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RESEARCH ARTICLE

Visual statistical learning in deaf and hearing infants and toddlers

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Abstract

Congenital hearing loss offers a unique opportunity to examine the role of sound in cognitive, social, and linguistic development. Children with hearing loss demonstrate atypical performance across a range of general cognitive skills. For instance, research has shown that deaf school-age children underperform on visual statistical learning (VSL) tasks. However, the evidence for these deficits has been challenged, with mixed findings emerging in recent years. Here, we used a novel approach to examine VSL in the action domain early in development. We compared learning between deaf and hearing infants, prior to cochlear implantation (pre-CI), and a group of toddlers post implantation (post-CI). Findings revealed a significant difference between deaf and hearing infants pre-CI, with evidence for learning only in the hearing infants. However, there were no significant group differences between deaf and hearing toddlers post-CI, with both groups demonstrating learning. Further, VSL performance was positively correlated with language scores for the deaf toddlers, adding to the body of evidence suggesting that statistical learning is associated with language abilities. We discuss these findings in the context of previous evidence for group differences in VSL skills, and the role that auditory experiences play in infant cognitive development.

1 | INTRODUCTION

Infants and toddlers spend most of their waking hours actively exploring their environment, as they observe the world with fascination and experience the sights and sounds of their own motor actions. These early sensory experiences guide the normal development of social and cognitive skills. Atypical development in one sensory modality can therefore have profound consequences for other sensory and cognitive functions. For instance, children with hearing loss demonstrate differences in performance across a range of domain-general cognitive tasks, including habituation (Monroy, Shafto, et al., 2019), attention (Dye et al., 2009), memory (Pisoni et al., 2016), sequence processing (Bharadwaj & Mehta, 2016), and statistical learning (Conway et al., 2011).

Statistical learning is a learning mechanism that is considered foundational to infant cognitive development. From the first days of life, infants are sensitive to the regularities in their environment and can detect statistical associations between syllables (Saffran et al., 1996), visual shapes (Kirkham et al., 2002), movement sequences (Stahl et al., 2014), and human actions (Monroy et al., 2017). These skills are thought to be an important mechanism through which young infants begin to construct a model of their environment (Saffran & Kirkham, 2018). A substantial body of research with typically developing infants suggests that SL mechanisms directly contribute to language acquisition, allowing infants to recognize statistical regularities within natural speech and predict upcoming sounds (Pelucchi et al., 2009). Evidence for this link comes from studies showing a positive association between domain-general statistical learning skills and language development. For instance, performance on a visual statistical learning (VSL) task in 6-month-old infants was shown to predict receptive and expressive vocabulary size at 22 months, regardless of maternal speech quality and general cognitive ability (Ellis et al., 2014). In another study, VSL performance—but not an explicit test of word learning—was also shown to predict grammar abilities in children (Kidd, 2012). These findings are examples of the body of evidence suggesting that domain-general SL mechanisms form a core component of language learning (Deocampo et al., 2018).

A few studies have provided evidence for differences in VSL in children with hearing loss, relative to their peers with normal hearing. Conway et al. (2011) tested implicit visual sequence learning in 5–10 year old deaf children with cochlear implants (CIs) and found no evidence for learning, while an age-matched group of hearing children did show learning. Their study featured a standard implicit learning task, in which participants are shown spatiotemporal sequences of colored shapes on a screen and are asked to replicate the sequences. In a more recent study, Gremp et al. (2019) implemented a serial repetition learning paradigm and also found better performance in hearing children compared to children with hearing loss (5–11-year-olds[1]).

To explain these findings, Conway et al. (2009) proposed the *auditory scaffolding hypothesis*. This hypothesis proposes that infants with congenital hearing loss, who have no access to sound at birth, experience delays in domain-general statistical learning mechanisms that may spread to other cognitive domains. Specifically, sound is a temporally organized signal that provides critical sensory input for the normal development of sequence processing abilities. In other words, sound enters our auditory system as a transitory sequence of acoustic frequencies—as opposed to vision, which is spatiotemporal—that facilitates the brain's general ability to process and learn sequential information. Delayed access to sound interferes with the development of this ability, disrupting other abilities that depend on sequence processing. These include (visual) statistical learning, working memory, language

[1] In their sample, groups were not matched on age. Their hearing loss group also included both children with cochlear implants and children with hearing aids.

acquisition, and even motor skills. Additional evidence for this hypothesis comes from Bharadwaj and Mehta (2016), who examined visual sequence processing in children with CIs, and Horn et al. (2006) who reported lower performance among children with CIs on a motor sequencing task.

