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Real-Time Processing of ASL Signs: Effects of Linguistic Experience and Proficiency

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1. Introduction

Word recognition in spoken language is known to be a dynamic, incremental, and continuous process. As words unfold in time, listeners activate a range of potential lexical candidates, including those that share semantic (Yee & Sedivy, 2006) and phonological (Allopenna, Magnuson, & Tanenhaus, 1998) features with the target word. Among the methodological techniques used to probe real-time recognition, the use of eye-tracking technology has been particularly informative, in that eye movements provide a rapid and detailed metric for determining the locus of the listener's visual attention.

In contrast, much less is known about how individual lexical items in a sign language are recognized as they unfold in real time. Signed languages such as American Sign Language (ASL), which are produced manually and perceived via the visual channel, have been shown to be acquired in a similar manner to spoken language when exposure begins at birth (Mayberry & Squires, 2006; Newport, 1985). It has been a challenge to probe the on-line recognition of signs, however, due to the fact that the visual channel is required both to recognize signs and to demonstrate comprehension via eye gaze.

Although sign languages share many linguistic properties with spoken language, the manual modality and visual perception of signs has led to questions regarding the degree of sub-lexical representation that exists for single signs. Commonly, signs are thought to be composed of at least three distinct parameters, namely handshape, location, and movement. These parameters have frequently been considered as contributing partial lexical information with varying degrees of salience. For example, in several gating studies, the order of parameter recognition as signs were presented in increasing segments led to the finding that location information was identified early in signs, followed by handshape, and finally movement information (Emmorey & Corina,1990; Clark

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& Grosjean, 1982). Additional studies using primed lexical decision have shown that ASL phonological primes can serve either to inhibit or facilitate sign recognition, depending on the language experience of the participants (Dye & Shih, 2006; Mayberry & Witcher, 2005) or the particular sign parameter being manipulated (Carreiras, Gutierrez-Sigut, Baquero, & Corina, 2008; Corina & Emmorey, 1993). These mixed results have suggested that sub-lexical properties of signs are activated at some point during sign comprehension, however the direction of the effects and the timing of activation of specific parameters has been difficult to discern.

The study of on-line sign recognition can also reveal insights about the effects of linguistic experience on lexical processing. Whereas in spoken language the vast majority of language users are exposed to at least one language from birth, that is not the case for the majority of sign language users. Over 95% of deaf children are born to hearing parents (Mitchell & Karchmer, 2005), and thus exposure to sign language as a first language often does not begin until a range of ages after birth. By investigating language processing in these "late-learners" of a first language, we can gain insight into how early linguistic experience affects on-line processing.

In the current study, we present a novel paradigm for measuring on-line sign recognition in signers from a range of linguistic backgrounds. Using an adaptation of the visual world paradigm (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), which has yielded important findings regarding spoken language recognition, we measured real-time processing of single signs as well as activation of phonological and semantic competitors during sign recognition. The specific questions we addressed were as follows: 1) Are semantic and sub-lexical properties of signs activated during sign recognition? 2) Is early language experience crucial for development of ability to process signs dynamically? And 3) Does early acquisition of L1 contribute to the ability to process signs dynamically as an L2?

To address the first question, we tested a group of native-learning deaf participants, i.e. individuals who were exposed to ASL from birth or very early in life. This group provided baseline information regarding real-time sign processing given typical language acquisition. To address the second question, we tested a group of late-learning signers. These were deaf individuals who were not exposed to a first language until childhood or later, at which point they began learning ASL. This group allowed us to explore whether delayed exposure to a first language leads to differences in real-time lexical processing. Finally, to disentangle late sign acquisition as a first vs. a second language, we tested a group of hearing, L2 learners of ASL.

2. Methods

2.1. Participants

Native signers: 18 native ASL signing congenitally deaf adults (8 female, M age = 25 years, range 18-50 years) participated. Sixteen participants had at least one deaf parent and were exposed to ASL from birth. The remaining two participants had hearing parents and were exposed to ASL before the age of two.

Late-learning signers: 21 deaf adults (12 female, M age = 31 years, range 18-58 years) who used ASL as their primary language participated. Participants had diverse backgrounds with regard to the age at which they were first exposed to ASL (between age 5 and age 14) and the number of years they had been using ASL (5 to 39 years of experience).

