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ASL LEXICAL RECOGNITION IN DEAF CHILDREN

Lexical recognition in deaf children learning ASL: activation of semantic and phonological
features of signs

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Abstract

Children learning language efficiently process single words, and activate semantic, phonological, and other features of words during recognition. We investigated lexical recognition in deaf children acquiring American Sign Language (ASL) to determine how perceiving language in the visual-spatial modality affects lexical recognition. Twenty native- or early-exposed signing deaf children (ages 4 to 8 years) participated in a visual world eye-tracking study. Children were presented with a single ASL sign, target picture, and three competitor pictures that varied in their phonological and semantic relationship to the target. Children shifted gaze to the target picture shortly after sign offset. Children showed robust evidence for activation of semantic but not phonological features of signs, however in their behavioral responses children were most susceptible to phonological competitors. Results demonstrate that single word recognition in ASL is largely parallel to spoken language recognition among children who are developing a mature lexicon.

Keywords: American Sign Language, deaf children, lexical recognition, eye-tracking

Perceiving and comprehending language involves rapidly retrieving words from the mental lexicon. The processes involved in mapping spoken word forms to meaning occur incrementally in response to unfolding speech, even among infants who are still at the early stages of word learning (Swingley, Pinto & Fernald, 1999). By adulthood, lexical recognition is highly efficient, with listeners sensitive to a plethora of linguistic and nonlinguistic cues to word meaning (see Huettig, Rommers, & Meyer, 2011 for a review). Adults map words onto an existing mental lexicon that is organized around semantic, phonological, and other properties of words (Gaskell & Marslen-Wilson 2002).

Most of our insights about lexical recognition are based on studies of spoken languages. Recent results suggest that in sign languages such as American Sign Language (ASL), adults also process signs as they are perceived visually (Lieberman, Borovsky, Hatrak, & Mayberry, 2015). While many aspects of sign language acquisition parallel spoken language acquisition, modality-specific features of ASL signs may lead children to take an alternative path to lexical recognition as they are acquiring language. For example, when perceiving an ASL sign, multiple phonological components are presented simultaneously (e.g. location and handshape, which are separate phonemic units), in contrast to the more sequential nature of spoken phonemes. Further, sign languages such as ASL have a greater degree of iconicity relative to spoken language, which appears to impact the particular set of signs learned at early ages (Caselli & Pyers, 2017). ASL also includes an extensive classifier system in which, for a subset of signs, multiple meaning units are combined to form complex constructions (Slobin et al., 2003), which may lead children to pay attention to specific features of signs. Given these and other modality-based differences in ASL, the degree of phonological and semantic activation during sign recognition may differ in young sign language learners from that observed in children acquiring spoken language. In the

current study, we examine lexical recognition of ASL signs in deaf children, to investigate how the developing mental lexicon in signers is organized and accessed with respect to phonological and semantic features of signs.

Word recognition in spoken language

Studies using the visual world paradigm have revealed that adults activate multiple potential word candidates as speech unfolds until a single referent can be identified. At the single word level, adults activate phonological features (Allopenna, Magnuson, & Tanenhaus, 1998), visual-spatial perceptual features (Dahan & Tanenhaus, 2005), and semantic features (Huetting & Altmann, 2005) of words during real-time comprehension, among others. The degree of both semantic and phonological activation co-varies with lexical properties of individual words including frequency and neighborhood density (Apfelbaum, Blumstein, & McMurray, 2011). Yee and Sedivy (2006) showed evidence for cascading phonological and semantic information; when presented with a spoken word *logs*, adults looked more at a competitor *key* that was semantically related to a phonological competitor of *logs*, in this case *locks*. Thus, phonological and semantic information are both clearly activated in adult listeners.

Infants learning words have a smaller lexicon from which possible referents can be drawn. Nonetheless, by 24 months infants demonstrate recognition of a familiar object label even before label offset (Fernald, Perfors, & Marchman, 2006), can use coarticulation cues (Mahr, McMillan, Saffran, Weismer, & Edwards, 2015), and show a delay in recognition when presented with two cohort competitors (e.g. *dog* and *doll*; Swingley et al., 1999). Although much research has focused on the first words children acquire and the mechanisms underlying early word learning, word learning does not stop in infancy. School age children continue to acquire words, expanding their lexicon and developing richer and more dense networks connecting the words they know (Ojima, Matsuba-Kurita, Nakamura, & Hagiwara, 2011; Vermer, 2001). Five-

year-old children show cascading activation of phonological and semantic information (Huang & Snedeker, 2011), look longer at a competitor that shares semantic features with the target than unrelated competitors, and take longer to resolve this competition than adults (Arias Trejo & Plunkett, 2010). Sekerina and Brooks (2007) found evidence for cohort competition during lexical recognition in five- and six-year-old Russian-speaking children. Even in adolescence, there is evidence for an increase in speed of activation and decrease in competitor activation in lexical recognition (Rigler et al., 2015). Thus, while many features of efficient word recognition are present in children from a young age, there is clear evidence for refinement and further sophistication in the organization and use of the mental lexicon throughout childhood and adolescence.

The ability to process known words efficiently is closely tied to word learning and overall language knowledge. In infants and preschool children, processing speed is a significant predictor of later vocabulary knowledge (Fernald et al., 2006; Law, Mahr, Schneeberg, & Edwards, 2017). Children who process familiar words efficiently are also better able to add new words to their lexicon (Lany, 2018; Bortfeld, Rathbun, Morgan, & Golinkoff, 2003; Shi, Werker, & Cutler, 2003). Finally, differences in activation among older children and adolescents are related to overall language knowledge (McMurray, Samuelson, Lee, & Tomblin, 2010). Rapid and efficient lexical recognition is thus closely tied to word learning ability and vocabulary size throughout development.

Sign recognition in deaf adults

Sign languages such as American Sign Language (ASL)—which are produced manually and perceived visually—are linguistically equivalent to spoken languages (Klima & Bellugi, 1979; Sandler & Lillo-Martin, 2006). In deaf adults who are exposed to a natural sign language from birth, sign processing largely parallels spoken language processing at both the behavioral

and neurological levels (Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008; MacSweeney, Capek, Campbell, & Woll, 2008). Sign languages are organized at lexical and sub-lexical levels (Emmorey & Corina, 1990; Klima & Bellugi, 1979; Orfanidou, Adam, McQueen, & Morgan, 2009). Unsurprisingly, sign processing in native-signing deaf adults involves recognition of sub-lexical features of signs (Carreiras et al., 2008; Caselli & Cohen-Goldberg, 2014; Mayberry & Witcher, 2005). Signers identify signs based on location neighborhoods and phonotactic cues, further paralleling spoken language processing (Orfanidou, McQueen, Adam & Morgan, 2015).

Studies of semantic processing in sign language have often focused on the role of iconicity. Sign languages are more iconic than spoken languages (Taub, 2001), yet the influence of iconicity on sign processing has been a matter of debate. Some studies have found that signers show facilitative effects of iconicity (Grote & Linz, 2003; Thompson, Vinson, & Vigliocco, 2009). Others have claimed that iconicity plays no significant role in sign processing (Bosworth & Emmorey, 2010; Newport & Meier, 1985; Orlansky & Bonvillian, 1984).