Other researchers have not been able to replicate the findings of Conway and colleagues. Torkildsen et al. (2018) compared learning in 7–12-year-old children with CIs and children with normal hearing and found no differences between the two groups on a standard VSL task. These researchers suggest that the observed inconsistences among these experimental findings may be due to task differences. Specifically, the VSL paradigms used in each study differed in the extent to which participants could recruit verbal rehearsal strategies, which are expected to be harder for children with hearing loss. Another study by Hall et al. (2017) compared VSL between three groups: deaf native ASL signers, deaf children with CIs, and hearing children. They found no group differences across two VSL tasks, claiming evidence against the auditory scaffolding hypothesis. However, participants in Hall et al. (2017) failed to learn at all, suggesting that there are methodological differences in how the SL task was implemented in this study. Both studies (Hall et al., 2017; von Koss Torkildsen et al., 2018) suffer from substantial methodological limitations that undermine the strength of their evidence in understanding the role of auditory experience in VSL development and highlight the need for additional research (for further discussion see Deocampo et al., 2018).

One important limitation of the current body of research on VSL in the deaf population is that it has focused on school-age children from a wide age range (e.g., 5–10 years of age in both the Conway et al. and von Koss Torkildsen et al., 2018 studies). No study has examined VSL early in life, even though statistical learning has been documented from birth (Teinonen et al., 2009). As a result, it remains unknown whether the previously observed differences between deaf and hearing children emerge prior to cochlear implantation (CI), as the *auditory scaffolding hypothesis* would predict, or whether they emerge later in childhood after years of divergent auditory and language experiences. To address this limitation, the current study tested VSL in deaf infants (pre-CI) and deaf toddlers (post-CI) with profound bilateral sensorineural hearing loss and age-matched peers with normal hearing.

To assess VSL in young infants and toddlers, we developed a novel paradigm in which participants observed an experimenter demonstrating a live action sequence. Our primary aim was to compare learning performance in real time between deaf and hearing infants (Siegelman et al., 2018). Therefore, we designed the action sequence to feature a very simple statistical structure, to maximize the likelihood that learning would occur. Participants observed the experimenter perform a repeating three-step action sequence with three novel objects. We recorded and analyzed anticipatory gaze latencies to the action steps. We expected gaze shifts to each step to become faster over the course of the demonstration, as both infants and toddlers have been shown to track statistical regularities within action sequences and predict upcoming actions (Monroy, Gerson et al., 2019; Monroy et al., 2017). Based on the findings of Conway et al. (2011), we would expect deaf toddlers (post-CI) to demonstrate weaker learning than toddlers with normal hearing. If the auditory scaffolding hypothesis is correct, we would also expect to observe weaker learning in deaf infants (pre-CI) compared to hearing infants.

To obtain a sensitive measure of learning, it was crucial to only include gaze data when infants were attentive to the demonstration. As infants are known to look away or decrease their looking times when they habituate to a stimulus (Fantz, 1964), it was important to exclude data points that occurred after the infant habituated to the demonstration and was no longer engaged with the task. Habituation has traditionally been assessed by using a 50% decrement criterion, in which the infants' first three trials are averaged and the criterion is reached when a subsequent window of three trials has an average that falls below 50% of the initial average (Oakes, 2010). However, Thomas and Gilmore (2004) established a model-based alternative approach to quantify the habituation behavior of individual infants, which formalizes the theoretical assumptions that underlie habituation and are agreed upon by most researchers. We implemented this model-based approach to identify a habituation threshold for each infant, and then included only the trials prior to habituation in our analysis of gaze latencies (Fassbender et al., 2012, 2014; Teubert et al., 2012; see also Oakes, 2010 for a discussion of best practices in habituation methodology). These trials were then analyzed to assess whether deaf and hearing infants and toddlers differed in the extent to which they demonstrated learning, as evidenced by a decrease in gaze latencies over the course of the action sequence (Kayhan et al., 2019). The data presented in the study and analysis files are available at https://osf.io/u8k29.

2 | METHOD

2.1 | Participants

2.1.1 | Deaf participants

Deaf infants and toddlers were diagnosed with bilateral severe-to-profound sensorineural hearing loss. All infants were scheduled to receive a CI and all toddlers had received a CI before 18 months of age. All parents of deaf participants had self-reported normal hearing, and families indicated a goal of spoken language acquisition for their child. Our final sample consisted of eight infants and 10 toddlers[2]; see Table 1 for characteristics. The etiology of hearing loss ranged from Connexin 29 ($n = 1$), a diagnosis of Noonan syndrome ($n = 1$), a diagnosis of EVA (enlarged vestibular aqueduct; $n = 1$), or genetic causes ($n = 2$). For the rest of the deaf participants ($n = 8$), the etiology of hearing loss was unknown.

2.1.2 | Hearing participants

Each participant in the deaf group was matched as closely as possible to a participant with normal hearing based on developmental age and gender (+/− 1 week, see Table 1).[3] All hearing participants passed a newborn hearing screening, had no history of recurrent acute or chronic otitis media (ear infections), and had no known developmental delays. This study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from parents of all participants prior to enrollment in the study. The study was approved by the Institutional Review Board committee of The Ohio State University.

