Real-time lexical comprehension in young children learning American Sign Language

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Research Highlights

- We develop precise measures that characterize the timecourse of eye movements during real-time comprehension of American Sign Language (ASL) by native ASL-learning children and adults.

- Parallel looking patterns for deaf and hearing ASL learners suggest that both groups are sensitive to modality-specific constraints of processing a sign language.

- ASL learners and adults rapidly shift visual attention as soon as they have enough linguistic signal to do so and prior to sign offset.

- Individual variation in speed of lexical access is linked to age/vocabulary, suggesting that skill in allocating visual attention in real-time is a language-general phenomenon.

Abstract

When children interpret spoken language in real time, linguistic information drives rapid shifts in visual attention, which can provide insights into developing efficiency of lexical access. But how does language influence visual attention when the linguistic signal and the visual world are both processed via the visual channel? We used precise measures of eye movements during real-time comprehension of a visual-manual language, American Sign Language (ASL) by 29 native, monolingual ASL-learning children (16-53 mos, 16 deaf, 13 hearing) and 16 fluent deaf adult signers. Deaf and hearing ASL-learners showed remarkably similar gaze patterns, suggesting comparable sensitivity to the constraints of processing ASL. All signers showed incremental language comprehension, initiating eye movements prior to sign offset. Finally, variation in children's ASL processing was positively correlated with age and vocabulary size. Thus, despite channel competition, deployment of visual attention during ASL comprehension reflects information processing skills that are fundamental for language acquisition.

Keywords: sign language, language processing, language acquisition, visual attention

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Finding meaning in a spoken or a signed language requires learning to establish reference during real-time interaction – relying on audition to interpret spoken words, or on vision to interpret manual signs. Starting in infancy, children learning spoken language make dramatic gains in their efficiency in linking acoustic signals representing lexical forms to objects in the visual world. Studies of spoken language comprehension using the looking-while-listening (LWL) procedure have measured children's gaze shifts while they look at familiar objects and listen to speech naming one of the objects (Fernald, Zangl, Portillo, & Marchman, 2008; Law & Edwards, 2014; Venker, Eernisse, Saffran, & Ellis Weismer, 2013). Such research finds that spoken language is processed incrementally, with eye movements occurring as soon as the auditory information is sufficient to enable referent identification (Allopenna, Magnuson, & Tanenhaus, 1998). Moreover, individual differences in spoken language processing efficiency predict vocabulary growth and later language and cognitive outcomes (Fernald, Perfors & Marchman, 2006; Marchman & Fernald, 2008).

Much less is known about how language influences visual attention during sign language comprehension. Do the findings from spoken language reflect language-general phenomena or are they specific to the auditory modality? Here, we address this question by developing the first measures of speed and accuracy in real-time *sign language* comprehension by children learning American Sign Language (ASL). First, we compare the time course of ASL processing in deaf and hearing native ASL-learners. Next, we compare the performance of young ASL-learners to adult signers and ask whether there are age-related increases in processing efficiency that parallel

those found in spoken languages. Then, we estimate the extent to which adults and children shift visual attention away from a language source and to a named referent prior to the offset of the target sign, showing evidence of incremental language processing. Finally, we measure links between variability in children's ASL processing skill and their expressive vocabulary development.

ASL processing in adults

Research with adults shows that language processing in signed and spoken languages is similar in many ways. As in spoken language, sign recognition is thought to unfold in a two-stage process at the lexical and sub-lexical levels. Moreover, sign processing is influenced by both lexicality and frequency; non-signs are identified more slowly than real signs (Corina & Emmorey, 1993) and high frequency signs are recognized faster than low frequency signs (Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008). Recent work using eye-tracking methods found that adult signers produce gaze shifts to phonological competitors, showing sensitivity to sub-lexical features, and that these shifts were initiated prior to the offset of the sign, showing evidence of incremental processing (Lieberman, Borovsky, Hatrak, & Mayberry, 2014). In addition, Caselli and Cohen-Goldberg (2014) adapted a computational model, developed for spoken language (Chen & Mirman, 2012), to explain patterns of lexical access in sign languages, suggesting that the languages share a common processing architecture.

However, differences between spoken and signed languages in both sub-lexical and surface features of lexical forms could affect the time course of sign recognition (for reviews, see Carreiras, 2010 and Corina & Knapp, 2006). For example, Emmorey and Corina (1990) showed deaf adults increasingly longer videos of signs in isolation and asked them to identify the signs in an open-ended response format. In the same study, English-speaking adults heard increasingly

longer segments of spoken words. Accurate identification of signs required less of the linguistic

signal compared to words (see also Morford & Carlsen, 2011), suggesting that features of visual-

manual languages, such as simultaneous presentation of phonological information, might

increase speed of lexical access. Moreover, Gutierrez and colleagues (2012) used EEG measures

to provide evidence that semantic and phonological information might be more tightly linked in

the sign language lexicon than in the spoken language lexicon.

    While there is evidence for parallels and differences in the processes underlying spoken

word and manual sign recognition, the majority of this work has relied on offline methods that

do not capture lexical processing as it unfolds in time (e.g., lexical decision tasks). In addition,

no previous studies have measured eye movements by *young* ASL-learners' during real-time

language comprehension, an important skill for children who must divide visual attention

between the language source and the visual world.

Lexical development in ASL

    Diary studies show that ASL acquisition follows a similar developmental trajectory as

that of spoken language (Lillo-Martin, 1999; Mayberry & Squires, 2006). For example, young

signers typically produce recognizable signs before the end of the first year and two-sign

sentences by their 2nd birthday (Newport & Meier, 1985). And as in many spoken languages

(Waxman et al., 2013), young ASL-learners tend first to learn more nouns than verbs or other

predicates (Anderson & Reilly, 2002).

