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Visual Sequence Repetition Learning is Not Impaired in Signing DHH Children

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Abstract

The auditory scaffolding hypothesis states that early experience with sound underpins the development of domain-general sequence processing abilities, supported by studies observing impaired sequence processing in deaf or hard-of-hearing (DHH) children. To test this hypothesis, we administered a sequence processing task to 77 DHH children who use American Sign Language (ASL) and 23 hearing monolingual children aged 7–12 years and found no performance difference between them after controlling for age and nonverbal intelligence. Additionally, neither spoken language comprehension scores nor hearing loss levels predicted sequence processing scores in the DHH group, whereas ASL comprehension scores did. Our results do not indicate sequence processing deficits in DHH children and do not support the auditory scaffolding hypothesis; instead, these findings suggest that factors related to experience with and/or proficiency in an accessible language during development may be more important determinants of sequence processing abilities.

Children who are deaf and hard-of-hearing (DHH) undergo cognitive and linguistic development in a sensory environment with limited or absent auditory input. Accordingly, those children are often taught a visual signed language, such as American Sign Language (ASL), and/or outfitted with hearing aids (HAs), or cochlear implants (CIs), which provide access to some semblance of auditory input. An enduring question is how such interventions might affect the cognitive and linguistic development of these children. Some studies report that DHH children have deficits in the processing of visual information over time (Dye & Bavelier, 2010; Horn et al., 2005; Quittner et al., 1994), in contrast to documented improvements in their spatial processing of visual information (Armstrong et al., 2002; Bosworth & Dobkins, 2002; Dye & Bavelier, 2012; Dye et al., 2009; Stevens & Neville, 2006). One hypothesis for these observed deficits in some DHH children is that the development of domain-general temporal sequencing abilities relies on auditory experience throughout early development (Conway et al., 2009). This auditory scaffolding hypothesis proposes that sound provides patterns of information based on serial order over time, which is integral to the development of sequence processing abilities in any domain, including vision. This theory is predicated on the idea that different sensory modalities encode information about the world in different ways. The auditory system encodes intensity, frequency and other spectral properties of acoustic energy in a signal that unfolds over time; these data are then used to extrapolate spatial properties of the signal's origin as needed. By contrast, vision encodes information in a primarily spatial format, and faces the challenge of then integrating that information over time to form a coherent spatio-temporal percept (Kanabus et al., 2002; Conway et al. 2009).

The auditory scaffolding hypothesis, as originally formulated, suggests that hearing bootstraps the process of learning how

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to interpret and process sequential information by providing exposure to serially ordered events (Conway et al., 2009). Such processing of sequential information can take several forms, including *sequence memory*, remembering given sequences of events, and *sequence learning*, learning the underlying structure across multiple sequences or the same sequence presented multiple times. Conway et al. (2011) reported results to suggest that, in contrast to a hearing control group, DHH children with CIs displayed little to no sequence learning. They administered a visual sequence learning task to 5–10-year-old DHH implanted children and a comparison group of hearing children. The task was based on the popular Milton-Bradley game named “Simon,” in which four differently colored shapes flash in a particular sequence of varying lengths, and the player must remember and repeat back the sequence afterwards. Unbeknownst to the participants in this study, the sequences were not random but had an underlying grammatical structure. Unlike the hearing children, DHH children did not show any benefit from underlying (sequential) grammatical structure. They concluded that auditory experience is crucial for the development of sequence learning ability, which in turn mediates language development, a conclusion in line with the auditory scaffolding hypothesis introduced in Conway et al. (2009).

More recently, Conway and colleagues extended this work by examining visual sequence processing in DHH children with CIs and/or hearing aids (Gremp et al., 2019). In addition to examining sequence memory (i.e., memory for random sequences), they also included a manipulation to examine a related form of sequence learning known as the *Hebb repetition effect* (e.g., Hebb, 1961; Page & Norris, 2009). This type of repetition learning, first explored in Donald Hebb’s seminal study over 50 years ago (Hebb, 1961), is a well-studied phenomenon that has received renewed interest in recent years (e.g., Page & Norris, 2009; Pisoni et al., 2016). Rather than assessing the extent to which children can learn the underlying grammatical structure of visual sequences as in Conway et al. (2011), Gremp et al. used repeating sequences where subsequent trials built upon earlier trials. For example, the children may see a *blue-yellow-red* sequence. If they correctly repeat back this sequence, the next trial might be *blue-yellow-red-blue*. Exposure to repeating sequences across trials allows the child to learn the sequence and improve their performance as trials progress; conversely, sequences that change randomly across trials prevent the child from utilizing their memory of past sequences to improve performance. Comparing performance between repeated and random sequences provides an index of how well a child can use the repeating structure of a sequence to boost recall performance, e.g., sequence learning via the Hebb repetition effect. Using an adaptive staircase procedure to vary sequence length on subsequent trials, Gremp et al. administered such *repeating* and *random* sequences to seventeen 5–11-year-old non-signing DHH children from two oral deaf schools (nine CI users, eight HA users) and to nineteen 6–9-year-old hearing children. Here, the auditory scaffolding hypothesis predicts sequence processing difficulties in the children who are DHH relative to the hearing children. Indeed, Gremp et al.’s results suggested that the DHH children performed worse than hearing children overall when collapsed across task type (DHH: 4.6 items, hearing: 6.0 items). Because there was no significant interaction between task type and group, this study did not find evidence for a lack of sequence *learning* in the DHH group; however, the presence of a significant main effect of group was interpreted as evidence for more general sequence *processing* deficits in DHH children. Although Gremp et al. stated that the results were consistent with the auditory scaffolding hypothesis as proposed by Conway et al. (2009), these results could also be construed as being only partially consistent with that framework because a specific sequence learning impairment was not observed as it was in Conway et al. (2011).

Gremp et al. (2019) also introduced a dichotomic *nameability* manipulation into their design because they observed that “one possible explanation for poorer performance by DHH children [on sequencing tasks] could be related to delayed acquisition of verbal labeling and verbal rehearsal” (p .3). However, Gremp et al. considered the existing evidence on this issue mixed; consequently, their proposed manipulation was designed to test the effect of input nameability (and by assumption, the use of verbal rehearsal strategies), on sequential processing in children who are DHH. To implement such a manipulation, the repeating and random sequences each occurred within two separate tasks: one used differently colored ovals, whereas the other used black squares. These were, respectively, considered relatively *nameable* and *unnameable* and were used to determine the influence of language-based rehearsal mechanisms on performance[i]. Gremp et al. found a significant interaction between group and nameability, which indicated a nameability benefit for the hearing children that was not apparent for the DHH children. Similar to what was reported by Conway et al. (2011), after controlling for chronological age, performance on the *nameable repeating* sequences predicted PPVT English vocabulary scores for the DHH children. These results were interpreted as “supporting the theory that a period of auditory (and/or linguistic) deprivation early in development may lead to domain-general deficits in sequential processing skills, especially for stimuli lending themselves to verbal representations” (Gremp et al., 2019, p. 13). Although one possible mechanism for such processing differences is that auditory input enables the use of vocal rehearsal processes, which would support the development of sequence processing abilities (see Conway et al., 2009), another possibility is that sound carries “modality-neutral” information, specifically “higher-level patterns of information related to temporal change and serial order” that promotes the development of sequencing skills (Conway et al., 2009, p. 288).

