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Does a lack of auditory experience affect sequential learning?

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ABSTRACT

To understand the interaction between sensory experiences and cognition, it is critical to investigate the possibility that deprivation in one sensory modality might affect cognition in other modalities. Here we are concerned with the hypothesis that early experience with sound is vital to the development of domain-general sequential processing skills. In line with this hypothesis, a seminal empirical study found that prelingually deaf children had impaired sequence learning in the visual modality. In order to assess the limits of this hypothesis, the current study employed a different visual sequence learning task in an investigation of prelingually deaf children with cochlear implants and normal hearing children. Results showed statistically significant learning in each of the two groups, and no significant difference in the amount of learning between groups. Moreover, there was no association between the age at which the child received their implant (and thus access to electric hearing) and their performance on the sequential learning task. We discuss key differences between our study and the previous study, and argue that the field must reconsider claims about domain-general cognitive impairment resulting from early auditory deprivation.

1. Introduction

A period of sensory deprivation during early childhood may affect broader aspects of cognition as a child develops. Especially striking is the possibility that deprivation in one sensory modality can adversely affect cognition in other modalities. The current study examined the possible link between early deafness and later visual sequence learning.

A number of studies have suggested that early deafness has an impact on an individual's cognition that extends beyond the auditory domain. For example, deaf children perform worse than children with normal hearing (NH) on visual tasks measuring design copying, visuomotor precision, and figure-ground perception (Erden, Otman, & Tunay, 2004; Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007). On the other hand, deaf individuals display enhanced performance in some other visual tasks, such as temporal processing of visual flashes (Iversen, Patel, Nicodemus, & Emmorey, 2015). In the tactile domain, deaf children have been found to outperform children with NH on measures of shape discrimination by blind palpation (Cranney & Ashton, 1982). For fuller information regarding neurocognitive effects of early deafness, see Bavalier and Neville (2002) and Kral, Kronenberger, Pisoni and O'Donoghue (2016).

Some of the differences in nonverbal cognition between deaf and NH individuals may result from neural reorganization related to experience with sign language (Lee et al., 2001; Weisberg, Koo, Crain, & Eden, 2012). Therefore children with cochlear implants (CI), who have experienced a period of auditory deprivation in infancy, but who have been provided with a sense of sound via CI and primarily use oral language, represent a unique source of information that may contribute to a more complete understanding of how early sensory experiences affect cognition. Some studies have found that children with CI appear to differ from their normal hearing peers in non-auditory cognition (Cleary, Pisoni, & Geers, 2001; Conway, Karpicke et al., 2011; Schlumberger, Narbona, & Manrique, 2004). Thus, empirical investigations of the impact of early deafness on children with CI compared to children with NH are a particular focus in this field of inquiry.

One influential theoretical framework regarding the effects of early auditory deprivation on cognition is the auditory scaffolding hypothesis (Conway, Pisoni, & Kronenberger, 2009). Based on the observation that sound is an inherently sequential signal, and that auditory perception relies fundamentally on serial order, it has been proposed that early sound exposure provides crucial experiences with tracking sequential patterns in the environment. Consequently, a lack of auditory input in infancy may "delay the development of general cognitive abilities related to representing temporal or sequential patterns" (Conway et al., 2009, p. 275).

Only two previous studies have directly investigated implicit

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learning of visual sequential information in individuals with hearing loss. In line with the auditory scaffolding hypothesis, Conway, Pisoni, Anaya, Karpicke, and Henning (2011) found a significant difference between the performance of prelingually deaf children with CI and children with NH on a serial recall task measuring implicit learning of visual sequential patterns. On average, the 23 children with CI (aged 5–10) showed no learning. By contrast, age-matched NH peers did show significant learning. In addition, there was a negative correlation between performance on the learning task and the age at which the child received their implant. The other study on this topic employed a serial reaction time (SRT) task to assess visual sequential learning in 18 adults with severe to profound hearing loss. That study reported impaired learning compared to adults with NH (Lévesque, Théoret, & Champoux, 2014). However, there was no relation between the degree of sequence learning and the age of hearing loss onset.