    However, because children learning ASL must rely on vision to process linguistic

information and to look at named objects, it is possible that basic learning mechanisms, such as

the allocation of visual attention might differ in how they support lexical development (Harris &

Mohay, 1997). For example, in a study of book reading in deaf and hearing dyads, Lieberman,

Hatrak, and Mayberry (2014) found that deaf children frequently shifted gaze to caregivers in order to maintain contact with the signed signal. Hearing children, in contrast, looked continuously at the book, rarely shifting gaze while their caregiver was speaking.

The competition for visual attention in ASL could lead to qualitatively different looking behavior during real-time ASL comprehension, thus complicating the link between eye movements and speed of lexical access. On the one hand, demands of relying on vision to monitor both the linguistic signal and the named referent might cause signers to delay gaze shifts until the end of the target sign, or even the entire utterance. In this case, eye movements would be less likely to reflect the rapid, incremental influence of language on visual attention that is characteristic of spoken language processing. Another possibility is that ASL-learners, like spoken language users, will shift visual attention as soon as they have enough linguistic information to do so, producing saccades prior to the offset of the target sign. Evidence for incremental language processing would further predict that eye movements during ASL processing could index individual differences in speed of lexical access, as previously shown in spoken languages.

Research questions

By adapting the LWL procedure for ASL, we address four questions. First, how do deaf and hearing ASL-learners compare in the time course of real-time lexical processing? Second, how do patterns of eye movements in ASL-learners compare to those of adult signers? Third, to what extent do children and adult signers shift their gaze away from a language source and to a named referent prior to the offset of the target sign? Finally, are individual differences in ASL-learners' processing skill related to age and to expressive vocabulary development?

Method

As shown in Table 1, participants were 29 native, monolingual deaf and hearing ASL-learning children (17 females, 12 males) and 16 fluent adult signers (all deaf). Since the goal of the current study was to document developmental changes in processing efficiency in native ASL-learners, we set strict inclusion criteria. The sample consisted of both deaf children of deaf adults and hearing Children of Deaf Adults (CODAs), across a similar age range. It is important to note that all children, regardless of hearing status, were exposed to ASL from birth through extensive interaction with at least one caregiver fluent in ASL and were reported to experience at least 80% ASL in their daily lives. Twenty-five of the 29 children lived in households with two deaf caregivers, both fluent in ASL. Although the hearing children could access linguistic information in the auditory signal, we selected only native monolingual learners who used ASL as their primary mode of communication in and outside the home (10 out of 13 hearing children had two deaf caregivers). Adult participants were all deaf, fluent signers who reported using ASL as their primary method of communication on a daily basis. Thirteen of the 16 adults acquired ASL from their parents and three learned ASL while at school.

Hearing Status	n	Mean	SD	Min	Max
Deaf	16	28.0	7.5	16	42
Hearing	13	29.4	11.2	18	53
All children	29	28.6	9.2	16	53

Table 1: *Descriptive statistics and age distributions for hearing and deaf ASL-learners. All ages are reported in months.*

Our final sample size was determined by our success over a two-year funding period in recruiting and testing children who met our strict inclusion criteria: monolingual, native ASL users. It is important to note that native ASL-learners are a small population. The incidence of deafness at birth in the US is less than .003%, and only 10% of the 2-3 per 1000 children born with hearing loss have a deaf parent who is likely to be fluent in ASL (Mitchell & Karchmer, 2004). In addition to the 29 child participants who met our inclusion criteria and contributed adequate data, we also recruited and tested 17 more ASL-learning children who were not included in the analyses, either because it was later determined that they did not meet our stringent criterion of exposure to ASL from birth ($n = 12$), or because they did not complete the real-time language assessment due to inattentiveness or parental interference ($n = 5$).

Measures

Expressive vocabulary size: Parents completed a 90-item vocabulary checklist, adapted from Anderson and Reilly (2002), that was developed specifically for this project to be appropriate for children between 1½ and 4 years of age. Vocabulary size was computed as the number of signs reported to be produced by the child.

ASL Processing: Efficiency in online comprehension was assessed using a version of the LWL procedure adapted for ASL learners, which we call the Visual Language Processing (VLP) task. The VLP task yields two measures of processing efficiency, reaction time (RT) and accuracy. Since this was the first study to develop measures of online ASL processing efficiency in children of this age, several important modifications to the procedure were made, as described below.

Procedure

The VLP task was presented on a MacBook Pro laptop connected to a 27" monitor. The child sat on their caregiver's lap, and the child's gaze was recorded using a digital camcorder set up behind the monitor. To minimize visual distractions, testing occurred in a portable 5' by 5' booth with cloth sides, which reduced visual distractions during the task. On each trial, pictures of two familiar objects appeared on the screen, a target object corresponding to the target noun, and a distracter object matched for visual salience. Between the two pictures was a central video of an adult female signing the name of one of the pictures. Participants saw 32 test trials with five filler trials (e.g. "YOU LIKE PICTURES? MORE WANT?") interspersed to maintain children's interest.

Coding and Reliability. Participants' gaze patterns were videorecorded and later coded frame-by-frame at 33-ms resolution by highly-trained coders blind to target side. On each trial, coders indicated whether the eyes were fixated on the central signer, one of the images, shifting between pictures, or away (off), yielding a high-resolution record of eye movements aligned with target noun onset. Prior to coding, all trials were pre-screened to exclude those few trials on which the participant was inattentive or there was external interference. To assess inter-coder reliability, 25% of the videos were re-coded. Agreement was scored at the level of individual frames of video and averaged 98% on these reliability assessments.

Stimuli

Linguistic stimuli. To allow for generalization beyond characteristics of a specific signer and sentence structure, we recorded two separate sets of ASL stimuli. Both sets were recorded

with a native ASL signer, using alternative ASL sentence structures for asking questions (see

Petronio and Lillo-Martin, 1997):

- Sentence-initial wh-phrase: "HEY! WHERE [target noun]?"