Together, these studies have been used to suggest that a child who has little experience with the temporal patterns provided by sound will have delays in the development of the cognitive abilities necessary to process such temporal signals. Subsequent auditory experience gained through a CI or HA may be instrumental in the development of temporal sequencing abilities following implantation (see also Conway et al., 2020; Deocampo et al., 2018; Pisoni et al., 2016). Later reviews have emphasized the potential role of the early communicative environment between the DHH child and their hearing parents in facilitating positive language and cognitive outcomes (see Pisoni et al., 2017). However, such reviews continue to focus solely on spoken communication, which is predicated on the child’s access to auditory information via cochlear implantation or hearing aids. Thus, these papers invariably imply that access to sound is a necessary precursor to ensuring appropriate cognitive and linguistic development in the DHH child.

The sequence processing evidence described above, however, cannot establish a *causal* relationship between a lack of auditory experience and the development of sequence processing and subsequent language development. As noted by Gremp et al. (2019) when discussing their observed correlation between sequence learning and PPVT scores, such associations do not necessarily indicate that sequence learning causally impacts language learning. Given that hearing loss is confounded with language acquisition, we must consider language, rather than auditory experience, as a potential determinant of sequence learning ability in DHH children. Alternatively, language acquisition and sequence processing may be mutually beneficial and reinforcing, and it is this dynamic process that is disturbed for DHH children who do not successfully acquire language on a typical developmental trajectory.

In teasing apart the effects of language versus audition on temporal processing skills, it is informative to study DHH children who acquire ASL early in life as a first language. They differ from DHH children with CIs acquiring only a spoken language in that they acquire a natural visual language on a typical developmental trajectory (Berk & Lillo-Martin, 2012; Bonvillian et al., 1983; Krentz & Corina, 2008; Palmer et al., 2012; Petitto, 1987; Singleton & Newport, 2004) and appear much less likely to experience the cognitive deficits that can accompany delayed language acquisition (Davidson et al., 2019; Marshall et al., 2015; Peterson et al., 2016). Since acquisition of ASL in the United States is a sociocultural phenomenon contingent on the decisions of the parent(s), rather than any physiological differences in degree of hearing loss, testing DHH children who learn ASL allows us to test hypotheses that disambiguate the roles of auditory experience and linguistic experience on cognitive development. A 2014 study found that DHH children with early sign exposure performed just as well as hearing children on a continuous performance task, which measures sustained attention (Dye & Hauser, 2014). Conversely, several earlier studies reported deficits in sustained attention in DHH non-signing children with CIs enrolled in oral- or total-communication programs[ii] (Horn et al., 2005; Quittner et al., 1994; Yucel & Derim, 2008). More relevantly, Hall et al. (2018a) recently found equivalent performance between hearing children, DHH oral children, and DHH native signing children on two implicit sequence learning tasks, though the way that Hall et al. (2018a) implemented the Simon task was different than previous studies, resulting in no learning being demonstrated in either hearing or DHH children (see Deocampo et al., 2018 for discussion; see also Torkildsen et al., 2018, for a study showing equivalent levels of learning in DHH children with CIs and hearing peers on a visual statistical-sequential learning task).

Such a stark disconnect between the trends of evidence on cognitive processes in DHH signing children versus DHH children raised in an oral- or total-communication environment raises questions about the true source of observed cognitive deficits in some, but not all, DHH children. The *language deprivation hypothesis* (Hall et al., 2017; Hall et al., 2018b) emphasizes patterned language experience, rather than audition, as a crucial determinant of domain-general cognitive skills such as executive function. Under the *language deprivation hypothesis*, deficits in performance on cognitive tasks shown by DHH children with CIs, and their increasing improvement with longer CI use, could be explained by the initial lack of, then the increased exposure to, a patterned temporal language in the form of spoken English. If this were indeed the case, we would expect children who have had access to ASL from birth—a natural language with a significant amount of temporal structure—to display typical sequence memory and learning abilities.

Here, we report data from a study comparing the sequence processing abilities of DHH signing children who are fluent early signers of ASL to a hearing control group. We evaluated their performance on the same four tasks reported by Gremp et al. (2019), which reflect sequence processing. These tasks measure both *sequence memory* (performance on random sequences) and *sequence learning* via the Hebb repetition effect (enhanced performance for repeating sequences). In comparing DHH fluent signing children and hearing children, we were able to test predictions of the *auditory scaffolding hypothesis* on visual sequence processing skills while controlling for the potential influence of language deprivation. The auditory scaffolding hypothesis makes the prediction that DHH users of sign language should still show difficulties with sequential processing due to their limited access to sound (Conway et al., 2011). Such difficulties might arise as a group difference in overall task performance in which DHH children underperform their hearing equivalents (*sequence memory*) or as a significant interaction between task type and hearing group, indicating particular difficulties with *sequence learning*. If DHH fluent signing children demonstrate sequence processing abilities on a par with their peers with typical hearing, in contrast to the DHH children in Gremp et al. (2019), then language rather than audition would seem to be the relevant variable in explaining deficits in DHH oral children, providing some support for the *language deprivation hypothesis*.

We also examined whether the DHH and hearing groups demonstrated improved performance for more easily nameable stimuli, to test whether we would replicate the finding in Gremp et al. (2019) that only hearing children seemed to benefit from highly nameable stimuli, which was interpreted as reflecting the use of (spoken) verbal rehearsal strategies less available to DHH children. Since the DHH children in this study are native ASL signers, a nameability benefit in this group might reflect a (signed) verbal naming strategy employed by the DHH children.

In addition, we examined the correlations among sequence processing scores and measures of language and audition within the DHH group to test several novel predictions. First, we examined whether DHH children with smaller hearing losses or better spoken language comprehension would display better sequence processing ability than DHH children with larger hearing losses or little-to-no spoken language comprehension. While the auditory scaffolding hypothesis in its original formulation dealt only with the presence or absence of sound during development, and did not make explicit predictions about whether degree of hearing loss would be correlated with sequencing abilities, such correlations would be consistent with the idea that experience with sound is a driver of the development of sequencing abilities. Conversely, we also examined whether DHH children with better sign language ability, as measured using two tests of ASL comprehension, would display better sequence processing ability. Such a relationship would be predicted by a variation upon the *language deprivation hypothesis* which emphasizes language *proficiency*, rather than language exposure, as a driver of the development of sequence processing abilities—a possibility discussed by Hall et al. (2018a).