2.2 | Procedure

Infants were seated in a child-size chair at a small table (61 × 91 × 64 cm). Infants were fitted with a mobile eye-tracker (Positive Science, Inc), which has an infrared camera directed toward the right eye and a head camera that records 90° of the visual field. Two additional cameras recorded third-person views of both the infant and the experimenter. All cameras recorded at 30 Hz and were synchronized

[2] Two deaf toddlers were tested but were excluded from the eyetracking analyses because we were not able to find and test age-matched peers, as testing in our lab was interrupted due to the Covid-19 pandemic. These toddlers were included in the correlation analyses between VSL and language (see Section 3.3).

[3] We matched infants based on their due date rather than their birth date, as some deaf infants were born earlier then their hearing counterparts.

TABLE 1 Participant characteristics

	M	SD	Range
Deaf infants ($n = 8$, n_{male} = fv 8)			
Age at test (months)	11.11	2.34	8.1–15.13
Age at CI activation	11.69	2.25	8.6–15.7
Hearing infants ($n = 8$, $n_{male} = 7$)			
Age at test	11.20	2.37	7.57–14.83
Deaf toddlers ($n = 10$, $n_{male} = 5$)			
Age at test	19.98	3.87	14.27–25.27
Age at CI activation	12.12	2.34	8.1–15.7
Hearing age	8.05	2.56	5.33–12.20
Hearing toddlers ($n = 10$, $n_{male} = 6$)			
Age at test	20.05	3.73	13.97–25.40

Note: Hearing age refers to how long the child had been experiencing access to sound, that is, the difference between age at CI activation and the date of the test.

offline using ffmpeg (https://ffmpeg.org). To calibrate the eye-trackers, an experimenter drew infants' attention by directing a laser pointer toward nine unique locations on the tabletop. These moments were used to calibrate eye gaze relative to the head camera recording offline using Yarbus software (Positive Science, Inc). Yarbus uses an algorithm to map each position of the pupil and corneal reflection from the eye-tracker recording to corresponding locations in the head camera recording. This yields a calibrated video with the estimated direction of gaze indicated by a crosshair and superimposed on the head camera recording.

Following calibration, the experimenter performed an action sequence involving three unique toys with distinct affordances: a red ball with a tassel that was squeezed, a green jar that was shaken, and a blue wooden rattle that was rattled. The experimenter would act on (e.g., squeeze, shake, or rattle), and then return each toy to the same original location with her right hand in a repeating three-step, deterministic spatiotemporal sequence (Figure 1). Between each action, the experimenter's hand returned to a neutral position underneath the table. The demonstration was repeated until participants became fussy (e.g., started crying, attempted to escape from their chair) or a maximum of 30 individual actions. The sequence order was always the same, so that any bias to the central object would be consistent across all infants.

2.3 | Data coding

Infant gaze was coded frame-by-frame by a trained coder who was blind to the participant's hearing status. The coder used still frames that were exported from the calibrated gaze video to annotate, for every frame, whether the infant's gaze fell on one of four regions of interest (ROI) and, if so, which ROI: the three toys or the experimenter's face. Saccades—when the eye was moving from one location to another—were not coded. Therefore, each participant yielded two data streams for infant gaze and experimenter actions, respectively, as shown in Figure 1. A second coder annotated all frames from 50% of all participants. Reliability was calculated by dividing the number of frames for which the two coders assigned the same ROI out of the total number of frames to yield a percentage of agreement, which ranged from 83% to 100% of frames (mean = 91.50%).

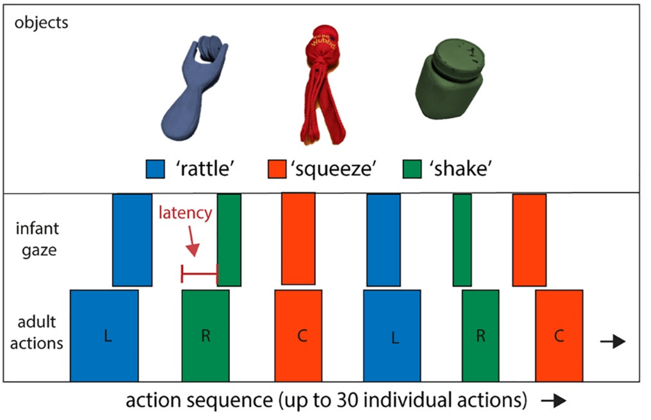

FIGURE 1 Top: Objects/actions used in the experiment. Bottom: Example visualization of the synchronized data streams from the child eye-tracker (upper row) and the experimenter actions (lower row). '*L*', '*R*', and '*C*' indicate the position on the table of the respective objects. Anticipatory gaze latencies were calculated by subtracting the onset of a child gaze fixation from the moment the experimenter's hand reached the object

Another trained coder used frames from the infant head camera images and the two third-person view cameras to code the experimenter's actions for the frames during which the experimenter was reaching for each of the three objects. The second coder annotated 25% of participants, with reliability ranging from 92% to 97% (mean = 95.07%).

