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EMPIRICAL STUDY

Lexical Recognition in Deaf Children Learning American Sign Language: 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. Participants were presented with a single ASL sign, target picture, and three competitor pictures that varied in their phonological and semantic relationship to the target. Participants shifted gaze to the target picture shortly after sign offset. Participants showed robust evidence for activation of semantic but not phonological features of signs. However, in their behavioral responses, participants were most susceptible to phonological competitors. Results demonstrated 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

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Introduction

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 insights about lexical recognition have been based on studies of spoken languages. Recent results have suggested that in sign languages such as American Sign Language (ASL), adults also process signs as they are perceived visually (Lieberman, Borovsky, Hatrak, & Mayberry, 2015). Although 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 an interlocutor is perceiving an ASL sign, multiple phonological components are perceived 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. This iconicity is somewhat overrepresented in the particular set of signs children learn at early ages (Caselli & Pyers, 2017, 2020). 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 the phonological and semantic activation observed in children acquiring spoken language. In the current study, we examined lexical recognition of ASL signs in deaf children to investigate how the developing mental lexicon in signers is organized and is accessed with respect to phonological and semantic features of signs.

Word Recognition in Spoken Language

Studies using the visual world paradigm have revealed that during real-time comprehension 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 (Huettig & Altmann, 2005) of words, among others. The degree of both semantic and phonological activation co-varies with the 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 co-articulation 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 denser networks connecting the words that they know (Ojima, Matsuba-Kurita, Nakamura, & Hagiwara, 2011; Vermeer, 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 do adults (Arias-Trejo & Plunkett, 2010). Sekerina and Brooks (2007) found evidence for cohort competition during lexical recognition in 5- and 6-year-old Russian-speaking children. And research has found evidence for an increase in speed of activation and a decrease in competitor activation in lexical recognition even in adolescence (Rigler et al., 2015). Thus, although 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 (Bortfeld, Rathbun, Morgan, & Golinkoff, 2003; Lany, 2018; 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 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 have been 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 on the basis of sign location neighborhoods and phonotactic cues (e.g., a major location change signifying a sign boundary), 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: a target picture, and three 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 target picture 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 toward the target picture before the offset of the sign. In addition, native signers showed a pattern of activation that suggested that they were sensitive to both semantic and phonological features of signs. Native signers were faster at fixating 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. Late-learning signers did not differ across conditions in target speed or overall looking to target on the basis of semantic or phonological competitors, but they showed 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 have been 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), and in the way signs are organized along lexical-semantic relationships (Mann, Sheng, & Morgan, 2016). 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 has suggested that early sign vocabularies are influenced by many of the same features as are 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 of ASL in children 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. Although 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, 1999). This may lead children to process signs as conceptual units rather than as combinations of sub-lexical units. If children do process signs as conceptual units, then one might expect to see a lesser degree of phonological activation during sign recognition relative to spoken language recognition. 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—along phonological dimensions, for example—among individual signs is likely to be salient in word recognition (Mann & Marshall, 2012). However, whether and how phonological activation manifests during sign lexical recognition in children are empirical questions.

Semantic development in deaf children has been investigated through assessment of semantic categorization abilities in both native and nonnative signing children (Courtin, 1997). 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 from a set of four the picture that matched the target (i.e., was in the same semantic category). The deaf children (both native and nonnative signers) were less accurate than the 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 was 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 nonnative signing deaf children, deaf children's ability to identify synonyms (Novogrodsky, Fish, & Hoffmeister, 2014) and antonyms (Novogrodsky, Caldwell-Harris, Fish, & Hoffmeister, 2014) increased with age. Younger children were more likely to choose a phonological foil in these tasks than were 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 has been found for hearing children due to deaf children's limited access to spoken phonology. Thus, although both phonological and semantic features of words are likely to be activated during recognition, neither what type of activation is dominant nor how these two features interact is established.

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. First, our overarching goal was to investigate how deaf children between the ages of 4 and 8 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 also 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 as the phonological features of spoken language are processed (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 (Mann et al., 2016). Finally, we investigated whether there are developmental changes in performance on the sign processing task. Here we predicted, in parallel with spoken language processing (Rigler et al., 2015), that 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.

Method

Participants

Twenty deaf children between the ages of 4 years, 2 months to 8 years, 1 month (M = 6 years, 5 months) participated. There were 12 females. Seventeen children had at least one deaf parent and had been exposed to ASL from birth. The remaining three children had two hearing parents and had been exposed to ASL by the age of 2 years. 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 for deaf children. One additional child was tested but was unable to complete the eye-tracking task. Participants also undertook a series of other tasks that were part of a larger project studying language processing in ASL (Lieberman, Borovsky, & Mayberry, 2018; Wienholz & Lieberman, 2019).

