaneous than serial structure; few minimal pairs) and many signs are iconic. Using an unprimed lexical decision task in American Sign Language (ASL) and the first available estimates of phonological neighborhood density for any sign language, we found that phonological neighborhood density had an inhibitory effect on latency among low frequency signs. This is the first clear evidence that phonological neighbors spontaneously compete during sign recognition. Iconicity negatively affected accuracy but not reaction times, suggesting that iconicity plays a role in task-related decision processes but not lexical retrieval. Many deaf signers have delayed first language acquisition, and we found that language deprivation had lasting, negative effects on phonological processing and sign recognition speed and accuracy. This work indicates that the lexicons of both spoken and signed languages are organized by form, that lexical recognition occurs through form-based competition (most evident for low frequency items), and that form-meaning mappings do not drive lexical access even when iconicity is pervasive in the lexicon.

Despite early beliefs that sign languages were not languages at all, the past several decades of research have demonstrated that they possess all the linguistic hallmarks of natural languages and are acquired and processed in broadly similar ways to spoken languages. At a computational level, however, psycholinguistic theories of sign recognition remain woefully underspecified. There does not currently exist any generally-accepted theory of sign recognition, which stands in stark contrast to the situation for spoken and written language processing. In their review of the literature, Carreiras, Gutiérrez-Sigut, Baquero, and Corina (2008) find many areas with contradictory empirical findings and provide the assessment that overall, "…sign language psycholinguistics is still at the data collection stage." (p. 102).

Building a theory of lexical recognition in sign language is clearly important in its own right. It also presents the opportunity to discover what are perhaps even deeper facts about processing that can only come from comparing processing across modalities: determining which aspects of lexical recognition are invariant and common to all language processing and which aspects are idiosyncratic and modality-specific. In this article we pursue both of these goals by investigating whether three unique properties of sign languages influence the process of sign recognition.

The first unique property is the formal organization of sign languages. Due to the nature of the articulators and the modality, signs are composed of different formal features than spoken and written languages (see Fig. 1). A second unique property of sign language lexicons is that they include many iconic signs—signs that visually resemble their meaning (e.g., Fig. 2). As a result of these differences, the signed mental lexicon may be organized according to different principles than spoken and written lexicons and the process by which the input signal is used to retrieve a sign may be fundamentally different from auditory or written word recognition.[1] The third unique property is the fact that the majority of deaf sign language users experience delayed first language acquisition (also known as *language deprivation*). This can have lasting effects on phonological processing though the exact nature of the effects

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[1] We use the term 'written word recognition' rather than the more commonly used 'visual word recognition' to avoid confusion because both signs and written words are recognized visually.

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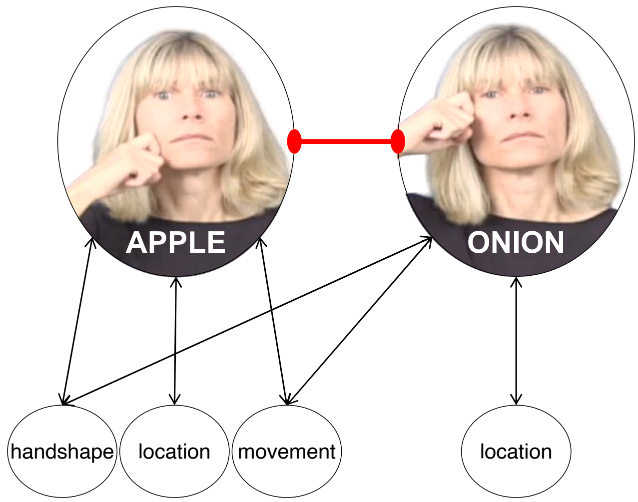

Fig. 1. Model of sign recognition (Caselli & Cohen-Goldberg, 2014). The lower level illustrates sub-lexical phonological representations and the upper level illustrates lexical representations. The images of the signs are just for illustrative purposes and are not intended to imply that visual information is stored in lexical representations. According to this theory, phonological representations can activate lexical representations and vice versa (illustrated by arrows), and lexical representations can laterally inhibit other lexical representations (illustrated by the red lateral connection).

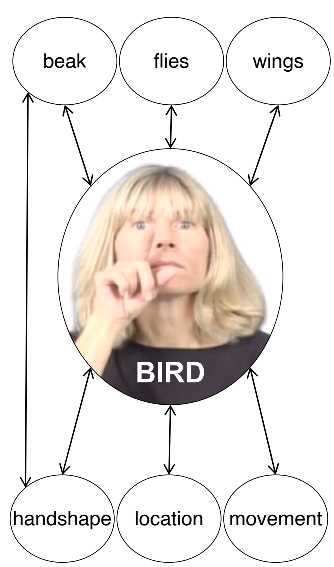

Fig. 2. Model of iconicity in sign recognition. The lower level illustrates phonological representations, the middle level illustrates lexical representations, and the top level illustrates semantic feature representations. In perceiving iconic signs like the ASL sign BIRD, activation may pass directly from phonological to semantic features.

is unclear. Language deprivation is extremely rare among hearing people, but tragically common among deaf people.

Our objective in this paper is to determine whether and how phonology, iconicity, and language deprivation influence sign recognition with the goals of 1) informing psycholinguistic theories of sign processing and 2) understanding the role that modality and acquisition play in structuring processing. At the level of sign processing, we ask two theoretical questions: do phonological neighbors become activated during sign recognition and do signers use iconic mappings between form and meaning to guide the recognition process? At the broader level, understanding how differences in modality and acquisition influence lexical recognition can help us determine which aspects of recognition are invariant and which are dependent upon experience.

The phonological structure of sign languages

Sign languages, like all human languages, have phonology: systems of discrete formal elements that are combined in specific ways to create lexical items. At a basic level, signs are comprised of a handshape, location, and motion, with each sign having a unique combination of these elements. There is a finite inventory of values that these features can take on and these values are often contrastive (e.g., compare APPLE and ONION; Fig. 1, which have the same handshape and motion but differ in their location). While this is broadly similar to the structure of spoken and written languages, the unique properties of sign phonologies result in a number of important differences that may be relevant for how signs are ultimately recognized.

