Published in final edited form as:

Ear Hear. 2019 ; 40(1): 213–217. doi:10.1097/AUD.0000000000000564.

Nonverbal Visual Sequential Learning in Children with Cochlear Implants: Preliminary Findings

Kelsey E. Klein, B.A., Elizabeth A. Walker, Ph.D., and J. Bruce Tomblin, Ph.D.

Department of Communication Sciences and Disorders, University of Iowa, Iowa City, IA

Abstract

Objectives—We tested the hypothesis that children with cochlear implants (CIs) experience domain-general deficits in sequential learning.

Design—Twenty children with CIs and 40 children with normal hearing (NH) participated. Participants completed a serial reaction time task that measured implicit sequential learning.

Results—During random sequence phases, the CI group had significantly slower reaction times than the NH group. However, there were no significant differences in the rates of sequential learning between groups. Age at implantation was not significantly associated with learning rate in the CI group.

Conclusions—Children with CIs demonstrated nonverbal sequential learning that is comparable to children with NH. Contrary to previous research, early auditory deprivation may not be associated with deficits in domain-general sequential learning, but may affect sequential processing. Further investigation is needed to understand the mechanisms underlying the overall delayed reaction times of children with CIs.

Keywords

cochlear implants; children; sequential learning; serial reaction time

INTRODUCTION

Sequential learning involves pattern recognition with ordered stimuli (Kidd 2012). Sequential processing is defined as encoding multiple stimuli presented non-simultaneously (Farmer & Klein 1995). Conway, Pisoni, and Kronenberger (2009) proposed that early experience with sound supports both sequential learning and processing due to the temporal nature of sound. According to this Auditory Scaffolding Hypothesis, early auditory deprivation negatively impacts domain-general cognitive sequencing functions.

Congenitally deaf children with cochlear implants (CIs) provide an opportunity to test the Auditory Scaffolding Hypothesis, which has led to a growing literature on sequence

Corresponding author: Kelsey E. Klein, 250 Hawkins Drive, University of Iowa, Iowa City, IA 52242, 360-581-9794, kelsey-e-klein@uiowa.edu.

Conflicts of Interest

The authors have no conflicts of interest to declare.

processing and learning in deaf individuals (Bharadwaj & Mehta 2016; Conway et al. 2009, 2011; Hall et al. 2017; Levesque et al. 2014; Torkildsen et al., 2018; Ulanet et al. 2014). The earliest studies testing the Auditory Scaffolding Hypothesis focused on learning sequential patterns presented within an artificial grammar. Conway et al. (2011) used a sequence learning task, adapted from the Milton Bradley Simon game, in which participants saw colored squares presented sequentially in specific locations on a touchscreen. Participants were instructed to attend to the color patterns, but they were unaware that the sequences stemmed from an artificial grammar. Following a learning phase, participants were assessed on their ability to reproduce sequences from the grammar used in the learning phase, as well as a novel grammar. Conway et al. suggested that differences in accuracy between the familiar and unfamiliar grammars indicated that participants were not simply reproducing a visuospatial pattern, but learning grammatical rules.

In Conway et al. (2011), children with normal hearing (NH) showed sequential learning, whereas children with CIs showed no evidence of sequential learning. Conway et al. also reported a marginally significant correlation between age at implantation and sequential learning ($p=.058$). Other researchers have provided additional evidence of sequential processing deficits in deaf individuals, in support of the Auditory Scaffolding Hypothesis. Ulanet et al. (2014) reported that children with CIs who demonstrated language delays had concurrent deficits on sequential processing tasks. Bharadwaj and Mehta (2016) showed that children with CIs had poor visuo-motor sequential processing. Levesque et al. (2014) found that deaf adults were less efficient at learning sequential patterns than NH adults on an implicit learning task, the serial reaction time task (SRTT).

Although deaf individuals showed impaired sequential learning or processing in the studies described above, the scope of the Auditory Scaffolding Hypothesis remains undefined. Conway et al. (2011) found that children with CIs showed deficits in the Simon task, which taps into implicit learning using colored squares that can be verbally encoded. They also found that better implicit learning was associated with stronger grammar skills, which they suggested is evidence that sequence learning influences language outcomes in children with CIs. Because the data were correlational, however, the direction of the association could be the opposite: stronger language skills could be an underlying mechanism of performance on the Simon task. In other words, children with stronger language abilities may have been more adept at using a verbal rehearsal strategy to aid in this task (Pisoni et al. 2016). If true, this would indicate that the Simon task measures the ability to learn sequential patterns with automatized verbal labels, but sequential learning deficits in children with CIs may not generalize to nonverbal stimuli that cannot be verbally encoded and easily rehearsed in working memory. Although Ulanet et al. (2014) and Bharadwaj and Mehta (2016) used nonverbal tasks, both of these tasks measured sequential processing, not learning. Levesque et al. (2014) used a nonverbal sequential learning measure, but their sample included adults rather than children.