These two previous studies have been interpreted as evidence that deaf or severely hearing impaired individuals acquire a domain-general sequence learning deficit. Although this is an intriguing possibility in and of itself, one reason that such a deficit has important ramifications is because it may adversely affect a broad range of other cognitive activities that draw on implicit sequence learning. For instance, compromised sequential learning may be one of a number of contributing factors that underpin below-average language skills typically observed in children with CI (e.g. Houston et al., 2012). Indeed, studies have found associations between individual differences in visual sequence learning and language processing in infants, children and adults with NH (Conway, Karpicke, & Pisoni, 2007; Kidd & Arciuli, 2016; Shafto, Conway, Field, & Houston, 2012).

In the current study, we used a different measure of visual sequential learning in order to explore the limits of the auditory scaffolding hypothesis. In doing this we sought to address some questions raised by the previous two studies that have been conducted. One question relates to the nature of stimuli used to assess sequential learning. A common feature of the two previous studies of implicit visual sequence learning is that they used stimuli that were highly familiar and thus may have lent themselves to the use of learning strategies such as verbal rehearsal processes.

The visual stimuli used in the study by Conway, Pisoni, et al. (2011) were squares of four different colors appearing in one of four different locations on the screen. The task was based on the Simon memory game where children view a sequence of colors and then are asked to reproduce the sequence by pressing colored response panels in the correct order (Cleary et al., 2001; Pisoni & Cleary, 2004). In the Conway, Pisoni, et al. 2011 study this game was used to test implicit learning: First, the child was presented with color sequences adhering to an underlying grammar, and then the experiment transitioned seamlessly into a test phase where the child was presented with both novel grammatical and novel ungrammatical sequences which they had to reproduce. Implicit learning was assessed by comparing the number of grammatical and ungrammatical sequences that were reproduced correctly. While participants were not told about the underlying grammar, they were instructed at the beginning of the experiment to "remember the patterns of colors you see on the screen." In their review paper, Pisoni, Kronenberger, Chandramouli, and Conway (2016) stated the following when describing a version of the Simon memory game:

> "…many of the participants, particularly the normal-hearing children, likely recoded the serial patterns using well-learned automatized verbal labels and coding strategies in order to create stable representations of the stimulus patterns in working memory for maintenance and rehearsal prior to response organization and motor output. When compared to the group of normal-hearing controls, the deaf children with CIs may have used a different encoding strategy and less efficient verbal rehearsal processes for maintaining temporal sequences of the color name codes in working memory."
>
> p.4

Thus, it is reasonable to suggest that verbal rehearsal strategies may have come into play in the study by Conway, Pisoni, et al. 2011. The fact that participants were given explicit instructions to remember patterns and that presentation rates were slow, may further have encouraged the use of explicit verbal strategies. The stimuli used in the Lévesque et al. (2014) were asterisks in specific locations on the screen which were associated with digits on the keyboard. As digits have well-learned automatized labels, this task also lent itself to verbal rehearsal strategies. Consequently it may be that group differences observed in the previous two studies were related to differences in verbal rehearsal strategies rather than sequence learning per se.

In line with this possibility, a number of studies have shown that short-term verbal memory is compromised in children with CI (Harris et al., 2013; Pisoni & Cleary, 2003). In an overview of this literature, Hirshorn and colleagues have suggested that differences between deaf and NH individuals "are specific to tasks that require serial order recall of linguistic material, with little to no consequences for cognition at large" (Hirshorn, Fernandez, & Bavelier, 2012, p. 90). Accordingly, this view predicts that differences in sequential learning between children who have experienced a period of deafness and NH individuals should be restricted to tasks that involve highly familiar stimuli with automatized verbal labels and sufficient time for verbal (i.e., phonological) rehearsal. Thus, using stimuli that are unfamiliar and do not have automatized verbal labels, allows us to test the possibility that the previous findings may reflect (at least to some degree) the effect of processing highly familiar stimuli.

The paradigms employed by Conway, Pisoni, et al. (2011) and Lévesque et al. (2014) are only two of a large number tasks which have been used to measure sequence learning skills in children and adults (for an overview, see Siegelman, Bogaerts, Christiansen, & Frost, 2017). One commonly used method is the embedded triplet paradigm (Arciuli & Simpson, 2011; Fiser & Aslin, 2002; Kidd & Arciuli, 2016; Turk-Browne, Jungé, & Scholl, 2005). In this paradigm participants view a continuous stream of individually presented stimuli during a familiarization phase with no instructions to learn or remember. Unbeknownst to participants the stream consists of stimuli that co-occur in triplets. Learning is assessed during a separate surprise test phase where participants undertake forced choice trials to identify embedded versus foil triplets. Often, responses are untimed and learning data is based on accuracy rates. In a study of adults, Siegelman and Frost (2015) found that the embedded triplet task of visual sequence learning (using complex visual shapes as stimuli) had better test–retest reliability than a number of other tasks used to measure implicit learning.