The phonological organization of sign languages is very different from spoken languages (Brentari, 1998; Sandler, 1989; van der Kooij, 2002). Spoken words are made up of concatenated, segmental phonemes, which are in turn made up of phonological features. In contrast, signs are made up of simultaneously articulated parameters that are all obligatory (i.e., a sign cannot be articulated without a handshape, location, motion, and palm orientation), and these parameters are made up of features, though many features occur only once per sign (e.g., a free morpheme can only have one set of selected fingers, Mandel, 1981). Most theories of lexical recognition posit that segmental units (phonemes, graphemes) are the basic units of processing at the form level and it is unclear how the mental lexicon would be structured without segmental phonemes. Second, sign languages are thought to have far fewer minimal pairs than spoken languages (e.g., Eccarius & Brentari, 2010). This may mean that contrastive phonological elements are a less useful organizing principle for the mental lexicon in sign languages than in spoken languages.

A particularly interesting and unique property of sign languages is that counter to the traditional view that lexical items are arbitrary forms generated through the combination of phonological parts (Hockett, 1960; Saussure, 1966), sign forms are often iconically motivated and resemble sensory or motoric experiences with their referents (Perlman, Little, Thompson, & Thompson, 2018; Perniss, Thompson, & Vigliocco, 2010; Taub, 2001). For example, the American Sign Language (ASL) sign BIRD is produced with the index finger and thumb in a pinching movement near the chin, with these phonological features seemingly corresponding to the shape, location, and movement of a bird's beak (see Fig. 2). We note that spoken languages also have iconic words. For example, in addition to onomatopoeia, words can convey repetition through reduplication, duration through vowel lengthening, or weight through consonant voicing (see Dingemanse, Blasi, Lupyan, Christiansen, & Monaghan, 2015 for a review). Nonetheless, iconicity is likely far more prevalent and salient in sign languages.

Collectively these differences could have profound effects on how the mental lexicon is organized and how signers use the physical signal to determine which signs were produced, as outlined below.

Lexical recognition

To date, nearly all psycholinguistic theories of word recognition have been developed to account for the processing of auditory and written words. These theories generally hold that lexical recognition involves a two-stage process whereby the physical signal is first parsed into sub-lexical units (e.g., in written comprehension: visual features, abstract letter identities; in auditory comprehension: acoustic features, phonemes, syllables) which are then used to retrieve lexical items from the mental lexicon (e.g., Goldinger, Luce, & Pisoni, 1989; Marslen-Wilson & Tyler, 1980; McClelland & Elman, 1986; Norris & McQueen, 2008). During this process partially matching words (e.g., orthographic or phonological neighbors) are also activated and become candidates for selection. This occurs because sub-lexical units spread activation to (or in Bayesian theories, provide evidence for) the lexical items that contain them. The final stage is semantic access, where activated or selected lexical representations provide access to word meaning.

If signs are recognized through a similar two-stage process, the visual signal of an unfolding sign would be first parsed into the recurring sub-lexical units of the language (e.g., the sign's location, handshape, and motion). These sub-lexical features would then be matched in some way against stored lexical representations and these in turn would become active and provide access to semantic representations (see Fig. 1; Caselli & Cohen-Goldberg, 2014). Indeed, a handful of studies have reported evidence supporting a two-stage procedure in sign recognition (Carreiras, 2010; Carreiras et al., 2008; Corina & Hildebrandt, 2002; Dye & Shih, 2006; Meade et al., 2021; Corina and Emmorey, 1993; Mayberry & Witcher, 2005).

While sign recognition seems to involve the same general stages as auditory and written word recognition, very little is known about how it specifically occurs. We focus here on two key aspects: whether phonological neighbors become activated during recognition and whether or not signers can make use of iconic form-meaning relationships during the recognition process.

The role of neighbors in sign recognition

To date, no direct evidence has been found for the spontaneous activation of phonological neighbors in sign processing. Several studies have found that phonologically related signs can influence sign recognition when they are explicitly presented as stimuli, for example as primes in lexical or semantic decision studies (Corina & Emmorey, 1993; Dye & Shih, 2006; Corina & Hildebrandt, 2002; Mayberry & Witcher, 2005; Meade, Lee, Midgley, Holcomb, & Emmorey, 2018) or as distractors in the visual world paradigm (Lieberman & Borovsky, 2020). However, these effects could arise simply because the related sign was always presented in close temporal or physical proximity to the target sign. Thus, while these studies demonstrate that co-activated signs influence the recognition of target signs, they do not tell us whether phonological neighbors spontaneously become activated and affect processing during the normal course of sign recognition.

The standard way to demonstrate the spontaneous influence of neighbors during processing is to show that a stimulus word's *neighborhood density*—the number of words differing from the target word by one phoneme/letter—affects how quickly or accurately participants process that word. Numerous studies have demonstrated neighborhood density effects in written word recognition (Andrews, 1997; Coltheart, Davelaar, Jonasson, & Besner, 1977; Grainger, Muneaux, Farioli, & Ziegler, 2005; Yates, Locker, & Simpson, 2004) and auditory word recognition (e.g., Dufour & Peereman, 2003; Garlock, Walley, & Metsala, 2001; Goldinger et al., 1989; Luce, 1986; Luce & Pisoni, 1998; Magnuson, Dixon, Tanenhaus, & Aslin, 2007).

If neighbors spontaneously influence processing in sign languages, the process of recognition might be as follows. The visual signal of an unfolding sign (e.g., APPLE) would be first parsed into the recurring sub-lexical units of the language (e.g., the sign's location, handshape, and motion). These sub-lexical features would then be matched in some way (e.g., spreading activation, Bayesian inference) against stored lexical representations. When recognizing the sign APPLE, the shared sub-lexical units would cause both APPLE and ONION to become active. ONION could then influence the recognition of APPLE in some way, perhaps inhibiting it through lateral lexical-lexical connections, facilitating it through bidirectional connections with sub-lexical units, or both (Caselli & Cohen-Goldberg, 2014). Evidence of the spontaneous influence of phonological neighbors during sign recognition would lend support to existing theories of sign processing, and moreover would suggest that the two-stage organization is a language-general property of lexical recognition.

We are aware of only one study that has attempted to ask whether neighborhood density plays a role in sign recognition. Using an unprimed lexical decision task, Carreiras et al. (2008) found that in Spanish Sign Language (LSE), responses were slower for signs that use frequently occurring locations (have many "location neighbors") than those that use rare locations, and responses were faster for signs that use frequently occurring handshapes (have many "handshape neighbors") than those that use rare handshapes. The authors suggest that this reversal in the effects of handshape and location may be due to modality-specific properties of sign language; for example, handshapes have detailed, hierarchical phonological representations while locations do not. Unlike the studies described above in which a phonologically related sign is present in the experimental context, the effects of neighbors in Carreiras et al. (2008) cannot be attributed to exogenous activation. However, the definition of neighbors that Carreiras et al. (2008) used—the number of signs in the lexicon that share *one specific* sub-lexical unit—differs from traditional definitions of neighbors (the number of signs in the lexicon that share *all but one* sub-lexical unit). By the definition used by Carreiras et al. (2008), neighborhood density is identical to sub-lexical frequency (the frequency of a sub-lexical unit in the lexicon). While neighborhood density and sub-lexical frequency are presumably often correlated, in this case the two are numerically identical. There is thus not yet conclusive evidence that traditionally-defined phonological neighbors are spontaneously activated during sign recognition.