2.4 | Habituation

Prior to assessing whether participants learned the sequence, our first step was to identify a habituation criterion for each individual infant. Looking times during each trial were averaged over a sliding window of three trials (Oakes, 2010). Mean looking times for each window were entered into a nonlinear regression model, given by

$$E(Y|b) = \propto + \beta \exp\left[-\delta(b-1)^2\right]$$

which is model 3 in Thomas and Gilmore (2004). The parameters α, β, and δ reflect features of infant attention and are illustrated in Figure 2. The parameter α represents the infants' shortest looking time; β represents the maximum change in looking time, or the width of their looking time function; δ represents their rate of decline in looking time and can range from zero to one. Parameter estimates used least squares methods, implemented in Matlab 2019b (Mathworks, Inc) using the curve-fitting toolbox. After fitting the model to each individual infant's looking times, we defined the habituation threshold as the *settling time*, which is commonly defined as the time it takes for the error between the response and the steady-state response to fall within 2% of the final response (i.e., indicated by the arrow in Figure 2; Franklin et al., 2014). Trials occurring after the settling time were excluded from further analyses.

2.5 | Anticipatory gaze

After filtering infant gaze data based on habituation thresholds, the two data streams from infant gaze and experimenter reaching were aligned (Figure 1). Gaze fixations were offset by 200 ms to account

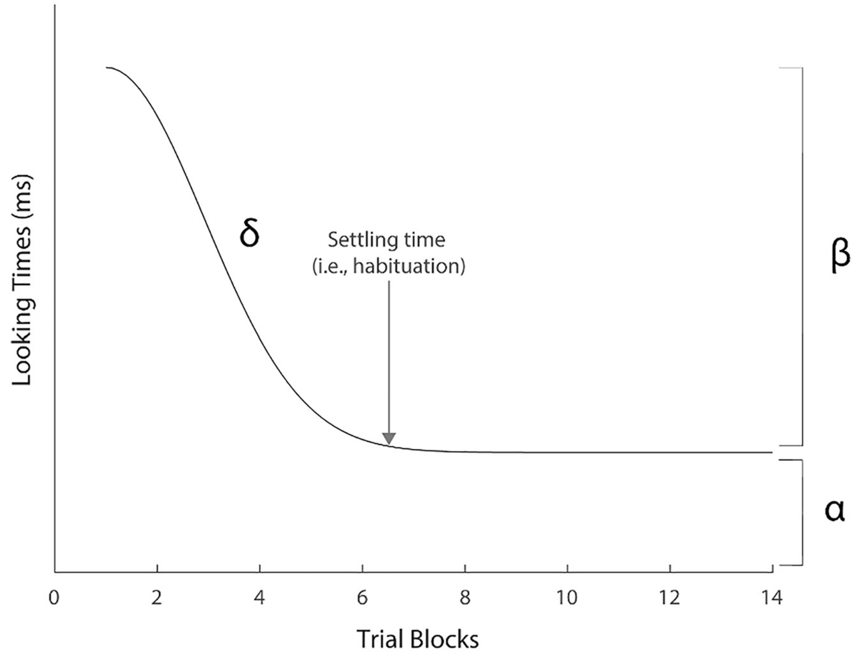

FIGURE 2 A hypothetical fitted function, with estimates for α, β, and δ. Individual infant looking time data were fitted to this function to determine when each infant habituated to the action demonstration

for the processing time of the oculomotor system (Gredebäck et al., 2010). Gaze latencies on each trial were calculated by taking the difference between the onset of a fixation to an object and the moment the experimenter's hand reached that object. As before, gaze latencies were averaged over a sliding window of three trials.

2.6 | Language measures

Preschool Language Scales (PLS-5), a standard test of oral receptive and expressive language, was administered to the deaf toddlers by a speech-language pathologist as part of their routine clinical care. PLS-5 is not administered to pre-CI infants, because prior to gaining access to sound, deaf infants have not yet experienced sufficient opportunity to develop any oral language. PLS-5 standard (age-normed) scores for auditory comprehension, expressive communication, and total language were collected from the clinical visit corresponding to the time of the experimental session.

3 | RESULTS

3.1 | Infants

Gaze latencies were analyzed with linear mixed-effect models using the R package *lme4* (Bates et al., 2015), separately for infants and toddlers. Each model included fixed effects of trial (1–30), group (1 = deaf, 2 = hearing), an interaction term of trial*group, and a random intercept for participant. The full model, fitted with the complete structure, was translated to *lmer(latency ~ group + trial + trial*group + (1|subject), data = data)*. Results from the *summary()* function for both models are reported in Table 2.