- Sentence-final wh-phrase: "HEY! [target noun] WHERE?"

To prepare the stimuli, two female native ASL users recorded several tokens of each sentence in

a child-directed register. Before each sentence, the signer made a hand-wave gesture commonly

used in ASL to gain an interlocutor's attention before initiating an utterance. These candidate

stimuli were digitized, analyzed, and edited using Final Cut Pro software, and final tokens were

chosen based on naturalness.

Visual stimuli. Target nouns consisted of eight object names familiar to most children

learning ASL at this age. Visual stimuli consisted of colorful digitized pictures of these objects

presented in four fixed pairs, in which the object names had minimal phonological overlap (cat—

bird, car—book, bear—doll, ball—shoe). Images were digitized pictures presented in fixed pairs,

matched for visual salience with 3–4 tokens of each object type. Each object served as target four

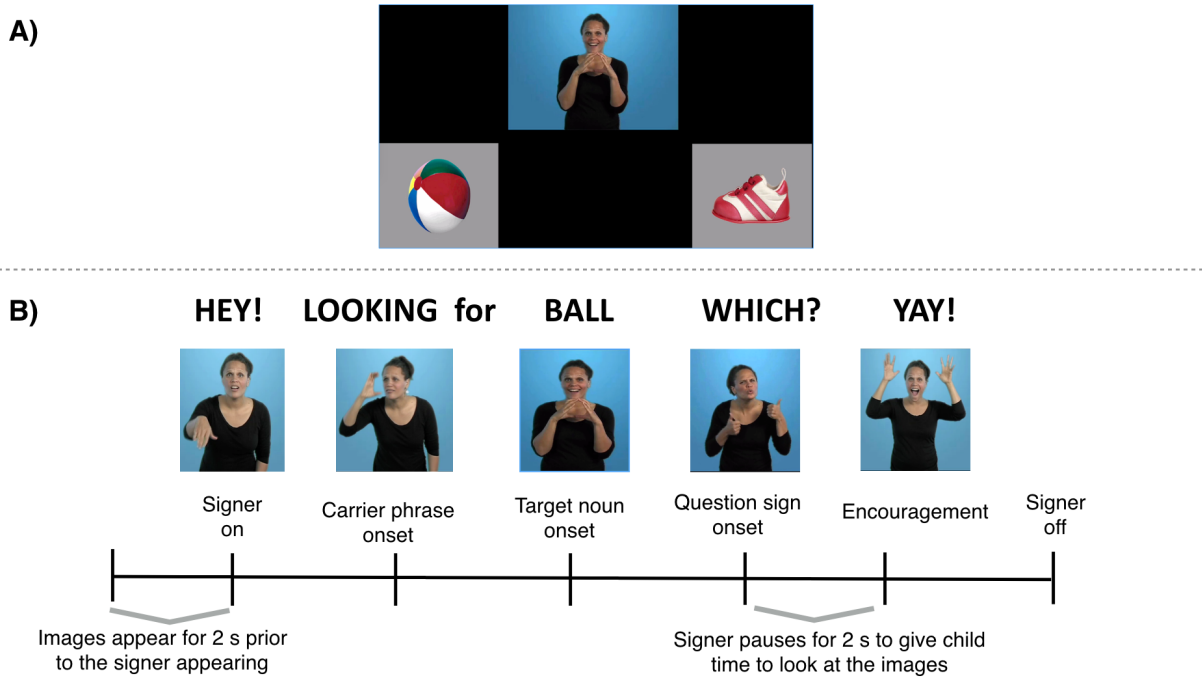times and as distracter four times. Side of target picture was counterbalanced across trials.

Trial Structure

Figure 1 shows the structure of a trial with a sentence-final *wh*-phrase, one of the two

question types in the VLP task. On each trial, children saw two images of familiar objects on the

screen for 2 s before the signer appeared, allowing time for children to inspect both images.

Next, children saw a still frame of the signer for 1 s, so they could orient to the signer prior to

sentence onset. The target sentence was then presented, followed by a question and 2-s hold,

followed by an exclamation to encourage attention to the task.

Calculating measures of language processing efficiency

Computing target sign onset and offset. In studies of spoken language processing, target

word onset is typically identified as the first moment in the auditory signal when there is acoustic

evidence of the target word. However, in signed languages like ASL, phonological information is

present in several components of the visual signal simultaneously – for example, in one or both

hands as well as in the face of the signer - making it difficult to determine precisely the

beginning of the target sign. Because sign onset is critical to operationalizing speed of lexical

access in this task, we applied an empirical approach to defining target-sign onset. Ten fluent

adult signers unfamiliar with the stimuli watched videos of the target signs while viewing the

same picture pairs as in the VLP task. For each sign token, the onset of the target noun was

operationalized as the earliest point in the signed sentence at which adults selected the correct

picture with 100% agreement. To determine sign offset, two native signers independently

marked the final point at which the handshape of each target sign was no longer identifiable.

Agreements were resolved by discussion. Sign length was defined as sign offset minus sign onset

(Median sign length was 1204 ms, ranging from 693 ms to 1980 ms).

Reaction Time. Reaction time (RT) corresponds to the latency to shift from the central

signer to the target picture on all signer-to-target shifts, measured from target-noun onset. We

chose cutoffs for the window of relevant responses based on the distribution of children's RTs in

the VLP task, including the middle 90% (600-2500 ms) (see Ratcliff, 1993). Incorrect shifts

(signer-to-distracter [19%], signer-to-away [14%], no shift [8%]) were not included in the

computation of median RT. The RT measure was reliable within participants (Cronbach's α =

0.8).