The role of iconicity in sign recognition

Iconicity seems to play an important role in coining new terms (Imai & Kita, 2014), learning new words/signs (Caselli & Pyers, 2017; Caselli & Pyers, 2019; Thompson, Vinson, Woll, & Vigliocco, 2012; Perry et al., 2015), and in supporting communication between people who do not share a language (Sakamoto, Ueda, Doizaki, & Shimizu, 2014), but the evidence is mixed with respect to whether it influences sign recognition.

In principle, iconicity could serve as a supplementary cue to recognize signs. Within the general psycholinguistic architecture of word recognition described above, iconicity—if it were to influence the recognition process—could act through direct connections between a sign's phonological and semantic features. In the same way that listeners can make use of sub-phonemic auditory cues like duration and pitch to disambiguate short and long words (e.g., Davis, Marslen-Wilson, & Gaskell, 2002; Blazej & Cohen-Goldberg, 2015), signers may utilize low-level phonological information to pre-activate semantic fields and sets of semantically related words. For example when viewing the sign BIRD, the extended thumb and index finger could directly activate the semantic feature [beak]. This could influence recognition by pre-activating semantic features and sending feedback activation to lexical items containing those features. However, a couple of theoretical factors suggest that iconicity may not play a role in sign recognition. First, while many signs are iconic, most signs are not highly iconic (see Caselli, Sevcikova Sehyr, Cohen-Goldberg, & Emmorey, 2017 for data about ASL), and so an architecture of sign recognition that includes iconic routes to lexical recognition may be inefficient. Second, the two-stage architecture suggested by findings from auditory and written word recognition does not include direct connections between sub-lexical and semantic levels; access to semantics is fundamentally mediated by lexical representations. If this architectural format represents a general processing principle for lexical recognition, iconicity would consequently not be a feature that could be used in sign recognition.

Empirical evidence for effects of iconicity in sign recognition are mixed. In a picture-sign matching task, iconicity facilitated response times when the picture highlighted a property that was iconically represented in the sign (Thompson, Vinson, & Vigliocco, 2009; Vinson, Thompson, Skinner, & Vigliocco, 2015). Iconicity also speeded response times in a verification task (e.g., is *beak* a feature of an eagle?) when the feature was an iconically motivated aspect of the sign (Grote & Linz, 2003). Iconicity has also been found to affect response times in a phonological decision task: iconicity slowed response times when participants were asked if the sign involved straight or curved fingers (Thompson et al., 2009) and speeded response times when asked if the sign included an upward or downward movement (Vinson et al., 2015). A recent study of spoken language showed facilitatory effects of iconicity on word recognition in a lexical decision task and a phonological lexical decision task, i.e., "does this letter string sound like a word?" (Sidhu, Vigliocco, & Pexman, 2020). Together these various studies suggest that iconicity can affect sign and word processing, but whether iconicity facilitates or inhibits recognition varies across tasks.

However, effects of iconicity are not consistently found. In a primed lexical decision task, Bosworth and Emmorey (2010) found that iconicity did not boost semantic priming and that lexical decision times to iconic signs did not differ from non-iconic signs. Similarly, Mott, Midgley, Holcomb, and Emmorey (2020) found no effects of iconicity on the response times for deaf signers using a cross-modal translation recognition task. Lastly, Emmorey, Winsler, Midgley, Grainger, and Holcomb (2020) found no ERP effects of iconicity during lexical access in a go/no-go semantic categorization task, even though hallmarks of lexical access–frequency and concreteness–were observed during this time window.

Emmorey (2014) has argued that the inconsistency in iconicity effects across studies may be due to differences in task demands, with iconicity effects emerging only in tasks that emphasize analyzing the relationship between a sign's form and its meaning. Another possibility is that iconicity, when observed, has effects at relatively late stages of processing (e.g., decision making) but not during relatively early stages of lexical recognition (e.g. lexical selection, semantic access). Consistent with this possibility, ERP studies have found that iconicity does not have effects during the time period associated with lexical access (400–600 ms), but does at late windows (800–1200 ms) that may be associated with decision making (Emmorey et al., 2020; Mott et al., 2020).

Effects of delayed first language exposure on lexical recognition

Studying sign processing offers another unique opportunity to understand the space of variance and invariance in word recognition processes through the lens of language acquisition. Sign language users are extremely heterogenous with respect to their early language experience. While some deaf children learn a signed language from their parents and peers just as hearing children learn spoken language, the majority of deaf children are born to hearing families (Mitchell & Karchmer, 2004), most of whom do not use sign language at home (Mitchell & Karchmer, 2005). Impoverished and/or delayed exposure to language affects proficiency at all linguistic levels including 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 skills (Mayberry & Fischer, 1989). Though it is possible to develop a lexicon later in childhood (Ramírez et al., 2013), delayed exposure to a signed language affects how easily lexical items can be processed (Carreiras et al., 2008; Lieberman et al., 2015). Understanding how language deprivation affects language processing offers a unique way of learning about the role of early language experience in the organization of the mental lexicon. There are few opportunities to ask these questions, as language deprivation does not exist outside the deaf population except in rare cases of child abuse.

Of particular interest here is that delayed language exposure appears to alter the way phonological information is recruited during lexical access. Late sign language learners—those who learned sign language after age nine—produce more phonological errors than early signers—those who learned sign language from birth from their deaf parents (Mayberry & Fischer, 1989). When phonologically related signs are presented as primes in a lexical decision task, they facilitate processing in early learners but inhibit processing in late learners (Mayberry & Witcher, 2005). In a visual world paradigm, Lieberman et al. (2015) also compared early and late ASL learners (before age 2 vs. after age five), and found different looking patterns to phonologically related signs for early and late learners. Together these results suggest that delayed sign language acquisition can disrupt phonological processing in sign recognition in adults, though the precise nature of this disruption is unclear. We ask here whether the spontaneous activation of phonologically related lexical items may also differ in early versus late signers.

Examining the influence of early language exposure thus allows us to ask which properties of lexical recognition are invariant (that is, that arise in any language user regardless of how they acquired language) and which are specifically dependent upon early and consistent exposure.