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

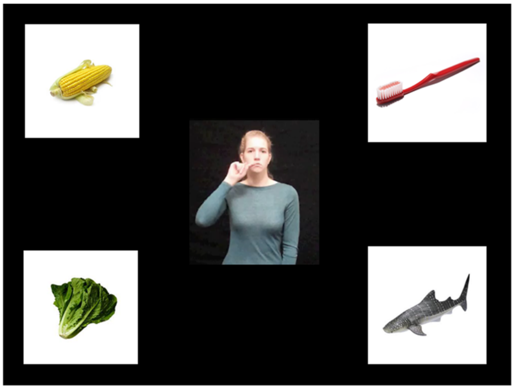

Figure 1 Example of layout of pictures and American Sign Language sign video stimuli. [Color figure can be viewed at wileyonlinelibrary.com]

et al., 2015). The stimulus pictures were color photo-realistic images presented on a white background square measuring 300 × 300 pixels. We presented the ASL signs via video. We filmed the signer against a black background and cropped the videos to a square also measuring 300 × 300 pixels. We presented the pictures and signs to the participants on a 17-in. 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 used 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. 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 one of 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. We defined semantic competitors as taxonomic pairs (e.g., *strawberry-grapes*, *gloves-jacket*) and selected target-competitor pairs to minimize ASL phonological overlap.[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 in total (Lieberman et al., 2015). Each image set consisted of either all one-handed signs or all two-handed signs, with the exception of 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, the target and phonological competitor signs differed in the number of hands used (for example, in the pair *bird-newspaper*, the sign BIRD is one-handed, but the sign 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, one of the competitors was a one-handed sign and the other was a two-handed sign in these three sets. Finally, we minimized phonological relationships between the English translations of the target and competitor items by excluding pairs whose English translations rhymed. 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, Sehyr, Cohen-Goldberg, & Emmorey, 2017). Mean iconicity for our stimuli signs was 3.78 compared to mean iconicity across the ASL lexicon of 3.39. This was not surprising given that we had chosen our signs to be familiar to children, and iconicity is overrepresented in children's early vocabulary. See Appendix S1 in the supporting information online for a list of all stimuli. Stimuli list and pictures are also available at the OSF site for this study (https://osf.io/gx6dj/); sign videos are available upon request from the authors.

During the experiment, we presented each picture set once. We counterbalanced items so that they appeared as either targets or competitors across versions of the stimuli except in the phono-semantic condition, which contained consistent targets across versions. We further counterbalanced the pictures such that the target picture was equally likely to occur in any location on the screen. We balanced the positional relationship between the target and related competitors across trials. Finally, we pseudo-randomized the order of trials 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, we filmed a deaf native signer producing multiple exemplars of each target. We then edited the clearest exemplar of each sign (as judged by another native signer) to be of uniform length such that each stimulus sign was exactly 666 milliseconds 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, we minimally increased or decreased the frame rate of the video. We defined the onset point for each sign 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). We removed all transitional movement from a resting position to the initial sign position to eliminate any variation in transition time, such as the difference in time it takes to move the hands to the torso versus 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.

Eye-Tracking Task

After obtaining parental consent, we brought the participants individually into the testing room and seated them in front of the LCD display and eye-tracking camera. We presented the stimuli using a PC computer running EyeLink Experiment Builder software (SR Research, 2011). We presented instructions in ASL on a prerecorded video, using child-friendly language. The signer told participants 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 matched the sign. We gave participants two practice trials before the start of the experiment. Next we conducted a five-point calibration and validation sequence. We then presented the experimental trials in two blocks of 16 trials, for a total of 32 trials. After the first block, we gave participants a break during which they first saw a signer producing a short, encouraging message (e.g., WOW GOOD JOB!) and then watched a 30- to 40-second engaging video.

Each experimental trial began with the four pictures presented on the four quadrants of the monitor. Following a 1,500-millisecond preview period, a central fixation cross appeared, with the pictures remaining on screen. When participants fixated their gaze on the cross, this triggered the onset of the video stimulus, again with the pictures remaining on the screen. The ASL sign disappeared immediately at sign offset. After 500 milliseconds (so as not to prematurely disrupt participants' fixations during sign processing), a cursor marker (a small square) appeared in the center of the screen. Once the participant pointed at one of the pictures, the experimenter sitting next to the participant moved the cursor to the corresponding picture using the mouse to click on it. This ended the trial (Figure 2).

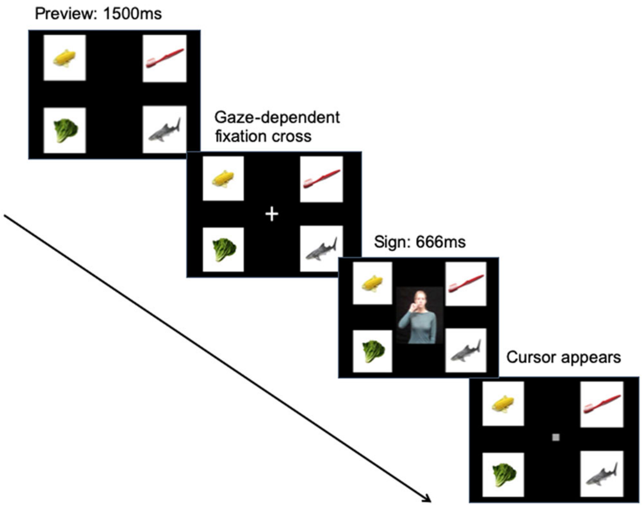

Figure 2 Example of trial sequence. [Color figure can be viewed at wileyonlinelibrary.com]

We recorded eye movements using an EyeLink 2000 eye tracker with remote desktop configuration at 500 Hz (SR Research, 2011). We adjusted the position of the display manually such that the display and eye-tracking camera were placed 580–620 mm from the participant's face. The participants wore a sticker on their forehead just above their right eye, which provided a fixed reference point that enabled the tracker to adjust for head movements relative to the camera. We recorded eye movements 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 participant completed a 174-word productive naming task (available on the OSF site for this study, https://osf.io/gx6dj/). The task consisted of presenting groups of pictures to the participants on a computer screen and asking them to produce the ASL sign for each picture. The pictures consisted primarily of concrete nouns ($n = 163$) plus a set of color words ($n = 11$). We chose the pictures to represent common, early-acquired lexical items. We showed the items in groups of three to six at a time and organized them according to semantic categories (e.g., animal pictures together; food items together). We did not give participants feedback about accuracy.