To understand the scope of the Auditory Scaffolding Hypothesis, further investigation is needed with implicit learning measures other than the Simon task. Hall et al. (2017) tested the limits of the Auditory Scaffolding Hypothesis using both the Simon task and SRTT. SRTT is similar to the Simon task in that both measure implicit sequential learning (Conway

et al. 2007; Kidd 2012). Both tasks contain a sequence of visual stimuli. The tasks differ regarding the dependent measure: SRTT uses reaction time and Simon uses accuracy. The methodologies also differ: SRTT involves implicitly learning a set 10-item sequence, whereas the Simon task involves implicitly learning abstract grammatical rules. Hall et al. replicated Conway et al. (2011)'s finding that children with CIs do not show evidence of sequential learning on the Simon task; however, they failed to replicate Conway et al.'s finding of implicit sequence learning in NH children. In contrast to the Simon task findings, both the NH and CI groups showed robust sequential learning on the SRTT. Similarly, Torkildsen et al. (2018) used a visual sequential learning task with embedded triplets (i.e., cartoon-like figures) and found no differences in learning between children with CIs and NH children. Neither Hall et al. nor Torkildsen et al. found a significant association between sequential learning and age at implantation. Given the mixed results between Conway et al., Hall et al., and Torkildsen et al., it remains unclear whether auditory deprivation leads to domain-general deficits in sequential learning and processing. These studies suggest the need to consider a narrower scope of the Auditory Scaffolding Hypothesis.

Study Questions

1. Do children with CIs show differences in sequential learning relative to NH children?
2. Is age at implantation associated with sequential learning rate?

The Auditory Scaffolding Hypothesis predicts that early auditory deprivation impacts processing and learning of non-auditory sequential stimuli. Accordingly, we predicted that 1) children with CIs would show impaired sequential learning relative to NH children on the SRTT, and 2) later age at implantation would be associated with poorer sequential learning.

MATERIALS AND METHODS

Participants

Twenty children (10 girls) with CIs ($M=9.4$ years, $SD=1.5$, range=7.3–11.8 years) and 40 children (23 girls) with NH ($M=9.8$ years, $SD=1.6$, range=6.3–12.3) participated. All children with CIs had congenital severe-profound hearing loss. Table 1 shows CI group demographics. Vocabulary, executive function, and visuospatial processing measures were obtained for the CI group only. Parents indicated that children were cognitively within normal limits. Parents of NH children indicated that cognitive-linguistic skills were within normal limits.

Procedure

Children completed SRTT, a visuo-spatial implicit sequential learning measure (Nissen & Bullemer 1987). SRTT minimizes the use of verbal rehearsal during sequential learning by presenting the same image (a green monster) in rapid succession throughout the task. Four boxes on the computer screen correspond to four physical buttons on a button box. The monster appears for 2 seconds in one box at a time, followed by a 0.4-second interval with no stimulus. Because there are no memory storage requirements to complete this task, verbally encoding the sequence of spatial locations is unnecessary. The child presses the

button corresponding to the box containing the monster as soon as he/she sees it. Reaction time (RT) is measured on each trial. For the first 100 trials (Random Phase 1), the monster appears pseudo-randomly. For the next 200 trials (Pattern Phase), the monster appears in a set 10-trial sequence. For the final 100 trials (Random Phase 2), the monster again appears pseudo-randomly. We analyzed the median RT across blocks of 20 trials for each individual. Median RT was used rather than mean RT to control for outlier trials within subjects. There were no between-group differences in accuracy on the random block, $t(27.05) = -1.8$, $p = .09$, or the pattern block, $t(58) = -1.3$, $p = .20$. Only correct responses were analyzed.