Hearing L2 signers: 21 hearing adults who had learned ASL as a second language participated. Participants were pre-screened to ensure that they had a high level of ASL proficiency, i.e. they had used ASL beyond the classroom setting for at least 3 years. Despite this pre-screening, two participants did not meet the minimum proficiency requirement on the ASL vocabulary production task, and were excluded from the final sample. The final sample contained 19 hearing adults (12 females, M age = 26 years, range 19-34 years).

2.2. Background questionnaire

Participants completed a language background questionnaire regarding their age of onset of hearing loss, age of identification of deafness, and age of first regular exposure to ASL. They also completed a self-assessment of language proficiency, including comprehension and production of ASL, fingerspelling, spoken language, and written English. Hearing L2 signers completed a modified version of the questionnaire that included questions about their exposure to and proficiency in ASL.

2. 3. Language measures

Vocabulary production: Participants completed a 142-item picture naming task, with the items consisting of all the pictures presented in the eye-tracking task. An item was marked as correct if the produced sign was identical to the target sign used in the eye-tracking task. The vocabulary measure was also used to verify that individuals shared the same representation as intended for each sign in the eye-tracking task.

Narrative comprehension: Participants were administered an ASL narrative comprehension task as a measure of ASL receptive fluency. Participants first viewed a three minute video of a deaf, native signer telling a detailed narrative in ASL. Participants were asked a series of 12 questions designed to assess both recall of facts from the narrative, and the ability to infer additional information. Participants' answers were scored as being correct or incorrect, yielding a narrative comprehension score out of 12.

ASL Reception (Late-learning and Hearing L2 signers): Participants were administered the ASL Receptive Skills Task (Enns, Zimmer, Boudreault, Rabu, & Broszeit, 2013). This is a 42-item task adapted from a similar task in British Sign Language (Herman, Holmes, & Woll, 1999) in which subjects see a single sign or signed utterance, followed by four pictures, from which they must choose the picture that best matches the sign(s). The task is designed to assess comprehension of a range of ASL structures, including negation, classifiers, non-manual markers, and verb agreement. Although the task was initially designed for children it was used here with adults as an additional measure of receptive skill. It was not given to the native signers as it was assumed they would be at ceiling on the task.

2.4. Eye-tracking materials

Thirty-two sets of four pictures served as the stimuli for the lexical recognition task. Each set consisted of a target picture and three competitor pictures, which were related to the target picture as follows: The *Unrelated (U)* 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 (P)* condition consisted of a target picture, a phonological competitor, in which the corresponding ASL sign was a phonological minimal pair with the target sign, and two unrelated competitors. The *Semantic (S)* condition consisted of a target picture, a semantically related competitor, and two unrelated competitors. The *Phono-Semantic (PS)* condition consisted of a target, a phonologically-related competitor, a semantically-related competitor, and one unrelated competitor. In addition to the above criteria, we minimized phonological relationships between the English translations of the target and competitor items. Each image set consisted of either all one-handed signs or all two-handed signs, with exceptions for four sets in which the phonological pairs precluded this possibility.

To create the final stimulus set, each picture set was presented twice, such that each item was equally likely to appear as either a target or a competitor across versions of the stimuli sets. The pictures were further counterbalanced such that the target picture was equally likely to occur in any position, and the positional relationship between the target and related competitors was balanced across trials. Finally, the order of trials was pseudo-randomized such that the first trial always fell into the Unrelated condition, and there were never more than three trials in a row of any given condition.

The pictures used were color photo-realistic images presented on a white background square measuring 300 by 300 pixels. The ASL signs were presented on a black background square also measuring 300 by 300 pixels. The pictures and signs were presented on a 17-inch LCD display with a black background, with one picture in each quadrant of the monitor and the sign positioned in the middle of the display (see Figure 1).

To produce the ASL signs, a deaf native signer was filmed producing multiple exemplars of each target sign. The best exemplar of each sign was then chosen. In order to ensure that articulation length did not influence looking time to the sign, each sign was edited using Adobe Premier software to be exactly 20 frames (666ms) long, by removing extraneous frames at the end of the sign. The onset point for each sign was defined as the first frame in which all parameters of the sign (i.e. handshape, location, and movement) were in their initial position. Thus all transitional movement from a resting position to the initial sign position was removed. To further control for variation among signs the signer produced each sign with a neutral facial expression.