Method

Participants

Written or online informed consent was obtained from a parent or legal guardian prior to testing, and written informed assent was obtained from every child each time a testing session began. Each child was compensated with $20 per hour of participation (pro-rated on a half-hour basis). Background information was obtained via a questionnaire presented in person or online and completed by parents or legal guardians, who were paid $20 for completing the survey. This questionnaire asked about the children's demographics and language experience, as well as household income, education level of the primary caregiver, the child's family members (including whether any were DHH), and

Table 1 Demographic characteristics of the hearing and DHH groups; cochlear implant use, hearing aid use, familial deafness, and ASL use in the DHH group. All children's demographics are reported, including for children who did not complete all four Simon tasks ($N = 100$)

		DHH	Hearing
	N	77	23
	Mean age (SD)	9.57 (1.26)	10.21 (1.65)
	# Male/# female/# other	37/39/1	10/13/00
Race	White/Caucasian	53	14
	Black/African–American	4	0
	Hispanic/Latinx	6	0
	American Indian or Alaskan Native	1	0
	Asian	1	0
	More than one race	10	9
	Prefer not to answer	1	0
	No response	1	0
Hearing aid use	Yes, have had HAs	51	—
	Mean age first worn in years (SD)	2.22 (2.25)	—
	Range	0–8	—
	Still wear them today	27	—
	No	23	—
	No response	1	—
Cochlear implant use	Yes, have had CIs	3	—
	Mean age first implanted in years (SD)	2.50 (.50)	—
	Range	2–3	—
	Still wear them today	3	—
	No	71	—
	No response	3	—
Familial deafness	At least one deaf parent or guardian	62	—
	No deaf parents	13	—
	No response	2	—
ASL use	Mean age child first learned ASL in years (SD)	0.33 (.65)	—
	Range	0–3	—
	Mean age parent first learned ASL in years (SD)	6.76 (11.79)	—
	Range	0–44	—

Table 2 Language, IQ, and audiological measures (means with SD in parentheses). All children's scores are reported, including for children who did not complete all four Simon tasks ($N = 100$)

Measure	DHH	Hearing
OWLS–listening comprehension (raw)	17.28 (23.26)	91.23 (12.94)
OWLS–LC (standardized)	—	99.85 (11.16)
ASL receptive skills test (raw)	32.74 (3.43)	—
ASL comprehension test (raw)	21.23 (4.03)	—
KBIT–matrices subtest (standardized)	104.00 (15.14)	102.74 (17.63)
Unaided hearing level in better ear (pure tone average in dB)	82.05 (28.19)	—

parental language experience. This study was approved by the Institutional Review Board at Rochester Institute of Technology, and by research review boards at participating schools where required by state law.

DHH Children Data were collected at five residential schools for the deaf across the United States, with a total sample of 76 DHH children. All schools utilized a bilingual curriculum that employed ASL as the primary language of communication between students, teachers, and non-teaching staff, and English as the primary written language. Students were recruited through the schools' typical communication strategies with parents, including social media posts, letters, emails, and in-person recruitment at school events and after-school pickups.

The inclusion criteria were that children should be aged between 7 and 12 years of age, have some degree of diagnosed hearing loss, and be receiving an education where ASL was the primary means of instruction. Exclusion criteria were limitations in arm/hand mobility, and documented learning or intellectual disabilities. ADHD was not an exclusion criterion, and seven DHH children had a reported ADHD diagnosis. Demographic data for all children are reported in Table 1, and language assessment, IQ and audiological data are presented in Table 2. The use of hearing aids or cochlear implants was not an exclusion criterion, as all previous studies that discovered sequence processing deficits in DHH children had reported widespread use of hearing aids or cochlear implants by the children in their samples, suggesting that the auditory access provided by HAs or CIs are insufficient to support the development of sequencing abilities that might rely on audition. In our sample, 3 reported use of CIs and 51 reported current or past use of HAs, although HA use was widely reported to be temporary or inconsistent, with 27 children having stopped use of HAs at the time of testing (see Table 1).

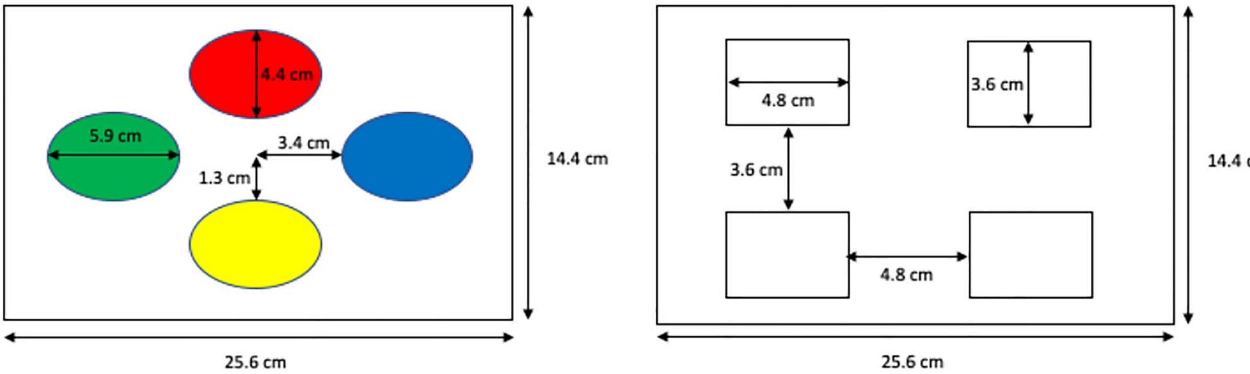

Figure 1 The dimensions and distances of the shapes displayed in the Simon task, as measured on the tablet used in the study.

Hearing Non-Signing Children Twenty-one hearing non-signing children were recruited from a local school district in the Rochester NY metropolitan area through mailings sent to parents by the school. None reported knowing any ASL and all indicated English was their first language. There were no hearing non-signing children who had a reported ADHD diagnosis.

Design

The Simon task reported in this article is the same as that reported by Gremp et al. (2019). The task comprises four subtests with 20 trials each, for an approximate testing time of 20–30 minutes. In each trial, shapes appeared one at a time in one of four outlined locations on a tablet with a touchscreen. The children were asked to watch and memorize the sequence of stimuli and then were prompted to repeat the observed sequence immediately afterwards. The dimensions of the stimulus shapes displayed in the test are given in Figure 1. Within each trial, the duration of each stimulus screen was 700 ms; inter-stimulus intervals (a blank screen) lasted 500 ms; a 500-ms blank screen also appeared before the response prompt screen, which displayed all four fully colored shapes; when a shape on the response screen was pressed, the shape changed color for 100 ms. The number of stimuli in a sequence on each trial varied: the first trial always contained just one stimulus, with subsequent trial lengths determined by a 1-up 1-down adaptive staircase procedure, increasing when the previous trial response was correct and decreasing when it was incorrect (starting with 1 stimulus on the first trial, for a maximum of 20 stimuli on the last trial if the child gets all trials correct). At the conclusion of each trial stimulus sequence, children were prompted to begin replicating the sequence manually on the touchscreen. Children pressed a button labeled "DONE" once they felt they had completed the sequence, at which point the next trial started immediately.

