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Effects of early auditory experience on word learning and speech perception in deaf children with cochlear implants: Implications for sensitive periods of language development

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Abstract

Hypothesis—That early word learning and speech perception skills have different sensitive periods and that very early implantation may affect later vocabulary outcomes more than speech perception outcomes.

Background—Several studies have found that deaf children who receive cochlear implants before three years of age tend to have better speech perception outcomes than children implanted later. Recent studies have not found age-at-implantation effects on speech perception or central auditory processing among children implanted under two years of age, suggesting that there may be a sensitive period for speech perception skills that closes by around three years of age. There has been very little work investigating possible sensitive periods for other language skills, such as the ability to learn words. Recent work suggests the possibility that the development of word-learning skills may have an earlier sensitive period than the development of speech perception skills.

Methods—Assess speech perception and vocabulary outcomes in children implanted before 13 months of age and in children implanted between 14 and 22 months of age.

Results—Children implanted during the first year of life had better vocabulary outcomes than children implanted during the second year of life. However, earlier implanted children did not show better speech perception outcomes than later implanted children.

Conclusions—There may be an earlier sensitive period for developing the ability to associate the sound patterns of words to their referents than for developing speech perception and central auditory processing skills.

Introduction

An important and pervasive finding among research teams who investigate cochlear implantation in children is that while cochlear implants (CIs) provide individuals with profound hearing loss access to sounds, there is a large amount of individual variability in language outcomes after implantation[1]. Although many children achieve age-appropriate language after implantation, many others have much poorer language outcomes. Trying to understand this variability is what motivates much of the research on CI outcomes.

Over the past 25 years, investigators have identified a number of factors that have been found to contribute to the variability found in language outcomes. These include: age at implantation; amount of residual hearing before implantation; duration of deafness, duration

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of CI use, number of electrodes inserted, communication mode, amount of speech-language therapy, and etiology of hearing loss. One of the most important factors has been age at implantation. Children implanted at earlier ages tend to have better language outcomes than children implanted later[2–8].

Findings showing that earlier implantation leads to better language outcomes lead to the question: How early is early enough? Increased risks associated with surgery on very young infants makes this an important clinical question[9]. And this question leads to another question: What are the important sensitive periods for language development? Answering this latter question will help to determine how early in development access to auditory information is needed to acquire the skills necessary for good language development.

Sensitive Periods of Development

In an excellent review of sensitive periods, Knudsen[10] wrote that sensitive periods: "… represent periods in development during which certain capacities are readily shaped or altered by experience…." and that "… the experience must be of a particular kind and it must occur within a certain period if the behavior is to develop normally." Applied to language development, this means that there are periods of development in which specific experiences and sensory inputs are necessary for language skills to develop normally. Knudsen also asserted that: "Complex behaviors may comprise multiple sensitive periods." Language is a very complex behavior, so there is good reason to believe that different language skills will have different sensitive periods.

Second-language acquisition—Much of the research that addresses sensitive periods of language development has been conducted on second-language learning. Studies of second language acquisition have found that age of onset of acquisition plays an important role in how well a language is learned[11–14]. For example, Johnson and Newport[13] investigated the effects of age of immersion in an English-speaking environment on native Chinese- and Korean-speaking adults' mastery of English. The participants had moved to the United States between 3 and 39 years of age and had at least five years of experience with English. Using several measures of grammaticality judgment, the investigators found that language mastery was strongly correlated with age of arrival and uncorrelated with duration of English experience, amount of formal instruction, degree of identification as an American, motivation to learn English, or self-consciousness. Notably, the effect of age of immersion appears to be linear rather than discontinuous[12,15], which is in contrast to a "critical period" view of language acquisition[16].