In addition to exploring these issues regarding the nature of stimuli and instructions to participants, we also wanted to assess visual sequence learning in those with CI versus normal hearing peers using a larger sample size than the previous two studies, which is especially important when examining the link between age of implantation and capacity for sequence learning. Conway, Pisoni, et al. (2011) found a significant negative correlation between sequential learning and age of implantation in a sample of 22 children. However, in the study by Lévesque et al. (2014), there was no significant difference in sequence learning performance between the 9 prelingually and the 9 postlingually deaf adults. Thus, to further our understanding of how auditory deprivation may influence sequence learning, there is a need for studies of larger samples with detailed information regarding age of hearing loss and age of implantation.

In sum, there may be a number of reasons why deaf children and adults have been found to perform poorly on visual sequential learning in the two previous studies by Conway et al. (2009) and Lévesque et al. (2014). Before we can draw firm conclusions about domain-general sequence learning impairment as a secondary cognitive consequence of early deafness, it is critical to investigate sequence learning in other tasks. In the present study we used the embedded triplet paradigm with stimuli that were unfamiliar and that did not have automatized verbal labels. Further, we used relatively fast stimulus presentation times and did not provide participants with instructions to learn or to remember patterns. We compared performance on this task in children with CI who had undergone a period of auditory deprivation in infancy and in NH children. For the children with CI we examined a possible relation between the age of implantation and capacity for sequence learning. In doing so, we aimed to provide complementary evidence regarding the relation between auditory deprivation and sequential learning in the visual modality that could contribute to discussions about refining the auditory scaffolding hypothesis.

2. Method

2.1. Participants

The two previous studies that compared implicit sequence learning in individuals with hearing impairment and normal hearing, found effect sizes for the group differences ranging from 0.6 to 1.2 (Conway, Pisoni, et al., 2011; Lévesque et al., 2014). A power analysis shows that the present study, with 34 participants in each group, is adequately powered (1-beta = 0.8, i.e. type-II error probability: 20%) to detect an effect of d = 0.6, which is comparable to the smallest effect observed in the previous studies (G*Power software; Faul, Erdfelder, Buchner, & Lang, 2009).

Participants were sixty-eight children, 34 prelingually deaf children with CI (17 boys, 17 girls) and 34 children with NH who were pairwise matched on age and gender with children with CI. All children with NH showed presence of otoacoustic emissions, indicating normal inner ear function and normal hearing with hearing thresholds better than 30 dB HL (Stach, 2010). Inclusion criteria for the CI group were age 7–12:11, onset of profound hearing loss (90 dB or greater) by age 2, cochlear implantation by age 4, and duration of CI use minimum 3 years. Thirty-three of the 34 children with CI had oral Norwegian as their main native language. One child used both oral Norwegian and sign language to communicate with family members, but only oral Norwegian with people outside the family. All children had bilateral CIs except one child who had a CI in one ear and a hearing aid in the other ear.

Pediatric cochlear implant operations in Norway are all carried out in one national center, at Oslo University Hospital. Thus, the participating children were implanted and received follow-up at the same hospital. In the period after implantation, all children were followed up at the CI clinic every third month during the first year, every sixth month during the second year and then yearly. In addition, 79% of parents received regular individual counselling from educational institutions in their local community on how to support their child's oral communication development. According to parent report on the Speech Intelligibility Rating, a five-point rating scale developed by Cox and McDaniel (1989), all but one of the children with CI had speech which was easily intelligible to all listeners at the time of testing. The remaining child had speech which was intelligible to listeners in a known context with concentration. Ninety-one percent of the children with CI attended mainstream schools, while 9% attended special schools for hearing impaired children. Eighty-eight percent received some special education services, but more than half of the children (54%) received only 1–5 h of special education per week. The CI and NH group were comparable in terms of mothers' education (84% of mothers in the NH group and 79% of mothers in the CI group had completed at least one year of university studies).

For 27 of the 34 children with CI, the medical journals confirm that they were born deaf. Of the seven remaining children, five became deaf during their first two years of life, one child had an unclear hearing status at birth, but a confirmed hearing loss larger than 90 dB before age 2, and one child was born with a severe hearing loss which progressed to deafness before age 2.