The four subtests were defined by changing the stimulus shapes' appearance and/or changing the type of sequence shown. First, the shapes were either *colored* and easily nameable (distinctly identifiable colors in a north/south/east/west configuration) or *monochromatic* and less easily named (black-outlined shapes in an upper right/upper left/lower right/lower left configuration). Comparing performance between tasks that vary in nameability allows us to study if, and to what extent, having covertly or overtly generated linguistic labels for stimuli aids temporal recall. Second, the sequence was either *repeated* throughout all trials in a subtest, or *random* for each trial. A repeated-sequence subtest contains the same order of color-locations across all trials; only the length of the stimulus sequence changes across trials. In a random-sequence subtest, the order of color locations shown changes at random between trials. Comparing the random sequence subtests to the repeated sequence subtests allow us to study the relative benefit of having previous sequential information available—i.e., learning that is specific to the particular sequence presented—rather than relying solely on short-term memory or displaying general task learning effects (i.e., performance improvements over time due to increased familiarity with the task). The four subtests were labeled as follows[i]: colored repeated, monochrome repeated, colored random, and monochrome random. The subtests are each visually represented in Figure 2.

Apparatus

The Simon tasks were administered on a GETAC F110 tablet computer with an integrated 11.6″ HD touchscreen (resolution 1,366-by-768 pixels; brightness 800 nits). Responses were recorded via touchscreen. Spoken language tests were administered using a Dell Latitude E7470 14″ laptop connected to a Bose SoundLink Mini II stereo speaker. All tasks were implemented using E-Prime 2.0 running on a Windows 7 operating system.

Procedure

Testing was performed on-site in conjunction with the schools' testing or administrative departments (for DHH children) or in a quiet testing room at the National Technical Institute for the Deaf (for hearing children). Most testing with the DHH children was conducted during the school day; some children were tested after school, in compliance with schools' or parents' preferences. Tests were individually administered in an isolated room free of distractions, with only the researcher and child present. The researcher was Deaf and signed with all DHH children; with the hearing children, the researcher spoke and was accompanied by a hearing researcher to facilitate communication as necessary. A battery of attention, language, and cognition tests was given to each participant over two sessions. Sessions were limited to one hour and separated by no less than a day and no more than two weeks. The first session was comprised of attention and visual learning tasks, including the four Simon tasks; the second session was comprised of language and cognition measures[iii]. Measures were counterbalanced in all sessions, with the exception of the language assessments for the DHH children, which

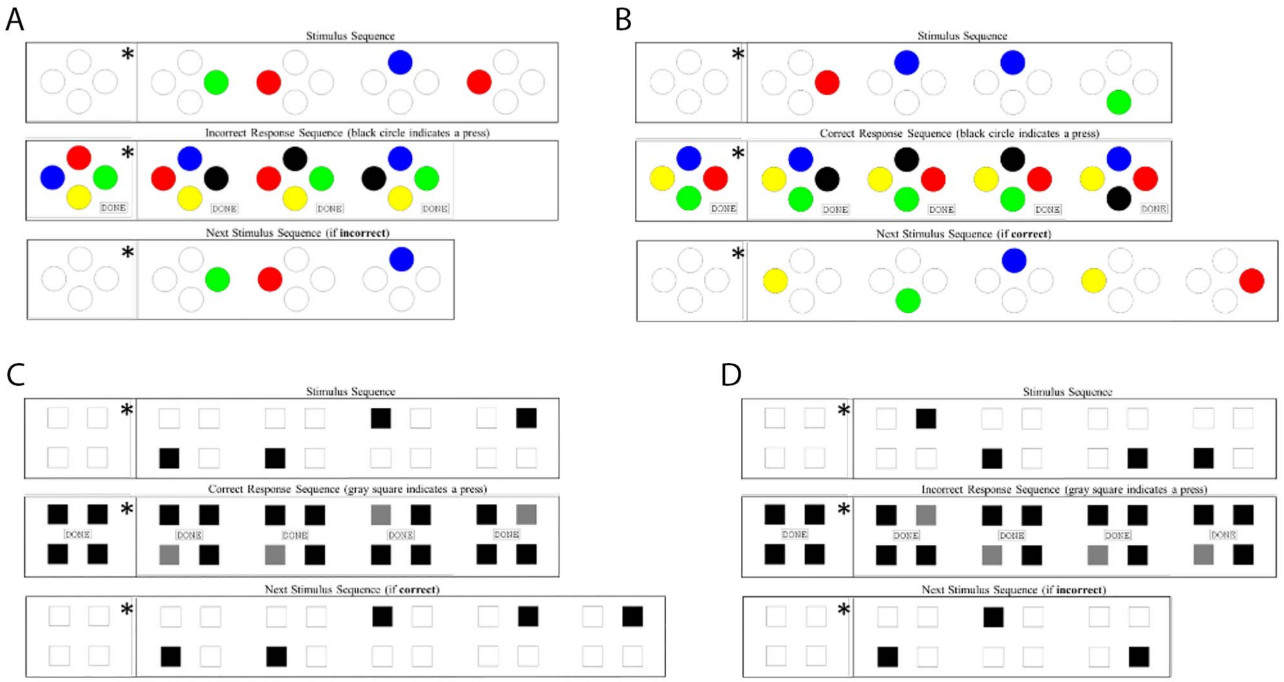

Figure 2 (A). An example of two trials in the fixed-sequence colored subtest. After a sequence of $n = 4$ is met with an incorrect recall, the next sequence of $n = 3$ is given. The asterisked images appear at the beginning and in between each stimulus or response image. (B). An example of two trials in the random-sequence colored subtest. After a sequence of $n = 4$ is met with a correct recall, the next sequence of $n = 5$ is given. The asterisked images appear at the beginning and in between each stimulus or response image. (C). An example of two trials in the fixed-sequence monochrome subtest. After a sequence of $n = 4$ is met with a correct recall, the next sequence of $n = 5$ is given. The asterisked images appear at the beginning and in between each stimulus or response image. (D). An example of two trials in the fixed-sequence monochrome subtest. After a sequence of $n = 4$ is met with an incorrect recall, the next sequence of $n = 3$ is given. The asterisked images appear at the beginning and in between each stimulus or response image.

were given at the end of the session to avoid potential stereotype threat from administering tests of spoken and signed language to DHH children in a bilingual-bicultural environment[iv].

Spoken English receptive skill was assessed using the OWLS-II Listening Comprehension Subscale (Carrow-Woolfolk, 1995). This test requires children to listen to a spoken sentence and then select which one of four pictures correctly corresponds to what they heard. Stimulus items assess a range of linguistic structures including lexical/semantic, syntactic, pragmatic, and supralinguistic. The researcher who administered all tests was deaf and tested children at all of the different locations across the United States; a consistent live presentation of verbal stimuli was therefore not possible. Instead, a hearing colleague was filmed speaking each of the items. The items were presented as individual video files on a laptop. The laptop was positioned in front of the child, with the response book next to it, and the speaker was placed directly in front of the laptop. The child was prompted to pay attention to the laptop before each item was played; they were not allowed to touch the table or the speaker to feel the vibrations (a common request). After test completion, to minimize stereotype threat or associated negative feelings the child was reassured that their performance on this test was not critical. While a hearing research assistant was on hand with the hearing children, they were still given the same video-format OWLS-II test as the DHH children. Standardized scores are only reported for the hearing group because no DHH population norms exist for the test and the minimum standardized score of 40 obscures much of the variability in DHH scores.