In a previous study (Lieberman et al., 2015), we investigated processing of ASL signs in two groups of deaf adults—native or early signers, who were exposed to ASL at or shortly after birth, and late-learning signers, who were first exposed to ASL as a first language at a range of ages after birth. We used a modified visual world paradigm to present adult signers with a single ASL sign followed by four pictures that varied in their phonological and semantic relationship to the target sign. We measured the speed with which signers shifted gaze from the sign video to the picture that matched the target, as well as the proportion of time spent looking at the target picture, the phonological and semantic competitor pictures, and the unrelated picture. Adult signers from all backgrounds showed evidence for incremental processing of signs. Signers began to shift gaze away from the sign and towards the target picture before the offset of the sign. In addition, native signers showed a pattern of activation that suggested they were sensitive

to both semantic and phonological features of signs. Native signers were faster to fixate the target and spent more time looking at the target when there were no competitors relative to when there were phonological or semantic competitors. They also showed increased looks to semantic and phonological competitors relative to unrelated competitors. In contrast, late-learning signers did not differ in target speed or overall looking to target based on semantic or phonological competitors, but they did show increased looks to these related competitors relative to unrelated distractors (Lieberman, Borovsky, Hatrak, & Mayberry, 2016). Thus, in the adult deaf population this initial study revealed that signers process signs in a way that is largely parallel to spoken language activation, particularly if they are exposed to sign language from an early age.

Sign acquisition in childhood

Sign language acquisition, when begun at birth, parallels spoken language acquisition in the general timetable and achievement of linguistic milestones (Lillo-Martin, 1999; Mayberry & Squires, 2006; Petitto et al., 2000). However, little is known about the specific features of signs that might be most salient to child learners of a visuo-spatial language. Recent evidence suggests that early sign vocabularies are influenced by many of the same features as spoken vocabularies, such as frequency and neighborhood density, but that iconicity, a feature unique to sign, also plays a role in the composition of early sign vocabularies (Caselli & Pyers, 2017; Thompson, Vinson, Woll, & Vigliocco, 2012).

Phonological development in children ASL has largely been studied through early error patterns, which has led to a timetable for development of features (Marentette & Mayberry, 2000), but it is currently unclear how phonological activation contributes to sign recognition. Whereas spoken language is perceived through the sequential perception of sounds, in sign language several phonemes (e.g. handshape and location) can be produced simultaneously (Brentari, 1998). This may lead children to process signs as conceptual units rather than as

combinations of sub-lexical units. If this were the case, then we might expect to see a lesser degree of phonological activation during sign recognition relative to spoken language recognition, particularly in child language learners who may be attuned to the semantics of the sign. Of course, perceiving signs as conceptual units does not preclude the possibility that children will notice particular surface features such as phonology; clearly the visual similarity among individual signs is likely to be salient in word recognition. However, whether and how phonological activation manifests during sign lexical recognition in children is an empirical question.

Semantic development in deaf children has been investigated through assessment of semantic categorization abilities in both native and non-native signing children (Courtin, 1997; MacSweeney, Gossi, & Neville, 2004). Ormel and colleagues (Ormel et al., 2010) investigated semantic categorization ability in deaf 9- to 12-year-old children by presenting either pictures or written words and asking children to select the best-matching picture from a set of four. Deaf children (both native and non-native) were less accurate than hearing children on both tasks, including categorization that involved matching two exemplars of a single category (e.g. apple-cherry), and matching a superordinate category to an exemplar (e.g. furniture-table). It is not entirely clear why semantic categorization lagged in this group of deaf children, although it was likely mediated by overall sign language ability. In a large-scale study of ASL acquisition in native and non-native signing deaf children (Novogrodsky, Fish, & Hoffmeister, 2014), deaf children's ability to identify synonyms, a semantic task, increased with age. Younger children were more likely to choose a phonological foil in this task than older children, a similar trajectory to that found in hearing children. Semantic cues are also known to be recruited when deaf children learn to read written language (Miller, 2000), perhaps to an even greater extent than is found for hearing children due to deaf children's limited access to spoken phonology.

Thus while both phonological and semantic features of words are likely to be activated during recognition, it is unknown what type of activation is dominant nor how these two features interact.

The current study

In the current study, we sought to understand how deaf children mentally organize the links among signs that they know, in order to provide insight into the mental lexicon of the developing signer. To approach this question, we adapted our previous paradigm used to investigate sign processing in deaf adults to make it appropriate for children. Our overarching goal was to understand how deaf children between the ages of four and eight years process familiar ASL signs. In light of recent findings about sign recognition in toddlers (Macdonald, LaMarr, Corina, Marchman, & Fernald, 2018), we hypothesized that children at this age would be adept at processing familiar signs, and thus would be highly accurate in shifting gaze from a sign video to a target picture. Second, we investigated whether and how phonological and semantic information influence sign recognition, through the activation of semantic and phonological competitors (i.e. pictures of objects whose signs share phonological or semantic features with the target sign). Here, we predicted that semantic features of signs, which are known to be activated in spoken word recognition (Huang & Snedeker, 2011), would be similarly activated during sign recognition, suggesting a modality-independent process. We predicted that children would also show sensitivity to phonological features of signs, providing evidence that children process the individual phonological features of signs much like spoken language processing (Law et al., 2017). Activation of both semantic and phonological competitors would suggest that children encode relations between signs at multiple levels in the organization of their mental lexicon. Finally, we asked whether there would be developmental changes in performance on the sign processing task. Here we predicted that, in parallel with

spoken language processing (Rigler et al., 2015), older children would be faster than younger children in shifting gaze to the target, and that older children would show a higher overall proportion of target fixations as they become more efficient at accessing signs from their mental lexicons.

Methods

Participants

Twenty deaf children between the ages of 4;2 to 8;1 ($M = 6;5$) participated. There were twelve females. Seventeen children had at least one deaf parent and were exposed to ASL from birth. The remaining three children had two hearing parents and were exposed to ASL by the age of two. All parents reported that they used ASL as the primary form of communication at home. All but two of the children attended a state school for deaf children; two children attended public school programs. One additional child was tested but was unable to complete the eye-tracking task. Children participated in a series of tasks that were part of a larger project studying language processing in ASL.

Eye-tracking Materials

The eye-tracking materials and procedure were similar to those described in our previous study of real-time processing in adult ASL signers (Lieberman et al., 2015). The stimulus pictures were color photo-realistic images presented on a white background square measuring 300 by 300 pixels. The ASL signs were presented via video; the signer was filmed against a black background and videos were cropped to a square also measuring 300 by 300 pixels. The pictures and signs were presented on a 17-inch LCD display with a black background, with one picture in each quadrant of the monitor and the sign positioned in the middle of the display, equidistant from the pictures (Figure 1).

Thirty-two sets of four pictures served as the stimuli, with each set consisting of a target picture and three competitor pictures. We used a design similar to that in previous studies of lexical recognition in children (Rigler et al., 2015). There were four conditions in which we manipulated the relationship of the competitor pictures to the target as follows: The Unrelated Condition consisted of a target picture and three competitor pictures whose corresponding ASL signs shared no semantic or phonological properties with the target sign. The Phonological condition consisted of a target picture, a phonological competitor in which the corresponding ASL sign was a phonological minimal pair with the target sign (i.e. the sign differed only in handshape, location, or movement from the target), and two unrelated competitors. The Semantic Condition consisted of a target picture, a semantically related competitor, and two unrelated competitors. Semantic competitors were defined as taxonomic pairs (e.g. strawberry-grapes, gloves-jacket) and were selected to minimize ASL phonological overlap with the target.¹ The Phono-Semantic Condition consisted of a target, a phonologically-related competitor, a semantically-related competitor, and one unrelated competitor. There were eight trials in each condition. Our previous study with adult signers used an identical design but with twice as many trials (Lieberman et al., 2015). Each image set consisted of either all one-handed signs or all two-handed signs, with exceptions for three sets (two in the phonological condition and one in the phono-semantic condition) in which the phonological pairs precluded this possibility. In these three sets, one of the signs was produced with one hand and the phonological competitor was produced with two hands (for example, in the pair BIRD-NEWSPAPER, BIRD is one-handed, produced at the mouth, while NEWSPAPER is two-handed). This adjustment was necessary to identify sufficient phonological pairs that were concrete and imageable nouns and were assumed to be acquired by school age. To ensure that participants did not use number of hands as a clue to the target identity, in these three sets one of the competitors was a one-handed sign and the other

was a two-handed sign. Finally, we minimized phonological relationships between the English translations of the target and competitor items. We did not control specifically for iconicity, but the signs in our stimuli set had slightly higher than average iconicity according to iconicity ratings from ASL-LEX (Caselli, Sehry, Cohen-Goldberg, & Emmorey, 2017: mean iconicity for our stimuli signs was 3.78 compared to iconicity across the ASL lexicon of 3.39. This is not surprising given that our signs were chosen to be familiar to children, and iconicity is overrepresented in children's early vocabulary. See Appendix for a list of all stimuli; stimuli list and pictures are available at the OSF site for this study (<https://osf.io/gx6dj/>), sign videos are available upon request.