There are several possible explanations for why age-at-exposure matters for second-language acquisition. One possibility is that the later the onset of the second language, the more the first language is entrenched in the brain and interferes with learning the second language. Another possibility is that general cognitive mechanisms are better suited for learning language early in life than later in life. In her "less-is-more" hypothesis, Newport proposed that by having shorter working memory spans, younger children may be better able to focus their attention on smaller units of information, providing an important constraint on the amount of information that is processed[17]. More recently, it has been proposed that language may be more difficult to learn at later ages because of a shift in the type of cognitive computations utilized. Felser and Clahsen[18] propose that children may use procedural memory more while adults make more use of the declarative memory system.

Sign-language acquisition—Studies of first-language acquisition in deaf children bear on the above issues in several ways. First, studying first-language acquisition neutralizes any effects of interference from another language. Second, because early auditory deprivation has been found to affect various general cognitive processing skills, the role of general cognitive processing skills on language acquisition can be further investigated. Most studies on first-language acquisition have been conducted on congenitally deaf individuals' acquisition of sign language. Similar to the studies on second-language acquisition, several studies have shown that sign language is learned better earlier in life[19–22]. Moreover, there seems to be a carryover effect on second-language acquisition from age at first-language acquisition. Deaf adults are better able to comprehend written English if they learned sign language early in life than if they learned sign language later in life[23].

Taken together, the findings with second-language acquisition and first-language acquisition both suggest that early experience in important for language development. It is possible that some of the difficulty learning a second language is due to interference from the first language; but findings with deaf individuals who use sign language suggest that there may be more general maturational constraints that limit language acquisition in children as they grow older. What these areas of research do not address is how early access to sensory information in a particular modality affects the ability to learn language in that sensory modality. It is possible that in addition to sensitive periods for learning linguistic structure, there may also be sensitive periods for being able to process and encode linguistic information in a particular sensory modality. This possibility can be addressed by assessing the effects of age-at-implantation on linguistic processing skills in deaf children who receive CIs.

Spoken-language acquisition in deaf children after cochlear implantation—The advent of cochlear implantation has opened the door for research into the role of early access to auditory input on the development of auditory processing skills and spoken language development. Several studies have investigated the effects of age-at-implantation on language outcomes and found that earlier implantation leads to better language outcomes[2–8]. For example, Dettman et al[3] found that children implanted before 12 months of age performed significantly better on measures of receptive and expressive language than children implanted between 12 and 24 months of age, suggesting that there may be a sensitive period for spoken language development at less than 12 months of age.

The possibility that there is an early sensitive period for spoken language development raises several questions. Which linguistic processing skills must be developed at an early age for successful language development to occur? Do different skills have different sensitive periods? Which ones are most affected by early auditory deprivation? Answering these questions is important for understanding sensitive periods and for determining possible benefits that might be gained from implantation at earlier ages.

Auditory processing and speech perception: An obvious candidate for a linguistic processing skill that might be affected by early auditory deprivation is auditory processing. Recently, Anu Sharma and her colleagues have investigated central auditory development in deaf infants and children before and after cochlear implantation by measuring latencies of auditory evoked potentials. P1 and N1 latencies decrease over development in normal-hearing children and thus may serve as indicators of maturation for aspects of the central auditory system. These investigators found that P1 and N1 latencies declined more in earlier-implanted children: Latencies usually fell within normal ranges in children implanted before 3.5 years of age after less than 1 year of CI experience; latencies rarely ever fell within normal ranges in children implanted after seven years of age; and latency results are highly variable among children implanted between 3.5 and seven years of age[24–26]. The authors interpret these findings as suggesting that there is a sensitive period cut-off for central auditory development at around 3.5 years of age[27]. Findings from recent studies comparing speech perception skills in children implanted before or after 3 to 5 years of age are consistent with an auditor processing sensitive period that ends at around 3.5 years of age[28,29]. However, very few studies have investigated the effects of age-at-implantation on speech perception skills among children implanted at earlier ages.