RESULTS

We utilized growth curve analysis using a mixed model to test whether each of the groups' RT slopes during the Random and Pattern Phases were significantly smaller than 0. If sequential learning occurs, RT will decrease during Pattern Phase as an indication of anticipating the location of the next stimulus. A slope that is significantly smaller than 0 indicates sequential learning during Pattern Phase. Growth curve analysis for RT performance in Random Phase 1 showed that the main effect of RT was not significantly different from 0 (slope = .08, $p = .19$), indicating that RT did not significantly change during Random Phase 1. The interaction between group and slope in Random Phase 1 was also not significant ($p = .18$). However, there was a significant group difference in RT, suggesting that children with CIs were slower in responding, $F(1,177) = 4.61$, $p = .03$. In the Pattern Phase, the main effect of decreasing RT across blocks was significant, slope = -6.56 ; $F(1,58) = 9.57$, $p = .003$. There was no interaction between change in RT over blocks and group ($p = .49$), nor was there a difference in RT between groups ($p = .30$). This suggests that participants responded increasingly faster across trials during Pattern Phase. This gain was equivalent for CI and NH groups. In Random Phase 2, as in Random Phase 1, there was a significant group difference in RT, $F(1,178) = 7.69$, $p = .0003$; however, there was no significant change in RT across blocks as reflected in a non-significant main effect of trials ($p = .31$), nor was there a significant interaction of groups and block ($p = .13$)¹.

Figure 1 shows mean RT in each block for CI and NH groups. We computed a difference between RT on the last five blocks of the Pattern Phase and RT on the five blocks of Random Phase 2. This difference measures the interference effect of pattern knowledge on responses during subsequent random trials. If sequential learning occurs, RT in Random Phase 2 is slower than RT in the final blocks of Pattern Phase. The mean difference between the last five blocks of Pattern Phase and the five blocks of Random Phase 2 was significantly greater than 0, $\bar{x} = 41.37$, $SD = 70.54$; $t(59) = 4.54$, $p < .0001$. This effect was not significantly different between groups ($p = .80$). This suggests that CI and NH groups did not differ in their degree of sequential learning, as measured by the interference effect.

¹We tested associations between learning rates in the CI group during the pattern blocks and pre-operative pure-tone average, vocabulary scores, and visuospatial processing abilities. Using mixed models, we found no significant relationship between individual learning rates in the CI group and any of these variables (all p -values $> .05$). We also examined associations between median RT in the random phases and 1) age at CI and 2) pre-operative pure-tone average. Neither relationship was significant ($r = .28$, $p = .23$; $r = -.23$, $p = .34$, respectively).

Finally, we examined the association between age at implantation and learning rate in the CI group using growth curve analysis. This association was not significant ($p=.30$).

DISCUSSION

We investigated whether children with CIs show differences in sequential learning using an implicit learning task, SRTT. First, we asked whether there was a differential rate of sequential learning during the Pattern Phase. We did not find evidence suggesting differential learning effects, as reflected in a nonsignificant interaction between group and RT slope in the growth curve analysis. This indicates that the CI and NH groups did not significantly differ in their rates of sequential learning. We also did not find evidence of differential learning reflected in an interference effect in Random Phase 2, as both groups showed a similar increase in RT after the Pattern Phase. Age at implantation was not associated with sequential learning rate.

The results of this study related to sequential learning are inconsistent with the Auditory Scaffolding Hypothesis, which predicts that early auditory deprivation causes domain-general deficits in sequential learning. Conway et al. (2011) showed that children with CIs experience deficits in visual sequential learning. Their task, however, may be supported by verbal encoding and rehearsal, as described in Conway et al. (2007). Children with CIs may show deficits on sequential learning tasks due to weakness in processing phonological sequential material specifically, rather than domain-general deficits. The present results support this view because SRTT assesses nonverbal visual sequential learning that does not require information storage in memory, and thus does not lend itself to verbal mediation strategies (although further research is needed to confirm the absence of verbal mediation in the SRTT). The present results are also consistent with findings by Hall et al. (2017) and Torkildsen et al. (2018). Because the children with CIs did not show sequential learning deficits on nonverbal visual tasks in Hall et al., Torkildsen et al., or the current study, deficits in domain-general sequential learning in children may be specific to stimuli that can be verbally mediated. Interestingly, Levesque et al. (2014) found an interference effect of sequential learning in deaf adults, consistent with the current results; however, the implicit learning effect was significantly reduced relative to NH adults. Further research is needed to investigate domain-general deficits in sequential learning in adults with long-term deafness, which would partially support the Auditory Scaffolding Hypothesis.

It is unsurprising that age at implantation was not associated with sequential learning rate, given the absence of group differences. Conway et al. (2011) reported that age at implantation was associated with sequential learning, but the effect was marginally significant. Hall et al. (2017) and Torkildsen et al. (2018) examined the relationship between the strength of implicit sequential learning with duration of deafness or age at implantation, respectively, and did not find significant associations. It is worth noting that both the current study and Conway et al. had a restricted range of age at implantation. Thus, age at implantation may have a stronger effect on sequential learning rate in children who receive their CIs after 3.5 years, when the central auditory system shows less plasticity (Sharma et al. 2002).