During the experiment, each picture set was presented once. Items were counterbalanced to appear as either targets or competitors across versions of the stimuli, except in the Phono-Semantic condition which contained consistent targets across versions. The pictures were further counterbalanced such that the target picture was equally likely to occur in any location on the screen. The positional relationship between the target and related competitors was balanced across trials. Finally, the order of trials was pseudo-randomized such that the first trial always fell into the Unrelated condition, and there were never more than three consecutive trials of any one condition.

To create the stimulus ASL signs, a deaf native signer was filmed producing multiple exemplars of each target. The clearest exemplar of each sign (as judged by a native signer) was then edited to be of uniform length such that each stimulus sign was exactly 666ms long. This ensured that articulation length did not influence looking time to the sign. To achieve uniform stimuli duration, we removed extraneous frames at the beginning or end of the sign, and in a few instances by minimally increasing or decreasing the frame rate of the video. The onset point for each sign was defined as the first frame in which all parameters of the sign (i.e. handshape,

location, and movement) were in their initial position, following common convention for creating sign stimuli (Caselli et al., 2017). All transitional movement from a resting position to the initial sign position was removed to eliminate any variation in transition time, such as the difference in time it takes to move the hands to the torso vs. to the face. We chose this conservative approach to eliminate uncertainty about true sign onset, and to be consistent with current recommended approaches to studying sign recognition (Emmorey, 2019). To further control for variation among signs, the signer produced each sign with a neutral facial expression.

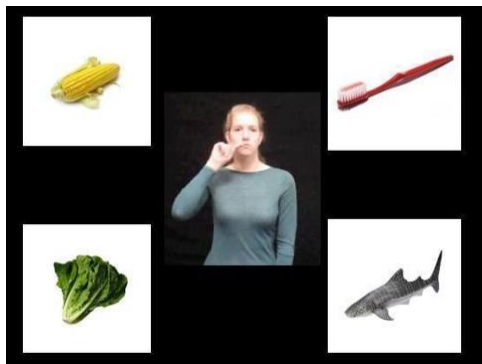


Figure 1. Example of layout of pictures and ASL sign video stimuli

Experimental Task

After obtaining parental consent, participants were brought into the testing room and seated in front of the LCD display and eye-tracking camera. The stimuli were presented using a PC computer running EyeLink Experiment Builder software (SR Research). Instructions were presented in ASL on a pre-recorded video. Instructions were presented in a child-friendly way; the signer told children that they would be playing a game, where they would see pictures followed by an ASL sign, and that they should point to the picture that matches the sign. Participants were given two practice trials before the start of the experiment. Next a 5-point calibration and validation sequence was conducted. The experimental trials were then presented

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in two blocks of sixteen trials, for a total of 32 trials. After the first block, participants were given a break during which they watched a short engaging animated video.

On each experimental trial, the pictures were first presented on the four quadrants of the monitor. Following a 1500ms preview period, a central fixation cross appeared. When the participant fixated gaze on the cross, this triggered the onset of the video stimulus. After the ASL sign was presented, it disappeared immediately at sign offset. There was then a 500ms timer (so as not to prematurely disrupt children's fixations during sign processing), followed by the appearance of a cursor marker (a small square) in the center of the screen. After the participant pointed at one of the pictures, the experimenter sitting next to the child moved the cursor using the mouse to the corresponding picture to click on it. This ended the trial (Figure 2).

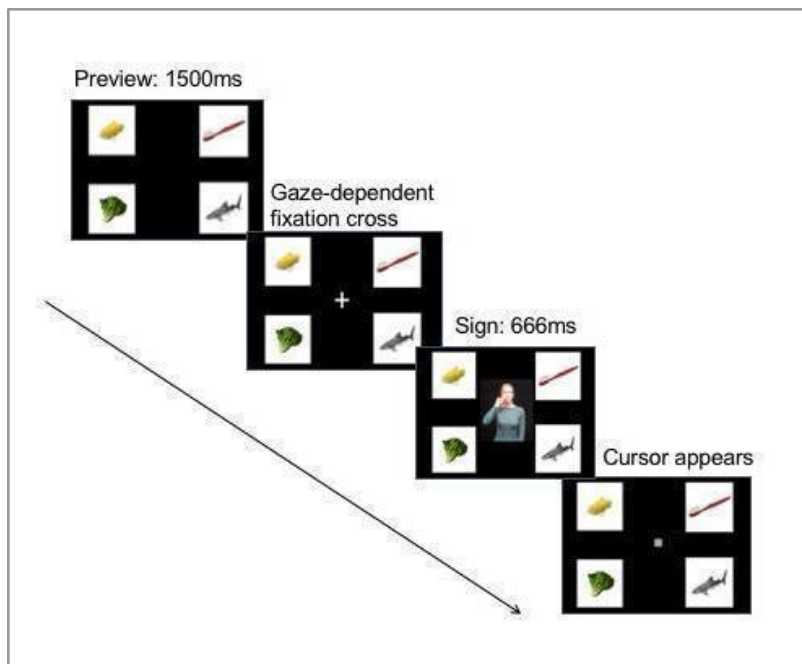


Figure 2. Example of trial sequence

Eye movements were recorded using an EyeLink 1000 eye-tracker with remote desktop configuration (SR Research) at 500 Hz. The position of the display was adjusted manually such

that the display and eye-tracking camera were placed 580-620 mm from the participant's face. The participant wore a sticker over the right eye which provided a fixed reference point that enabled the tracker to adjust for head movements relative to the camera. Eye movements were recorded on each trial beginning at the initial presentation of the picture sets and continuing until the experimenter clicked on the selected picture.

Picture Naming Task.

Following the eye-tracking task, each child completed a 174-word productive naming task (available on OSF). The task consisted of presenting groups of images to the child on a computer screen and asking the child to produce the ASL sign for each image. The images consisted primarily of concrete nouns (n=163) plus a set of color words (n=11). The images were chosen to represent common, early-acquired lexical items. Items were shown in groups of 3-6 at a time, and were organized according to semantic categories (i.e. animal signs were shown together; food items were shown together). Participants were not given feedback about accuracy. The task was videotaped for later scoring. An item was scored as correct if the participant produced the target sign with no more than minimal phonological substitutions or errors common to young children (e.g. substitution of a simple handshape for a complex handshape was counted as correct). Scoring was carried out by a native signer. Any uncertain scores were discussed with a second native signer until a joint decision was reached.

All 128 pictures that appeared in the eye-tracking task were included in the picture naming task. This allowed us to verify, for each participant, whether the child knew the ASL sign for the target items, so that we could analyze the data taking into account the child's ability to produce each target sign. Thus the goals of the picture naming task were twofold: first, we used this task to verify that children knew the stimulus signs and that their own sign for each

image matched the signs we used in the study; second, we used high performance on this measure as an indicator of general familiarity with common signs in ASL.