The present investigation

In the present study, we explore the mechanisms of lexical recognition in sign language. We make use of an unprimed lexical decision task in ASL for a number of reasons. First, the lexical decision task has been extensively used in spoken and written language research, allowing us to make comparisons across the modalities. Second, the fact that only target signs are presented as stimuli allows us to determine whether phonological neighbors are spontaneously activated during sign comprehension, a key prediction of the two-stage lexical access account. Finally, this task does not specifically ask participants to attend to sign form, meaning, or their pairing, allowing us to determine if iconicity influences sign recognition in a general context.

A novel component of our study is the use of precise phonological neighborhood density counts and frequency estimates in our analyses. Until recently there were no estimates of phonological neighborhood density in any sign language, so studies of sign language recognition have had to present a phonologically related sign alongside a target in experiments (e.g., a prime in priming studies or a distractor in the visual world paradigm). We define sign neighbors in a way that is more analogous to that used for spoken language (i.e., defining neighbors by the number of features that overlap, rather than the exact feature that overlaps). This definition allows us to ask for the first time whether the number of phonological neighbors (and not the frequency of phonological properties) affects sign perception. We also make use of systematically collected lexical frequency estimates which have also been unavailable for ASL until recently. This allows us to not only investigate the effect of frequency in sign recognition but to investigate whether there is an interaction between neighborhood density and frequency. Studies of spoken and written word recognition have often found that neighborhood density effects are stronger in low frequency words (e.g., Andrews, 1989, 1992; Lim, 2016; Vitevitch & Sommers, 2003; Yap & Balota, 2009). One explanation for this interaction is that high frequency words are so easy to access or so robustly represented that they are not sensitive to the more subtle effects of competition among phonological neighbors. As such, we also examine whether such an interaction is present in sign recognition.

In this study we ask:

1. Do phonologically related items spontaneously compete during sign recognition (i.e., when no competitors are present in the experimental context)? Specifically, is there a frequency by neighborhood density interaction, as found in spoken and written language?
2. Does iconicity spontaneously affect sign recognition (i.e., in a task that does not emphasize form-meaning mappings)?
3. Does early language experience affect sign recognition?
4. Do effects of neighborhood density or iconicity differ as a function of language deprivation in early childhood?

If we observe differences in how signs are processed and how spoken and written words are processed (e.g., no effects of neighborhood density, speeded access to semantics via iconicity), such findings would indicate language modality can have a profound impact on the architecture of processing. If we observe similarities (e.g., neighborhood effects, no effect of iconicity), it would suggest that the principles in question are largely invariant. If we find that delayed first language exposure alters these effects, it would indicate that the mechanisms that underpin lexical recognition are shaped by the nature of early language experiences. If we find that delayed first language exposure has no effect on processing, it would indicate that lexical recognition is one of the few aspects of language processing that is robust to language deprivation.

Methods

Participants

Seventy-seven deaf participants (female = 44, male = 31, unspecified = 2) who considered themselves to be fluent signers of ASL and became deaf before age three were recruited (M_{age} = 39 years, *SD* = 13 years). Because the target population is small, we recruited as many participants as possible during the recruitment period. Participants' place of residence at the time of testing was distributed geographically across 26 US states and two Canadian provinces; one person lived elsewhere outside the US and one did not report.

Participants completed a questionnaire about language exposure during childhood. The survey was administered by a hearing native ASL user, and participants could choose to access each question in written English, ASL, or both. Most participants were deaf at birth (n = 54), 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* = .77). *Age of First ASL Exposure* ranged from birth (n = 32) to age 22. We also calculated *Quantity of ASL Exposure* based on the number of people who signed to the participant in early childhood (one point for each of the following: parents, siblings, friends, teachers), and the amount of time spent in an ASL educational placement (one point for each of the following: preschool, elementary, junior high school, high school). The composite score for Quantity of ASL Exposure was calculated as the proportion of points out of the maximum possible points. While traditionally studies have examined language background among signing deaf people based on parental hearing status and/or age of ASL acquisition, quantifying ASL exposure offers a more nuanced, and in some ways more direct, measure of early language experience. The distribution of Age of First ASL Exposure and Quantity of ASL Exposure are presented in Fig. 3.

Procedure

After the consent form, participants completed a lexical decision task, developed with the experimental software SuperLab, 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 color-coded keys on a keyboard (left/yellow = real, right/blue = 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 1000 ms.

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 recognize to be 'real' even if they might personally prefer to use a different lexical item (e.g., there are at least two widely used signs that mean 'hospital,' and some people prefer to use one over the other). They were also told that all of the real signs would be well-known, generic sign forms, and not constructions that would only be possible in very specific, unusual contexts (e.g., the generic sign SURGERY is canonically produced on the palm of hand, though it might be modified and produced on any other body part to precisely describe an incision on that body part). After the instructions, they completed 20 practice trials (ten real and ten non-signs) and received feedback for each answer. There were eight evenly spaced breaks, and a notice was given when the experiment was halfway complete. The demographic questionnaire was completed after the lexical decision task.

Materials

Signs were drawn from ASL-LEX 1.0 (Caselli et al., 2017),[2] which contains nearly forty different pieces of information about approximately 1,000 signs, including estimates of frequency and iconicity. It also includes a phonological description of each sign, which enabled the first neighborhood density counts in any sign language. ASL-LEX is publicly available via an interactive website (www.asl-lex.org). Having all of this information about a large swath of the lexicon makes it possible for the first time to adequately control for these possible confounds.

A subset of 300 picturable signs were selected from the ASL-LEX database (Caselli et al., 2017). Pictures representing the meaning of each sign were shown to a white, female, deaf, native signer who was filmed producing the sign at a medium-close camera angle that provided a view of the signer from just above the lap to a few inches above the head. Signs were elicited from the model using pictures so as to ensure productions were as naturalistic as possible (i.e., we were concerned that using English words as prompts might encourage the model to mouth English words more often than she naturally would). Of the 300 signs, 3 were removed prior to data collection because of poor video quality or sign production, and 21 were removed from the analysis because their articulation differed from the productions used in ASL-LEX, causing the ASL-LEX neighborhood density estimates (which are based on the formal characteristics of each sign) to differ from the neighborhoods of the stimuli.