ASL receptive skill was assessed using the ASL–receptive skills test (ASL-RST; Enns et al., 2013) and the ASL comprehension test (ASL-CT; Hauser et al., 2016). The ASL-RST comprises 42 multiple-choice items in which the child watches an ASL sentence and selects one of four possible illustrations that they feel best matches the sentence. The ASL-CT comprises 30 multiple-choice items. Each item presents either an ASL sentence for which the respondent selects the best match from four possible depictions, or a depiction for which the respondent selects the best match from four possible ASL sentences; depictions are either a line illustration, a photo, or a video of a nonlinguistic event. While both tests measure ASL receptive skill, the ASL-RST was designed for use with children aged 3–12 years, whereas the ASL-CT was designed and validated with a sample of college-aged students (Allen & Enns, 2013; Hauser et al., 2016). The ASL-CT was added to the test battery to avoid a potential ceiling effect and capture higher-level variation in ASL receptive skill.

Nonverbal intelligence (NVIQ) was assessed using the matrices subtest of the Kaufman Brief Intelligence Test, Second Edition (KBIT-2) (Kaufman & Kaufman, 2004). This subtest, the only one of three in the KBIT-2 that tests *nonverbal* intelligence, is appropriate for use with people between the ages of 4–90. Each question in this subtest presents the child with a visual puzzle, which has an incomplete segment, and six possible answers that might fit. The child is asked to point to the correct answer or give the corresponding letter; only the correct answer will fit the pattern presented in the puzzle. Questions increase in difficulty, and the test continues until the child reaches the end of the test or gives four consecutive incorrect responses. All KBIT scores have been converted to standardized scores for the analyses in this study.

Anonymized audiometric data were obtained from the schools' audiology departments, with parental and school consent. Since the schools performed regular audiometric testing of their students, all participants in the study reported here had complete audiometric data. In cases for which audiometric data from multiple testing sessions was received, data from the most recent session were used. Pure tone averages (PTA) from the right and left ears were documented, and the PTA for the better ear were used in the analyses. In the event that PTAs were not explicitly noted on the audiograms, they were calculated by averaging the dB HL ratings at 500, 1,000, and 2,000 Hz; if one or more of these values were not measurable due to profound hearing loss (denoted by NR on the audiogram), then only the observed values were averaged together. This therefore represents a conservative measure for those children with the most profound hearing losses.

Results

Assessing Replicability of Gremp et al. with DHH Signing Children

Following Gremp et al. (2019), we computed the maximum sequence length at which a child had at least once correct response (*maximum span*) for each condition. While sample sizes were unequal, the variances of maximum span scores did not significantly differ between hearing and DHH groups (all P's > .05). In order to compare our data with that reported by Gremp et al. (2019), we fitted a 2 × 2 × 2 linear mixed model with maximum span as a dependent variable, participant group (DHH, hearing), sequence type (random, repeated) and nameability (monochrome, colored) as fixed effects, and subjects as random effects, and a criterion of $\alpha = .05$. We used the lme4 R package (Bates et al., 2015). The overall model's explanatory power was substantial (conditional $R^2 = .65$; marginal $R^2 = .38$). We found a large and significant fixed main effect of sequence type ($\beta = -4.07$, SE = .33, 95% CI = [−4.72, −3.41], $p < .001$), with longer spans for repeated ($M = 1.50$, SD = 3.54) than for random ($M = 6.37$, SD = 1.34) sequences. The fixed main effects of group and nameability, the two-way interactions, and the three-way interaction were all not statistically significant given a criterion α of .05. Thus, while we replicated the main effect of sequence type reported by Gremp et al. (2019), we found no evidence of a group difference in performance nor any interaction between group and the manipulated variables. We also did not find any evidence of a nameability effect. Maximum spans per task and group are reported in Table 3.

As a stronger control for the potential influence of any auditory input via HA or CI use on sequence processing performance, the 2 × 2 × 2 mixed ANOVA was repeated excluding any DHH child who reported continued use of HAs or CIs. The pattern of significant results did not change (see Supplementary Materials).

Next, within the sample of DHH children, we computed partial Kendall's tau correlations between maximum span scores for each of the conditions and the spoken language and hearing measures, controlling for age at time of testing (see Table 4) using the ppcor R package (Kim, 2015). Predictably, there was a significant positive correlation between OWLS-II Listening Comprehension scores and hearing levels (dBHL) in the DHH children ($\tau = -.290$, $p < .001$)[v]. Turning to the Simon task span scores, Gremp et al. (2019) reported that performance in the colored-repeated condition had the strongest relationship to language scores (PPVT scores in their study). In the data reported here, only the correlation between maximum span in the colored-random condition and OWLS-II Listening Comprehension raw scores was

Table 3 Mean (SD) group performance on each Simon task, quantified as the maximum span length correctly recalled (maximum span), along with range (min–max) and sample size (*n*) per group for each task. All task scores are reported, including for children who did not complete all four Simon tasks (total $N = 100$)

Maximum span	DHH	Hearing
Colored repeated	10.46 (3.52)	11.71 (3.45)
	4–20	6–20
	$n = 76$	$n = 21$
Colored random	6.36 (1.45)	6.95 (1.12)
	3–12	5–9
	$n = 75$	$n = 21$
Monochrome repeated	10.24 (3.60)	10.55 (3.49)
	3–20	6–18
	$n = 75$	$n = 22$
Monochrome random	6.15 (1.33)	6.62 (.97)
	2–8	5–8
	$n = 74$	$n = 21$

statistically significant ($\tau = .179$, $p < .05$). We conducted a linear regression analysis of OWLS-II scores on age, NVIQ, and colored-random task scores using the lm R package. The resulting model was not statistically significant with an a priori criterion of $\alpha = .05$ ($F(3,65) = .740, p = .532$); after controlling for age and NVIQ, the predictive power of colored-random task scores was also not statistically significant ($\beta = 2.425$, $t = 1.087$. $p = .281$).

Assessing the Impact of American Sign Language

The study reported here added two measures of ASL processing skills: the ASL Receptive Skills Test (ASL-RST) and the ASL Comprehension Test (ASL-CT). Controlling for age, the ASL measures were significantly and positively correlated with each other ($\tau = .267$, $p < .01$). Furthermore, both ASL measures were significantly and positively correlated with maximum span scores from all four conditions except the correlation between ASL-RST scores and colored-repeated span scores (see Table 4). The ASL measures were thus entered into separate linear regression models, alongside age and NVIQ, to predict maximum span in each of the four Simon conditions. Whereas Gremp et al. were interested in the extent to which poor performance on the Simon tasks predicted spoken language abilities in their population, the DHH children in this study displayed typical, albeit variable, language abilities in the visual signed modality. We therefore sought to determine whether their language abilities predicted performance on the sequencing tasks.