Results

Picture Naming Task

Mean performance on the picture naming task was 82% (SD = 18.8%, range 32% to 97%). Of the 20 child participants, one completed only 117 (out of 174) items due to lack of attention. Over half of the participants scored at least 90% on the task. As expected, children were largely familiar with the items that were selected for the task. Two participants (both of whom were 57 months at the time of testing) had low scores on the naming task (32% and 33% accuracy). After verifying that the overall pattern of results did not change when these two participants were removed, these participants were not excluded from the subsequent analyses. Nevertheless, the low score of these two participants and the high scores of other participants led us to interpret the picture-naming results conservatively.

We used performance on the picture naming task to narrow our set of analyzed items on the eye-tracking task. Specifically, we excluded from the eye-tracking task any trials for which the child had not produced the correct target sign during picture naming (i.e. they produced an incorrect sign or no sign for that target item). There were 56 trials in the eye-tracking task across all participants for which children did not produce the correct target sign during picture naming. These trials were excluded from subsequent analyses to ensure that results could be interpreted as recognition of familiar signs.

Eye-tracking Analysis

Pointing responses. We analyzed pointing responses as a measure of overall accuracy. We defined accuracy on the task as the child pointing to the correct target sign, and identified all incorrect trials. There were 61 incorrect trials out of 716 total completed trials. In the Phono-

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Semantic condition, there were 29 incorrect trials; of these, children chose the phonological competitor most often (n=19) and the semantic competitor (n=5) and unrelated competitor (n=5) less frequently. In the Phonological condition, there were 19 errors; children chose the phonological competitor (n=9) or the unrelated competitors (n=10). In the Semantic condition, there were 7 errors; of these, in only 2 instances did the child choose the semantic competitor, the remaining (n=5) were unrelated competitors. Finally, in the Unrelated condition there were 6 errors, all of which were (by definition) unrelated competitors. We performed a logistic linear-mixed effects model (Baayen, Davidson, & Bates, 2008) including condition as a fixed effect and random effect intercepts of participants and items to determine whether error rates varied by condition (Model: Accuracy ~ Condition + (1 | Participant) + (1 | Item)) . The Unrelated condition was the base against which other conditions were compared. This model uses a conservative approach, because across conditions there are more opportunities to make an unrelated error than a phonological or semantic error. The model revealed that errors in the Phonological and Phono-Semantic conditions significantly exceeded that of Unrelated conditions, while errors in the Semantic condition did not (see Table 1). Overall, our error analysis suggests that children were generally quite accurate on the task, but that they were susceptible to competitors that had phonological overlap with the target. This suggests that children were activating phonological features of signs during lexical recognition.

Table 1. Results of logistic mixed-effects regression model assessing distribution of errors across experimental conditions. Significant effects are highlighted in bold.

	Estimate (SE)	95% CI	Z-value	p-value	Cohen's D
Intercept	-4.56 (0.71)	[-6.14, -3.29]	-6.42	<.0001	

Phono-Semantic	2.03 (.68)	[.72, 3.51]	2.99	.0028	1.16
Phonological	1.40 (.69)	[.08, 2.90]	2.04	.041	.63
Semantic	0.14 (.75)	[-1.37, 1.67]	.18	.86	-.03

Next, we removed trials ($n = 56$) for which children did not produce the correct sign during the picture naming task, as described above. Finally, we removed trials which exceeded the trackloss threshold of 80% (i.e. children were looking at the display for less than 20% of the time during the window from sign onset until 1500ms after sign offset). We set the threshold for trackloss based on previous studies using a similar paradigm with young children (e.g. Borovsky, Ellis, Evans & Elman, 2016). This resulted in removal of 9 additional trials. Following these steps, three participants who contributed fewer than two trials per condition were removed from further analysis. The final dataset consisted of 481 trials contributed by 17 participants, over which all subsequent analyses were performed.

Approach to eye-tracking analysis. Our goal was to determine whether and when children recognize familiar signs, and to see how recognition changes based on the presence of competitors and the child's age. To investigate *when* children identify a target sign, we plotted the timecourse of children's gaze beginning at sign onset and continuing for 2000ms. We used an onset switch analyses (Dink & Ferguson, 2015) to measure mean timing of the first shift from the video or competitor picture towards the target image, with mean switch time as the dependent variable and condition and age as independent variables. Having established the timecourse of sign recognition, our remaining analyses were directed towards our second goal, which was to explore *how* semantic and phonological features of signs were activated during sign recognition. This was operationalized in two separate analyses of fixations to the pictures on the screen starting at sign offset and continuing for 1500ms. The first analysis focused on target fixations

as a function of condition, to explore whether children spend variable amounts of time fixating the target when semantic or phonological competitors are present. The dependent variable was mean log-transformed proportion of fixations to target, with condition and age as predictors. The second analysis delved deeper into the activation of specific competitor types, addressing our research question about the effects of semantic and phonological features of signs on gaze patterns. We compared fixations to phonological and semantic competitors across conditions. For this set of analyses, the dependent variable was the mean log-transformed proportion of fixations, with competitor type (phonological, semantic) and age as predictors. Each main step (time course plotting, target analysis, competitor analysis) is reported in detail below. R scripts and the cleaned dataset that contributed to our statistical analyses are available on the OSF site for this study (<https://osf.io/gx6dj/>).

Timing of gaze to sign video and pictures. We plotted the time course of looks to the sign video, target, phonological competitors, semantic competitors, and unrelated competitors averaged across conditions (Figure 3). Time course was plotted as the proportion of fixations to each area of interest beginning at sign onset and continuing for 2000ms. Visual inspection of the time course revealed that when the sign video was being presented, children fixated gaze on the video. The sign video was relatively short (666ms) and did not include co-articulation from the resting position to the placement of the hands in the correct position. As target sign onset was defined at the point where all phonological parameters were already in place, children did not have co-articulation or transitional movement information available to aid in detecting the target sign. Thus the onset was intentionally the same as the sign recognition point. After the sign video, children began to shift away from the video and towards the target and competitor pictures. The time course plot also suggests that the earliest looks to the target began even as the

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sign itself was still being produced, which means that in some cases children were using information from partial information from the sign to make decisions about the sign's identity.