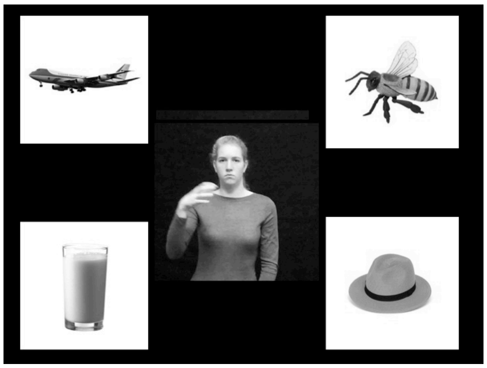

Figure 1: Example of layout of pictures and video stimuli

2.5. Procedure

After obtaining consent, participants were seated in the experiment room in front of the LCD display and eye-tracking camera. The stimuli were presented using a PC computer running Eyelink Experiment Builder software (SR Research). Instructions were presented in ASL on a pre-recorded video. Participants were told that they would be seeing a set of pictures followed by an ASL sign, and were instructed to "click on the picture that matches the sign." Participants were given two practice trials before the start of the experiment. Next, a 5-point calibration and validation sequence was conducted. In addition, a single-point drift correct was performed before each trial. The experimental trials were then presented in eight blocks of eight trials, for a total of 64 trials.

On each experimental trial, the pictures were first presented on the four quadrants of the monitor. Following a 750ms preview period, a central fixation cross appeared. Once the participant fixated gaze on the cross, this triggered the onset of the video stimulus. After the ASL sign was presented, the video disappeared and, following a 500ms interval, a small square cursor appeared in the center of the screen. The participants then used the mouse to drag the cursor to the picture and click on it. The pictures remained on the screen until participants selected and clicked on a picture, which ended the trial.

Eye movements were recorded using an Eyelink 2000 remote eye-tracker with remote arm configuration (SR Research) at 500 Hz. The position of the display was adjusted manually such that the display and eye-tracking camera were placed 580-620mm from the participant's face. Eye movements were tracked automatically using a target sticker affixed to the participant's forehead. Fixations were recorded on each trial beginning at the initial presentation of the picture sets and continuing until the participant clicked on the selected picture. Offline, the data were binned into 10-ms intervals.

3. Results

3.1. Language measures

Native signers: Of the 18 participants, two did not complete the naming task. The mean accuracy for the 16 remaining participants was 95% (range 85% to 100%). However, it should be noted that "errors," in which the participant's sign was not an exact match with the target sign for a given picture, were often due to regional variations in signer's dialects. In the ASL comprehension task, mean score on the 12 narrative comprehension questions ranged from .17 to .92 (2-11 answers correct).

Late-learning signers: One participant did not complete the vocabulary production task or the ASL receptive skills task. The mean score on vocabulary production for 20 participants was 86% (range 56% to 100% accuracy). On the ASL receptive skills task, mean accuracy was 75% (range 57% to 90%). All participants completed the narrative comprehension task. Mean score was 39% (range 8% to 75%, 1-9 questions answered correctly). Although there was wide individual variation on linguistic measures, pairwise correlations showed significant relationships between scores on the narrative comprehension task and ASL receptive skills task ($r = .63$, $p < .005$), and between scores on narrative comprehension and vocabulary production ($r = .49$, $p < .05$), but not between the ASL receptive skills and vocabulary production tasks ($r = .1$, $p > .1$)

Hearing L2 signers: Performance on the vocabulary production task averaged 80% (range 68% to 95%) correct. Performance on the ASL Receptive skills task averaged 80% correct (range 64% to 95%). One participant did not complete the narrative comprehension task. Scores on the narrative comprehension task averaged 43% (range 0 to 100%, 0-12 questions correct). Scores on the vocabulary production were correlated with scores on the ASL receptive skills task ($r = .45$, $p = .05$) and the narrative comprehension task ($r = .56$, $p < .05$); scores on the narrative comprehension task and the ASL receptive skills task were marginally correlated ($r = .42$, $p = .08$). Proficiency across groups is summarized in Table 1.

Table 1. Mean (SE) scores on language measures in each participant group

Group	Vocab Production M (SE)	Narrative Comprehension	Receptive Skills
Natives (N) (n=18)	.95 (.02)	.79 (.06)	n/a
Late-learners (LL) (n=21)	.86 (.02)	.40 (.05)	.75 (.02)

Hearing L2s (n=19)	.80 (.02)	.43 (.05)	.80 (.02)
Group Diffs:	N > LL > L2 ($p < .0001$)	N > LL, L2 ($p < .0001$)	L2 > LL ($p < .05$)

3.2. Eye-tracking measures

3.2.1. Accuracy on the eye tracking task

Native signers: Accuracy (i.e. correct picture chosen) was 98.5% (range 94% to 100%). Across participants, there were 17 errors (on 1152 trials). Participants selected a phonological competitor 10 times and a semantic competitor 7 times.