2.2. Materials and procedure

The present data is part of a larger study where all children completed a battery of neuropsychological tests. Approval to conduct the study was granted from the Norwegian Regional Committees for Medical and Health Research Ethics. Children were tested in a quiet room at their school or at the Oslo University Hospital.

2.3. Measures of speech perception and nonverbal cognition

Speech perception was measured by a test where the child is instructed to repeat 50 phonetically balanced Norwegian single syllable words (Øygarden, 2009). Each monosyllable was scored as correct/incorrect, and the percentage of correct repetitions was used as a variable in the analyses. The test was conducted in an anechoic chamber.

To measure general nonverbal abilities, we used Raven's Colored Progressive Matrices (CPM) for children aged 7;0–8; 11 and Raven's Standard Progressive Matrices – Plus version (SPM+) for children aged 9;0–12;11 (Raven & Court, 2003). Both tests consist of a series of visual patterns with a part of the pattern missing. The child was presented with a number of options and was instructed to select the correct part to complete the designs.

As the sequence learning test involved viewing of a stream of visual stimuli over time, we speculated that variability in visual memory or visual sustained attention could affect learning. In order to examine these abilities in our two groups, we administered three subtests from the Leiter International Performance Scale- Revised (Roid & Miller, 1997): Forward Memory (FM), Reverse Memory (RM) and Attention Sustained (AS). In the FM subtest, the administrator pointed to a given sequence of pictures. The child was instructed to copy that sequence by pointing to the pictures in the correct order. RM used the same pictures as FM, but in this test the child was instructed to copy the administrator's sequence in the reverse order. The number of pictures in each sequence varied from 1 to 8 items.

For the AS test, the child was presented with a collection of geometric shapes on a page, with one target shape at the top of the page. The child was then instructed to cross out as many of the target shapes (e.g. squares) as possible within the given time. The test consisted of four pages, with increasingly complex shape combinations.

2.4. Implicit visual sequential learning

Implicit visual sequential learning of embedded triplets was assessed using a task originally reported by Arciuli and Simpson (2011). Stimuli were 18 unfamiliar cartoon-like figures that did not have well-learned automatized labels – none resembled any known animals, people, or popular cartoon characters. Moreover, none of the figures could easily be described based on a single physical attribute. Of these figures, 6 were used solely for practice. The remaining 12 were divided into four groups of triplets for use during the experiment proper. For stimuli, see the Appendix in Arciuli and Simpson (2011).

The task was comprised of two phases: a familiarization phase which contained a cover task unrelated to visual sequential learning as well as a separate surprise test phase which participants were not informed about until they had completed familiarization. Both phases were delivered via Eprime v.2 (Psychology Software Tools Inc., 2012).

The familiarization phase consisted of a continuous stream of individually presented figures, each appearing on the computer screen for 400 ms, with an inter stimulus interval of 200 ms. Each triplet was included in the familiarization stream 24 times (96 triplets in total). The order of triplets was randomized with the exception that the same triplet could not appear twice in a row. In 6 out of 24 instances, a figure was presented twice in a row (i.e., repeated) in order to provide a cover task. Participants pressed a button whenever they noticed such repetition. Repetitions were counterbalanced among the characters within each triplet.

Table 1
Participant characteristics.

	Children with CI			Children with NH					
	M	SD	Range	M	SD	Range	t (66)	p	Cohen's d
Age	125.5	18.7	87–155	125.2	19.4	86–155	-0.07	0.95	0.02
Age implant	17.6	9.7	5–45	–	–	–	–	–	
CI duration	107.9	21.7	53–140	–	–	–	–	–	
Speech perc	86.5	8.9	66–100	99.4	0.9	98–100	7.70	< 0.001	1.99
Raven	99.1	11.6	75–120	97.4	11.3	75–120	-0.61	0.55	0.15
Leiter R FM	11.1	2.7	6–17	11.9	2.4	6–16	1.17	0.25	0.31
Leiter R RM	11.1	2.2	7–16	11.9	1.9	7–16	1.65	0.10	0.38
Leiter R AS	8.6	2.9	0–14	8.5	2.0	5–15	-0.70	0.95	0.02

Note. Scores for Age, Age of implantation (Age implant) and CI duration of use (CI duration) are given in months. Scores for speech perception (monosyllables) are percent correct. Scores for Raven's matrices (Raven) are standard scores. Scores for Leiter International Performance Scale- Revised subtests Forward Memory (FM), Reverse Memory (RM) and Attention Sustained (AS) are scaled scores. Speech perception scores are missing for 6 children with NH, but all children with NH passed the hearing screening with otoacoustic emissions.