We constructed hierarchal linear regression models for each of the four Simon tasks. In each model, we first added age at time of testing and NVIQ, and then added each of the two ASL measures separately. The resulting standardized beta coefficients and associated significance levels, adjusted R^2 values, and changes in R^2 values as well as their significance levels are all reported in Table 5. Adding ASL-RST to the model explained significantly more variance in the model in both of the random-sequence tasks, but not for either of the repeated-sequence tasks, and ASL-RST scores significantly predicted performance in the two random-sequence conditions after controlling for age and NVIQ. Adding ASL-CT to the model explained more variance in the model in three of the four tasks, with the exception of the monochrome-repeated task. After controlling for age and NVIQ, ASL-CT scores significantly predicted scores in three of the four

Table 4 Correlation matrix showing Kendall's Tau-b for relationships between maximum span scores for each experimental condition and audiology/speech/sign measures for DHH children (* $p < .05$ ** $p < .01$ *** $p < .001$). Only DHH children with all scores were included ($N = 65$). All were partial correlations controlling for age at testing, *except* the correlations with PTA dBHL (italicized), which were semi-partial correlations in which PTA dBHL was not controlled for age

	ASL-RST (raw)	ASL-CT (raw)	*PTA dBHL*	OWLS-LC (raw)	Colored repeated	Monochrome repeated	Colored random
ASL-CT (Raw)	0.267**	—	—	—	—	—	—
PTA dBHL	0.101	0.067	—	—	—	—	—
OWLS-LC (raw)	0.101	0.067	−0.29***	—	—	—	—
Colored repeated	0.143	0.267**	0.040	0.130	—	—	—
Monochrome repeated	0.226**	0.249**	0.080	0.119	0.463***	—	—
Colored random	0.262**	0.212*	−0.107	0.179*	0.370***	0.324***	—
Monochrome random	0.235**	0.206*	0.053	0.093	0.293***	0.273**	0.380***

Table 5 Hierarchal linear regression models for each task score. Beginning with no predictors, age at time of testing and NVIQ (as measured by KBIT-II Matrices) were added and change in R^2 calculated. Then each of the two ASL comprehension tests (ASL-RST and ASL-CT) were added to the (age + NVIQ) model, and change in R^2 calculated. Note that ASL measures were added separately, meaning that change in R^2 for the ASL-CT models denotes change from the (age + NVIQ) models, not the ASL-RST models. Significance of changes in R^2 between models was assessed with *F*-tests. Beta coefficients and associated significance tests for each model are given. For each model, only the DHH children who had a complete set of scores for that model were included (*N*'s = 67–70)

Task Score	Predictor	Age + NVIQ	+ ASL-RST	+ ASL-CT
Colored repeated	*Model*	$F(2,67) = 13.78$ ***	$F(3,66) = 10.20$ ***	$F(3,66) = 11.87$ ***
	Age	1.10***	0.91**	0.78*
	NVIQ	0.09***	0.08**	0.08**
	ASL-RST		0.18	
	ASL-CT			0.23*
	Adjusted R^2	0.27	0.29	0.32
	ΔR^2	0.29 ***	0.03	0.06 *
Colored random	*Model*	$F(2,66) = 9.80$ ***	$F(3,65) = 1.95$ ***	$F(3,65) = 9.02$ ***
	Age	0.52***	0.34**	0.38**
	NVIQ	0.02	0.01	0.01
	ASL-RST		0.16**	
	ASL-CT			0.11*
	Adjusted R^2	0.21	0.31	0.26
	ΔR^2	0.23 ***	0.11 **	0.07 *
Monochrome repeated	*Model*	$F(2,66) = 8.72$ ***	$F(3,65) = 7.17$ ***	$F(3,65) = 7.25$ ***
	Age	0.95**	0.71*	0.69*
	NVIQ	0.07**	0.06*	0.06*
	ASL-RST		0.24	
	ASL-CT			0.20
	Adjusted R^2	0.19	0.21	0.22
	ΔR^2	0.21 ***	0.04	0.04
Monochrome random	*Model*	$F(2,65) = 10.17$***	$F(3,64) = 12.57$ ***	$F(3,64) = 9.91$ ***
	Age	0.50***	0.34**	0.37**
	NVIQ	0.01	−0.00	−0.00
	ASL-RST		0.16***	
	ASL-CT			0.10**
	Adjusted R^2	0.22	0.34	0.29
	ΔR^2	0.24 ***	0.13 ***	0.08 **

* $p < .05$.
** $p < .01$.
*** $p < .001$.

tasks, again with the exception of the monochrome-repeated task ($\beta = .201$, $t = 1.905$, $p = .061$).

DHH Children with ADHD Diagnoses

We considered the potential influence of ADHD, given the presence of seven DHH children in the sample who had a parent-reported ADHD diagnosis. The mean scores on the Simon tasks for DHH children with and without an ADHD diagnosis are reported in Table 6. While the small ADHD sample size precludes meaningful statistical analysis, the maximum span scores were, on average, roughly equivalent between DHH children with and without an ADHD diagnosis.

Socioeconomic Status and Parental Education

Group differences in parental education and household income, as reported on the background questionnaire, were assessed

Table 6 Mean (SD) performance on each Simon task for DHH children with an ADHD diagnosis as compared to DHH children without an ADHD diagnosis, along with range (min–max) and sample size (*n*). Performance was quantified as the maximum span length correctly recalled (maximum span). All task scores are reported for DHH children with a reported ADHD diagnosis or an *explicitly reported absence* of an ADHD diagnosis ($N = 70$)

Maximum span	No ADHD diagnosis	ADHD diagnosis
Colored repeated	10.60 (3.59)	10.28 (3.68)
	4–20	6–15
	$n = 63$	$n = 7$
Colored random	6.32 (1.50)	6.29 (1.25)
	3–12	5–8
	$n = 62$	$n = 7$
Monochrome repeated	10.35 (3.84)	9.43 (2.30)
	3–20	8–14
	$n = 62$	$n = 7$
Monochrome random	6.08 (1.31)	6.57 (1.81)
	2–8	4–8
	$n = 61$	$n = 7$

with Kruskal–Wallis H tests. The hearing children had slightly higher household incomes (χ^2 (1) = 5.06, $p = .024$) and parental education levels (χ^2 (1) = 4.22, $p = .040$) than did the DHH children. If anything, the slightly lower income and education levels would appear to put the DHH group at a disadvantage; yet their performance on the Simon tasks was statistically indistinguishable from the typical hearing group.

Discussion

Predictions of the auditory scaffolding hypothesis were tested using visual sequencing tasks that have previously been reported to reveal deficits in young DHH children with cochlear implants and/or hearing aids (Cleary et al., 2001; Deocampo et al., 2018; Gremp et al., 2019; Pisoni et al., 2016). Those studies have attributed such deficits to an absence of sufficient access to sound and/or insufficient access to a spoken language. Unlike in these previous studies, the DHH children in this study were fluent users of American Sign Language, most of whom have never used cochlear implants[vi]. Investigating sequence processing in this population allows us to examine predictions offered by the auditory scaffolding hypothesis (Conway et al., 2009) while controlling for potential effects of language deprivation in the DHH group. The auditory scaffolding hypothesis predicts impairments to sequential processing in DHH children who are fluent signers, whereas the language deprivation hypothesis predicts no such impairments.