For infants, the critical interaction between trial and group was significant, $\chi^2(1, n = 323 \text{ observations}) = 10.89$, $p < .001$; Figure 3. We followed up on this interaction effect in two ways. First, we conducted a pairwise comparison with the R package *emmeans*(), with group as the predictor variable. This confirmed a significant difference between deaf and hearing infants across all trials (estimate = 467 ms, $t(13.9) = 3.563$, $p = .003$), indicating a pattern of faster gaze latencies for the hearing group compared to the deaf group. Across groups, gaze latencies did not significantly change over trials ($p = .82$). To quantify the relative strength of this model, we calculated Bayes factor using the R package *BayesFactor*, which indicated that there is "strong" evidence in favor of the alternative hypothesis (BF = 25.04 ± 1.36%; Jeffreys, 1961).

Secondly, to determine whether learning occurred in one group but not the other, we ran separate models for each group with trial as a fixed effect and participant as a random effect. For the hearing infants, the model revealed a significant effect of trial (estimate = −18.47 ms, $\chi^2(1, n = 190) = 36.95$, $p < .0001$) indicating that gaze became faster over the course of the action sequence. For the deaf infants, the model showed no effect of trial (estimate = .17 ms, $\chi^2(1, n = 133) = .001$, $p = .98$) indicating no change in gaze latencies over trials. In sum, these findings reveal evidence for VSL in the hearing infants but not in the deaf infants.

The function powerSim in the R package simr was used to calculate observed power. The estimated models in Table 2 were used as the assumed effect sizes, and 10,000 simulations were used to determine the power of the likelihood ratio test to detect significant effects at the 5% significance level. For the group*trial interaction in the infant data, the power is estimated to be 90.8% with the current sample size of 16 infants.

3.2 | Toddlers

For toddlers, the interaction between trial and group was not significant ($p = 0.40$), indicating a similar decrease in gaze latencies over the course of the action sequence for deaf and hearing toddlers (Figure 4). A main effect of trial indicated that gaze latencies became faster over trials across groups ($\chi^2(1, n = 455 \text{ observations}) = 5.36$, $p = .02$). Across trials, the difference in gaze latencies between groups was not significant, $p = .99$. These findings reveal evidence for learning in both groups, with no differences between groups. A Bayes factor analysis indicated "moderate" evidence in favor of the *null* hypothesis (BF = .26 ± 4.45%; Jeffreys, 1961).

TABLE 2 Linear mixed-effects model predicting gaze latencies

Fixed effects	Estimate	SE	*t*	*p*
Infants				
Trial	1.07	4.68	.23	.82
Group	−220.88	144.40	−1.538	.14
Trial*group	**−19.37**	**5.87**	**−3.3**	**.001****
Toddlers				
Trial	**−9.05**	**3.91**	**−2.32**	**.02***
Group	1.39	122.425	.01	.99
Trial*group	4.99	5.96	−.84	.40

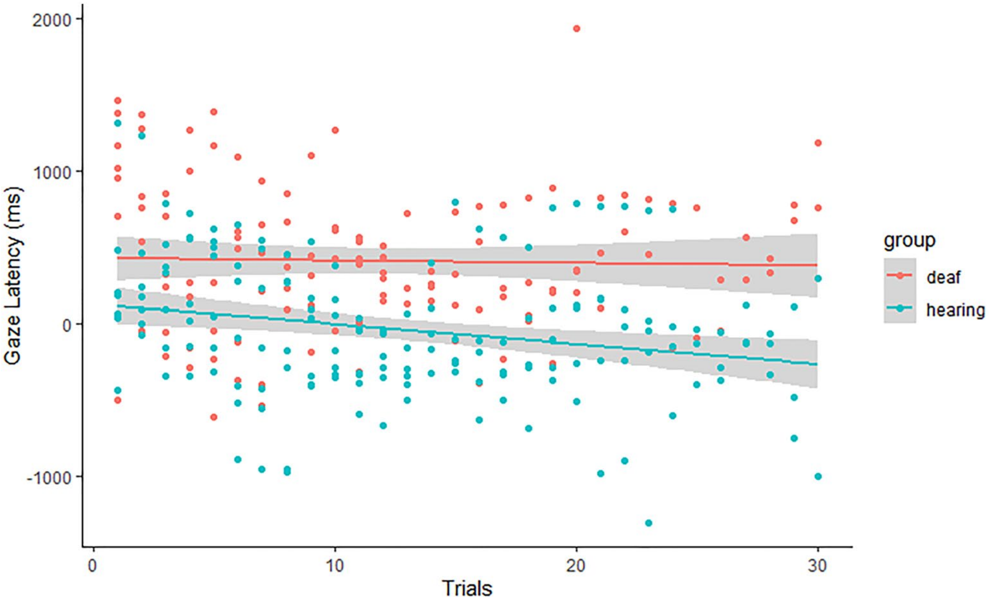

FIGURE 3 Scatterplot showing gaze latencies across trials for individual infants, plotted with a best-fitting linear regression line. Shaded regions indicate standard deviations