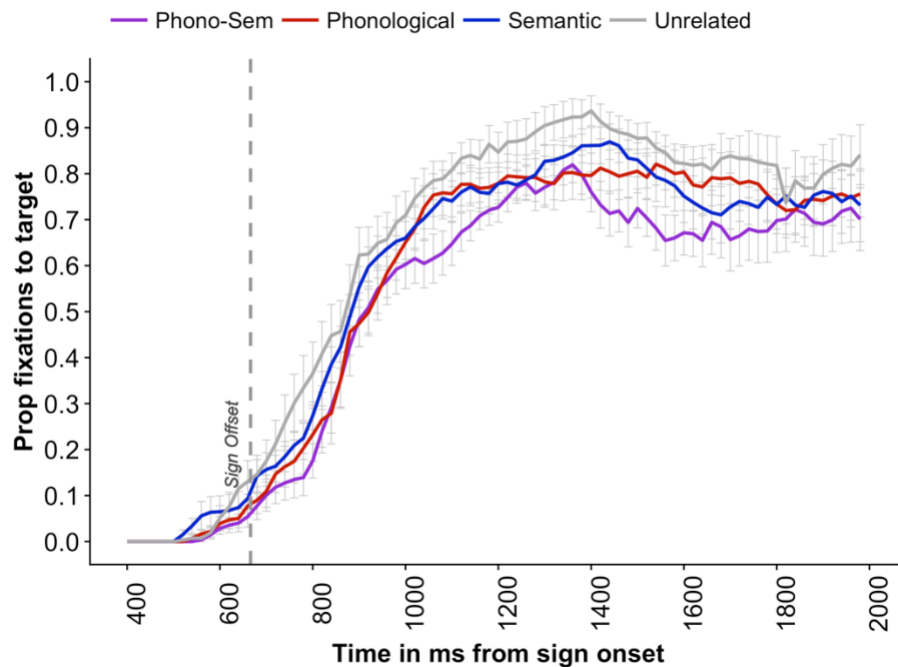
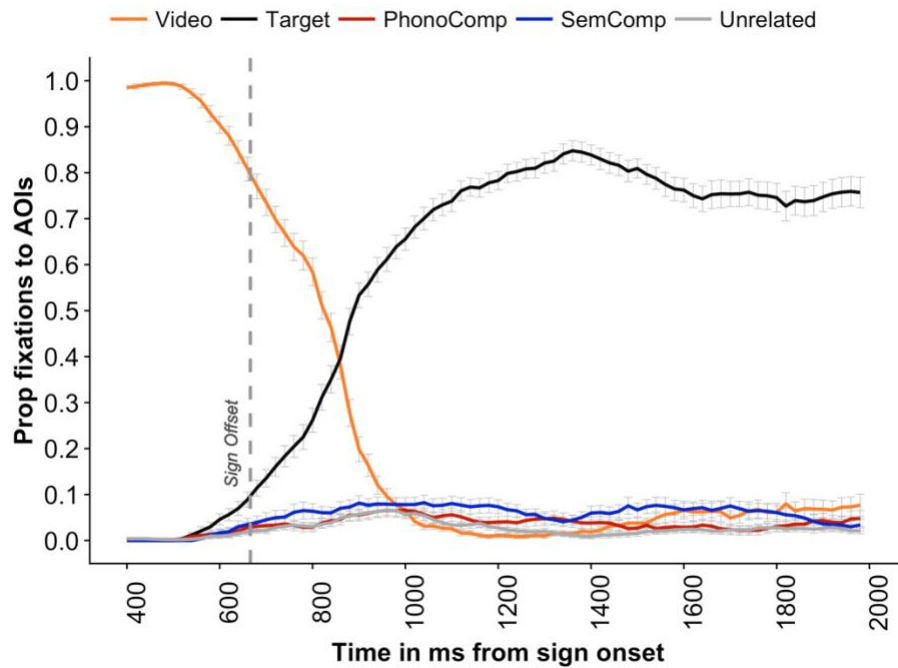


Figure 3: Top: Mean proportion of fixations to each area of interest (i.e. sign video, target picture, semantic competitor, phonological competitor, unrelated competitor) from 400-2000ms from sign onset. Fixations are averaged across conditions. Bottom: Mean proportion of fixations to the target picture from 400-2000ms following sign onset in each condition (i.e. Unrelated, Phonological, Semantic, Phono-Semantic). The vertical line in each graph represents sign offset at 666ms.

Timing of first fixation to target. To determine whether children's identification of the target was driven partially by the presence of related competitors, we compared the time point at which children first switched gaze to the target sign across conditions (i.e. onset switch analysis). An onset switch was defined as the mean time point at which children initiated their first gaze shift from the sign video or any of the competitor pictures to the target picture starting at target onset. We compared onset switch time across conditions using a linear mixed effect regression (lmer) modeling approach (Barr, 2008). We sum-coded and centered Condition so that we could infer main effects across conditions. The onset-switch model included fixed effects of condition (Unrelated, Phonological, Semantic, and Phono-Semantic). Age (centered and scaled) was additionally entered into the model as a continuous variable to determine whether developmental differences contributed to the timing and pattern of target looking. We included random effects for participants only [Model: Switch-time ~ condition + age + (1 | participant) + (1 | item)]. The lmer analysis of onset switches showed an effect of condition and no effect of age (Table 2). Follow-up pairwise comparisons revealed only a non-significant effect in which gaze switches in the Phono-Semantic condition occurred later than those in the Unrelated condition ($t(445) = 2.53$, $SE = 35.90$, $p = .057$). Table 2b shows mean switch times for each condition. This pattern of results suggests that both phonological and semantic competitors have an influence on

children's response time, but that it is only in the presence of multiple competitor types that the timing of children's gaze shifts are significantly impacted relative to the Unrelated condition. It is also possible that children were responding to the presence of two related competitors in the Phono-Semantic condition, while in the other conditions there were either zero or one related competitors. Nevertheless, there is clear evidence for competitor influence on the timing of first fixations to the target picture.

Table 2: Timing of fixation to target relative to video onset by condition and child age

a) Results of linear mixed-effects regression on fixations to target

	Estimate (SE)	95% CI	t-value	p-value	Cohen's D
Intercept	938.32 (21.53)	[893.65, 982.88]	43.58	<.0001	
Condition	-29.68 (11.27)	[-51.81, -7.53]	-2.63	.009	-.25
Age	-33.58 (21.06)	[-77.20, 9.87]	-1.59	.13	-.75

b) Mean (SE) time of gaze switch to target (ms) measured from sign video onset.

Condition	First switch to target (ms from sign onset)
Phono-Semantic	996.23 (32.68)
Phonological	955.92 (25.87)
Semantic	924.79 (28.47)
Unrelated	898.77 (36.18)

Pattern of fixations to target across conditions. While the onset switch analysis is helpful for understanding the timing of fixations, we were also interested in the overall proportion of fixations to the target picture across conditions in the window of time when

children had perceived the sign and were actively gazing towards the pictures. To measure relative differences in target fixations as a function of competitor type, we analyzed fixations to the target picture over a broad time window that began at the offset of the target sign and continued for 1500ms (Figure 4). Similar time windows have been used in previous studies of lexical processing in sign language (MacDonald et al., 2018; Lieberman et al., 2015). We log transformed target to competitor looking using the formula $\log_{10}(\text{target fixations} / \text{competitor fixations})$. Fixations are defined as the mean proportion of fixations across the window of analysis. As fixation proportions are not linearly independent (that is, more looks to one item mean fewer to another), log gaze proportion ratios allowed us to assess the bias to view an object relative to others. Additionally, this transformation supports a better normal approximation of the data compared to raw proportions which vary between 0 and 1.

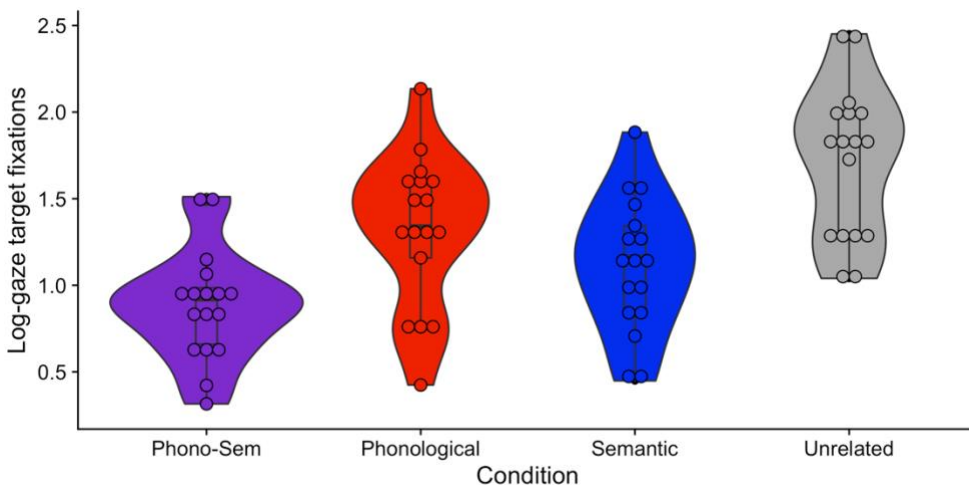


Figure 4: Mean proportion of fixations to target by condition in the time window from 0-1500ms following sign offset

We probed for effects of condition using a linear mixed-effects regression model with fixed effects of condition and age and random effects of participant and item (i.e. target sign)

[Model: LogGaze ~ condition + age + condition:age + (1 | item) + (1 | participant)] (Table 3).