An additional 300 non-signs were created by modifying one phonological parameter of each real sign used in this study. The replacement parameters were randomly 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. In rare cases where the modified sign happened to also be an existing sign, a second parameter was changed. The distributions of the phonological features and neighborhood density among the non-signs were similar to that of the ASL lexicon (see Appendix A). One hearing and one deaf native signer (the first author and the model, respectively) agreed that all of the non-signs were indeed non-signs and were phonologically plausible in ASL. The non-signs and real signs were filmed in alternating order to keep the filming conditions the same across conditions. The non-signs were elicited by presenting pictures of the corresponding real signs as well as an indicator of the replacement parameter. The model used mouthing as she felt was natural; she used mouthing on some of the real and non-signs. Seven of these non-signs were removed because of poor video quality or sign production. Videos of the signs and non-signs are available at https://osf.io/8a7tb/.

All lexical and phonological variables were taken from the ASL-LEX lexical database. In the following section we provide descriptive statistics for each of these variables for the stimuli used in the present study (see Table 1). We also provide a brief summary of how these properties were defined; more detail can be found in Caselli et al. (2017).

Frequency: Subjective lexical frequency ratings were collected by asking deaf signers to rate how frequently a sign appears in everyday conversation on a scale of 1–7. Ratings were used in lieu of corpus counts because there are currently no large ASL corpora available. Subjective frequency is correlated with corpus-based frequency estimates in signed language (Fenlon, Schembri, Rentelis, Vinson, & Cormier, 2014) and spoken language (Balota, Pilotti, & Cortese, 2001). The average z-

[2] An updated version of this database, ASL-LEX 2.0, is now available (Sevcikova Sehyr, Caselli, Cohen-Goldberg, & Emmorey, 2021), but the present study was conducted with the phonological coding data from ASL-LEX 1.0, as described in Caselli et al. (2017).

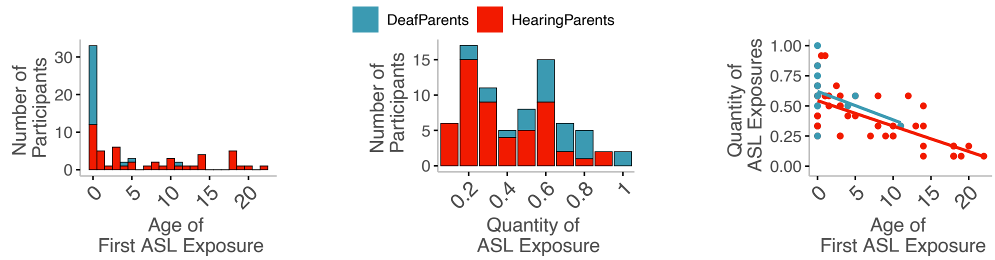

Fig. 3. Distribution of Age of First Exposure (years) and Quantity of Exposure (percent) to ASL, as well as the correlation between the two.

Table 1

Means (M), standard deviations (SD), and correlations with confidence intervals for lexical variables. Three measures of neighborhood density were included: Maximal Neighborhood Density (the number of signs that share any four out of five phonological properties with the target), Minimal Neighborhood Density (the number of signs that share any one out of five phonological properties with the target), and Parameter-Based Neighborhood Density (the number of signs that share the selected fingers, flexion, major location, and path movement with the target). Note that frequency and iconicity are z transformed.

Variable	*M*	*SD*	1	2	3	4
1. Maximal Neighborhood Density	32.77	26.90				
2. Minimal Neighborhood Density	769.53	106.97	.60** [.51, .67]			
3. Parameter Neighborhood Density	5.49	6.87	.78** [.73, .82]	.52** [.43, .60]		
4. Frequency	−0.05	0.68	.18** [.06, .29]	.13* [.01, .24]	.06 [−.06, .18]	
5. Iconicity	0.13	0.85	.10 [−.02, .21]	.11 [−.01, .22]	.15* [.03, .26]	−.15* [−.26, −.03]

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

transformed ratings from ASL-LEX were used in all analyses here.

Neighborhood Density: Because neighborhood density has not yet been thoroughly investigated in ASL or sign languages in general, it is not clear how best to define it. ASL-LEX contains phonological descriptions including the selected fingers (the group of fingers that move), flexion, movement, major location (head, body, arm, hand, and neutral space), and sign type (one handed, two-handed and symmetrical etc.). It also includes three estimates of neighborhood density that were generated from the phonological descriptions: *Maximal Neighborhood Density* (the number of signs that share any four out of five phonological properties with the target), *Minimal Neighborhood Density* (the number of signs that share any one out of five phonological properties with the target), and *Parameter Based Neighborhood* Density (the number of signs that share the selected fingers, flexion, major location, and path movement with the target). *Maximal Neighborhood Density* is most akin to the definitions commonly used in spoken language where neighboring signs share all but one sub-lexical unit. Parameter-based neighborhood density most closely parallels definitions of phonological overlap commonly used in the sign language literature (e.g., overlap among handshape, location, and movement), which generally do not include sign type.

Iconicity: Iconicity ratings by English-speaking non-signers were collected by asking non-signers to rate how much a sign looks like its English translation on a scale of 1–7. These ratings are highly correlated with iconicity ratings from deaf signers (Sevcikova Sehyr & Emmorey, 2019). The average z-transformed ratings from ASL-LEX were used in all analyses here. Because the real sign stimuli in this study were all picturable, we first tested to make sure that they were not also more iconic than other signs in the lexicon. There was no evidence that the average iconicity of these items differed from the other 717 signs in the original ASL-LEX database ($M_{ASL\text{-}LEX} = .05$, $SD_{ASL\text{-}LEX} = 0.80$, $M_{Stimuli} = .13$, $SD_{Stimuli} = 0.85$, $W = 102{,}024$, $p = 0.41$). We had iconicity ratings from deaf signers for a large subset of signs, and confirmed that all following analyses are qualitatively the same if the deaf iconicity ratings are used.

Sign Onset, Offset, and Duration: Videos were trimmed so that they began while the model's hands were in her lap. There was a short but variable amount of time at the beginning of the video but before sign onset as her hands transitioned to the place of articulation. Sign onset and offset times were coded using the same system used in ASL-LEX (Caselli et al., 2017) which is similar to the conventions used by Johnson and Liddell (2011) and Crasborn, Bank, Zwitserlood, van der Kooij, de Meijer, and Sáfár (2015). Sign onset was the first frame in which the fully formed handshape arrived at its location, and sign offset was the last frame in which the hand made contact with its location or the last frame before it transitioned back to resting position. The distribution of sign onset and offset is illustrated in Fig. 4.

Trial data

We included three regressors to address dependencies among trials (Baayen & Milin, 2010). *Trial Number* was included because participants may either become faster (as they adapt to the task) or slower (due to fatigue) as the experiment progresses. The log transformed *Previous Trial Reaction Time* was included; this likely predicts reaction times since participants may experience local transient phases of speed-up and slow-down processing speed (e.g., due fluctuations of attention). Lastly, *Previous Trial Accuracy* was included because there may be a recovery period after an error has been made.