The surprise test phase contained 64 forced-choice trials. On each trial participants were required to choose between 2 triplets: a triplet which had occurred during the familiarization phase versus a foil triplet which had never occurred during the familiarization phase, but which was composed of the figures from the familiarization phase. Presentation order of embedded versus foil triplets was counter-balanced. Across forced-choice trials each embedded and foil triplet was seen an equal number of times (16 times), and each individual figure was seen 32 times. This ensured that any possibility of continued learning during the test phase applied equally to all triplets being presented. The order of test trials was randomized across participants.

3. Results

As shown in Table 1, there was a statistically significant difference between the children with CI and NH on the speech perception test. There were no significant group differences on tests of nonverbal IQ, visual memory, or visual attention.

The mean proportion of correctly identified triplets during the surprise test phase was 57.7 (SD 11.6) for children with CI and 58.3 (SD 11.9) for children with NH. See Fig. 1 for individual scores on the visual sequential learning test in the two groups.

One sample t-tests showed that VSL was significantly above chance for children with CI (t (33) = 3.9, $p < 0.001$, Cohen's d = 0.67) and also for children with NH (t (33) = 4.1, $p < 0.001$, Cohen's d = 0.70). To determine if there was a difference in the amount of visual statistical learning between the two groups, an independent samples *t*-test was conducted. The results showed that the difference in learning between groups was not statistically significant (t (66) = 0.19, p = 0.85). The observed effect size of d = 0.05 fell well below Cohen's (1992) classification for a small effect (i.e., d = 0.2), indicating a substantial overlap between the score distributions in the two groups (cf. Fig. 1). A power analysis showed that we would need 4947 participants in each group for an effect of this size to reach statistical significance (Faul et al., 2009). The data were also examined by calculating the Bayes Factor (BF) using the R package BayesFactor (Morey & Rouder, 2015). A BF can be used to compare the fit of the data under the null hypothesis (no difference between groups) and an alternative hypothesis (a difference between groups). The analysis suggested that the data are more in line with the null hypothesis of no difference between the two groups, as indicated by a BF of 3.96 for the comparison of the null hypothesis over the alternative hypothesis in contrast to a BF of 0.25 for the comparison of the alternative hypothesis over the null hypothesis.

For the CI group, we calculated partial correlations between visual sequence learning and the variables age of implantation and speech perception, controlling for age. There were no significant relations

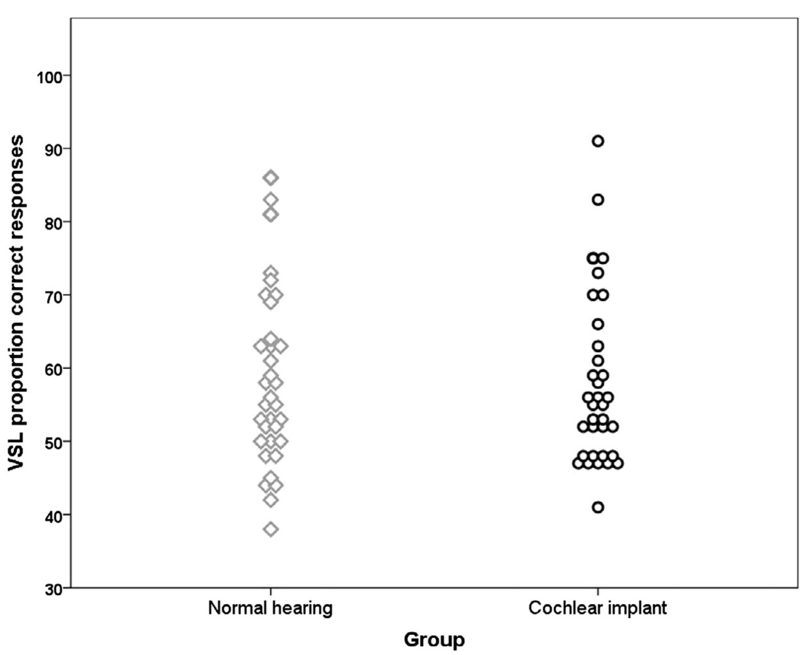

Fig. 1. Distribution of individual scores on the visual sequence learning (VSL) task in children with normal hearing and children with cochlear implants.