We video-recorded the task for later scoring. We scored an item as correct if a participant produced the target sign with no more than minimal phonological substitutions or errors common to young children (e.g., for a sign like BALL we counted substitution of a simple "5" handshape for a more complex "bent 5" handshape as correct). A native signer scored the task and discussed any uncertain scores with a second native signer until they reached a joint decision. We did not explicitly calculate interrater reliability for this task.

We included all 128 pictures that appeared in the eye-tracking task in the picture naming task. This allowed us to verify for each participant whether that participant knew the ASL sign for the target items so that we could analyze the data taking into account participants' ability to produce each target sign. Thus, the goals of the picture naming task were twofold. First, we used this task to verify that participants knew the stimulus signs and that their own sign for each image matched the signs that we used in the study; second, we used performance on this measure as an indicator of the extent 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%–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 we had expected, participants were largely familiar with the items that we had selected for the task. Two participants (both of whom were aged 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, we did not exclude these participants from the subsequent analyses. Nevertheless, the low score of these two participants and the high scores of other participants led us to interpret the picturenaming 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 a participant had not produced the correct target sign during picture naming (i.e., the participant 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 participants did not produce the correct target sign during picture naming. We excluded these trials from subsequent analyses to ensure that results could be interpreted as recognition of familiar signs.

Table 1 Logistic mixed-effects regression model assessing accuracy of pointing responses by condition (accuracy in each condition measured relative to accuracy in the unrelated condition)

Parameter	*b* (*SE*)	95% CI	*z*	*p*
Intercept	−4.56 (0.71)	[−6.14, −3.29]	−6.42	<.001
Phono-semantic	2.03 (0.68)	[0.72, 3.51]	2.99	.003
Phonological	1.40 (0.69)	[0.08, 2.90]	2.04	.041
Semantic	0.14 (0.75)	[−1.37, 1.67]	0.18	.860

Note. Model: Pointing Accuracy ∼ Condition + (1 | Participant) + (1 | Item).

Eye-Tracking Task

Pointing Responses

We analyzed pointing responses as a measure of overall accuracy, defined as a participant's point to the correct target sign. There were 61 incorrect trials out of a total of 716 completed trials across all participants. We analyzed responses by condition. In the phono-semantic condition, there were 29 incorrect trials for which participants 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 in which participants chose the phonological competitor ($n = 9$) or the unrelated competitors ($n = 10$). In the semantic condition, there were seven errors. In only two of these errors participants chose the semantic competitor; for the remaining five errors, participants chose unrelated competitors. Finally, in the unrelated condition, there were six errors, all of which were (by definition) unrelated competitors. All analyses were carried out in R version 3.5.3 (R Core Team, 2019). We performed a logistic mixed-effects model analysis (Baayen, Davidson, & Bates, 2008) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015), including condition as a fixed effect and random effect intercepts of participants and items to determine whether error rates varied by condition. Table 1 presents the results of this model. The unrelated condition was the base against which we compared other conditions. We selected this model for its conservative approach because, across conditions, there were more opportunities to make an unrelated error than a phonological or semantic error. We used an alpha level of .05 for this and all subsequent statistical tests. The model revealed that errors in the phonological and phono-semantic conditions but not in the semantic condition significantly exceeded those in the unrelated condition. Overall, our analysis of the participants' errors indicated that participants were generally quite accurate on the task but that they were susceptible to competitors that had phonological overlap with the target. This suggests that the participants were activating phonological features of signs during lexical recognition.

Next, we removed trials ($n = 56$) for which participants had not produced the correct sign during the picture naming task described above. Finally, we removed trials that exceeded the trackloss threshold of 80% (i.e., participants were looking at the display for less than 20% of the time during the window from sign onset until 1,500 milliseconds after sign offset). We set the threshold for trackloss on the basis of previous studies using a similar paradigm with young children (e.g., Borovsky, Ellis, Evans, & Elman, 2016). This resulted in the removal of nine additional trials. Following these steps, we removed from further analysis three participants who contributed fewer than two trials per condition. 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 in the presence of competitors and with children's ages. To investigate when children identify a target sign, we plotted the time course of participants' gaze beginning at sign onset and continuing for 2,000 milliseconds. We used an onset switch analysis (Dink & Ferguson, 2015) to measure mean timing of the first gaze shift from the video or a competitor picture toward the target picture, with mean gaze shift time as the dependent variable and condition and age in months as predictors.