For deaf participants, a correlation analysis revealed a significant correlation between learning (mean difference in RTs) and age at activation ($r = .74$, $p = .004$, CI = [.32–.92]). Toddlers who were activated earlier showed stronger learning effects than toddlers who were activated later. However, there was no correlation with hearing age ($p = .40$): at the time of testing, toddlers with longer experience with their CIs did not differ significantly from toddlers with less CI experience. Across all participants (deaf and hearing), there were no correlations between learning and chronological age in either infants ($p = 0.15$) or toddlers ($p = .15$).

3.3 | Correlations with language scores

The mean PLS-5 standard score across deaf toddlers was 89.7 for auditory comprehension (range = 63–117), 91.1 for expressive communication (range = 69–113), and 89.9 for total language score (range = 67–116). Mean scores are within 1 SD of age norms for hearing age-matches (85 or higher), though several toddlers were below average. To assess whether performance on the VSL task was associated with language growth for the deaf participants, we conducted a correlation analysis between PLS-5 scores and the mean change in gaze latencies over trials. Mean change in gaze latencies was calculated by averaging across the difference between all adjacent trials to produce one learning score for each child:

$$\text{mean}\left((t_2 - t_1), (t_3 - t_2) \ldots (t_i - t_{i-1})\right)$$

with t representing a given trial and i representing the total number of trials for a given participant. This analysis revealed a significant correlation between VSL and all three language subscales of the PLS-5 (Table 3). Toddlers who demonstrated stronger learning (i.e., average change in gaze latency i.e., more negative, indicating a steeper slope) also had higher standardized language scores (Figure 5).

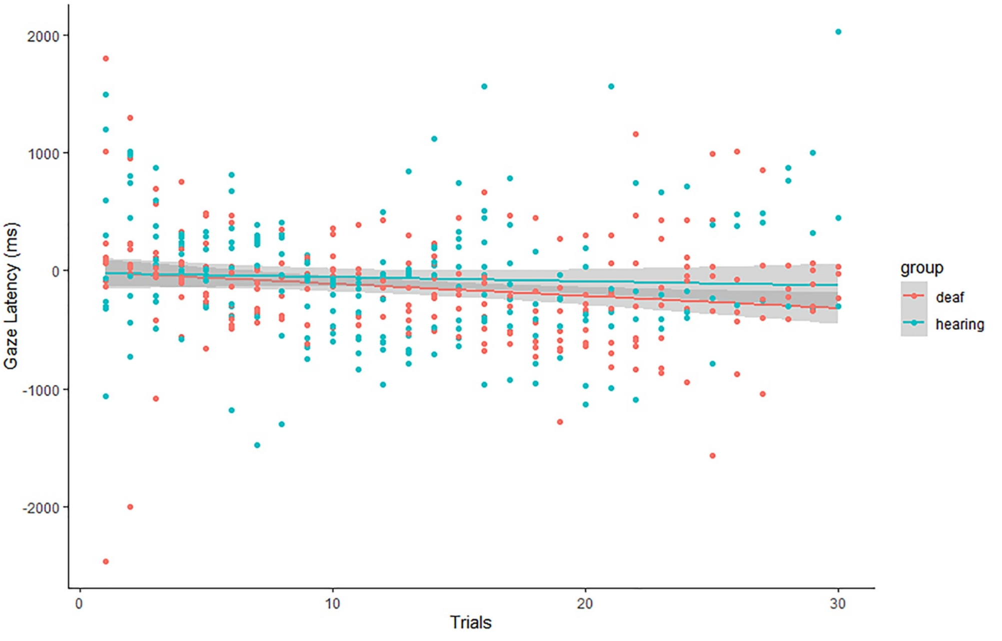

FIGURE 4 Scatterplot showing gaze latencies across trials for individual toddlers, plotted with a best-fitting linear regression line. Shaded regions indicate standard deviations

TABLE 3 Correlations between PLS-5 scores and VSL

	Auditory comprehension	Expressive communication	Total language
r	−.810**	−.690*	−.79**
p	.003	.02	.004
N	11	11	11

Note: ***p* < .01 level, **p* < .05 level.