A)

B)

| HEY! | LOOKING for | BALL | WHICH? | YAY! |

| Signer on | Carrier phrase onset | Target noun onset | Question sign onset | Encouragement | Signer off |

Images appear for 2 s prior to the signer appearing

Signer pauses for 2 s to give child time to look at the images

Figure 1: Stimuli layout (1A) and trial structure (1B) for one question type (sentence final wh-phrase) shown in the central video on the VLP task.

Target Accuracy. Accuracy was the mean proportion of time spent looking at the target picture out of the total time looking at either target or distracter picture over the 600 to 2500 ms window from target noun onset. This measure of accuracy reflects the tendency both to shift quickly from the signer to the target picture in response to the target sign and to maintain fixation on the target picture. Mean proportion looking to target was calculated for each participant for all trials on which the participant was fixating on the center image at target sign onset. To make accuracy proportion scores more suitable for modeling on a linear scale, all analyses were based on scores that were scaled in log space using a logistic transformation. The Accuracy measure was reliable within participants (Cronbach's $\alpha = 0.92$)

Proportion Sign Processed Prior to Shifting. As a measure of incremental processing, we use the mean proportion of the target sign that children and adults saw before generating an

initial eye movement away from the central signer. Because target signs differed in lengths

across trials, we took the RT for each trial with a correct shift, added 200 ms ($\frac{RT}{Sign\ Length+200\ ms}$),

since previous research on spoken language suggests that at least 200 ms is required to program

an eye-movement (Salverda, Kleinschmidt, & Tanenhaus, 2014), and divided this value by the

length of the corresponding target sign. Mean proportion of sign processed was computed for

each token of each target sign and then averaged over all target signs within participants,

reflecting the amount of information signers processed before generating an eye movement, on

average. A score of ≥ 1.0 indicates that a signer tended to initiate eye movements to the target

pictures after sign offset. An average < 1.0 indicates eye-movements were planned during the

target sign, reflecting the degree to which signers showed evidence of incremental language

processing.

Analysis Plan

We use Bayesian methods to estimate the associations between hearing status, age,

vocabulary, and RT and accuracy in the VLP task. Bayesian methods are desirable for two

reasons: First, Bayesian methods allowed us to quantify support in favor of a null hypothesis of

interest – in this case, the absence of a difference in real-time processing skills between age-

matched deaf and hearing ASL learners. Second, since native ASL learners are rare, we wanted

to use a statistical approach that allowed us to incorporate relevant prior knowledge to constrain

our estimates of the strength of association between RT/accuracy on the VLP task and

age/vocabulary.

Concretely, we used prior work on the development of real-time processing efficiency in

children learning spoken language (Fernald et al., 2008) to consider only plausible linear

associations between age/vocabulary and RT/accuracy, thus making our alternative hypotheses more precise. In studies with adults, the common use of eye movements as a processing measure is based on the assumption that the timing of the first shift reflects the speed of their lexical access (Tanenhaus, Magnuson, Dahan, & Chambers, 2000). However, studies with children have shown that early shifts are more likely to be random than later shifts (Fernald et al., 2008), suggesting that some children's shifting behavior may be unrelated to real-time lexical access. We use a mixture-model to quantify the probability that each child participant's response is unrelated to their real-time lexical access (i.e., that the participant is responding randomly, or is "guessing"), creating an analysis model where participants who were more likely to be guessers have less influence on the estimated relations between RT and age/vocabulary. Note that we use this approach only in the analysis of RT, since "guessing behavior" is integral to our measure of children's mean accuracy in the VLP task, but not to our measure of mean RT. The Supplemental Material available online provides more details about the analysis model, as well two additional sensitivity analyses, which provide evidence that our results are robust to different specifications of prior distributions and to different analysis windows. We also provide an analogous set of analyses using a non-Bayesian approach, which resulted in parallel findings.

To provide evidence of developmental change, we report the strength of evidence for a linear model with an intercept and slope compared to an intercept-only model in the form of a Bayes Factor (BF) computed via the Savage-Dickey method (Wagenmakers et al., 2010). To estimate the uncertainty around our estimates of the linear associations, we report the 95% Highest Density Interval (HDI) of the posterior distribution of the intercept and slope. The HDI provides a range of plausible values and gives information about the uncertainty of our point

estimate of the linear association. Models with categorical predictors were implemented in

STAN (Stan Development Team, 2016), and models with continuous predictors were

implemented in JAGS (Plummer, 2003). Finally, we chose the linear model because it a simple

model of developmental change with only two parameters to estimate, and the outcome measures

– mean RT and Accuracy for each participant – were normally distributed. All of the linear

regressions include only children's data and take the form: $processing\ measure \sim age$ and

$processing\ measure \sim vocabulary$.

Results

First, we compare real-time ASL comprehension in deaf and hearing children to ask if

access to auditory information leads to qualitative changes in looking behavior. Next, we

compare ASL-learners' processing skills to those of adult signers. Third, we estimate the degree

to which children and adults tended to initiate eye-movements prior to target sign offset,

exploring evidence for incremental ASL processing. Finally, we measure the relations between

individual variation in children's efficiency in ASL comprehension and their productive

vocabularies.

Real-time ASL comprehension in deaf and hearing children and deaf adults

Do deaf and hearing native signers show a similar time course of lexical processing,

driven by their similar language experiences and the immediate modality-specific constraints of

interpreting a sign language in real time? Or would deaf children's reliance on vision to monitor

both the linguistic signal and the potential referents in the visual world result in a qualitatively

different pattern of performance, e.g., their waiting longer to disengage from the signer?