We chose to include a random intercepts-only model, rather than a maximal model specification following current recommendations to balance Type 1 error with power, given the modest sample size of the study (Matuschek, Kliegl, Vasishth, Baayen & Bates, 2017). Condition was sum-coded and centered to enable us to infer main effects across all levels and to reduce potential problems with collinearity among factors. LogGaze values above 0 indicate increased proportion of fixations to the target relative to competitors; values below 0 indicate increased proportion of fixations to the competitors relative to the target. Thus in this model, the intercept term provides additional information about whether all responses varied from 0, with significantly positive terms indicating a target preference overall. Analysis revealed that, across conditions, participants looked significantly more to the target than to competitors, as indicated by the positive and significant intercept value. There was also a significant main effect of condition. Planned pairwise comparisons suggested that this effect was driven by a difference in target fixations in the Phono-Semantic vs. Unrelated conditions ($M_{\text{phono-semantic}} = .83$; $M_{\text{unrelated}} = 1.69$, $SE = .21$, $t(56) = -3.94$, $p = 0.0008$ with tukey adjustment for comparing a family of 4 estimates). There was also a significant difference in looking between the Semantic and Unrelated conditions ($M_{\text{semantic}} = 1.12$, $SE = .18$, $t(74) = -3.11$, $p = .01$). Age (centered and scaled) was added as a continuous variable to the model but did not significantly contribute to target looking, either as a main effect, nor as an interaction term with condition (see Figure 5).

In summary, the analysis of target fixations revealed that there were fewer fixations to the target in the Phono-Semantic and Semantic conditions compared to the Unrelated condition. These findings suggest that children were influenced primarily by semantic competitors. Although proportionally children were impacted by phonological competitors as well (i.e. fewer

fixations to the target in the Phonological vs. Unrelated conditions), this difference was not significant.

Table 3. Results of logistic mixed-effects regression model assessing target fixations across experimental conditions. Significant effects are highlighted in bold.

	Estimate (SE)	95% CI	t-value	P-value	Cohen's D
Intercept	1.26 (0.09)	[1.08, 1.43]	14.34	<.0001	
Condition	.25 (.07)	[.11, .38]	3.69	.0004	.89
Age	.03 (.07)	[-.11, .16]	.41	.69	.18
Condition x Age	.03 (.05)	[-.06, .12]	.58	.56	.05

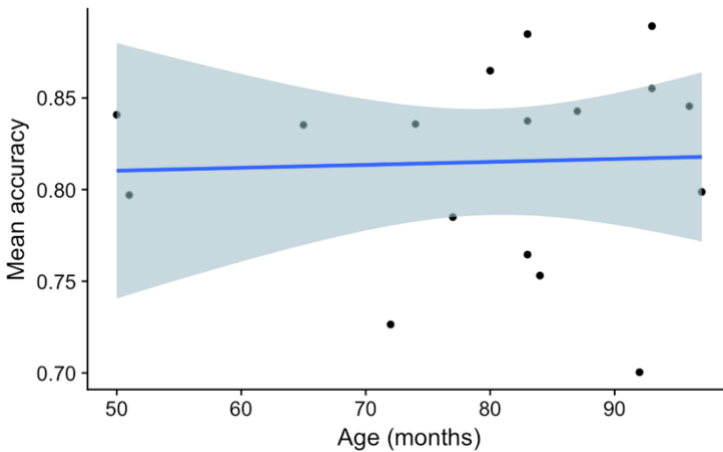


Figure 5: Mean accuracy (defined as proportion of looks to the target picture divided by looks to all pictures) by age in the 1500ms window following sign offset

Pattern of fixations to phonological and semantic competitors. To delve deeper into the lexical phenomena that underlie the patterns of lexical recognition seen in the previous analysis, we compared fixations to semantic and phonological competitors across the same

1500ms time window as the previous analysis. For this analysis, fixations to competitors were aggregated across conditions, as it enabled inclusion of a greater number of trials for each competitor type (i.e. 16 trials for each competitor type instead of 8 for each condition), and it allowed for investigation of effects of the *type* of competition (phonological or semantic) rather than the presence or absence of competitors across conditions. Specifically, we compared looks to phonological vs. unrelated competitors (averaging across Phonological and Phono-Semantic conditions), and looks to the semantic vs. unrelated competitors (averaging across the Semantic and Phono-Semantic conditions). Finally we directly compared relative looking to the Phonological vs. Semantic competitors across conditions.

Phonological activation. We compared fixations to phonological vs. unrelated competitors using a log-transformed ratio [$\log_{10}(\text{fixations to phonological competitor} / \text{fixations to unrelated competitors})$] including trials from the Phonological and Phono-Semantic conditions. Participants fixated the phonological competitors for 6.82% of the time period, compared to 4.07% fixations to unrelated competitors. We fit a linear mixed-effects model with age as a fixed effect and participants and items as random effects [Model: $\text{PhonoLogGaze} \sim \text{age} + (1 \mid \text{item}) + (1 \mid \text{participant})$]. Adding condition (Phonological, Phono-Semantic) to the model yielded no effect of condition. Although the intercept estimate value was positive, it was not significantly different than 0, indicating that looks to the phonological vs. unrelated competitors were not statistically different (Table 4a). Thus, in this analysis children did not show evidence for activation of phonological features of signs.

Semantic activation. We compared fixations to semantic vs. unrelated competitors using a log-transformed ratio [$\log_{10}(\text{fixations to semantic competitor} / \text{fixations to unrelated competitors})$] including trials from the Semantic and Phono-Semantic conditions. Participants fixated the semantic competitors 12.53% of the time, compared to 4.07% fixations to unrelated

competitors. We fit a linear mixed-effects model with age as a fixed effect and participants and items as random effects [Model: SemanticLogGaze ~ age + (1 | item) + (1 | participant)]. Adding condition (Semantic, Phono-Semantic) yielded no effect of condition. The intercept term was significant; children looked significantly more to semantic than to unrelated competitors across this time window (Table 4b). This supports our prediction that children are activating semantic features of signs during lexical recognition.

Semantic vs. Phonological Competitor activation: Finally, we used the log-gaze ratios of phonological vs. unrelated and semantic vs. unrelated competitors to directly compare looks to the phonological and semantic competitors. In this linear mixed-effects model we entered competitor type (semantic or phonological) as the fixed effect, in which “semantic” refers to the log-transformed ratio of semantic to unrelated competitor looking, and “phonological” refers to the log-transformed ratio of phonological to unrelated competitor looking. Phonological was coded as the reference level. We entered participant and target item as random effects [Model: LogGaze ~ competitor + (1 | item) + (1 | participant)]. We found a main effect of competitor type: participants looked more to the semantic than the phonological competitors, providing further evidence for activation of semantic, but not phonological features of signs during lexical recognition (Table 4c).

Across all comparisons of competitor fixations, age was additionally entered into the model as a continuous variable (centered and scaled), but did not contribute significant variance. This suggests that fixations to competitors were consistently distributed across the age range of the children in this sample.