Having established the time course of sign recognition, we directed our remaining analyses toward our second goal, which was to explore how semantic and phonological features of signs are activated during sign recognition. We operationalized this in two separate analyses of fixations to the pictures on the screen starting at sign offset and continuing for 1,500 milliseconds. The first analysis focused on target fixations as a function of condition, allowing us to explore whether children spend variable amounts of time fixating the target when semantic or phonological competitors are present. The dependent variable was the mean log-transformed proportion of fixations to target, with condition and age in months as predictors. The second analysis delved more deeply 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 in months as predictors. We have reported each main step (time course plotting, target analysis, competitor analysis) in detail below. Analysis scripts and the cleaned dataset that we used in our statistical analyses are available on OSF (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). We plotted time course as the proportion of fixations to each area of interest beginning at sign onset and continuing for 2,000 milliseconds. Visual inspection of the time course revealed that when the sign video was being presented, children fixated gaze on the video. However, the time course plot also illustrates that the earliest looks to the target began even as the sign itself was still being produced, which meant that, in some cases, participants were using partial information from the sign to make decisions about the sign's identity. The sign video was relatively short (666 milliseconds) and did not include coarticulation from the resting position to the placement of the hands in the correct position. Because we defined target sign onset at the point where all phonological parameters were already in place, participants did not have coarticulation or transitional movement information available to aid in detecting the target sign. Thus, the sign onset was intentionally the same as the sign recognition point. After the sign video, participants began to shift away from the video and toward the target and competitor pictures.

Timing of First Fixation to Target

To determine whether participants' identification of the target was driven partially by the presence of related competitors, we compared the time point at which they first shifted gaze to the target sign across conditions (i.e., onset switch analysis). We defined an onset switch as the mean time point at which participants initiated their first gaze shift from the sign video or any of the competitor pictures to the target picture, starting at the sign video onset. We compared onset switch time across conditions using a linear mixed-effects 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). Additionally, we entered age (centered and scaled) 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. Table 2 presents the results of this

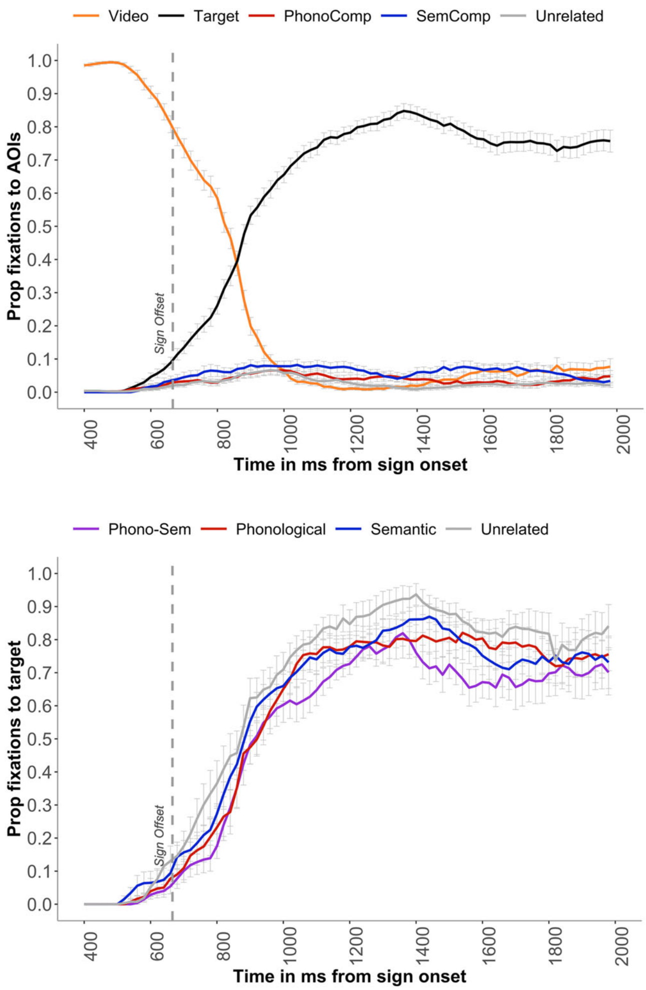

Figure 3 Top: Mean proportion of fixations to each area of interest (i.e., sign video, target picture, semantic competitor, phonological competitor, unrelated competitor) from 400 to 2,000 milliseconds from sign onset. Fixations are averaged across conditions. Bottom: Mean proportion of fixations to the target picture from 400 to 2,000 milliseconds following sign onset in each condition (i.e., unrelated, phonological, semantic, phono-semantic). The vertical line in each graph represents sign offset at 666 milliseconds. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2 Linear mixed-effects regression model on timing of first gaze switch to the target picture relative to sign video onset, by condition and participant age

Parameter	*b* (*SE*)	95% CI	*t*(*df*)	*p*
Intercept	938.32 (21.53)	[893.65, 982.88]	43.58 (17.67)	<.001
Condition	−29.68 (11.27)	[−51.81, −7.53]	−2.63 (442.22)	.009
Age	−33.58 (21.06)	[−77.20, −9.87]	−1.59 (18.64)	.130

Note. Model: Switch-time ~ Condition + Age + (1 | Participant).