Figure 2A presents an overview of looking behavior in the VLP task for deaf and hearing children. This plot shows changes in the mean proportion of trials on which participants fixated the signer, the target image, or the distracter image at every 33-ms interval of the stimulus sentence. At target-sign onset, all participants were looking at the signer on all trials. As the target sign unfolded, mean proportion looking to the signer decreased rapidly as participants shifted their gaze to the target or the distracter image. Proportion looking to the target increased sooner and reached a higher asymptote, compared to proportion looking to the distracter, for both hearing and deaf children. After looking to the target image, participants tended to shift their gaze rapidly back to the signer, shown by the increase in proportion looking to the signer around 2000 ms after target-noun onset.

Overall, deaf and hearing children showed a remarkably similar time course of looking behavior: shifting away from the signer, increasing looks to the target, and shifting back to the signer at similar time points as the sign unfolded. To quantify this difference, we compared the posterior distributions for mean accuracy (Figure 2C) and mean RT (Figure 2D) across the deaf
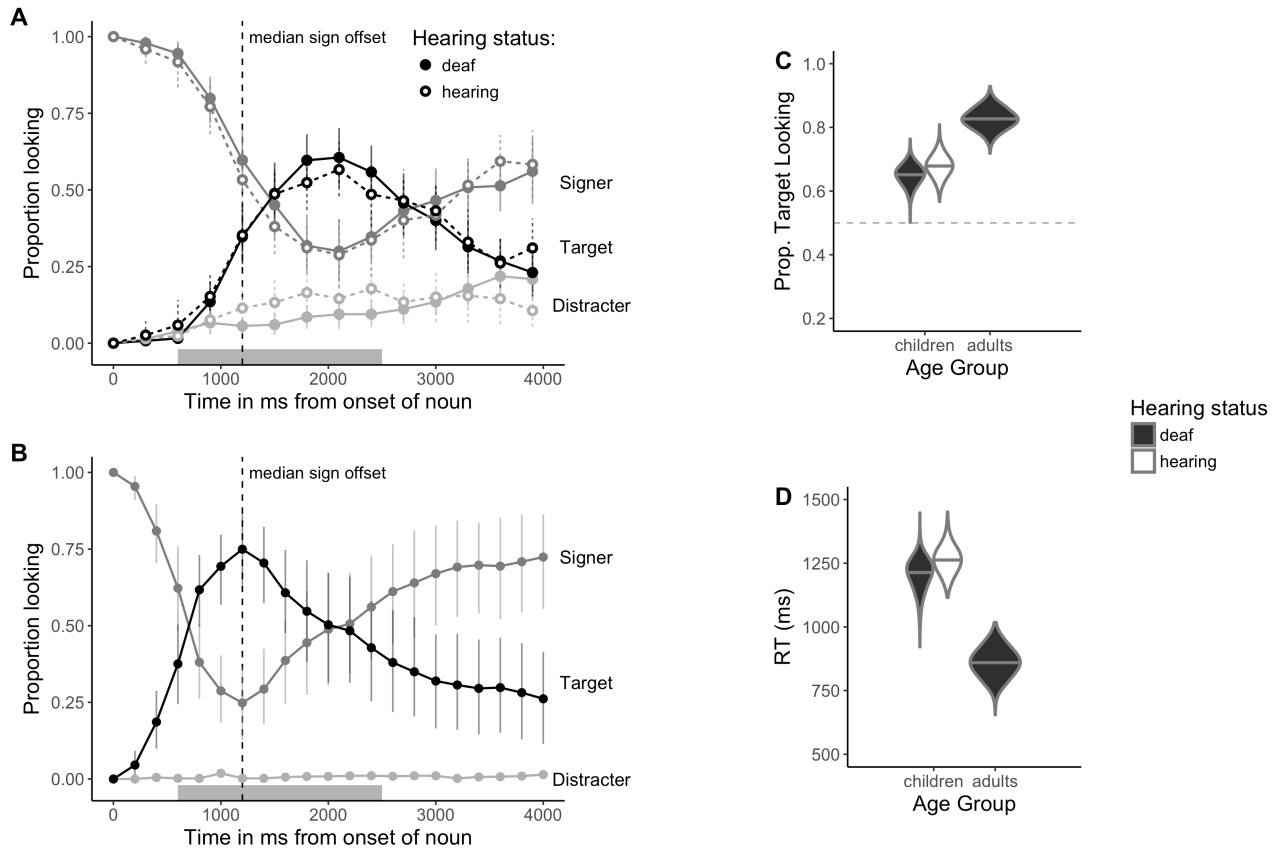
Figure 2. *The time course of looking behavior for young deaf and hearing ASL-learners (2A) and ASL-proficient adults (2B). The curves show mean proportion looking to the signer (dark grey), the target image (black), and the distracter image (light grey). Filled circles represent deaf signers, while open circles represent hearing signers; the grey shaded region marks the analysis window (600-2500ms); error bars represent +/- 95% CI computed by non-parametric bootstrap. Panels C and D show full posterior distributions over model estimates for mean Accuracy (2C) and Reaction Time (2D) for children and adults. Fill represents hearing status of the children. (Note that there were no hearing adult signers in our sample).*

and hearing groups. We did not find evidence for a difference in mean accuracy ($M_{hearing} = 0.68$, $M_{deaf=}0.65$; $\beta_{diff} = 0.03$, 95% HDI [-0.07, 0.13]) or RT

($M_{hearing} = 1265.62\ ms$, $M_{deaf=}1185.05\ ms$; $\beta_{diff} = 78.32$ ms, 95% HDI [-86.01 ms, 247.04

ms]), with the 95% HDI including zero for both models. These analyses provide evidence that

same-aged hearing and deaf ASL-learners showed qualitatively similar looking behavior during

real-time sentence processing, reflecting parallel sensitivity to the modality-specific constraints

of processing a sign language. Moreover, they provide additional justification for analyzing all

the native ASL-learning children together, regardless of hearing status, in all subsequent

analyses.