Table 4: Comparison of fixations to competitors vs. unrelated distractors in the 1500ms window following sign offset

ASL LEXICAL RECOGNITION IN DEAF CHILDREN

	Beta-estimate (SE)	95% CI	t-value	p-value	Cohen's D
a) Phonological vs. Unrelated competitors					
Intercept	.03 (.12)	[-.23, .28]	.21	.84	
Age	-.03 (.11)	[-.25, .20]	-.26	.80	-.13
b) Semantic vs. Unrelated competitors					
Intercept	.58 (.15)	[.28, .88]	3.99	.0008	
Age	-.05 (.12)	[-.31, .20]	-.44	.66	-.20
c) Phonological vs Semantic competitors					
Intercept	-.24 (.13)	[-.51, .15]	-1.87	.07	
Distractor type	.32 (.09)	[.14, .50]	3.48	.0005	.27
Age	-.03 (.09)	[-.22, .15]	-.37	.72	-.18

Discussion

We began by asking how deaf children process and comprehend familiar ASL signs, and whether children show activation of phonological and semantic features of signs during lexical recognition. To address these questions, we tested deaf children between the ages of four and eight in a modified visual world paradigm. Based on prior research of sign processing in adults, we predicted that children would likely show activation of both semantic and phonological features of signs. We also predicted that children would show developmental changes in the speed and nature of lexical processing strategies. Our data illustrate several important findings. First, as indicated by the time course and onset switch analysis, we found that by age four, deaf children can rapidly identify sign meanings, by shifting their gaze from a sign video to a target picture shortly after the sign is presented. Second, in our analysis of fixation patterns in the 1500ms following sign offset, deaf children showed sensitivity to semantic features of signs, demonstrated by the fact that there were fewer fixations to the target when semantic competitors

were present, and greater fixations to semantic vs. unrelated competitors across conditions. In contrast, children did not show sensitivity to phonological features of signs in our analysis of target and competitor fixation patterns. However, the rate of errors in children's pointing responses did suggest that phonological features were salient to children when evaluating sign identity. Third, contrary to our predictions, children showed consistent patterns across the age range in all of our analyses, indicating that lexical recognition for familiar signs may be well established by early school age. Together, these findings present new evidence that processing familiar words in ASL shows many parallels to spoken language processing, with some potential differences that arise from processing language in the visual modality.

Recognition of Familiar Signs

Children in the current study showed rapid recognition of familiar signs: analysis of the timing of sign recognition (i.e. the first switch analysis) showed that children shifted gaze to the target sign shortly after sign offset. When presented with a target and three unrelated pictures, children fixated the target picture by about 230ms after sign offset. Given that it takes between 100-300ms to program a saccade in response to spoken language (Altmann, 2011), our results suggest that children are processing signs as they are presented and using this information to identify the referent. While we speculate that sign processing occurs incrementally as the sign unfolds, and certainly the time course of recognition shows that the earliest looks to the target begin as the sign is being produced, methodological and design features of our study make it difficult to determine exactly when in the time course of lexical recognition the earliest processing occurs. For example, in our stimuli we removed co-articulation information and transitional movement from a resting position to the target sign. These cues that occur before sign onset likely contribute to recognition in real-world sign comprehension. In addition, children may have identified the sign early in the timecourse but maintained gaze on the video

until the sign was complete. Nevertheless, our data provide compelling evidence that sign recognition is rapid and efficient.

Although sign and spoken language share many underlying structural features, the perception of language is clearly different across modalities. The task of learning words involves mapping words perceived in the input onto objects and events to determine their meaning. In spoken language, input is perceived through the auditory mode. Mapping words to their referents is a multi-modal process in spoken language acquisition: young children learning language must map the auditory signal onto objects and events in the world that are perceived through the visual mode. In contrast, perceiving signs relies much more heavily on the visual modality; visual perception serves “double duty” in that both the signs themselves and their real world referents are all perceived in a single modality. Thus in order to map signs perceived in the input to objects and events in the world, children acquiring sign language must learn precisely when to shift visual attention between linguistic and non-linguistic information (Lieberman, Hatrak, & Mayberry, 2014). These increased demands on visual attention may have led children to fixate much longer on signs, yet this is not what we found. Lexical recognition was highly efficient despite the increased demands on a single attentional system. The current results show remarkable adaptation among signers to the visual mode of language perception from a young age.

The current study joins a growing set of studies attempting to describe lexical recognition in ASL using similar techniques, and from these studies emerges a possible developmental trajectory. MacDonald et al. (2018) probed sign recognition in deaf toddlers (ages 16 to 53 months), using a similar technique though not identical to ours: the definition of sign onset in MacDonald et al.’s study was somewhat different from the one used in the current study, the stimuli were produced in child-directed signing (and thus were longer in duration), and toddlers

in Macdonald et al. were presented with two pictures instead of four. While a direct comparison is thus not possible, we note the response time in the current and previous studies as points of reference: toddlers in Macdonald et al.'s study shifted gaze at 1185ms after sign onset; children in the current study shifted gaze at 899ms after sign onset (in the Unrelated condition), and in our previous study of adult sign recognition, in which the stimuli were identical to those presented here, native-signing adults shifted gaze to the target starting at 863ms after sign onset (in the Unrelated condition). Converging evidence across these studies thus begins to paint a developmental picture in which the speed and efficiency of lexical recognition shows marked developmental change from toddlers to school age children, and again from school age children to adults. Individuals become faster at recognizing familiar signs over time. This protracted developmental pattern for sign recognition largely mirrors that found in studies of spoken language processing (McMurray et al., 2010; Rigler et al., 2015), and thereby suggests that the developmental timeline for lexical recognition is largely independent of language modality.

Sensitivity to phonological features of signs among deaf children

We found mixed evidence for activation of ASL phonology. In our behavioral data (i.e. pointing to the target picture) children made more than three times as many errors in identifying familiar signs in conditions in which a phonological competitor was present relative to conditions when no phonological competitor was present. Further, in the majority of these cases, children chose the phonological competitor rather than an unrelated or semantic competitor. However, this activation of phonology did not carry over to the gaze patterns observed in our eye-tracking data: children did not differ in target fixations based on the presence of a phonological competitor and did not fixate the phonological competitors more than the unrelated ones. There are several possible explanations for these mixed results. We speculate that the data from the gaze and pointing behaviors may reflect different types of activation at different time

points in lexical recognition. Specifically, switch time and fixation to the sign, target and competitors are indicative of the process of lexical retrieval, whereas picture selection reflects evaluation of the sign once lexical retrieval is complete. Thus phonological activation may occur relatively late in the process of sign recognition. Late activation has been shown for surface features of language, including case alternation (Perea, Vergara-Martínez, & Gomez, 2015) or letter rotation (Perea, Marcet, & Fernández-López, 2018) in written word recognition.

The pattern of results we observed is somewhat different from what has been found in the spoken language literature. Children perceiving spoken language are known to activate both phonological and semantic information about words as they are being processed (Huang & Snedeker, 2011). While there is clear evidence for processing sublexical features of signs in deaf adults (Dye & Shih, 2006; Emmorey & Corina, 2010), the path to this adult mental lexicon is undescribed. Among young children learning ASL, certain morphological features are first processed as holistic units. For example, children initially perceive fingerspelled words as unanalyzed units, and only later recognize that they are composed of individual letter handshapes (Padden, 2006). Similarly, when acquiring knowledge about verb agreement in ASL, children may initially derive their interpretations from the mimetic or iconic features of the agreement system (Meier, 2002), while only later recognizing that a single construction can contain multiple agreement morphemes. If indeed children learning ASL initially process some signs as conceptual units, then they might not have exhibited competition from signs sharing phonological features. Additionally, unlike spoken words, more than one aspect of phonological information (e.g. location and handshape) are largely present at sign onset, which may reduce the salience of any single phonological feature. These aspects of ASL signs may be partly responsible for the reduced degree of phonological activation we observed relative to the robust evidence for phonological activation in spoken language.

Further research is needed to determine if later processing of phonology is indeed a phenomenon related to sign language, as has been suggested in some character-based languages like Chinese (Chen & Shu, 2001). If so, our findings would support a more language- and modality-dependent process for phonological activation during lexical retrieval. Alternatively, the pattern of activation in our data may have arisen as a result of task demands of the current paradigm (Chen & Mirman, 2015). A third possibility is that the current dataset did not have sufficient power to detect phonological activation during the eye-tracking task, and that with a larger sample size there might be more robust evidence for phonological activation during sign retrieval.