Table 3 Timing (in milliseconds) of first gaze switch to the target picture measured from sign video onset

	First switch to target	
Condition	*M* (*SE*)	95% CI
Phono-semantic	996.23 (32.68)	[926.96, 1065.50]
Phonological	955.92 (25.87)	[901.07, 1010.76]
Semantic	924.79 (28.47)	[864.43, 985.15]
Unrelated	898.77 (36.18)	[822.08, 975.46]

model. The lmer analysis of onset switches showed an effect of condition and no effect of age. Follow-up pairwise comparisons revealed only a nonsignificant effect in which gaze switches in the phono-semantic condition occurred later than those in the unrelated condition, $t(442) = 2.54$, $SE = 35.80$, $p = .056$, $b(SE) = 90.7(35.9)$, 95% CI [−1.6, 183]. Table 3 shows mean switch times for each condition. This pattern of results suggests that both phonological and semantic competitors had an influence on participants' response time, but that it was only in the presence of multiple competitor types that the timing of participants' gaze shifts were significantly impacted relative to the unrelated condition. It was also possible that the participants were responding to the presence of two related competitors in the phono-semantic condition, but, in the other conditions, there were either zero or just one related competitor. Nevertheless, there was clear evidence for competitor influence on the timing of first fixations to the target picture.

Pattern of Fixations to Target Across Conditions

While the onset switch analysis was 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 participants had

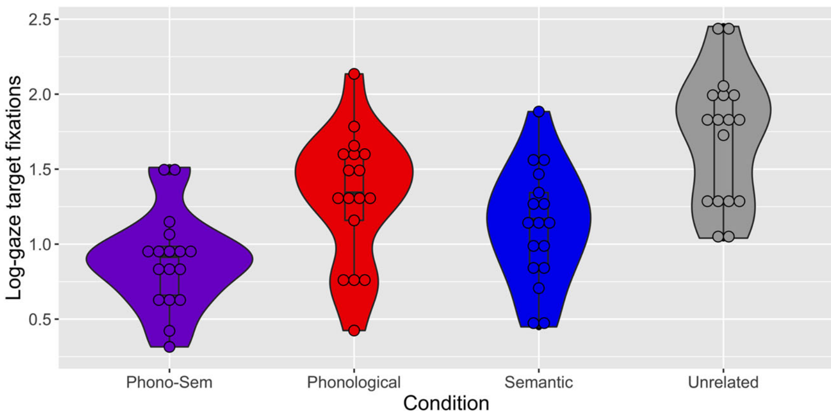

Figure 4 Mean log-gaze proportion of fixations to target vs. competitors by condition in the time window from 0 to 1,500 milliseconds following sign offset. [Color figure can be viewed at wileyonlinelibrary.com]

perceived the sign and were actively gazing toward 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 1,500 milliseconds (Figure 4). Similar time windows have been used in previous studies of lexical processing in sign language (Lieberman et al., 2015; MacDonald et al., 2018). We log transformed target to competitor looking ratio using the formula log10(target fixations/competitor fixations). We defined fixations as the mean proportion of fixations across the window of analysis. As fixation proportions are not linearly independent (i.e., more looks to one item mean fewer to another), log gaze proportion ratios allowed us to assess the bias of participants' viewing an object relative to other objects. Additionally, this transformation supports a better normal approximation of the data compared to raw proportions which vary between 0 and 1.

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). Table 4 presents the results of this model. 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). We sum-coded and centered condition to enable us to infer main effects across all levels and to reduce potential problems with

Table 4 Linear mixed-effects regression model assessing target fixations across experimental conditions

Parameter	*b* (*SE*)	95% CI	*t*(*df*)	*p*
Intercept	1.26 (0.09)	[1.08, 1.43]	14.34 (37.07)	<.001
Condition	0.25 (0.07)	[0.11, 0.38]	3.69 (69.03)	<.001
Age	0.03 (0.07)	[−0.11, 0.16]	0.41 (20.50)	.690
Condition × Age	0.03 (0.05)	[−0.06, 0.12]	0.58 (463.33)	.560

Note. Model: LogGaze ~ Condition + Age + Condition: Age + (1 | Item) + (1 | Participant).

collinearity among variables. LogGaze values above 0 indicate an increased proportion of fixations to the target relative to competitors; values below 0 indicate an 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 revealed that this effect was driven by a difference in target fixations in the phono-semantic condition ($M = 0.84$, $SE = 0.19$, 95% CI [0.46, 1.21]) versus the unrelated condition ($M = 1.69$, $SE = 0.13$, 95% CI [1.43, 1.95]), $t(53.7) = -3.94$, $p = .0013$, $b(SE) = -0.86(0.21)$, 95% CI [−1.43, −0.28], with Tukey adjustment for comparing a family of four estimates. There was also a significant difference in looking between the semantic condition ($M = 1.12$, $SE = 0.15$, 95% CI [0.82, 1.43]) and the unrelated condition, $t(73.8) = -3.03$, $p = .018$, $b(SE) = -0.57(0.19)$, 95% CI [−1.06, −0.075]. We added age (centered and scaled) as a continuous variable to the model, but age did not significantly contribute to target looking, either as a main effect or as an interaction of condition and age (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 suggested that the participants' gaze patterns were influenced primarily by semantic competitors. Although proportionally participants were impacted by phonological competitors as well (i.e., fewer fixations to the target in the phonological vs. unrelated conditions), this difference was not statistically significant.