To test the possibility that there are important sensitive periods for speech perception before 3.5 years of age, it is necessary to compare speech perception outcomes among children implanted before 3.5 years of age. Two studies have found age-at-implantation effects on speech perception among children implanted under 3 years of age. One study tested speech perception using a modified open-set word recognition task[7]; the other used a parental report of auditory skills development[30]. In both studies differences in speech perception skills were found in children implanted under two years of age compared to children implanted between two and three years of age. Two studies from our lab, which tested speech discrimination skills, found no age-at-implantation differences in speech discrimination performance among infants and toddlers implanted before two years of age[31,32]. These latter studies assessed speech discrimination skills within the first year and a half of implantation. It is possible that effects of age-at-implantation may emerge after more CI experience.

Word learning: While there have been several investigations that have investigated the effects of age-at-implantation on speech perception or general language skills, there has been very little work investigating sensitive periods of specific higher-level language skills, such as the ability to learn words. Word learning occurs throughout life. Thus, there is clearly not a sensitive period for when words can be learned. However, there may be a sensitive period for acquiring the ability to associate the sound patterns of words to their referents. Developing the ability to learn words is crucial for acquiring language, but very little is known about possible sensitive periods for acquiring this skill. The sensitive period for word learning may be earlier or later than the sensitive period for central auditory development. It is difficulty to predict because little is known about how early auditory deprivation affects the plasticity of neural circuits associated with central auditory development compared to how it affects the neural circuits associated with word-learning skills.

Vocabulary and Word Learning in Older Children

What little is known about sensitive periods of word-learning skills in children with CIs we know mainly indirectly from studies of vocabulary development, which show that children who are implanted at earlier ages tend to have larger vocabularies than children implanted at later ages[4,5]. However, this finding may be due to the fact that earlier implantation means that children have had more time to learn words. Or it might be that there is a sensitive period for acquiring word-learning skills such that earlier access to sound results in better word-learning skills.

Some recent studies have addressed word-learning skills in older children who use CIs[33–35]. For example, Willstedt-Svensson et al[35] assessed word-learning skills in 5.5- to 11.5-year-olds and found that word-learning skills were correlated with age at implantation and working memory. Houston, Carter et al.[33] found a weak-to-moderate correlation between age-at-implantation word-learning performance in 2.5- to 5.5-year-olds with 1 to 3 years of CI experience. These findings provide some evidence for age-at-implantation effects on word learning. However, these studies did not investigate the effects of very earlier implantation – during the first year of life. Moreover, the studies were conducted with children who were well beyond the ages at which word-learning skills begin to develop, even in terms of their “hearing ages” (i.e., duration of CI use). Word learning begins as young as six months of age[36], and children begin producing words at around 12 months of age and begin to rapidly learn words by 18 months[37]. Thus, to investigate sensitive periods on early word-learning skills, it is necessary to study word learning at younger hearing and chronological ages.

Early Word-Learning Skills in Early Implanted Infants

We recently conducted two studies to address the effects of very early implantation on early word-learning skills[38,39]. Both studies compared infants who had their CIs switched on by 13 months of age and infants who had their CIs switched on between 14 and 24 months of age. Both studies used a version of the intermodal preferential looking paradigm (IPLP).

In the IPLP, infants are seated on their caregiver's lap in front of a large TV monitor, which displays the auditory and visual stimuli. During a training phase, infants are presented with two pair of novel words and novel objects, one at a time. Houston, Ying et al[38] presented infants with sound patterns (e.g., hop hop hop) that were associated with dynamic stimuli (e.g., a toy kangaroo hopping in rhythm to the sound). Thus the auditory and visual pairings had intersensory redundancy (e.g., rhythmic synchrony) to make associating the auditory and visual stimuli easier than in a typical word-learning situation. These relatively easy stimuli were used so that we could validate the IPLP with CI infants and investigate the very beginnings of being able to associate speech sounds with visual events. Houston, Stewart, et al[39] presented infants with novel words (e.g., blick) that were associated with novel objects.