Unexpectedly, children with CIs showed slower RTs than NH children in both Random Phases. Slower RTs to sequentially presented stimuli may be indicative of poor sequential processing, rather than sequential learning. Bharadwaj and Mehta (2016) reported that children with CIs showed slower RTs and longer P300 latencies on a visual sequential processing task, compared to NH children. The RT during the Random Phases may be construed as partial support for the Auditory Scaffolding Hypothesis, which proposes that reduced auditory experience may affect sequential processing as well as sequential learning. Further research should investigate the mechanisms underlying the overall delayed RTs of children with CIs. These investigations may inform us about the extent to which neural pathways reorganize following periods of early auditory deprivation.

Limitations of the current study include no data regarding grammar abilities, which are associated with sequential learning (Tomblin et al. 2007). We also did not have access to complete data on cognitive-linguistic abilities for the NH group, which limits our ability to determine comparability between the NH and CI groups. It should be noted that the CI group was generally high functioning in terms of visuospatial processing: of the 14 children for whom visuospatial processing standard scores were available, eight (57%) scored at least one standard deviation above the normative mean. The overall strong nonverbal skills in this sample may have contributed to the discrepancy in findings between this study and previous studies, although our analyses showed no association between visuospatial processing and learning rate in the CI group.

Additional limitations included being restricted to one measure of sequential learning, SRTT. We acknowledge that results from the Simon task (Conway et al. 2011) and SRTT are not directly comparable because the methodologies differ in a number of ways besides verbal mediation, as described in the introduction. Children in the current study were older and there were more children with bilateral CIs (six in the current study; two in Conway et al.). It is possible that bilateral implantation could improve perceptual processing, although further research is needed to test this hypothesis. Furthermore, the SRTT in the current study involved a 10-item repeating sequence. More challenging SRTTs (second-order conditional sequences; Gabriel et al. 2013) might result in significant between-group differences. Future directions should include multiple measures of implicit learning (e.g., pursuit rotor; Grafton et al. 1994), to determine the robustness of the Auditory Scaffolding Hypothesis.

Our preliminary results indicate that children with CIs do not have significant deficits in nonverbal visual sequential learning. However, the slower RTs of children with CIs in this study may be indicative of sequential processing deficits. The current study was limited to a single measure of sequential learning. Future research with multiple verbally-mediated and non-verbal implicit learning measures would further inform us about the association between auditory deprivation and sequential processing and learning.

Acknowledgments

Source of Funding:

This research was supported by the following grants: NIH-NIDCD: P50DC000242 and American Speech-Language-Hearing Foundation Clinical Research Grant. The authors had full editorial control of this work and manuscript.

References

- Bharadwaj SV, Mehta JA. 2016; An exploratory study of visual sequential processing in children with cochlear implants. *International Journal of Pediatric Otorhinolaryngology*. 85:158–165. [PubMed: 27240516]
- Conway CM, Karpicke J, Pisoni DB. 2007; Contribution of implicit sequence learning to spoken language processing: Some preliminary findings with hearing adults. *Journal of Deaf Studies and Deaf Education*. 12(3):317–334. [PubMed: 17548805]
- Conway CM, Pisoni DB, Anaya EM, Karpicke J, Henning SC. 2011; Implicit sequence learning in deaf children with cochlear implants. *Developmental Science*. 14(1):69–82. DOI: 10.1111/j.1467-7687.2010.00960.x [PubMed: 21159089]
- Conway CM, Pisoni DB, Kronenberger WG. 2009; The importance of sound for cognitive sequencing abilities: The auditory scaffolding hypothesis. *Current Directions in Psychological Science*. 18(5): 275–279. [PubMed: 20725604]
- Farmer ME, Klein RM. 1995; The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review*. 2(4):460–493. [PubMed: 24203785]
- Gabriel A, Maillart C, Stefaniak N, Lejeune C, Desmottes L, Meulemans T. 2013; Procedural learning in specific language impairment: effects of sequence complexity. *Journal of the International Neuropsychological Society*. 19(3):264–271. [PubMed: 23298411]
- Grafton ST, Woods RP, Tyszka M. 1994; Functional imaging of procedural motor learning: Relating cerebral blood flow with individual subject performance. *Human Brain Mapping*. 1(3):221–234. [PubMed: 24578042]
- Hall, ML; Eigsti, I-M; Bortfeld, H; Lillo-Martin, D. Auditory access, language access, & implicit sequence learning in deaf children; *Developmental Science*. 2017. e12575
- Kidd E. 2012; Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology*. 48(1):171–184. DOI: 10.1037/a0025405 [PubMed: 21967562]
- Levesque J, Theoret H, Champoux F. 2014; Reduced procedural motor learning in deaf individuals. *Frontiers in Human Neuroscience*. 8:1–6. DOI: 10.3389/fnhum.2014.00343 [PubMed: 24474914]
- Nissen MJ, Bullemer P. 1987; Attentional requirements of learning: evidence from performance measures. *Cognitive Psychology*. 19:1–32.
- Pisoni DB, Kronenberger WG, Chandramouli SH, Conway CM. 2016; Learning and memory processes following cochlear implantation: the missing piece of the puzzle. *Frontiers in Psychology*. 7doi: 10.3389/fpsyg.2016.00493
- Sharma A, Dorman MF, Spahr AJ. 2002; A sensitive period for the development of the central auditory system in children with cochlear implants: implications for age of implantation. *Ear and Hearing*. 23(6):532–539. [PubMed: 12476090]
- Tomblin JB, Mainela-Arnold E, Zhang X. 2007; Procedural learning in adolescents with and without specific language impairment. *Language Learning and Development*. 3(4):269–293. DOI: 10.1080/15475440701377477
- Ulanet PG, Carson CM, Mellon NK, Niparko JK, Ouellette M. 2014; Correlation of neurocognitive processing subtypes with language performance in young children with cochlear implants. *Cochlear implants International*. 15(4):230–240. [PubMed: 24840711]
- Torkildsen J, Arciuli J, Haukedal CL, Wie OB. 2018; Does a lack of auditory experience affect sequential learning? *Cognition*. 170:123–129. [PubMed: 28988151]