Reaction time

Reaction time was calculated as the number of milliseconds between the onset of the stimulus sign (not video onset) and the decision

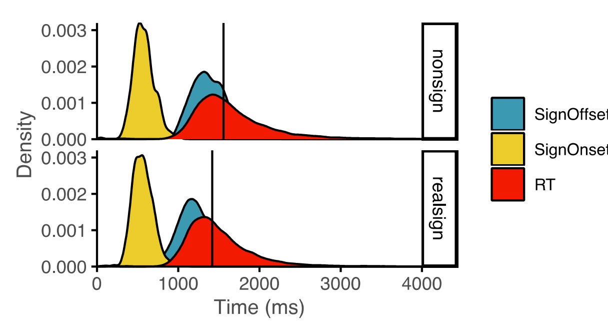

Fig. 4. The distribution of the time course of sign onset and offset, and reaction times (RT) on correct trials. Time reflects the number of milliseconds from video onset. The vertical line indicates the median reaction time to help compare reaction times in real and non-signs.

keypress. This was then log transformed in order to better approximate a normal distribution of reaction times (Baayen & Milin, 2010).

Results

Data, code, code output, stimuli, and all supplementary figures and tables from this manuscript are available at https://osf.io/8a7tb/. Of the 43,787 trials (number of items times the number of participants), there were 21,372 real sign trials and 22,415 non-sign trials in total. There were 9 non-signs that had an error rate greater than 40%. Inspection revealed that they closely resembled existing signs so these items (686 trials) were removed from all following analyses. Responses faster than the minimum sign onset time (48 ms; N = 25) or slower than two standard deviations above the participant's mean reaction time (N = 8215) were then removed. We also removed incorrect responses from the latency analyses. There remained 32,626 correct responses, and 2,235 errors. The time course of correct responses with the data trimmed as described is illustrated in Fig. 4. The average accuracy rate of the remaining data was 93.6% for real signs (SD = 6.4%) and 93.0% for non-signs (SD = 8.8%).

Modeling procedure

A series of mixed-effects regressions were constructed using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015) and the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017) of the statistical program R. Tables and figures were generated with the *sjPlot* package (Lüdecke, 2020). In the first set of models the dependent variable was log reaction time from the sign onset and only correct trials were included, and in the second set of models the dependent variable was accuracy. The complete reaction time and accuracy models were the same aside from the dependent variable and regression type (linear vs. logistic). All models included participant age, age of first ASL exposure, quantity of ASL exposure, parent hearing status, and four trial-level variables (sign duration, trial number, previous trial accuracy, and previous trial reaction time). All models also included the following lexical variables: iconicity, sign frequency, and one measure of neighborhood density. All models also included sign onset and offset time. Because frequency interacts with many lexical variables and we were interested to see if the patterns differed as a function of early language experience, we included three-way interactions between sign frequency, parent hearing status, and all lexical variables. All continuous predictors were centered and scaled except Iconicity and Lexical Frequency, as these values were z-transformed to begin with. All models also included random intercepts for participants and items.

Because some variables were correlated, we confirmed the effects of the lexical variables using a 'peel-away' technique wherein we built the complete model, and then removed each lexical variable or highest order interaction term including a lexical variable in turn to see whether the inclusion of that term significantly improved the model fit using a log-likelihood test.

Reaction time analysis

We focus our analyses of neighborhood density using Parameter Based Neighborhood Density because this model had a better fit, indicated by a lower AIC (−17,304.02), than models including Maximal (−17,294.92) and Minimal Neighborhood Density (−17,300.04).

See Table 2 and Table S1 for the model results. There were significant effects of sign onset, sign offset, trial number, and previous trial reaction time. Participants with deaf parents responded faster than participants with hearing parents, and younger participants were faster than older participants. There were no effects of the other variables related to language background (Age of First ASL Exposure or Quantity of ASL Exposure). Participants responded more quickly to high frequency signs than low frequency signs. There were no effects of iconicity.

Table 2
Linear mixed-effect models of log *reaction time in the lexical decision task.* P-values estimated with conditional F-tests using the Kenward-Roger approximation for the degrees of freedom using the pbkrtest package in R. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

	Reaction Time		
Predictors	*B*	*t*	*p*
(intercept)	7.489 ***	283.876	<0.001
Parent Hearing Status (hearing)	0.091 **	2.789	0.005
Age	0.046 **	2.953	0.003
Age of First ASL Exposure	−0.007	−0.367	0.713
Quantity of ASL Exposure	0.019	0.982	0.326
Sign Onset	−0.026 ***	−6.358	<0.001
Sign Offset	0.024 ***	5.705	<0.001
Trial Number	−0.002 *	−1.987	0.047
Previous Trial Accuracy (error)	0.005	1.357	0.175
Previous Trial Reaction Time	0.019 ***	15.380	<0.001
Parameter Based Neighborhood Density	0.008	1.842	0.065
Frequency	−0.033 ***	−5.363	<0.001
Iconicity	0.002	0.449	0.653
Parameter Based Neighborhood Density: Frequency	−0.016 **	−2.795	0.005
Parent Hearing Status (hearing): Parameter Based Neighborhood Density	−0.002	−0.646	0.518
Parent Hearing Status (hearing): Frequency	−0.001	−0.225	0.822
Frequency: Iconicity	−0.006	−0.809	0.418
Parent Hearing Status (hearing): Iconicity	0.003	0.875	0.381
Parent Hearing Status (hearing): Parameter Based Neighborhood Density: Frequency	0.008 *	2.177	0.029
Parent Hearing Status (hearing): Frequency: Iconicity	0.001	0.295	0.768
Observations	15,461		
Marginal R^2 / Conditional R^2	0.115 / 0.520		

* $p < 0.01$ ** $p < 0.01$ *** $p < 0.001$.