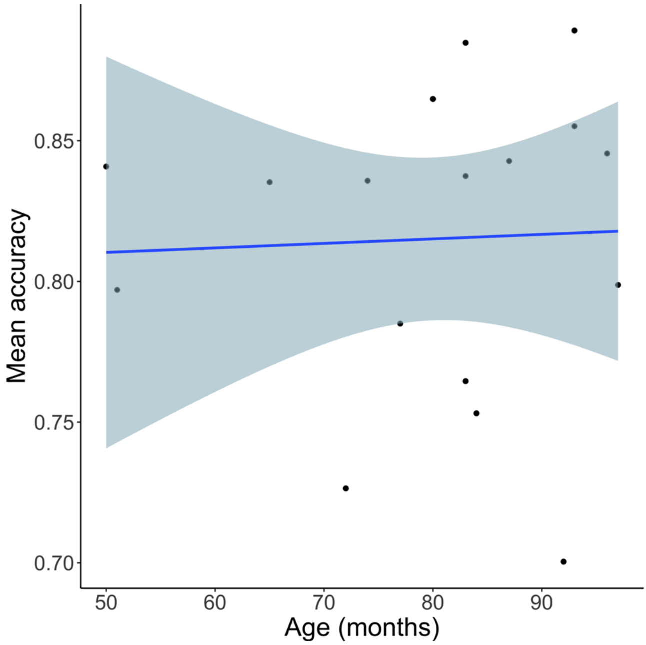

Figure 5 Mean accuracy (defined as proportion of looks to the target picture divided by looks to all pictures) by age in the 1,500 milliseconds window following sign offset. [Color figure can be viewed at wileyonlinelibrary.com]

Pattern of Fixations to Phonological and Semantic Competitors

To further examine 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 1,500-millisecond time window as for the previous analysis. For this analysis, we aggregated fixations to competitors across conditions because it enabled us to include a greater number of trials for each competitor type (i.e., 16 trials for each competitor type instead of eight for each condition), and it allowed us to investigate the 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 versus unrelated competitors (aggregating across phonological and phono-semantic conditions) and looks to the semantic versus unrelated competitors (aggregating across the semantic and phono-semantic conditions). Finally we directly compared relative looking to the phonological versus semantic competitors across conditions.

Table 5 Comparison of standardized regression coefficient estimates ($b*$) for fixations to competitors versus unrelated distractors in the 1,500 millisecond window following sign offset

Parameter	$b*$ (SE)	95% CI	$t(df)$	p
Phonological vs. unrelated competitors[a]				
Intercept	.03 (.12)	[−.23, .28]	0.21 (13.27)	.840
Age	−.03 (.11)	[−.25, .20]	−0.26 (17.28)	.800
Semantic vs. unrelated competitors[b]				
Intercept	.58 (.15)	[.28, .88]	3.99 (19.28)	<.001
Age	−.05 (.12)	[−.31, .20]	−0.44 (19.51)	.660
Phonological vs. semantic competitors[c]				
Intercept	−.24 (.13)	[−.51, .15]	−1.87 (46.29)	.070
Competitor type	.32 (.09)	[.14, .50]	3.48 (659.27)	<.001
Age	−.03 (.09)	[−.22, .15]	−0.37 (17.94)	.720

[a]Model: PhonoLogGaze ~ Age + (1 | Item) + (1 | Participant).
[b]Model: SemanticLogGaze ~ Age + (1 | Item) + (1 | Participant).
[c]Model: LogGaze ~ Competitor + (1 | Item) + (1 | Participant).

Phonological activation. We compared fixations to phonological versus unrelated competitors using a log-transformed ratio, including trials from the phonological and phono-semantic conditions, using the formula log10(fixations to phonological competitor/fixations to unrelated competitors). Participants fixated the phonological competitors for 6.82% of the time window compared to 4.07% of the time window for unrelated competitors. We fit a linear mixed-effects model with age as a fixed effect and participants and items as random effects (see Table 5, phonological vs. unrelated competitors). 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 from 0, indicating that looks to the phonological versus unrelated competitors were not statistically different. Thus, in this analysis participants did not show evidence for activation of phonological features of signs.

Semantic activation. We compared fixations to semantic versus unrelated competitors using a log-transformed ratio, including trials from the semantic and phono-semantic conditions, using the forumula log10(fixations to semantic competitor/ fixations to unrelated competitors). Participants fixated the semantic competitors for 12.53% of the time window compared to unrelated competitors which they fixated for 4.07% of the time window. We fit a linear mixed-effects model with age as a fixed effect and participants and items as random effects (see Table 5, semantic vs. unrelated competitors). Adding condition (semantic, phono-semantic) yielded no effect of condition. The intercept term was significant; participants looked significantly more to semantic than to unrelated competitors across this time window. This supports our prediction that children are activating semantic features of signs during lexical recognition.

Semantic versus phonological competitor activation. Finally, we used the log-gaze ratios of phonological versus unrelated and semantic versus 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 referred to the log-transformed ratio of semantic to unrelated competitor looking, and phonological referred to the log-transformed ratio of phonological to unrelated competitor looking. We coded phonological as the reference level. We entered participant and target item as random effects. Table 5 (phonological vs. semantic competitors) presents the results of this model. We found a main effect of competitor type. Participants looked more to the semantic than the phonological competitors (when each was compared to unrelated competitors), providing further evidence for activation of semantic but not of phonological features of signs during lexical recognition.