Late-learning signers: Mean accuracy was 97% (range 89% to 100%). Of the 40 errors, participants chose the phonological competitor on 23 trials, the semantic competitor on 7 trials, and an unrelated competitor on 10 trials.

Hearing L2 signers: Mean accuracy was 95% (range 89%-100%). Of the 55 errors, participants chose the phonological competitor on 34 trials, the semantic competitor on 7 trials, and the unrelated competitor on 14 trials.

3.2.2. Proportion of fixations to target

We calculated proportion of total time spent fixating the target picture between 600ms and 1800ms post target sign onset. The goal in choosing a time window was to capture the most meaningful looks to the target and competitor pictures, i.e. those that best represented looks in response to the video stimuli. To determine this window we analyzed the time course of looking across participants. The starting point of 600ms following sign onset was chosen as this was the point, across all conditions, at which participants were beginning to direct at least 10% of all fixations away from the sign. The end point of 1800ms was chosen because after this point, participants' gaze to the pictures dropped below 80% of all fixations. Thus we captured looking time over a 1200ms window that represented meaningful looking time.

Overall fixations to the target for each group are presented in Figure 2. We conducted separate one-way ANOVAs for each participant group with overall looking to target as the dependent measure and with trial condition (Unrelated, Semantic, Phonological, and Phono-Semantic) as the independent variable. There was a significant main effect of condition among the native signers ($p < .001$) and the hearing L2 signers ($p < .05$), but no such effect for the late-learning signers. Further analyses revealed that the native-signers looked longer to the target in conditions containing phonological competitors than in conditions containing no competitors or semantic competitors only; in contrast, hearing L2 signers only showed a decrease in target looking relative to conditions with no competitors when *both* semantic and phonological competitors were present.

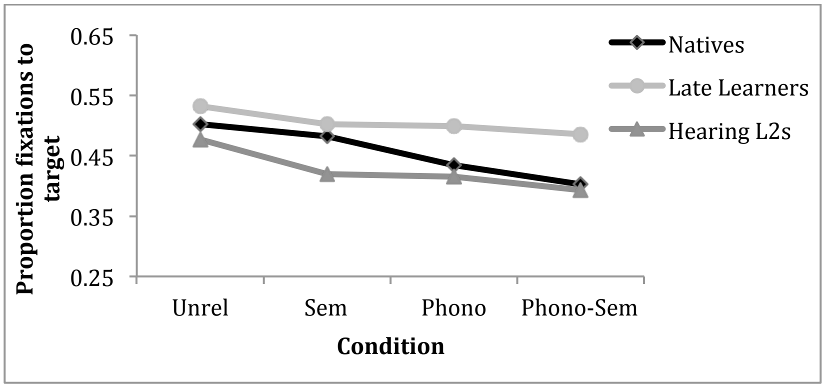

Figure 2: Mean fixation proportion to target 600-1800ms after target onset

3.2.3. Reaction time

Time course analyses were carried out to determine when participants shifted gaze to the target picture relative to the onset of the ASL sign. We calculated the saccade latency of looks that landed on the target picture starting from the onset of the target sign. Separate one-way ANOVAs for each participant group revealed that there was a main effect of condition among the native signers ($p < .01$), but no main effect in either the late-learning signers or the hearing L2 signers (Figure 3).

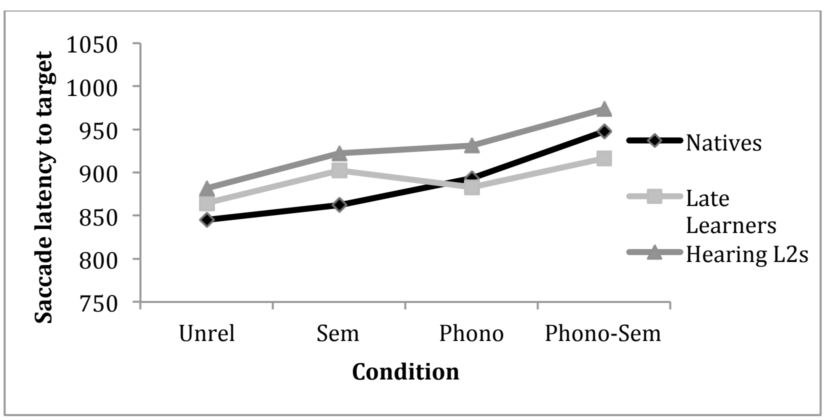

Figure 3. Mean saccade latency to target following sign onset.