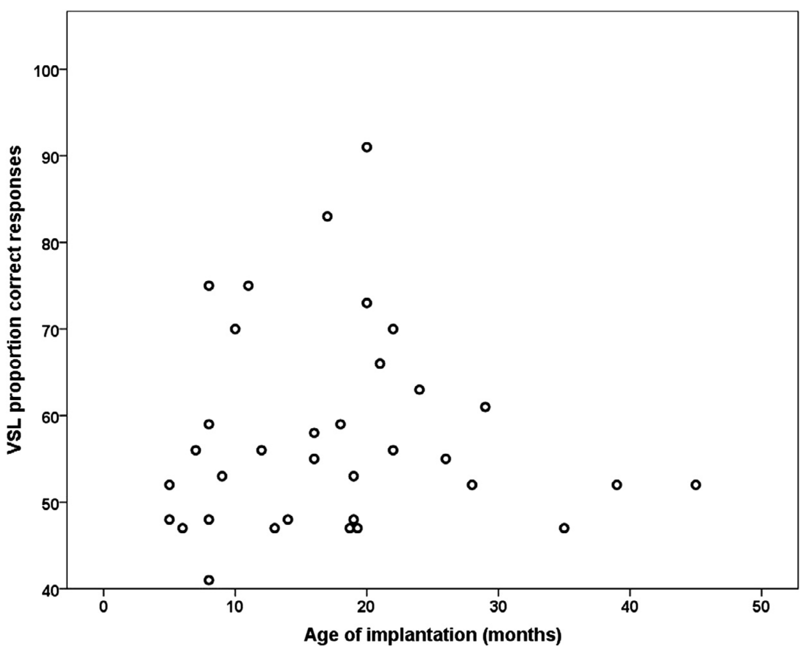

Fig. 2. Relation between scores on the visual sequential learning (VSL) task and age of implantation.

between the visual sequential learning score and age of implantation (r = 0.03, p = 0.89) (see Fig. 2), or speech perception (r = -0.18, p = .32). We also examined these relations using a Bayesian approach as implemented in the R package BayesMed (Nuijten, Wetzels, Matzke, Dolan, & Wagenmakers, 2015). For both analyses, the data are more in line with the null hypothesis of no relation as indicated by BFs of 5.26 (for visual sequence learning and age of implantation, controlling for age) and 3.13 (for visual sequence learning and speech perception, controlling for age) as opposed to BFs of 0.19 and 0.32 respectively for the alternative hypotheses of a relation between these variables.

To further examine a possible link between complete auditory deprivation before implantation and subsequent visual sequential learning ability, we performed the same analyses on the subset of 27 children in the CI group who were born deaf and the 27 age-and-gender-matched children with NH. The average amount of visual sequential learning in this group of children with CI was 58.2 (SD 12.3), compared to 58.1 (SD 12.3) in children with NH. There was no significant difference in visual sequential learning between the two groups (t (52) = 0.03, p < 0.97, Cohen's d = 0.04). A Bayes Factor analysis also suggested that the data are more in line with the null hypothesis of no difference between the two groups, as indicated by a BF of 3.65 for the comparison of the null hypothesis of over the alternative hypothesis in contrast to a BF of 0.27 for the comparison of the alternative hypothesis against the null hypothesis.

For the subset of children with CI who were born deaf, the partial correlations (controlling for age) between visual sequential learning and age of implantation (r = 0.03, p = 0.89) and speech perception (r = −0.13, p = .52) were not statistically significant. A Bayesian analysis also indicated that the data were more consistent with the null hypothesis of no relation between these variables, as indicated by BFs of 4.76 (no relation between visual sequential learning and age of implantation, controlling for age) and 3.85 (no relation between visual sequential learning and speech perception, controlling for age) as opposed to BFs of 0.21 and 0.26 respectively for the alternative hypotheses of a relation between these variables.