There was a two-way interaction between neighborhood density and frequency, as well as a three-way interaction between neighborhood density, frequency, and parent hearing status. Visualization of the interaction indicates that the effect of neighborhood density was inhibitory but only among low frequency signs, and this pattern was stronger for those with deaf parents than those with hearing parents (see Fig. 5). This interpretation was confirmed by a simple slope analysis that revealed that neighborhood density had a significant effect only in the low frequency signs (deaf parents: $t = 3.9$; hearing parents: $t = 2.2$). Effects of neighborhood density were not significant for medium or high frequency signs in either group of participants (all t's < 1.96). Together, the significant three-way interaction and simple slopes analyses indicate that there was a frequency by neighborhood density interaction, which was significantly weaker among those with hearing parents than those with deaf parents.[3]

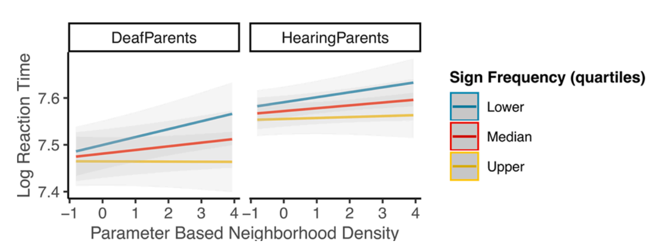

Fig. 5. Interaction between Neighborhood Density, Frequency, and Parent Hearing Status.

[3] Median split analyses align with these interpretations (see Table S3).

Accuracy analysis

We again report the model that included Parameter Based Neighborhood Density rather than other definitions of neighborhood density because the fit of the model containing Parameter-based Neighborhood Density (AIC = 5080.65) was better than both that containing Maximal Neighborhood Density (AIC = 5084.04) and Minimal Neighborhood Density (AIC = 5082.48). The results are qualitatively the same using Maximal and Minimal Neighborhood density. See Table 3 and Table S2 for a summary of the results; in these models, the dependent variable was coded as Error = 1, Correct = 0. Participants with higher quantities of ASL exposure in childhood had higher accuracy compared to those with less ASL exposure. There were no effects of the other demographic variables. Participants responded more accurately to high frequency signs than low frequency signs. There was an interaction between iconicity and parent hearing status whereby iconic signs were more susceptible to error than non-iconic signs, and the effect was stronger in those who had deaf parents (see Fig. 6). We further explored this two-way interaction by examining the simple slopes and found that the effect of iconicity was significant among those with deaf parents ($z = 2.46$; $p = 0.01$) but not among those with hearing parents ($z = 0.74$; $p = 0.46$). There were no effects of the other lexical variables.

Lexicality and accuracy analysis

Finally, we analyzed the entire dataset, not just the real signs, to examine effects of lexicality and overall accuracy using mixed-effects models that included the participant variables and the trial-level variables described in the preceding section plus random effects of item and participant. Participants responded more quickly ($B = -0.05$, *s.e.* $= 0.005$, $t = -10.82$, $p < 0.01$) and made fewer errors ($B = -0.43$, *s.e.,* $= 0.15$, $z = -2.85$, $p < 0.01$) on real sign trials than non-sign trials. Response times were slower on incorrect trials ($B = 0.08$, *s.e.,* $= 0.004$, $t = 18.26$, $p < 0.01$). These patterns are consistent with behavior in auditory lexical decision tasks (Tucker et al., 2019) and reading lexical decision tasks (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Keuleers, Diependaele, & Brysbaert, 2010).

Table 3
Logistic mixed-effect model of errors in the lexical decision task.

	Error		
Predictors	*Log-Odds*	*Statistic*	*p*
(intercept)	−3.83 ***	−16.67	<0.001
Parent Hearing Status (hearing)	−0.08	−0.33	0.744
Age	−0.15	−1.46	0.143
Age of First ASL Exposure	0.06	0.54	0.591
Quantity of ASL Exposure	−0.27 *	−2.06	0.040
Sign Onset	0.02	0.17	0.867
Sign Offset	0.02	0.16	0.875
Trial Number	0.14 ***	3.36	0.001
Previous Trial Accuracy (error)	0.12	0.81	0.419
Previous Trial Reaction Time	−0.06	−1.13	0.259
Parameter Based Neighborhood Density	0.14	0.94	0.345
Frequency	−0.89 ***	−3.91	<0.001
Iconicity	0.43 *	2.49	0.013
Parameter Based Neighborhood Density: Frequency	−0.25	−1.27	0.205
Parent Hearing Status (hearing): Parameter Based Neighborhood Density	0.05	0.43	0.664
Parent Hearing Status (hearing): Frequency	−0.02	−0.12	0.907
Frequency: Iconicity	0.30	1.21	0.227
Parent Hearing Status (hearing): Iconicity	−0.32 **	−2.67	0.008
Parent Hearing Status (hearing): Parameter Based Neighborhood Density: Frequency	−0.04	−0.31	0.759
Parent Hearing Status (hearing): Frequency: Iconicity	−0.24	−1.43	0.152
Observations	16,385		
Marginal R^2 / Conditional R^2	0.080 / 0.548		

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

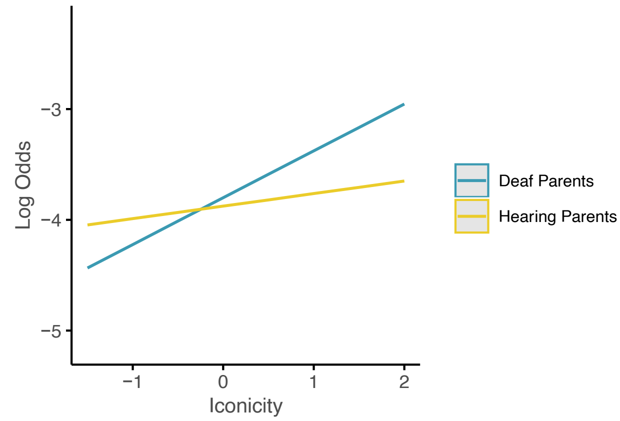

Fig. 6. Predicted log odds of error illustrating the interaction between iconicity and parent hearing status in lexical decision accuracy.

Discussion

One goal of this study was to fill in critical gaps in psycholinguistic theories of sign recognition by determining if neighborhood density and iconicity influence unprimed lexical decision responses. We found a significant interaction between phonological neighborhood density and frequency such that participants responded to low frequency signs with many phonological neighbors more slowly than low frequency signs with few neighbors. This effect was present but weaker in participants with hearing parents. The neighborhood density by frequency interaction is similar to what has been found in spoken and written word recognition (e.g., Andrews, 1989, 1992; Lim, 2016; Vitevitch & Sommers, 2003; Yap & Balota, 2009) and is the first clear evidence that phonologically related signs are spontaneously activated during sign processing. Moreover, it provides evidence that signs are recognized in a two-stage process and that like auditory word recognition, phonologically related signs compete for selection. As has been proposed in spoken word recognition, this pattern could indicate that high frequency signs are more robustly represented or are recognized before lexical competition has time to impact processing.