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

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 4 and 8 years in a modified visual world eye-tracking paradigm. On the basis of prior research of sign processing in adults, we predicted that our child participants would likely show activation of both semantic and phonological features of signs. We also predicted that participants 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 the age of 4 years, deaf children could rapidly identify sign meanings by shifting their gaze from a sign video to a target picture shortly after the sign was presented. Second, in our analysis of fixation patterns in the 1,500 milliseconds following sign offset, deaf children showed sensitivity to semantic features of signs, demonstrated by the fact that there were proportionally fewer fixations to the target when semantic competitors were present and by the fact that there were proportionally more fixations to semantic versus unrelated competitors across conditions. In contrast, participants did not show sensitivity to phonological features of signs in our analysis of target and competitor fixation patterns. However, the rate of errors in participants' pointing responses did suggest that phonological features were salient to them when they identified the target sign. Third, contrary to our predictions, the participants 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–spatial modality.

Recognition of Familiar Signs

Children participating in the current study showed rapid recognition of familiar signs. Analysis of the timing of sign recognition showed that participants shifted gaze to the target sign shortly after sign offset. When presented with a target and three unrelated pictures, participants fixated the target picture by about 230 milliseconds after sign offset. Given that it takes between 100 and 300 milliseconds to program a saccade in response to spoken language (Altmann, 2011), our results suggest that children process signs as they are presented and that children use this information to identify the referent. Although 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 coarticulation 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, participants may have identified the sign early in the time course but maintained gaze on the video until the sign was complete. Nevertheless, our data provide compelling evidence that sign recognition is rapid, efficient, and can even occur before sign offset.

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 mainly through the auditory mode (though visual cues such as gesture, gaze, and mouth movements contribute to perception as well). Mapping words to their referents is a multimodal process in spoken language acquisition; young children learning language must map the primary 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 nonlinguistic information (Lieberman, Hatrak, & Mayberry, 2014). These increased demands on visual attention might have led the participants to fixate much longer on signs, yet this was 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 investigating lexical recognition in ASL using similar techniques, and from these studies has emerged a possible developmental trajectory. Recently, MacDonald et al. (2018) probed sign recognition in deaf toddlers (ages 16 to 53 months), using a technique similar, 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 were presented with two pictures instead of four. Although a direct comparison is thus not possible, we note the response time in the current and previous studies as points of reference. The deaf toddlers in Macdonald et al.'s study shifted gaze to the target picture at 1,185 milliseconds after sign onset; children in the current study shifted gaze at 899 milliseconds after sign onset (in the unrelated condition). 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 844 milliseconds after sign onset (in the unrelated condition) (Lieberman et al., 2015). 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 a smaller change from school age children to adults. Individuals become faster at recognizing familiar signs over time. This protracted development of the speed of isolated familiar 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

We found mixed evidence for activation of ASL phonology. In our behavioral data (i.e., pointing to the target picture), participants made more than three times as many errors in identifying familiar signs in conditions in which a phonological competitor was present relative to conditions in which no phonological competitor was present. Further, in the majority of these cases, participants 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. Participants did not differ in target fixations in 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, gaze shift time and fixation to the sign, the target, and the competitors reflect 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 that 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 the words are being processed (Huang & Snedeker, 2011). Although there is clear evidence for processing sub-lexical features of signs in deaf adults (Dye & Shih, 2006; Emmorey & Corina, 1990), the path to this adult mental lexicon is largely undescribed. Among young children learning ASL, certain morphological features are first processed as holistic units. For example, children initially perceive finger spelled 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) and only later recognize that a single verb construction can contain multiple agreement morphemes (i.e., an ASL verb can incorporate subject and object by way of the path movement of the sign). If indeed children learning ASL initially process some signs as conceptual units, then our participants 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 that we observed relative to the robust evidence for phonological activation in spoken language at similar ages (Huang & Snedeker, 2011).

Further research is needed to determine if processing of phonology at the later stages of lexical access is indeed a phenomenon related to sign language. 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 the 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

Participants showed a contrasting pattern for semantic activation relative to activation of phonological features. As measured by behavioral responses (pointing to the target picture), participants were highly accurate in identifying a familiar sign even when they were presented with a semantic competitor. However, analysis of gaze patterns revealed that during sign processing, participants fixated less on the target picture when a semantic competitor was present and looked significantly more toward 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. Such activation in sign processing parallels spoken language patterns. Children with growing vocabularies develop richer semantic category knowledge and stronger semantic networks, both of which help 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 predict 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 variable because 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, our participants, who were between the ages of 4 and 8 years, were consistent in their timing of sign recognition and in their activation of phonological and semantic competitors across the age range. Age was not a significant predictor of the speed with which the participants 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 5 years of age 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 7-year-old children are as sensitive to lexical competition as are 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, the fact that our participants between the ages of 4 and 8 years were consistent in their gaze patterns suggests that these aspects of lexical recognition are stable across this age 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 age range that we 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 is 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, those with larger productive ASL vocabularies show faster and more accurate sign recognition than children with smaller vocabularies (MacDonald et al., 2018). We were limited in the current study by the fact that there is currently no existing widely available instrument that is appropriate for measuring ASL vocabulary knowledge among children in our age range, and so we could not reliably account for vocabulary knowledge. The picture naming task that we used in this study provided an index of knowledge of concrete nouns. However, we chose these nouns because they are acquired early, and, further, we used this task 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 vocabulary such that the impact of vocabulary size can be reliably entered as a variable in analyses.