4. Discussion

Individuals who have undergone a period of sensory deprivation in infancy constitute a unique source of information that may contribute to our understanding of how early sensory experiences affect cognition. The auditory scaffolding hypothesis proposes that early auditory deprivation affects modalities other than audition and results in domain-general cognitive impairments related to the representation of sequential patterns in the environment (Conway et al., 2009). A seminal study by Conway, Pisoni, et al. (2011) found support for the auditory scaffolding hypothesis by showing impaired visual sequence learning in prelingually deaf children with CI. The aim of the current study was to test the hypothesis that using a different visual sequence learning task, where stimuli were unfamiliar and participants were not provided with explicit instructions, would produce a different finding. Our results provide support for this hypothesis. The prelingually deaf children with CI displayed intact sequence learning at a level comparable to that of age and gender-matched children with NH. Moreover, there was no significant relation between sequence learning performance and the variables age of implantation or speech perception ability for the children with CI. These findings indicate that the presence of a sequence learning deficit in children with CI may be closely tied to the nature of the task used. In addition, our study raises some new hypotheses regarding which characteristics of early experiences that may affect sequence learning.

Our study is in line with growing interest in the area of memory and learning processes in children with CI (for a review, see Pisoni et al., 2016). Two recent studies of children with CI have investigated sequence *processing* in the auditory and visual modalities (Bharadwaj & Mehta, 2016; Ulanet, Carson, Mellon, Niparko, & Ouellette, 2014). Bharadwaj and Mehta (2016) found differences between children with CI and NH in the ability to reproduce sequences of finger movements. The authors suggest, however, that the observed group differences in the of sample 18 CI users and 19 NH peers, might be due to the substantial individual differences seen among the CI-users with regard to age of implantation, duration of implant use, hearing history, mode of communication and bilateral/unilateral CI use. Ulanet et al. (2014) found that a group of children with CI who had language scores below expectations (N = 13) performed significantly worse than children with CI who met expectations (N = 9) on tests measuring verbal and motor sequence processing. However, age of CI activation did not predict sequence processing scores. Other recent studies of children with CI have examined the ability to make use of statistical properties in auditory or linguistic input (Conway, Deocampo, Walk, Anaya, & Pisoni, 2014; Guo, McGregor, & Spencer, 2015; Studer-Eichenberger, Studer-

Eichenberger, & Koenig, 2016) as well as working memory and other executive functions (Beer et al., 2014; Kronenberger, Beer, Castellanos, Pisoni, & Miyamoto, 2014). However, none of these studies have investigated implicit visual sequential *learning*. The present study is thus critical for examining the limits of the auditory scaffolding hypothesis, especially as it has a sample which is larger than the previous studies and which is well-described with regard to medical, hearing-related and cognitive variables.

The results of the current study differ from the results of the two previous studies of implicit visual sequence learning in individuals with CI (Conway, Pisoni et al., 2011; Lévesque et al., 2014). However, due to a number of task differences between the studies, we are inclined to posit that these seemingly opposite findings may in fact be complementary in helping us to understand the limits of the auditory scaffolding hypothesis and refine it.

A key difference between the tasks used in the present and the two previous studies concerns how easily the tasks lend themselves to verbal rehearsal strategies. First, the stimuli used in the tasks by Conway et al. and Lévesque et al. were highly familiar stimuli associated with automatized verbal labels, while the current study used stimuli which were unfamiliar and that did not have pre-existing labels. Second, while the study by Conway, Pisoni et al. used slow presentation rates (stimulus duration of 700 ms and inter-stimulus interval of 500 ms), which encourage explicit learning strategies, the present study used substantially faster presentation rates (stimulus duration of 400 ms and inter-stimulus interval of 200 ms). Recent studies of adults suggest that presentation times influence the degree to which participants are able to benefit from instructions to make use of explicit learning strategies (Arciuli, Torkildsen, Stevens, & Simpson, 2014; Bertels, Destrebecqz, & Franco, 2015). Third, Conway, Pisoni, et al. gave participants explicit instructions to remember stimuli ("your job is to try to remember the pattern of colors you see on the screen"), while the present study did not contain instructions to learn or remember anything, but rather used a cover task to avoid the use of explicit learning strategies. These three factors may have lead children to use verbal rehearsal strategies to a larger degree in the previous than in the present study. Reliance on verbal strategies may have contributed to the group differences seen in the previous studies, as children with CI tend to perform worse than children with NH on measures tapping phonological working memory and verbal rehearsal (e.g. Lyxell et al., 2008; Pisoni & Cleary, 2003).