With regard to iconicity, we found that deaf people who had deaf parents were less accurate at classifying iconic signs relative to non-iconic signs; no such effect was found for participants with hearing parents. Crucially, however, iconicity had no effect on reaction time in either group (replicating Bosworth & Emmorey, 2010). In other words, when responding correctly, deaf participants responded at the same speed to low- and high-iconicity signs. This result, in conjunction with time-course data from ERP studies (Emmorey et al., 2020; Mott et al., 2020), suggests that iconicity does not influence the early stages of sign recognition (i.e., lexical and semantic access). The fact that when iconicity did have an effect, it negatively influenced accuracy is consistent with the notion that iconicity plays a role in the decision making process, which ERP data indicate happens at a relatively late stage. Effects of iconicity on accuracy may arise because iconic signs are more likely to be pantomimic (Caselli & Pyers, 2019), and so signers may have had difficulty categorizing them as real signs.

This study represents a significant step forward in the development of theories of sign processing. Estimating phonological neighborhood density requires a detailed phonological description of the lexicon and the estimates from ASL-LEX that we used represent the first attempt to capture this phonological structure. While it may turn out that more precise estimates can be achieved through more detailed phonological descriptions or through other means of estimating frequency, the effects we see here indicate that the values currently included in ASL-LEX capture important, psychologically real elements of sign recognition.

The second goal of this study was to shed light on the question of which aspects of lexical recognition are universal and which are shaped by modality. Despite the immense formal differences between sign language and spoken and written language, we observed remarkable similarities in the way lexical recognition unfolds. Just as in spoken and written word processing, sign recognition involves the spontaneous activation of phonological neighbors and more specifically, this is an effect that interacts with lexical frequency. ASL sign recognition moreover does not seem to be influenced by iconicity, even though the structure of the language affords this opportunity. These results suggest that these properties of lexical recognition are largely invariant and not dependent upon modality.

In addition, we found that sign recognition processes are shaped by early language exposure. Signers with hearing parents were slower at recognizing signs, exhibited a weaker neighborhood density by frequency interaction in RT, and demonstrated no effect of iconicity in their responses. Additionally, signers with less ASL exposure during childhood were less accurate than signers with greater childhood ASL exposure. Together these results suggest that early and consistent exposure to a natural language may be critical to developing the two-stage organization of lexical access and sensitivity to iconic mappings. It is noteworthy that all of the participants in this study were fluent in ASL and had years (in many cases decades) of signing experience—childhood language experience still had measurable effects on sign recognition despite this proficiency.

We attribute differences between those with hearing and deaf parents to the fact that deaf people with hearing parents are at unique risk for language deprivation. Since their parents generally learn sign language alongside them—if their parents learn a sign language at all—-their language input is often disfluent and delayed. The results here indicate that while people with language deprivation may readily learn new signs (Ramírez et al., 2013), early language experience can still have lasting effects on how efficiently and accurately they are processed. More work is needed to disentangle which aspects of early language exposure matter the most for sign recognition (e.g., quality, quantity, and/or age of language exposure). These effects of early language exposure on lexical recognition are parallel to work suggesting that spoken language bilinguals have slower word recognition in their second language (e.g., Costa, Caramazza, & Sebastian-Galles, 2000; Costa, La Heij, & Navarrete, 2006). In sum, this study indicates that while language modality has relatively little effect, language exposure in early childhood has substantial, lasting effects on sign recognition.

At a processing level, the patterns we observed provide evidence that language deprivation results in a 'phonological bottleneck' or difficulty with phonological processing (Mayberry & Fischer, 1989). The weaker influence of neighborhood density in signers with hearing parents could result from processing difficulty at the sub-lexical phonological level. These signers may have difficulty activating or selecting phonological features and/or activating signs on the basis of those features. The fact that the neighborhood effects were diminished suggests that the difficulty was not in the lexical selection mechanism—in such a scenario we might expect greater competition among phonologically related signs, manifesting behaviorally as stronger inhibitory effects. An alternative explanation for weaker neighborhood effects is that people with language deprivation may have smaller vocabularies and so fewer signs compete during sign recognition. However, the results here are similar to those reported by Lieberman et al. (2015) who found weaker effects of phonological competitors among late signers in a visual world task. As both the target and competitor signs were present in the experimental context, their effect cannot be explained by vocabulary size.

The second pattern that is consistent with a phonological bottleneck is that signers at risk for language deprivation (those with hearing parents) were not sensitive to iconicity while those with deaf parents were. It is possible that difficulty processing phonological information interferes with semantic processing in either an offline fashion (preventing the formation of long-term structured mappings between form and meaning; Emmorey, 2014) or online in the moment of processing. Because iconicity depends on both form and meaning, decreased or slowed sub-lexical, lexical, and/or semantic activity could manifest in decreased sensitivity to iconicity. Though the results are consistent with a phonological bottleneck, more work is needed in order to more precisely understand the nature of the disruption.

The lexical signs studied here are all simple and were generally not morphologically complex, classifier constructions, or depicting constructions. For this reason, the stimuli include items that are perhaps most akin to spoken words, and further work will be needed to understand lexical recognition of more complex signs. The phonological composition and iconic motivations of these other sign types is often quite different from the simple lexical items studied here (e.g., Brentari & Padden, 2001), which may manifest in important differences in processing. Lastly, early and late signers differ in their use of simple and morphologically complex signs (e.g., Karadöller, Sumer, & Ozyurek, 2017), which may also affect sign recognition. The patterns observed here, including the parallels between sign recognition and auditory/written word recognition, may not extend to other domains within sign language lexicons.

Conclusion

In sum, this study provides evidence that the architecture of lexical recognition is largely modality-independent: phonological neighbors influence recognition in all three modalities, while iconicity—a prominent feature of sign languages—does not. These results indicate that theories of lexical recognition do not need to be modified to account for the unique phonology and iconicity of sign languages. The invariance of lexical recognition processes is remarkable given the differences in the structure of signed, spoken, and written words. However, this similarity appears to be limited to those individuals who receive early exposure to a first language. We found that there are long-term effects of early language experience on sign recognition in general and on phonological processing in particular. In combination, our results suggest that language deprivation and early language experience may play a larger role than modality in shaping the basic functioning of language processes. Theories of language development must therefore include data on language deprivation and should attempt to describe the role of early language experience in shaping the phonological organization of the lexicon. This work affirms that characterizing the mechanisms of sign language processing is important in its own right, and can also provide a valuable means of testing and informing theories of language processing in general.

CRediT authorship contribution statement

Naomi K. Caselli: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Karen Emmorey:** Conceptualization, Methodology, Writing - review & editing. **Ariel M. Cohen-Goldberg:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jml.2021.104282.

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