Sensitivity to semantic features of signs among deaf children

Deaf children showed a contrasting pattern for semantic activation relative to activation of phonological features. As measured by behavioral responses (pointing to the target picture), children were highly accurate in identifying a familiar sign even when presented with a semantic competitor. However, analysis of gaze patterns revealed that during sign processing, children fixated less on the target picture when a semantic competitor was present, and looked significantly more towards a semantic competitor relative to an unrelated competitor. Thus our eye-tracking results indicate that sign processing involves clear activation of lexical candidates within semantic categories. This parallels spoken language patterns. Children with growing vocabularies develop richer semantic category knowledge and stronger semantic networks, which helps them acquire new words (Borovsky & Elman, 2006). Further, as children begin to learn to read, their semantic networks expand and they provide semantically-related responses in a word association task (Cronin, 2002). Among learners of a sign language, recent debates have centered around the role of iconicity in facilitating acquisition (Ormel, Hermans, Knoors, & Verhoeven, 2009). Evidence suggests that only certain types of iconicity may be predictive of

acquisition rate, and other features of signs such as frequency and neighborhood density may also correlate with sign learning (Caselli & Pyers, 2017). In the current study, iconicity cannot be ruled out as a contributing factor, as signs in our dataset had slightly higher iconicity ratings than signs in the ASL lexicon. However our findings suggest that semantic category information is highly active during sign recognition in young school-age signing deaf children.

Sign Recognition Across Childhood

Surprisingly, children between the ages of four and eight years were consistent in their timing of sign recognition and in their activation of phonological and semantic competitors. Age was not a significant predictor of the speed with which children recognized the target sign, nor were there age effects in either target or competitor fixations across the window of interest. We interpret the lack of age effects as initial evidence that the basic mechanisms involved in familiar sign recognition are largely in place by early school age. Studies of spoken word recognition among hearing children have similarly revealed that children as young as five years have mature lexical retrieval and recognition abilities and activate competitors in many ways like adults (Huang & Snedeker, 2011; Sekerina & Brooks, 2007). Henderson and colleagues found that seven-year-old children are as sensitive to lexical competition as adults both in isolation and with sentential context (Henderson, Weighall, Brown, & Gaskell, 2013). In the current study we did not directly compare child and adult lexical recognition, however our finding that children between the ages of four and eight were consistent in their gaze patterns suggests that these aspects of lexical recognition are stable across this range in childhood. Further research will be necessary to replicate and expand our findings to other elements of lexical recognition, such as particular aspects of phonology or types of semantic associations between words, and to explore how these patterns maintain or change in younger and older children. For example, it is possible

that, even if lexical recognition is stable in the current age range studied, specific aspects of recognition could continue to develop in adolescence and into adulthood (Rigler et al., 2015).

Another explanation for the lack of observed age effects is that, in ASL as in spoken language, vocabulary knowledge is a better predictor of lexical recognition than age. Spoken language studies have found a correlation between vocabulary and processing efficiency from infancy (Fernald et al., 2006) through late childhood, as well as among adults (Borovsky, Elman, & Fernald, 2012). Similarly, among toddlers learning ASL, participants with higher productive ASL vocabularies show faster and more accurate sign recognition than participants with lower vocabularies (MacDonald et al., 2018). We were limited in the current study by the fact that there is currently no existing instrument that is appropriate for measuring ASL vocabulary among children in our age range, and so we could not reliably account for vocabulary. The picture naming task that was used in this study provided an index of knowledge of concrete nouns; however these nouns were chosen to be early acquired, and further this task was used as an exclusionary criterion for specific trials in the eye-tracking experiment. As part of our process, children who did not know many of the signs in the picture naming task would likely not have contributed sufficient data to be included in the final analyses. In future work, we hope to be able to implement an independent measure of ASL such that the impact of vocabulary size can be reliably entered as a factor in analysis.

In the current findings, children with early exposure to ASL appear to have developed mature lexico-semantic networks. Crucially, deaf adults who do not have access to a full language early in life show persistent deficits in linguistic processing, particularly at the level of phonology (Mayberry & Fisher, 1989). For these late-learning adults, such processing deficits may arise from differences in the organization of the mental lexicon as vocabulary and syntax were acquired on an atypical timescale. In our previous findings (Lieberman et al., 2015, 2016),

late-learning deaf adults doing the same task as the one presented here showed no difference in target looking when semantic or phonological competitors were present. This underscores the significance of the current findings, in which children as young as four showed clear evidence for activation of semantic competitors.

The fact that children as young as four years were able to shift gaze to a target item so rapidly may be a benefit of early exposure to ASL. Infants and toddlers who are exposed to ASL from birth or early in life must quickly develop strategies to shift gaze rapidly between linguistic information and visual information, both of which are perceived visually. This rapid gaze shifting skill develops as parents scaffold early interactions with their deaf children (Swisher, 2000; Harris, Clibbens, Chasin, & Tibbitts, 1989), and by the age of two deaf children are adept at shifting gaze between a picture or object and parental language input (Lieberman et al., 2014). Strategic and rapid gaze shifting likely supports deaf children's ability to quickly and efficiently process familiar signs from a young age, as demonstrated in the current results. Further, the known relationship between parental input and children's vocabulary is likely mediated in this population by the child's ability to know when and how to alternate gaze efficiently between linguistic and visual input.

Limitations and issues for consideration

The sample size in this study is modest, and thus we cannot rule out the possibility that a larger sample would have yielded different findings. However, our sample is comparable to other recent studies of deaf children's lexical recognition (MacDonald et al., 2018) and deaf children's development of gaze (Brookes, Singleton & Meltzoff, 2019), and is a reflection of the low-incidence of the population; deafness occurs in approximately 1 in 1000 individuals, and of those only five percent have native exposure to ASL (Mitchell & Karchmer, 2004). While our study sample detected main effects, we acknowledge the possibility of increased Type 1 as well as

Type 2 errors in our analyses. In particular, our lack of findings for activation of phonological features of signs in our eye-tracking data, and lack of age effects across our analyses, may be partly explained by our sample size. Second, while our stimuli were created and vetted by Deaf, native signers, any manipulation of natural sign production may have affected the ease of recognition. In particular, our stimuli included signs for which all coarticulation was removed, which does not map completely onto how signs are perceived in natural input. Finally, there are potential methodological limitations. Our study provides insight into both the phenomenon of interest and the approach we used to investigate it. Our primary motivation was to determine how lexical recognition unfolds among deaf children learning ASL, and what this can tell us about the organization of the mental lexicon in young learners of ASL. Previous work suggests that the visual world paradigm is one fruitful approach that can shed light on these processes. However the task demands, specifically the need to allocate attention to both incoming input and visual information, may limit our ability to establish firm evidence for the exact timing of lexical processing relative to the unfolding linguistic signal. We point to studies where the linguistic signal unfolds over a longer time (i.e. at the sentence level; Lieberman, Borovsky, & Mayberry, 2018; Wienholz & Lieberman, 2019) as more appropriate for honing in on specific timing of incremental processing of ASL.

Conclusion

Children acquiring ASL showed rapid recognition of familiar signs after sign offset, activated semantic features of signs during recognition, and showed sensitivity to phonological features of signs in their behavioral responses. By the age of four, the mechanisms involved in efficient recognition of familiar signs appear to be largely in place among deaf children with early ASL exposure. We find many parallels between sign and spoken lexical recognition. In future research it will be crucial to further delineate whether the visual modality of sign

processing leads to unique aspects of lexical recognition in language learners. This study is a first step in understanding how the ASL lexicon develops over time among deaf children with early and consistent input to language.

Notes:

1. We compared each target and semantic competitor pair using Latent Semantic Analysis (LSA) (Landauer, Foltz, & Laham, 1998), applying the term-to-term comparison with the general reading semantic space (retrieved from lsa.colorado.edu). Semantically related items had a mean LSA value of .39; in contrast, pairs of items in the Unrelated condition had a mean LSA value of .05; a one-sample t-test verified that semantically related items had higher mean LSA values than unrelated items ($p < .001$).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website as well as on the OSF site for this study (<https://osf.io/gx6dj/>).

Appendix S1. List of stimuli by condition