Note that the types of information that children had to learn also differed between the present study and that by Conway, Pisoni, et al. (2011). In the study by Conway, Pisoni et al. each stimulus had its own consistent location – children could learn either by remembering the order of the stimulus items themselves or the order of their locations. A previous study suggests that children with NH may be more efficient than children with CI in exploiting such redundant cues to serial order (Cleary et al., 2001). By comparison, in the embedded triplet paradigm, the stimulus items were presented (consecutively) in the same location – serial order was the only source of information. Another point of difference is that the task used by Conway, Pisoni et al. assessed generalization ability to a larger extent than the present study as both the grammatical and ungrammatical color strings used in the test phase were novel to the participants, while in the present study only the incorrect test strings were novel combinations of items. On the other hand, the present study assessed the capacity for segmentation to a larger degree than that of Conway, Pisoni et al. as the stimuli were presented as a continuous stream and the child had to extract the units (triplets) by identifying their boundaries. By contrast, each string was presented separately in the study by Conway, Pisoni, et al.

Differences in the length of sequences may also have contributed to the discrepancy in results between the present study and the previous studies. Sequences in the current study were consistently 3 items long, while the sequences used in the test phase of the Conway, Pisoni et al. study varied from 3–5 items. It is unclear whether children with CI have a lower memory capacity for visual stimuli than children with NH. While some studies have found that children with CI perform worse than controls on tasks of visual sequential memory or visuo-motor memory (Bharadwaj & Mehta, 2016; Cleary et al., 2001), other studies of visual sequential memory and visual pattern memory have found that children with CI performed comparably to children with NH or population norms (Edwards & Anderson, 2014; Khan, Edwards, & Langdon, 2005; Lyxell et al., 2008). Results from the present study, which found no significant differences in visual memory span between children with CI and NH, are in line with the latter studies.

In sum, there were a number of differences between the tasks used in the two studies. Importantly, however, the fact that children with CI performed comparably to children with NH in the present study cannot be attributed to the task simply being easy. As is clear from our results, there were no ceiling effects on the visual sequence learning task.

While task differences were likely the most important contributor to the discrepancy in results between the two previous studies and the present study, participant characteristics are worthy of consideration. Age of implantation and duration of CI use have been shown to have an impact on the development of cognitive abilities (e.g. Ching et al., 2013; Richter, Eißele, Laszig, & Löhle, 2002; Tomblin, Barker, Spencer, Zhang, & Gantz, 2005). Children in the present study were on average about 3 years older than those in the study by Conway, Pisoni et al., and had a correspondingly longer duration of CI use. Thus, children in the current study had more time to catch up with their NH peers. Additionally, the average age of implantation was three and a half months younger in the present study than in that of Conway, Pisoni et al. On the other hand, none of the nine CI users in the study by Lévesque et al. had experienced a period of auditory deprivation in infancy (age of onset of deafness varied between 5 and 58 years), but they still performed worse than controls on the sequence learning task.

Of particular interest is the fact that all of the children in the present study had bilateral hearing, while all of the CI participants in the Lévesque et al. study and all but three of the children in the Conway et al. study had only one implant. A recent study by Guo et al. (2015) found that children with bilateral implants, but not children with unilateral implants, demonstrated a sensitivity to language statistics similar to that of normal hearing children, possibly due to the enhanced perception of acoustic information provided by binaural input (Dunn et al., 2010; Kühn-Inacker, Shehata-Dieler, Müller, & Helms, 2004). As shown in the above studies, binaural input appears to be especially beneficial in noisy conditions, which are typical of pre-schools and schools. Thus, it is possible that the enriched hearing of the children in the present study allowed for a more fine-grained segmentation and processing of sound sequences compared to that of individuals in the two previous studies, thus contributing to a more typical development of domain-general sequence learning skills. As outlined in the methods section, children with CI in the present study also received frequent hospital follow-ups post implantation, and the great majority of parents received regular individual counselling on how to support their children's communicative development. While Conway, Pisoni et al. did not report details of the habilitation or education of their participants, such factors may also have contributed to the observed differences in sequence learning between the two studies. Even so, the current study is important in raising these factors to shed light on the limits of the auditory scaffolding hypothesis. In the original formulation of the hypothesis, none of the above-mentioned characteristics of children's early hearing experiences were mentioned as potentially mediating sequential learning.

In sum, the present study found intact and comparable implicit visual sequence learning in prelingually deaf children who use CI and NH children. We argue that the field needs to carefully consider claims about a domain-general sequence learning deficit resulting from a period of early deafness. Any differences between CI and NH children might be closely pinned to the nature of the sequential learning task that is used.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.09.017.

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