We investigated whether DHH fluent signing children and hearing children would differ in their performance on the four visual sequence processing tasks in this study, as predicted by the auditory scaffolding hypothesis. Our sample of DHH signing children demonstrated sequence processing abilities on a par with their hearing peers, contrary to predictions made by the auditory scaffolding hypothesis. We also found a significant main effect of sequence type, with both the DHH and hearing children showing an advantage on reproducing sequences that contained a repeating structure compared to sequences that contained no structure, which reflects a Hebb repetition effect. This indicates that both DHH and hearing groups displayed some sequence learning ability, and there were no differences in sequence learning between groups, as demonstrated by the lack of an interaction between sequence type and hearing status. This pattern of results differs from findings using the same tasks with DHH children who use spoken language and have undergone cochlear implantation and/or use hearing aids on a regular basis (though, as described above, Gremp et al., 2019 found a general sequence processing impairment but not a specific sequence learning impairment in DHH children). Furthermore, hearing levels as measured by pure tone thresholds did not predict performance on any of the sequence processing tasks in the DHH group. While this final analysis was not a direct test of the auditory scaffolding hypothesis, which only predicts that profound hearing loss would result in atypical sequence processing as compared to the hearing population, this finding suggests that degree of auditory access within the DHH population is not related to the development of sequence processing abilities.

Gremp et al. (2019) also reported that, in the DHH group, PPVT scores were predicted by maximum span scores in conditions where stimuli were more easily nameable. Here, using OWLS-II Listening Comprehension scores instead, we found that maximum span in the colored-random condition, but not the other three conditions, was correlated with standardized listening comprehension scores. However, a linear regression model that included age and a NVIQ measure as covariates did not replicate Gremp et al.'s finding that these maximum span scores predict English language abilities. Therefore, we did not find evidence for a relationship between spoken language and sequential processing ability in our sample of DHH children, a result inconsistent with hypotheses that point to *spoken* language development as supporting, or being supported by, sequential processing ability in DHH children (as discussed in Deocampo et al., 2018).

As a replication of Gremp et al. (2019), we compared the performance of hearing and DHH children on Simon tasks that only differed in the nameability of their stimuli in order to investigate whether both groups might be using verbal labeling and rehearsal strategies to enhance their sequencing performance. While Gremp et al. (2019) did not find a main effect of nameability, they found a *nameability x group* interaction: they reported that the hearing children performed better on more easily nameable tasks while DHH children did not, although follow-up pairwise comparisons found only a marginally significant difference between nameability conditions for the hearing group ($p = .06$ as compared to $p = .33$ for the DHH group). We also did not find a main effect of nameability; however, we did not replicate Gremp et al.'s finding of a *nameability* × *group* interaction. The nameability manipulation did not affect task performance in our study, nor did it interact with any other variables to affect task performance. Thus, while Gremp et al. (2019) concluded that hearing children were employing verbal rehearsal strategies to successfully boost performance and DHH children were unable to do so, we did not find evidence that *either* hearing or DHH children were employing verbal rehearsal strategies to boost task performance.

Where, then, does this leave the auditory scaffolding hypothesis? It is important to note that there remains documented reports of sequence processing deficits in some DHH children. However, these deficits seem to be confined to DHH children who are exposed only to spoken language, and who require cochlear implants and/or hearing aids in order to access that linguistic signal. In contrast, DHH children who are taught sign language from early childhood do not seem to experience those deficits. This has parallels with other cognitive functions that were previously thought to be susceptible to impairment as a result of hearing loss. For example, while it has been argued that deafness results in temporal visual attention deficits (Horn et al., 2005; Quittner et al., 1994; Smith et al., 1998), studies with DHH children from DHH signing families have found no such deficits (Dye, 2014; Dye & Hauser, 2014). The same is true for theory of mind (Morgan et al., 2020; Tomasuolo et al., 2013), some aspects of executive function (Hall et al., 2017; Hall et al., 2018b; Jones et al., 2020), and statistical learning (Giustolisi & Emmorey, 2018).

The putative goal of studies that document cognitive deficits in some DHH children is to attempt to explain the highly variable, and often poor, spoken language outcomes following cochlear implantation. Such studies discuss the potential for a “cascading effect” of a lack of early auditory stimulation on the spoken language-learning environment of DHH children, including their early intersubjective experiences with caretakers, which culminate in poor spoken language outcomes (Gremp et al., 2019; Pisoni et al., 2016). However, studies which attempt to identify neurocognitive factors that might explain variable spoken language outcomes in implanted DHH children (Kral et al., 2016; Pisoni et al., 2017), run the risk of misidentifying such factors as mediators of language outcomes when they may themselves be an outcome of poor language growth. That is, in assuming that auditory stimulation via cochlear implantation is a necessary precursor for intersubjective experiences that support future language growth, it is important to consider the possibility that those neurocognitive deficits may themselves be the result of prior language delays rather than hearing loss per se.

It has been argued that early access to a natural signed language, such as ASL, can prevent cognitive dysfunction in DHH children and promote their cognitive health (Clark et al., 2019; Hall et al., 2019; Humphries et al., 2016). While comparing DHH signing children and hearing children cannot provide direct evidence to corroborate predictions made by the language deprivation hypothesis, within-group analyses indicate that while some of the DHH signing children in our study do have experience with sound and spoken language (as seen from their variable OWLS-II scores and hearing levels), it seems that their sign language proficiency is the relevant factor in predicting temporal sequencing abilities. We observed significant correlations between indices of ASL receptive skills and comprehension and maximum spans on the Simon tasks. Indeed, linear regression models that included age and NVIQ as covariates revealed that, largely, these ASL measures were significant predictors of Simon task performance. ASL measures predicted performance on the random-sequence conditions more consistently than the repeated-sequence conditions, which might signify a greater role of language knowledge in visual sequence memory processing than sequence learning. It also might simply reflect the success of different strategies children utilized for remembering sequences in the (more difficult) random-sequence tasks than for remembering the single sequence in the (easier) repeated-sequence tasks. In all, within-group comparisons of the DHH signing children in this study seem to support a role of signed language proficiency in visual sequential processing, although this is not evidence that a *lack* of signed language access will specifically cause sequence processing deficits.

The predictive power of ASL measures on nonlinguistic sequence processing tasks, and the assertion that cognitive deficits observed in DHH children are due to lack of experience with language, might be surprising as one may expect the deficits to be observed only on tasks where language can be employed, such as when the stimuli can be encoded with a verbal label to facilitate task performance. However, a number of studies have shown sequencing deficits in children who are DHH on tasks that are nonlinguistic (and non-auditory) in nature (e.g., Bharadwaj et al., 2012; Bharadwaj & Mehta, 2016; Conway et al., 2020; Levesque et al., 2014; Ulanet et al., 2014). Such findings suggest that either the nature of the problem is not language per se, or that a lack of access to language during sensitive periods in development results in cognitive deficits that extend well beyond the linguistic domain.