Figure 1. Group mean reaction times (in ms) across trial blocks for the cochlear implant (CI) and normal hearing (NH) groups. Each trial block consists of 20 trials. Error bars indicate standard error.

Table 1

Characteristics of participants with cochlear implants (CIs).

Subject Number	Age at Test (years)	Sex	Age at 1 st CI (years)	Age at 2 nd CI (years)	Configuration at Testing	PPVT SS	BRIEF GEC t-score	NEPSY BC SS	BE-PTA
CI-1	8.2	F	1.1	--	Unilateral	94	43	14	118.8
CI-2	7.3	F	1.1	4.6	Bilateral	72	38	DNT	111.3
CI-3	8.2	M	1.2	--	Unilateral	90	44	12	118.8
CI-4	8.3	M	1.2	--	Unilateral	69	57	DNT	118.8
CI-5	9.5	M	1.2	5.5	Bilateral	95	DNT	10	118.8
CI-6	9.4	M	1.3	--	Unilateral	79	51	18	87.5
CI-7	9.9	F	1.4	8.1	Bilateral	110	46	DNT	118.8
CI-8	7.8	M	1.4	--	Bimodal	40	54	8	111.3
CI-9	9.6	F	1.5	--	Unilateral	68	57	7	96.3
CI-10	11.5	F	1.6	9.4	Bilateral	115	52	DNT	113.8
CI-11	11.8	F	1.6	--	Unilateral	91	63	13	118.8
CI-12	11.4	F	1.6	--	Unilateral	75	54	13	118.8
CI-13	9.6	M	1.7	--	Bimodal	99	54	DNT	92.5
CI-14	10.9	M	1.7	--	Unilateral	44	34	14	118.8
CI-15	10.1	F	2.1	--	Unilateral	60	52	1	102.5
CI-16	7.7	M	2.7	6.9	Bilateral	55	57	13	92.5
CI-17	11.2	F	3.1	--	Bimodal	92	43	13	83.8
CI-18	10.3	M	3.1	--	Unilateral	57	58	13	111.3
CI-19	7.9	M	3.9	--	Unilateral	63	68	12	83.3
CI-20	7.6	F	3.9	6.1	Bilateral	89	43	DNT	92.5
Mean (SD)	9.4 (1.5)	--	1.9 (0.9)	6.8 (1.8)	--	77.9 (21.0)	50.9 (8.6)	11.5 (4.0)	106.4 (13.5)

Note: "Bimodal" = use of a hearing aid in the non-implanted ear; Age at 2nd CI is only reported for children with bilateral CIs; PPVT SS = Peabody Picture Vocabulary Test-3rd edition (Normative mean = 100; SD = 15); BRIEF GEC = Behavior Rating Inventory of Executive Function Global Executive Composite (Normative mean = 50; SD = 10); NEPSY BC SS = Developmental Neuropsychological Assessment Block Construction Scaled Score (Normative mean = 10, SD = 3); DNT = Did not test; BE-PTA = pre-operative better-ear pure-tone average (4-frequency for 18 participants, 3-frequency for 1 participant, sound field for 1 participant).