3.4 | Habituation

Finally, we compared the number of trials it took to habituate for deaf and hearing participants, separately for each age group. For infants, there was no significant difference in the number of habituation trials ($p = .14$). There was also no difference in the number of trials for the toddlers ($p = 0.71$). This also means that there was no difference in the numbers of included trials between groups at both ages. There were no correlations between habituation and learning (mean difference in RT) for infants ($p = 0.09$) or for toddlers ($p = .65$).

4 | DISCUSSION

The current study investigated VSL in infants and toddlers with and without hearing loss. Participants observed a live demonstration of a continuous, three-step action sequence with novel objects. We analyzed the change in gaze latencies to action steps over the course of the demonstration as an index of learning. We found evidence for learning in both the hearing toddlers and the deaf toddlers (who have cochlear implants), with no differences between the groups. We also found that age at implan-

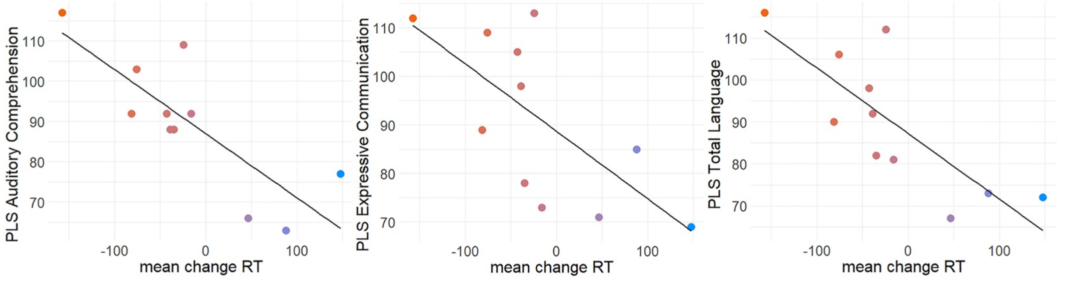

FIGURE 5 Scatterplot depicting the correlations between VSL (the mean change in latencies over trials) and language scores for the deaf toddlers

tation was associated with learning for the deaf toddlers. However, learning differed significantly between hearing infants and deaf infants (tested prior to cochlear implantation). Our findings shed new light on the mixed body of evidence demonstrating deficits in VSL in deaf children. Unlike prior work, which has focused on broad age ranges of school-age children, we included prelingual deaf infants—who have experienced no functional auditory input and limited language input—and deaf toddlers, who have between 6 and 12 months of hearing experience with their cochlear implants.

One interpretation of this pattern of findings is through the auditory scaffolding hypothesis. This hypothesis posits that early experience with sound stimuli is important for the normal development of domain-general statistical learning skills through one of two potential mechanisms: first, sound (a temporally ordered signal) draws attention to the statistical structure in continuous sequences. The second possible mechanism is that sound uniquely provides domain-general information about sequential order and temporal change, which can only be accessed through hearing (Conway et al., 2009). Either way, this auditory input activates cortical processes in frontal and temporal brain regions that become reorganized in infants with hearing loss. Consistent with this hypothesis, we found no evidence for learning only in the deaf infants, who have had no meaningful experience with sound in their lives thus far. All other participants—hearing infants, toddlers with cochlear implants, and hearing toddlers—have experienced some degree of access to auditory signals and all demonstrated learning.

This interpretation may suggest that the 6–12 months of auditory experience through a cochlear implant could be sufficient to reverse the cortical reorganization resulting from deafness and affecting VSL development. Given that no VSL differences were found in the toddlers, another possibility is that deaf toddlers have acquired compensatory strategies rather than a reversal of cortical reorganization. Though there have been no studies examining cortical reorganization following cochlear implantation in human infants, evidence from animal studies suggests that early-implanted animals show rapid cortical reorganization within a few months after cochlear implantation (Kral & Sharma, 2012). In one case study, a child with single-sided deafness showed dramatic morphological changes and cortical activation between 6 and 8 months post-implantation of her deaf ear, even though the child was 9 years old when she received her implant (Sharma et al., 2016; see also Polonenko et al., 2017 for a similar finding). This finding is also consistent with another recent study showing that three-year-old implanted children demonstrate age-appropriate cortical responses to auditory stimuli by 8 months post-implantation (Sharma et al., 2002). Taken together, there is strong evidence to suggest that cortical reorganization following early cochlear implantation is characterized by dramatic changes in neural pathways. Our findings raise the question of whether these changes also include the pathways involved in visual processing and domain-general learning mechanisms, an open question for future electrophysiology and neuroimaging research.