3.2.4. Phonological parameter analysis (native signers)

Given the significant effect of phonological competitors on native-signing participants' overall fixations to target and competitor pictures, we conducted further analyses in this group to determine whether this effect was driven by a specific phonological parameter. We conducted a one-way repeated-measures ANOVA on the subset of trials that contained a phonological competitor (i.e. trials in the Phonological and Phono-Semantic conditions), using parameter (movement, handshape, location) as the within-subjects variable. Parameter here refers to the single parameter by which the target and phonological competitor varied. Analysis revealed that overall looking time to the target in the 600-1800ms window did not differ based on the type of parameter variation, nor did other measures of looking to the target differ by parameter. However, a one-way repeated measures ANOVA on looks to the phonological competitor did suggest some differences based on the specific parameter by which the target and competitor differed. Participants looked more to the phonological competitor when it differed from the target in handshape than when it differed in location or movement, although the difference was not significant ($p = .09$). Furthermore, participants had a greater number of fixations to the phonological competitor when it differed from the target in handshape or movement than when it differed in location [$F(2, 34) = 4.27$, $p < .05$]. Thus, while there is some evidence that minimal pair signs that varied on the handshape parameter provided the greatest competition, the overall phonological effect was not driven by a single parameter in this task.

3.3. Relationship between age of acquisition, ASL proficiency, and eye-tracking measures

In order to determine whether there were lexical processing differences among participants based on their age of first language acquisition, we analyzed performance among the late-learning signers in greater detail. The late-learning signers were first divided into two subgroups—those who were first exposed to ASL "Early," (i.e. between the ages of 5 and 8), and those who were first exposed to ASL "Late," (i.e. after the age of 8). These age grouping have been used in several previous studies of age-of-acquisition effects (e.g. Mayberry & Lock, 2002). Using these criteria, 12 participants fell into the Early subgroup, while only 6 participants fell into the Late subgroup. Of the remaining three participants, two were first exposed to ASL after the age of 8, yet they had significant exposure to spoken English prior to learning ASL. Thus their ASL experience was likely more similar to second language acquisition than to first language acquisition. One additional participant was exposed to a different sign language in childhood and learned ASL when he came to the United States as an adult. These three participants were excluded from the subgroup analyses.

To determine whether Early and Late signers had different background characteristics and language proficiency, we compared them on the language measures (see Table 2). As expected, Early learners exhibited greater proficiency on the language measures than Late learners. A t-test analysis confirmed that Early learners performed significantly better than Late learners on vocabulary production ($p < .05$) and narrative comprehension ($p <.01$) but not on the ASL Receptive Skills Test ($p = .1$).

Table 2. Mean accuracy on language measures in Early and Late learners:

AoA	Number of participants	Vocabulary production	Narrative comprehension	ASL Receptive Skills Test
Early	12	0.91	0.50	0.76
Late	6	0.85	0.29	0.72

We hypothesized that Early learners would look at the target faster and for longer overall than Late learners. However, contrary to expectations none of the measures of overall looking nor reaction time to the target were significantly different in Early and Late learners. We then conducted two-way repeated measures ANOVAs with competitor type (phonological, semantic, unrelated) as a within-subjects variable and age of acquisition (Early vs. Late) as a between subjects variable, for each condition. In the Phono-Semantic condition, there was a main effect of group, [$F(1, 16) = 5.58$, $p < .05$]. Late learners looked more at the competitors than Early learners (Late 5.7%, Early 2.6%). There was also a main effect of competitor type [$F(2, 32) = 19.71$; $p < .001$]. As expected, participants looked more at the Phonological (5.4%) and Semantic (5.6%) than the Unrelated (1.5%) competitors. There was also an interaction between age of acquisition and competitor type, driven by the fact that late learners looked more at the phonological competitors (8.1%) than early learners (2.7%). In the Phonological condition, there was a main effect of competitor type [$F(1, 16) = 10.62$, $p < .01$]; participants looked more at the phonological competitor than the unrelated competitor (3.7% vs. 1.9%). No effect of age of acquisition and no significant interactions were present. Finally, in the Semantic condition, there was a main effect of competitor type [$F(1, 16) = 27.81$; $p < .0001$]. Participants looked more to the Semantic competitors than the Unrelated competitors (6.7% vs. 1.7%);]. There was also a main effect of age of acquisition [$F(1, 16) = 5.52$, $p < .05$]. Late learners looked at the competitors more than Early learners (5.6% vs. 2.8%). There was no significant interaction. Thus across conditions, in addition to the overall increased looks to related competitors vs. unrelated competitors, there was a consistent trend in which Late learners had a higher proportion of fixations to competitors than Early learners.