Next, we compared real-time processing efficiency of ASL-learners to adult signers.

Figure 2B shows the mean proportion of trials on which adults fixated the signer, the target

image, or the distracter image at every 33-ms interval. Mean proportion looking to the signer

decreased rapidly as participants shifted their gaze to one of the images. Adults tended to shift to

the target picture sooner in the sentence than did children, and well before the average offset of

the target sign. Moreover, adults rarely looked to the distractor image at any point in the trial.

Figures 2C and 2D show the full posterior distribution for adults' mean Accuracy and RT.

Overall, adults were more accurate ($M_{adults} = 0.85, M_{children} = 0.68, \beta_{diff} = 0.17, 95\%$ HDI

for the difference in means $[0.11, 0.24]$) and faster to shift to the target image compared to

children ($M_{adults} = 861.98$ ms, $M_{children} = 1229.95$ ms; $\beta_{diff} = $ -367.76 ms, 95% HDI for the

difference in means [-503.42 ms, -223.85 ms]).

Evidence of incremental ASL processing

One of the behavioral signatures of proficient spoken language processing is the rapid

influence of language on visual attention, with eye movements occurring as soon as listeners

have enough information to identify the named object. Would young ASL-learners and adult

signers also show evidence of rapid gaze shifts in response to signed language, despite the

apparent competition for visual attention between the language source and the nonlinguistic

visual world? Or would signers delay their shifts until the very end of the target sign, or even

until the end of the utterance?
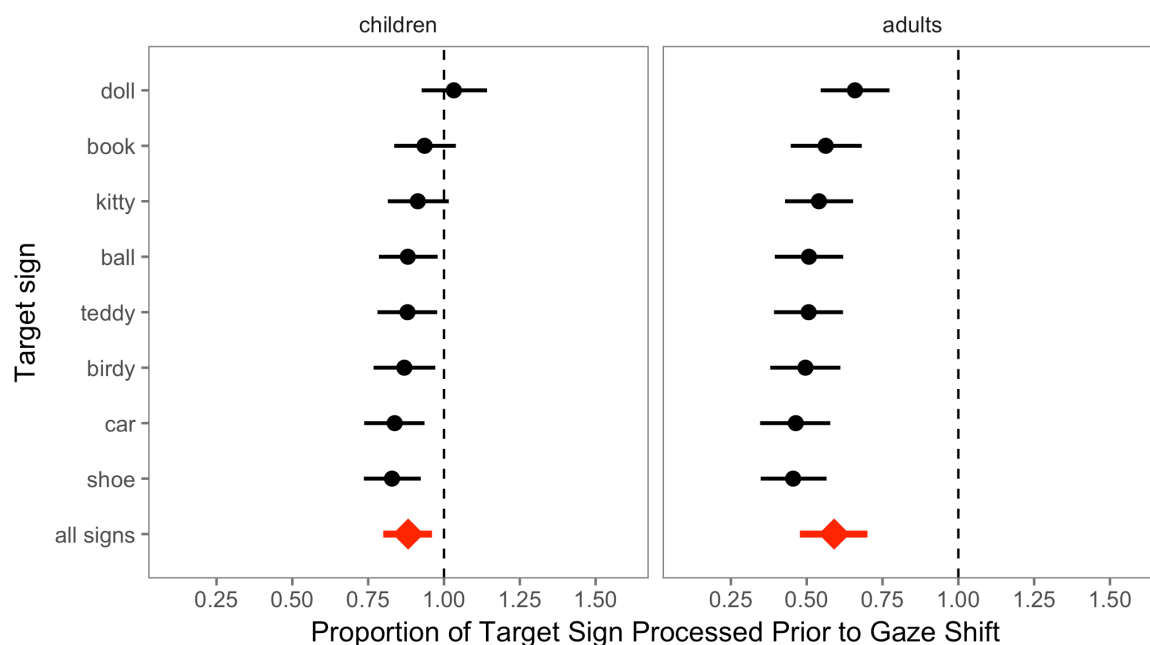
Figure 3: *The mean proportion of each target sign processed prior to shifting visual attention away from the language source to a named object for children and adults. The diamond indicates the mean estimate for all signs. The dashed vertical line corresponds to a median proportion of 1.0. A median of < 1.0 reflects response latencies that occur prior to the offset of the target sign; a median of ≥ 1.0 reflects response latencies that occur after target sign offset. Error bars represent 95% HDIs.*

To answer this question, we conducted an exploratory analysis, computing the proportion of each target sign that participants processed before generating an eye movement to the named object. Figure 3 shows this measure for each target sign for both children and adults. Adults shifted prior to the offset of the target sign for all items and processed on average 57% of the target sign before generating a response (M = 0.57, 95% HDI [0.38, 0.69]). Children processed more of the target sign before shifting their gaze compared to adults, but children did reliably initiate saccades prior to the offset of the target sign (M = 0.85, 95% HDI [0.76, 0.94]) and for five out of the eight signed stimuli. This analysis provides evidence that both adults and young signers process signs incrementally as they unfold in time. Moreover, this result suggests that eye

movements in the VLP task can provide an index of speed of lexical access, allowing us to estimate links between individual variation in processing speed and variation in age/vocabulary.

Links between children's age and processing efficiency

Next we used Bayesian linear regressions to estimate the relations between young ASL learners' age-related increases in the speed and accuracy with which they interpreted familiar signs (see Table 2 for point and interval estimates). Mean accuracy was positively associated with age (Figure 4A), indicating that older ASL learners were more accurate than younger children in fixating the target picture. The Bayes Factor (BF) indicated that a model including a linear association was 12.8 times more likely than an intercept-only model, providing evidence for developmental change. The β estimate indicates that, for each month of age, children increased their accuracy score by 0.007, i.e., an increase of ~1% point, meaning that over the course of one year the model estimates a ~12% point gain in accuracy when establishing reference in the VLP task. Mean RTs were negatively associated with age (Figure 4A), indicating that older children shifted to the target picture more quickly than did younger children. The BF was ~14, providing evidence for a linear association. The model estimates a ~11 ms gain in RT for each month, leading to a ~132 ms gain in speed of lexical access over a year of development.