If temporal sequence processing deficits do exist in DHH oral children, but not DHH or hearing children who have had early and rich language access, there is a need to address exactly what it is about early access to natural language that supports the processing of temporal sequences. One answer may lie in the hierarchical and temporal structure of language itself. That is, language may represent a stimulus that provides unique challenges to the developing nervous system, allowing that system to represent and manipulate hierarchical and temporally structured representations in non-linguistic domains. However, such a hypothesis might reasonably predict that acquisition of a spoken language may be more advantageous for the development of sequential processing ability than is acquisition of a signed language. This would arise from the divergent properties of each language’s structure, leading to different processing demands. ASL utilizes less sequential structure and more spatial structure than spoken languages, which rely much more heavily on temporal sequences (Wilbur, 2008; Wilson & Emmorey, 1997). While signed languages do involve substantial temporal structure (Braem, 1999), the temporal processing demands of signed languages may be lower than for spoken languages. This disparity in cognitive demands can affect general cognitive processing, such as short-term memory. In hearing English-ASL bilinguals, spoken English digit span tasks result in better performance (larger spans) than span tasks performed using ASL, indicating that temporal encoding is the predominant process used in the former, compared to spatial encoding in the latter (Boutla et al., 2004; Emmorey & Wilson, 2004).

An alternative account may focus less upon the language itself and more upon the environment in which language is acquired. A recent proposal has stressed the importance of intersubjectivity during critical periods in development for the successful acquisition of language and the promotion of healthy cognition (Morgan & Dye, 2020). Under this account, it is the reciprocal interactions between parents and their children, facilitated by mutually accessible communication that leads to the development of mimicry, joint attention, and the successful emergence of executive functions to support a range of attentional and cognitive abilities. This account also deemphasizes the role of language’s temporal structure, which would explain why DHH children who sign and hearing children who speak did not differ in their temporal sequence learning abilities, despite the divergent temporal structures of ASL and English. The importance of the early communicative environment to later language and cognitive outcomes in DHH children has also been discussed in recent papers (see Kronenberger & Pisoni, 2020) and was alluded to in Conway et al. (2009), but those papers assume that such experience can only begin to occur post-implantation, since they focus on oral/auditory communication.

Prior sequential processing studies cited above have been conducted either with DHH children who communicate in the oral modality with the assistance of hearing aids or cochlear implants (e.g., Conway et al. 2011; Gremp et al. 2019) or with DHH children who are born to DHH parents (e.g., Dye & Hauser, 2014; Hall et al. 2017). Similarly, the majority of DHH children in this study (62 out of 77) had DHH parents. There is a clear need for further research on the role, if any, of visual reciprocal communication between DHH children and their hearing parents in fostering the development of cognitive skills such as sequential processing. Concerns that the positive outcomes experienced by DHH children born to DHH parents have no practical relevance to understanding how to treat DHH children born to hearing parents are unfounded in consideration of accounts that emphasize early parent–child intersubjectivity rather than temporal structure (of language or audition). While hearing parents might not be able to achieve *immediate* fluency in a signed language upon the birth of their DHH child, with appropriate resources and education there is no reason to doubt their capacity to provide a sufficient communicative environment in the visual modality for their growing DHH child, with or without the aid of amplification devices (see Morgan & Dye, 2020, for more discussion). Indeed, a recent study has demonstrated that DHH children with hearing parents are able to develop age-appropriate sign language abilities if exposed early enough (Caselli et al., 2021). It is also important to note that there are other differences between DHH children from deaf families and those from hearing families, including factors such as reported parental stress (Jean et al., 2018; Meinzen-Durr et al., 2008; Wiseman et al., 2021; although see also Blank et al., 2020 and Dirks et al., 2016, for reports of similar stress in parents of children with and without hearing loss which suggest a complex set of factors surrounding parent-reported stress in families with deaf children) and differences in etiology of deafness that have been suggested to affect behavioral and cognitive outcomes (Hauser et al., 2006; King et al., 1998).

To recap, in this study we show that DHH children who acquired ASL as a first language demonstrate visual sequence processing abilities on a par with their hearing peers. Thus, while similar to DHH children who use cochlear implants and learn spoken language in terms of their lack of access to sound early in development, DHH children who use ASL as a first language do not show the same pattern of deficits observed in DHH children who are exposed to spoken language. This suggests that the underlying cause of observed sequence processing deficits in DHH children with cochlear implants (or hearing aids) is not a lack of access to sound and/or spoken language. We also show that signed language proficiency predicts sequence processing abilities in DHH signing children; however, such a relationship is not evidence for any sequence processing deficits which might arise from deafness or a lack of language exposure. Because sequence processing is likely composed of multiple subcomponents and can be measured in many different ways (Arciuli & Conway, 2018), it is necessary to examine performance on a variety of additional sequencing tasks (such as those incorporating more complex sequential patterns) and with children with varying degrees of hearing and language experiences to fully understand how temporal sequencing deficits might arise. Critically, there is a need to study how early *visual*, rather than auditory, communicative experiences of DHH children with hearing parents might affect their later sequence processing skills. Nevertheless, the data from signing DHH children reported here indicate that hearing loss per se does not result in deficits in visual sequence processing, and that the more proficient a child is with a natural sign language, the better their visual sequencing abilities.

Supplementary Data

Supplementary material is available at *Journal of Deaf Studies and Deaf Education*.

Author Contributions

The tasks were designed by CMC; the study was devised by MWGD and CMC; data collection was done by BTC; statistical analysis was performed by MWGD and BTC; the manuscript was prepared and submitted by BTC, CMC and MWGD.

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Conflicts of Interest

No conflict of interest was reported.

Endnotes

[i] The term monochrome is used for accuracy, whereas Gremp et al. (2019) used the term unnameable. It is important to note that stimuli in these conditions were simply harder to linguistically label. Likewise, the term nameable denotes stimuli which would be easier to label with names of colors or cardinal directions, but do not explicitly encourage a verbal labeling strategy nor do they contain explicit linguistic stimuli. Here we use the label colored for these stimuli.

[ii] While total-communication incorporates visual communication in service of augmenting spoken language learning, such methods lack the natural, structured grammar of ASL; the visual aspect of total-communication is inconsistent and does not exist as a standalone communication system, nor does it incorporate the facial expressions and torso movements essential to communication in all sign languages.

[iii] Several other tasks were administered as part of a larger project with the deaf children, necessitating two sessions. For the hearing children, all testing took place in a single session with the order of test administration counterbalanced within that session.

[iv] Hearing children did not receive the sign language assessments, and the spoken language assessment was counterbalanced within the session along with the attention and cognition measures.

[v] Since higher PTA values signify lower hearing levels, this correlation translates to a better listening comprehension being associated with higher hearing levels.

[vi] The $2 \times 2 \times 2$ linear mixed model was repeated excluding any DHH child who reported continued use of HAs or CIs. The pattern of significant results did not change—see Supplementary Materials.

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