Our findings cannot rule out the possibility that it could be language that affects the development of general learning mechanisms like VSL, rather than sound. In a paper describing the *language scaffolding hypothesis*, Hall et al. (2017) argues that "the development of implicit learning skills may depend less on the temporal and linear structure of sound and more on the temporal, hierarchical, and inherently social structure of language" (p. 3). Although these authors focus on *implicit* and not *statistical* learning skills—which have been treated as separate in the literature (though see Perruchet & Pacton, 2006 for an interesting discussion on this)—it is nevertheless possible that language deprivation could negatively affect the development of statistical learning skills. There is a strong body of evidence showing statistical learning skills are predictive of language ability (Arciuli & Simpson, 2012; Kidd & Arciuli, 2016; Romberg & Saffran, 2010; Shafto et al., 2012; Spencer et al., 2015), and in the current study we also found correlations between language and learning ability. On the other hand, established theories of statistical learning maintain that it is the general ability to detect structure in the environment that facilitates the acquisition of language. For instance, the seminal study by Saffran et al. (1996) showed that preverbal infants segment continuous syllable sequences into distinct units based (only) on transitional probabilities, and proposed that this ability is a necessary precursor to being able to learn words. Statistical learning abilities have been demonstrated even in newborns (Teinonen et al., 2009), suggesting that these skills emerge from the earliest moments of life. In sum, there is strong evidence to suggest that statistical learning skills drive language acquisition, rather than language acquisition driving the development of statistical learning skills. Still, in the current study, we cannot conclusively say whether the failure to learn in the deaf infants can be attributed to lack of auditory or language experiences. This question will need to be answered in future research, possibly by using neuroimaging approaches to examine the specific neurocognitive mechanisms involved during learning (e.g., Cortesa et al., 2019).

Our paradigm differed in several important ways from prior research. First, we identified a habituation threshold for each individual infant based on the model-based method from Thomas and Gilmore (2004). We then used that habituation threshold to exclude data collected after the infant or toddler had already habituated to the stimuli, thus ensuring that the data we analyzed reflected infant behavior while they were attentive and engaged with the task. Prior research has not addressed the issue of inattentiveness while measuring online learning in VSL tasks. For instance, the only other study we know of that attempted to measure VSL in infants was Shafto et al. (2012), who found no evidence for learning across all participants and explained this pattern as resulting from large variability among infants, with some infants demonstrating learning but others becoming bored and making progressively slower gaze shifts. While we may not have fully eliminated all behaviors reflecting boredom or fatigue, our approach provided a more sensitive measure of learning and allowed us to examine learning in real time as it unfolded. In contrast, past research has typically relied on comparing gaze behavior between learning and test phases to determine whether learning has taken place.

A second way is which our paradigm differed substantially from past research is the choice to use live action stimuli, rather than abstract computer stimuli like colored shapes (Shafto et al., 2012) or squares (Conway et al., 2011). Recently, it had been shown that infants rapidly learn the statistical structure of actions, as they do for statistic visual or auditory stimuli, and that their learning involves encoding a representation of the action itself and not simply the target object of the action (Monroy et al., 2017). Learning action sequences has also been shown to activate the motor system in infants and adults (Ahlheim et al., 2014; Monroy, Meyer et al., 2019), suggesting that there may be additional mechanisms involved in statistical learning of action stimuli that differ from those involved in static visual stimuli. An interesting question for future research is whether the motor system is also affected by hearing loss and could have played a role in pattern of observed findings. Another possible explanation is that the lack of access to the action-effects (i.e., the sounds that each toy naturally made when manipulated) could explain the lack of learning that was only observed in the deaf infant group. Although infants can learn statistical information in action sequences in the absence of any additional cues or sound effects (Monroy et al., 2017; Stahl et al., 2014), other research has shown that contingent action-effects help infants and toddlers process observed actions (Adam & Elsner, 2020). Deaf infants may notice less about actions in which the auditory effects are not perceived, compared with infants who do have access to these cues. This possibility also has implications for action perception and social interactions for deaf infants. We are currently pursuing these questions by examining action observation skills and motor proficiency in an ongoing study with the same population of infants and toddlers.

Finally, we note that our study does feature a sample size that is smaller than previous studies, in part due to loss of data collection from the COVID-19 pandemic and to the general challenges of recruiting young pre-CI infants. We also acknowledge that our pre-CI group of deaf infants comprised entirely males, due to only males being eligible for our study for unknown reasons, so it is possible that there could be gender effects that affected our results. This should be considered when interpreting our findings, and we hope that this will motivate future work in this area.

5 | CONCLUSION

Our goal in this study was to investigate action sequence learning in deaf infants (pre cochlear implantation) and deaf toddlers (post implantation) comparing with their age-matched hearing peers. Our study is the first to examine VSL during the early development of infants with hearing loss and adds to the body of evidence demonstrating that VSL skills are affected by hearing loss from infancy. These findings also provide additional evidence for links between VSL and language abilities, which has implication for clinicians who provide speech therapy and other early intervention services to toddlers with hearing loss. Future research is needed to further examine the respective contributions of auditory and language experiences to the statistical learning skills of infants with hearing loss.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest with regard to the funding source for this study.

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