Together, the accuracy and RT analyses showed that young ASL learners reliably looked away from the central signer to shift to the named target image in the VLP task. Importantly, children varied in their response times and accuracy, and this variation was meaningfully linked to age. Thus, like children learning spoken language, ASL learners improve their real-time

language processing skills over the second and third years of life as they make progress towards

adult levels of language fluency.
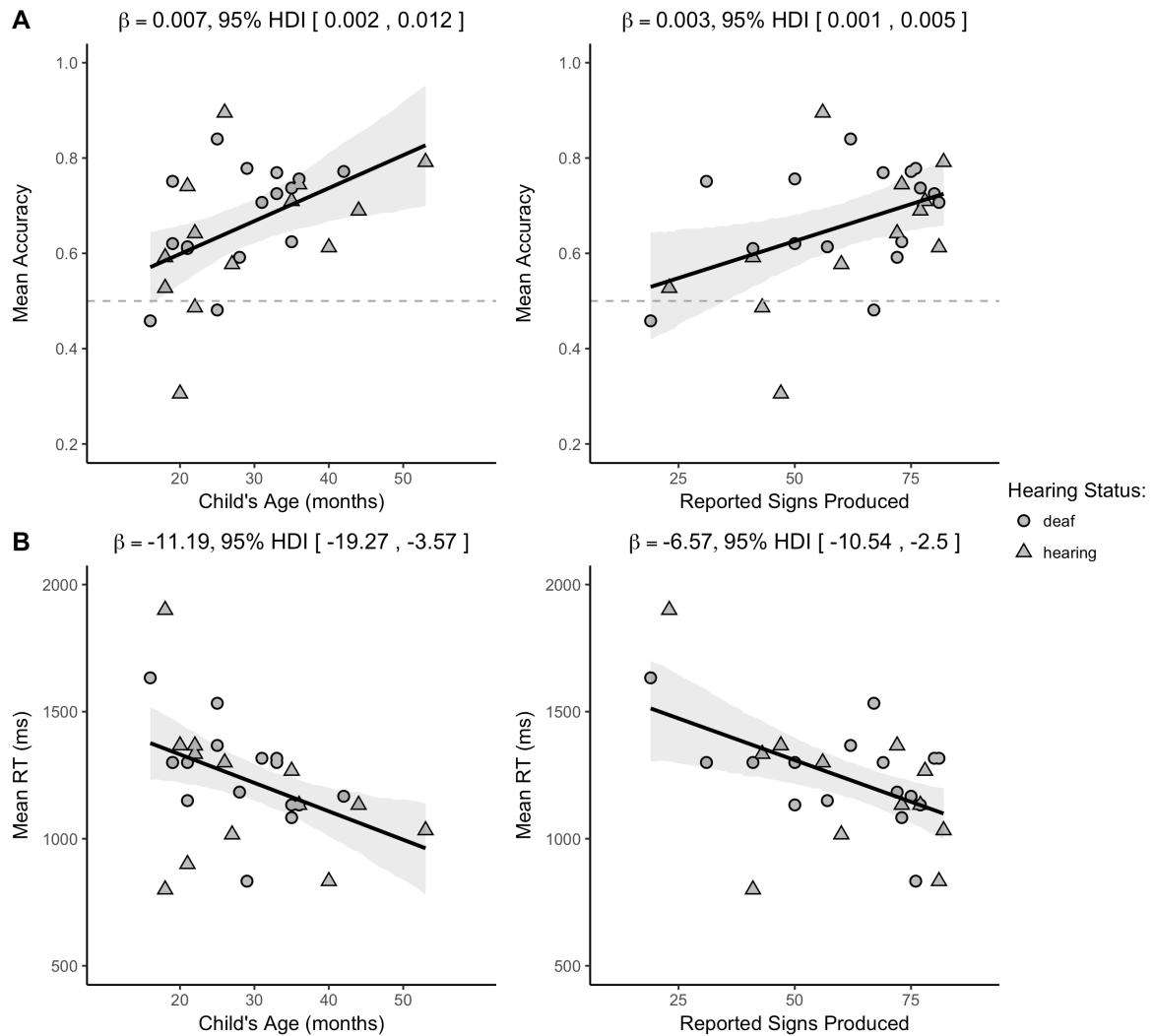
Figure 4: Scatterplots of relations between children's age and vocabulary and measures of their mean accuracy and mean RT in the VLP procedure. Shape represents children's hearing status. The solid black line is the maximum a posteriori model estimate for the mean accuracy at each age point. The shaded gray regions represent the 95% Highest Density Interval (range of plausible values) around the regression line.

Links between children's processing efficiency and vocabulary

The next question of interest was whether individual differences in processing skills were related to the size of children's ASL vocabularies. As shown in Figure 4B, children with higher accuracy scores also had larger productive vocabularies ($BF = 6.8$), with the model estimating a 0.003 increase for each additional sign known. Moreover, children who were faster to recognize ASL signs were those with larger sign vocabularies ($BF = 18.7$), with each additional sign resulting in a ~7 ms decrease in estimated RT. Taken together, older children and children with larger expressive vocabularies were more accurate and efficient in identifying the referents of familiar signs. It is important to point out that the independent effect of vocabulary size on ASL processing could not be assessed here given the correlation between age and vocabulary in our broad sample of children from one to four years. However, these findings parallel results in the substantial body of previous research with monolingual children learning spoken languages, such as English (Fernald et al., 2006) and Spanish (Hurtado, Marchman, & Fernald, 2007).