During test phases, infants were presented with both objects and one of the words (or speech patterns). Several studies using the IPLP have shown that if infants are able to learn the associations, then they will look longer at the object that was associated to the word during the training phase (the target) than to the other object (the distractor)[40]. The test phases were organized into four blocks of four test trials – two for each word. Between each test block, infants were presented with two *reminder trials* in which each word-object pairing was presented one-at-a-time to give the infants additional opportunities to learn the pairing. In both studies we found that the earlier-implanted infants showed word learning but the later implanted infants did not. These age-at-implantation findings among toddlers implanted before two years of age contrast with the lack of age-at-implantation findings in our speech discrimination studies and suggest that there may be an earlier sensitive period for developing word-learning skills than there is for developing speech perception skills.

Implications for Outcome Measures

How might multiple sensitive periods during the early stages of language acquisition affect speech perception and language outcomes? If there is an earlier sensitive period for word-learning skills than for auditory processing, then we should see bigger differences between earlier- and later-implanted children on outcomes directly related to word learning, such as vocabulary, than on outcomes more related to auditory processing, such as closed and open-set word recognition tasks. We explored this possibility by comparing speech perception and vocabulary outcomes among the earlier and later implanted children who participated in Houston and colleagues' speech discrimination and word learning studies.

Method

Participants

Of the children who participated in the above studies, there were fifteen who had minimal residual pre-CI hearing (PTA ≥ 105) and who had been tested on later vocabulary and/or speech perception outcome measures at 2 to 4 years after implantation. Displayed in Table 1 are the participants IDs, the age at which their CIs were switched on, their pre-CI PTAs, and the etiology of their hearing loss. The mean age at which their implants were switched on was 14.8 mos. Based on that mean, we divided participants into two groups: The *early* group had their CIs switched on between 7 and 13 months of age; the *late* group had their CIs switched on between 16 and 23 months of age.

Materials and Procedure

Speech perception was assessed using two closed-set word recognition tasks – the Grammatical Analysis of Elicited Language – Pre-Sentence Level (GAEL-P)[41] and the Pediatric Speech Intelligibility Test (PSI)[42] – and an open-set word recognition task – the Lexical Neighborhood Test (LNT)[43]. Vocabulary was assessed in children with CIs using the Peabody Picture Vocabulary Test (PPVT)[44]. Because vocabulary develops with age and our participants varied in age, raw scores were converted to standard scores for the PPVT. There are no standard scores for the speech perception measures because speech perception does not change significantly in normal-hearing children.

Outcome measures were assessed at two post-CI intervals. The GAEL-P, PSI (sentence component, presented auditory-only), and PPVT were administered after 2 to 2.5 years of CI experience. The LNT and PPVT were administered after 3 to 4 years of CI experience. All tests were administered by licensed speech-language pathologists in the DeVault Otologic Research Lab.

Results

Figure 1 displays the percent correct on two of the speech perception measures (GAEL-P, PSI) and the standard scores on the vocabulary measure (PPVT) during the first outcome interval for the two groups of children. There were no statistically significant differences between the groups on the measures of speech perception. However, the early-implanted group performed significantly better on the measure of vocabulary than the late-implanted group (t (12) = 2.35, p = .04). Figure 2 displays the performance on the speech perception (LNT) and vocabulary (PPVT) measures administered during the second outcome interval. As in the first interval, the groups did not differ significantly with respect to speech perception, but the early-implanted group performed significantly better on the vocabulary measure than the late-implanted group (t (t (9) = 2.38, p = .04).