In the current findings, children with early exposure to ASL appear to have developed mature lexico-semantic networks (Mann et al., 2016). 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 given that 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 or absent. This underscores the significance of the current findings in which participants as young as 4 years old showed clear evidence for activation of semantic competitors.

The fact that participants as young as 4 years old 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 (Brooks, Singleton, & Meltzoff, 2020). This rapid gaze shifting skill develops as parents scaffold early interactions with their deaf children (Harris, Clibbens, Chasin, & Tibbitts, 1989; Swisher, 2000), and, by the age of 2 years, 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 the current results have demonstrated. Further, the known relationship between parental input and children's vocabulary is likely mediated in this population by children's ability to know when and how to alternate gaze efficiently between the linguistic signal (i.e., the signed video) and visual referents (i.e., the surrounding pictures).

Limitations and Future Directions

This study was not without limitations. First, the sample size in this study was 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 following (Brooks et al., 2020), and the sample size reflects the lowincidence of deafness in the population. Deafness occurs in approximately 1 in 1,000 individuals, and of those only 5% have native exposure to ASL (Mitchell & Karchmer, 2004). Although 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 the lack of age effects across our analyses may be partly explained by our sample size. Second, although 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 differs from how signs are perceived in natural input. Third, there are potential methodological limitations. Our study has provided insight into both the phenomenon of interest and the approach that 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 has suggested 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 have limited 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 et al., 2018; Wienholz & Lieberman, 2019) as more appropriate for honing in on the specific timing of incremental processing of ASL.

Conclusion

Child participants acquiring ASL showed rapid recognition of familiar signs, activated semantic features of signs during recognition, and showed sensitivity to phonological features of signs in their behavioral responses. By the age of 4 years, the mechanisms involved in efficient recognition of familiar signs appear to be largely in place among deaf children with early ASL exposure. We found 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, such as in relation to phonological features. 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.

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Note

1 We compared each target and semantic competitor pair using latent semantic analysis (Landauer, Foltz, & Laham, 1998), applying the term-to-term comparison with the general reading semantic space (retrieved from lsa.colorado.edu). Semanticallyrelated items had a mean latent semantic analysis value of .39. In contrast, pairs of items in the unrelated condition had a mean latent semantic analysis value of .05. A one-sample *t* test verified that semanticallyrelated items had higher mean latent semantic analysis values than did unrelated items ($t(7) = 6.36, p < .001$).

Open Research Badges

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data are available at https://osf.io/guem7/.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1. List of Stimuli by Condition.

Appendix: Accessible Summary (also publicly available at https://oasis-database.org)

Deaf Children Perceive Signs in Their "Mind's Eye"

What This Research Was About and Why It Is Important

When children perceive language, they must retrieve words from their "mental lexicon," which is like a dictionary in the mind. Many words can be active in their mind at once. For example, when hearing the word *pear* children might activate words like *bear*, which sounds like *pear* (they share a similar form), or *apple*, which is in the same meaning category as *pear*. We wanted to know whether deaf children learning American Sign Language (ASL) perceive signs in a similar way, to understand the similarities and differences between learning sign and spoken languages. We found that children are fast and efficient at recognizing familiar signs, and that many features of sign language perception are similar to spoken language perception.

What the Researchers Did

- We tested 20 deaf children between the ages of 4 and 8 years who were learning ASL. Children had been learning ASL either from birth or started learning by the age of 2.
- Children watched a computer screen that included a video of an ASL sign (e.g., TRAIN), and four pictures: one matched the sign (train), one overlapped in form (e.g., chair, as the sign CHAIR looks like the sign TRAIN), one overlapped in meaning category (e.g., car, as train and car are both vehicles), and one that was unrelated (e.g., butterfly).
- As children saw the signs and pictures, we recorded their gaze. We measured how fast they looked at the matching picture, how much time they spent on the matching picture, and how much they looked at the other pictures on the screen.
- Using eye-gaze is a helpful way of measuring what words children are considering, because we naturally tend to look at something if it is active in our mind. We also asked children to point at the matching picture.

What the Researcher Found

- Children pointed at the correct picture most of the time. When they pointed at the wrong picture, they tended to choose the picture that overlapped in form with the target.
- Overall, children were fast and efficient at recognizing signs. They watched the sign video and quickly shifted their gaze to the matching picture, sometimes looking at the matching picture even before the sign had finished.
- When we analyzed where children's gaze was on the screen, we found they generally looked at the matching picture. However, they also looked at the picture that was in the same meaning category as the target.
- We did not find any differences in looking patterns based on the age of the child.

Things to Consider

- We show that deaf children are sensitive to both the form and meaning of ASL signs, and that many aspects of recognizing ASL signs are similar to the ways in which hearing children recognize spoken words.

- Our sample was somewhat small, so in future research it will be important to test a larger number of deaf children, and to include children who started learning ASL later in childhood.

Materials and data: Data are publicly available at https://osf.io/guem7/.
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