Model specification	*BF*	Mean β	95% HDI
Accuracy ~ Age	12.8	0.007	0.002, 0.012
Accuracy ~ Vocab	6.8	0.003	0.001, 0.005
RT ~ Age	14.4	-11.2 ms	-19.3 ms, -3.6 ms
RT ~ Vocab	18.7	-6.6 ms	-10.5 ms, -2.5 ms

Table 2: Summary of the four linear models using children's age and vocabulary size to predict accuracy (proportion looking to target) and reaction time (latency to first shift in ms). BF is the Bayes Factor comparing the evidence in favor of linear model to an intercept-only (null) model; Mean β is the mean of the posterior distribution for the slope parameter for each model (i.e., the linear association); and the Highest Density Interval (HDI) shows the interval containing 95% of the plausible slope values given the model and the data.

Discussion

Efficiency in establishing reference in real-time lexical processing is a fundamental component of language learning. Here, we developed the first measures of young ASL learners' real-time language comprehension skills. There are four main findings from this research.

First, deaf and hearing native signers, despite having differential access to auditory information, showed remarkably similar looking behavior during real-time ASL comprehension. While the hearing children could use vision and hearing to process incoming information, this experience did not change the timing of gaze shifts during ASL comprehension as compared to their deaf peers. Instead, both groups showed parallel sensitivity to the modality-specific constraints of processing ASL in real time.

Second, like children learning spoken language, young ASL-learners were less efficient than adults in their real-time language processing, but they showed significant improvement with age over the first four years. Moreover, although all target signs were familiar to children, older children identified the named referents more quickly and accurately. This result suggests that the real-time comprehension skills of children who are learning ASL in native contexts follow a similar developmental path to that of spoken language learners, as has been shown in previous work on language production (Lillo-Martin, 1999; Mayberry & Squires, 2006). However, by developing precise measures of real-time ASL *comprehension*, we were able to study children's language skills earlier in development as compared to other methods.

Third, both adults and children showed evidence of incremental ASL processing, shifting gaze prior to sign offset. This rapid influence of language on visual attention in ASL is perhaps even more striking since early gaze shifts could result in missing subsequent linguistic information relevant to the signer's utterance. Evidence of incremental gaze shifts also suggests

that eye movements during ASL processing provide an index of individual differences in speed of lexical access, as previously shown in spoken languages, which is important for future work on the psycholinguistics of sign language acquisition.

Fourth, we found a link between ASL processing skills and children's productive vocabularies. ASL-learning children who knew more signs were also faster and more accurate to identify the correct referent than those who were lexically less advanced. These results are consistent with studies with English- and Spanish-learning children, which find strong relations between efficiency in online language comprehension and measures of linguistic achievement (Fernald et al., 2006; Marchman & Fernald, 2008).

Limitations

This study has several limitations. First, while the sample size is larger than most previous studies of ASL development, it was still relatively small compared to many developmental studies since native ASL-learners are a rare population. Thus more data are needed to characterize more precisely the developmental trajectories of sign language processing skills. Second, testing children within a narrower age range might have revealed independent effects of vocabulary size on ASL processing, which could not be assessed here given the correlation between age and vocabulary size in our broad sample of children from one to four years. To facilitate replication and extension of our results, we have made all of our stimuli, data, and analysis code publicly available (http://kemacdonald.github.io/SOL).

A third limitation is that characteristics of our task make it difficult to directly compare our findings with previous work on ASL and spoken language processing. For example, in contrast to prior gating studies with adults (e.g., Emmorey & Corina, 1990; Morford & Carlsen, 2011), our stimuli consisted of full sentences in a child-directed register, not isolated signs, and

we used a temporal response measure rather than an open-ended untimed response. Moreover, the VLP task included the signer as a central fixation, resulting in different task demands compared to the two-alternative procedure used to study children's spoken language processing (e.g., Fernald et al. 1998). Thus, we cannot yet make claims about processing in signed vs. spoken languages in absolute terms. A direct comparison of signed and spoken language processing is a focus of our ongoing work. Nevertheless, the current results reveal parallels with previous findings showing incremental processing during real-time language comprehension. Moreover, we established links between early processing efficiency and measures of vocabulary in ASL-learners, suggesting that parallel mechanisms drive language development, regardless of modality.

Finally, our sample is not representative of most children learning ASL in the United States. Since most deaf children are born to hearing parents unfamiliar with ASL, they may have inconsistent exposure to sign language. We took care to include only children exposed to ASL from birth, but the development of real-time ASL processing may look different in children who have inconsistent or late exposure to ASL (Mayberry, 2007). An important step is to explore how variation in ASL processing is influenced by early experience with signed languages. Since children's efficiency in interpreting spoken language is linked to the quantity and quality of the speech that they hear (Hurtado, Marchman, & Fernald, 2008; Weisleder & Fernald, 2013), we would expect similar relations between language input and outcomes in ASL-learners. We hope that the VLP task will provide a useful method to track precisely the developmental trajectories of a variety of ASL-learners.

In conclusion, this study provides the first evidence that young ASL learners rapidly shift visual attention as soon as they have enough of the linguistic signal to do so. In addition,

individual variation in speed of lexical access is meaningfully linked to age and vocabulary.

These results contribute to a growing literature that highlights parallels between signed and

spoken language development when children are exposed to native sign input. Moreover, similar

results for deaf and hearing ASL-learners suggest that both groups were sensitive to the

modality-specific constraints of processing a sign language from moment to moment. Finally,

these findings indicate that eye movements during ASL comprehension are linked to efficiency

of lexical access, suggesting that skill in allocating visual attention in real-time is a language-

general phenomenon that develops rapidly in early childhood, regardless of language modality.

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