Discussion

Taken together, these preliminary results of the early behavioral testing and the later measures of speech perception and vocabulary outcomes raise the that very early implantation may affect learning associations between the sound patterns of words and their referents more so than it affects speech perception outcomes. Of course, given the small sample size of the studies, much more data is required to fully test this hypothesis. Further work is also needed to determine how early development of speech perception and word-learning skills impact on later speech perception and language outcomes. Recently, Houston et al[39] reported that performance on the word-learning task correlated strongly with vocabulary outcomes but did not correlate with speech perception outcomes; and Houston[45] reported that performance on the speech perception task in Houston, Pisoni, et al[31] correlated significantly with speech perception outcomes but not with vocabulary or language outcomes. The pattern of results suggests that very early implantation leads to better word-learning skills, which results in better vocabulary outcomes. In contrast, the variability in early speech perception skills that correlate with speech perception outcomes do not seem to be associated with differences in age-at-implantation. Additional work is necessary to determine the factors underlying the variability of early speech perception skills.

The fact that we did not find significant differences in speech perception performance between the two groups is consistent with findings by McConkey Robbins[30] who assessed auditory skill development among children implanted under three years of age. Using the IT-MAIS parental report, children implanted under two years of age were reported to have better auditory skills than children implanted between two and three years of age. However, there were no differences in reporting of auditory skills between children implanted between 18 and 24 months of age and those implanted between 12 and 18 months of age.

Implications for Sensitive Periods

The work reviewed here suggest that auditory experience under two or three years of age may be important for developing normal central auditory development but that auditory experience by one year of age may be important for developing normal word-learning skills. These findings suggest the possibility that there is an earlier sensitive period for developing the ability to learn words than for central auditory development. Moreover, auditory deprivation during the first two years of life may have longer lasting effects on vocabulary and language outcomes than on central auditory development.

Auditory deprivation may affect much more than the peripheral auditory system and even more than central auditory functioning. Early sensory experience forms the foundation of cognitive and linguistic development and so the nature of early sensory experiences is likely to have long-lasting effects on cognition and language acquisition. Thus, in order to further understand the effects of early auditory deprivation on language development, future work should investigate other sensitive periods important for language development by assessing the effects of age-at-implantation on cognitive and linguistic skills during infancy and the long-term effects of these skills on language outcomes. Investigating these sensitive periods and their long-term effects will be important for decisions regarding habilitation strategies and for deciding how early deaf infants should receive cochlear implants.

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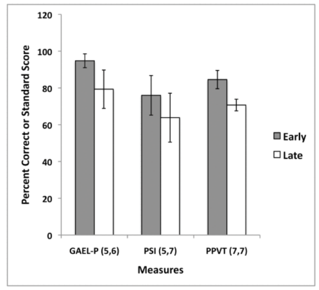

Figure 1.

Speech Perception and Vocabulary Outcomes: Interval 1

Note. Displays the mean percent correct on the GAEL-P and the PSI and the mean standard score on the PPVT for early- and late-implanted children. The numbers of participants tested in the early- and late-implanted groups are reported, respectively, in parentheses next to the name of each test. Bars indicate standard error.

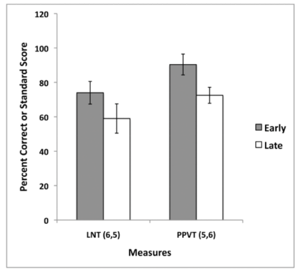

Figure 2.

Speech Perception and Vocabulary Outcomes: Interval 2

Note. Displays the mean percent correct on the LNT and the mean standard score on the PPVT for early- and late-implanted children. The numbers of participants tested in the early- and late-implanted groups are reported, respectively, in parentheses next to the name of each test. Bars indicate standard error.

Table 1

Participant Characteristics

Subject ID	Age CI Fit (Months)	PTA (dB)	Etiology
343	7.6	118	Unknown
536	8.3	118	Genetic
560	10.3	112	Unknown
487	11.8	113	Genetic
436	12.2	112	Unknown
476	12.7	118	Unknown
572	12.7	117	Unknown
503	16.1	118	Unknown
529	16.5	118	branchio-oto-renal-syndrome
507	16.8	118	Unknown
451	17.0	105	Unknown
452	17.4	113	Unknown
346	19.1	113	Unknown
461	20.9	107	Mondini formation
583	22.6	105	Unknown