We also did a split of late-learning participants by proficiency, based on scores on both the narrative comprehension task and the naming task. There were no significant differences between the groups in fixation proportion or saccade latency to the target based on scores on either proficiency measure.

ASL proficiency thus did not predict looking time in this group. Similarly, when we split the hearing L2 signers by proficiency, there were no significant differences in fixations to target for high proficiency vs. low proficiency hearing L2 signers.

4. Discussion

The current study was designed to explore the impact of linguistic experience on real-time processing of ASL signs. We approached this question using an eye-tracking paradigm that has been highly informative in spoken language processing research (Huettig, Romers, & Meyer, 2011) but has only recently been applied to probe lexical processing in a signed language (Thompson, Vinson, Fox, & Vigliocco, 2013). Real-time processing was first investigated in native signers to determine whether, in the case of typical language exposure, signers show processing of signs at both a semantic and sub-lexical level. Indeed, among the native signers we found robust evidence for real-time processing as evidenced by rapid gaze shifts to the target following the onset of the target sign. In addition, native signers were sensitive to both semantic and phonological, or sub-lexical, properties of signs during processing and showed significant decrease in target fixations and increases in reaction time for word recognition in the presence of phonological competitors. Thus, from this group there is evidence that lexical processing in a visual language parallels spoken word processing in that lexical candidates sharing phonological and semantic information with the target item are activated during word recognition.

The second question was whether early linguistic experience was crucial for the development of sub-lexical processing. To address this question we tested a group of late-learning signers, consisting of individuals who did not have exposure to an accessible language until the age of five or later. Although participants in this group did show evidence of phonological and semantic activation in real-time processing of ASL signs, the way this activation was expressed was quite different from the patterns observed among native signers. Specifically, late-learning signers showed no differences in target fixation or reaction time based on the presence of related competitors. Activation of semantic and phonological features of signs in this group was only evident in the increased fixations to related competitors relative to unrelated competitors. This suggests that early language experience may have a lasting impact on real-time linguistic processing, and that such on-line processing differences may be at least partially responsible for the linguistic deficits observed among late-learning signers even after years of experience with language (Mayberry, Lock & Kazmi, 2002). Furthermore, among the late-learning signers, those with the longest delay in first language acquisition spent the most time fixating on competitors, particularly phonological ones. This supports the notion that late exposure to language may lead to a processing strategy in which signers expend greater cognitive resources processing signs at the surface level, whereas native signers are able to access meaning directly (Mayberry & Eichen, 1991).

Finally, real-time processing of ASL signs was measured in a group of hearing L2 signers, to determine whether early linguistic experience in a spoken language would impact real-time processing of lexical items in a second language acquired later in life. The performance of the hearing L2 signers suggests that while these signers were slower and less accurate overall in their processing of ASL signs than early learners, their pattern of gaze fixations resembled that of native signers in that their overall fixations to the target sign were significantly impacted by the presence of phonological and semantic competitors.

Importantly, performance on this task, both among late-learning signers and hearing L2 signers, was not driven by proficiency. Thus real-time processing is not simply a reflection of linguistic ability; rather it is the underlying mental representation of language that appears to be impacted by early experience. The relationship between language proficiency and real-time processing ability must be examined further. A shortcoming of the current study is the fact that the tasks used to measure proficiency may not have accurately reflected linguistic proficiency. As tools for accurate assessment of sign language skills become more readily available and as norms for sign proficiency are developed, the ability to measure proficiency as a driving factor for sign processing efficiency will improve.

In conclusion, the current results suggest that, like spoken language, ASL signs are processed in real time in an incremental and dynamic manner. However, whereas native signers show activation of sub-lexical structure and semantic features of signs during real-time processing, signers with delayed onset of first language acquisition have different lexical recognition strategies. Thus early language deprivation appears to have a lasting impact on the real-time processing of language at the level of single words.

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