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# Developmental constraints on language development in children with cochlear implants

**Key Words**
Speech and language
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Critical periods
Age of implantation
Sensitive periods
Experience dependence
Fast mapping

## Abstract

Research on pediatric cochlear implantation has frequently shown that speech perception, speech production, and language outcomes are better for children who are implanted earlier in life than later. These findings are often explained on the grounds that earlier implantation takes advantage of a *critical* or *sensitive period*. This paper reviews the literature concerning sensitive periods within the framework of speech and language development. It particularly emphasizes two alternate mechanisms proposed for these periods: an experience-independent mechanism, and an experience-dependent mechanism. Based on this literature review we proposed that research in the field of pediatric cochlear implantation needs to carefully define what kind of evidence is needed to reflect a sensitive period for speech and language learning. The field also needs to consider designing studies that allow the viability of these two mechanisms to be tested. An example of such a study is provided within.

## *Sumario*

La investigación sobre la implantación coclear pediátrica ha mostrado con frecuencia que la percepción y la producción del lenguaje, y los resultados finales de adquisición del lenguaje son mejores en niños que se implantan más tempranamente que tarde en la vida. Estos hallazgos a menudo se explican sobre la base de que una implantación temprana saca ventaja de un *período sensible o crítico*. Este artículo revisa la literatura relacionada con los períodos sensibles dentro del marco de desarrollo del habla y el lenguaje. Enfatiza, en particular, dos mecanismos alternativos propuestos para estos períodos: un mecanismo independiente de la experiencia, y un mecanismo dependiente de la experiencia. Con base en esta revisión de la literatura proponemos que la investigación en el campo de la implantación coclear pediátrica necesita definir cuidadosamente qué tipo de evidencia se necesita para reflejar un período sensible en el aprendizaje del habla y el lenguaje. Este campo necesita también considerar el diseño de estudios que permitan evaluar la viabilidad de estos dos mecanismos. Se incluye un ejemplo de tal estudio.

Since the time children with congenital deafness began to receive cochlear implants, there has been a general trend toward considerations of earlier implantation. Initially, in the 1980s, most children receiving implants were around five years of age and many were well above ten years of age. In the mid-1990s, *early implantation* was viewed as occurring in children between two and five years of age; *late implantation* was viewed as occurring in children older than eight years of age. In recent years, the typical age at which children receive cochlear implants continues to decline. Now implantation after two years of age is viewed as late implantation and early implantation is viewed as occurring before one year of age. Several factors motivated this decline in children's ages at implantation, but one of these certainly has been the evidence-based belief that earlier implantation results in better speech, language, and listening outcomes. This belief coincides with observations made over the past 40 years that the acquisition of speech and language appears to be ontogenetically constrained. Broadly this constraint is revealed by a variety of evidence that indicates that humans seem to be better at learning speech and language when they are younger than when they are older. This observation led to the hypothesis that there is a special time in development, termed either *critical period* or *sensitive period*, during which these aspects of speech and language are learned efficiently.

Given that the placement of a cochlear implant in a child who is deaf possibly shifts her developmental trajectory, the construct of a critical or sensitive period for speech and language becomes an important notion for both research and clinical work dealing with children who receive cochlear implants. As researchers, it is particularly important to consider whether and why implantation at different ages may account for some of the variations in speech and language outcomes noted in these children (ASHA, 2003). The present paper reviews the literature concerning sensitive periods within the framework of speech and language development, while also illustrating the importance of sensitive periods within the field of pediatric cochlear implantation. We will be focusing on these issues with respect to speech and language and will not attempt to incorporate the research on sensitive periods and sensory deprivation effects on the primary auditory pathways. The paper begins with an overview of some of the research findings concerning age effects in speech and language development. We then consider two alternate classes of mechanisms proposed to explain these data: an experience-independent mechanism and an experience-dependent mechanism. Next we use the knowledge of these mechanisms to place the emerging research results demonstrating age-at-implantation effects into the context of the theory and research on sensitive periods for speech and language development. We specifically suggest that research in the field of pediatric cochlear implantation needs to carefully define what kind of evidence is needed to reflect a sensitive period. Finally, we present some preliminary evidence from a novel-word learning experiment that provides a

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framework for testing viability of experience-independent and experience-dependent mechanisms.

## Critical and sensitive periods

The terms critical period and sensitive period are often used somewhat interchangeably in the literature. Although the term *critical period* is the most dominant, in recent years those concerned with complex behaviors such as speech and language favor the use of *sensitive period*. Commonly, *sensitive periods* are defined as a time in development in which the organism is particularly responsive to experience (Bruer, 2001). Alternatively a *critical period* is viewed as a time in development in which experience, or the absence of experience, results in irreversible changes in the brain (Bruer, 2001). Sensitive periods, in contrast, do not necessarily result in a complete irreversible change in the brain.

Another way these terms are distinguished is related to the shape of the sensitivity function during the period. Bruer (2001); Werker & Tees (2004); and Newport et al (2001) described critical periods as having very sharp onsets and offsets with stable levels of sensitivity to input in the interim (see the upper panel of Figure 1). Sensitive periods are described as having gradual onsets with a peak in sensitivity at some point in the period that is followed by a loss of sensitivity (see the lower panel of Figure 1). Thus, critical periods are described by the metaphor of a window quickly opening, remaining open for the duration of the period, and then rapidly closing while subsequently being highly resistant to the effects of experience. In contrast, sensitive periods have slower and more continuous dynamics, thus the metaphorical window may never close completely. Along with the differences in the temporal course of sensitive periods and critical periods, we would expect there to be differences in the mechanisms that drive these different types of constraints on development. However, within the speech and language developmental literature we are not able to document that these terms are differentiated with respect to the mechanism involved. Therefore, we will use the term sensitive period in this paper to refer to both these accounts.

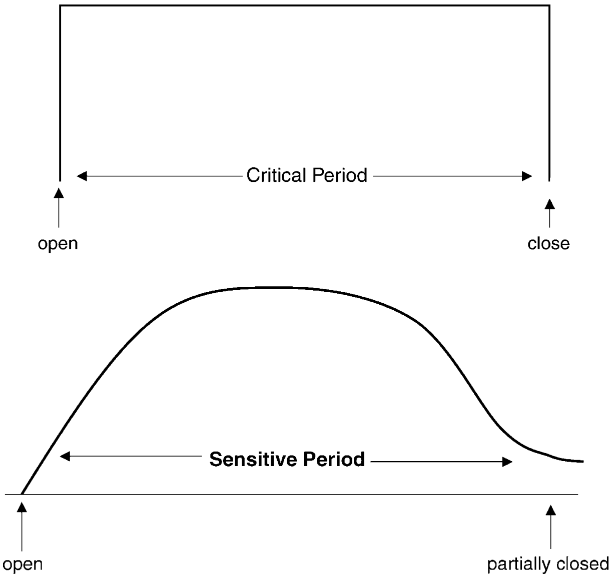

**Figure 1.** Contrasting characterizations of the temporal course of a hypothetical critical period (top) versus a sensitive period bottom.

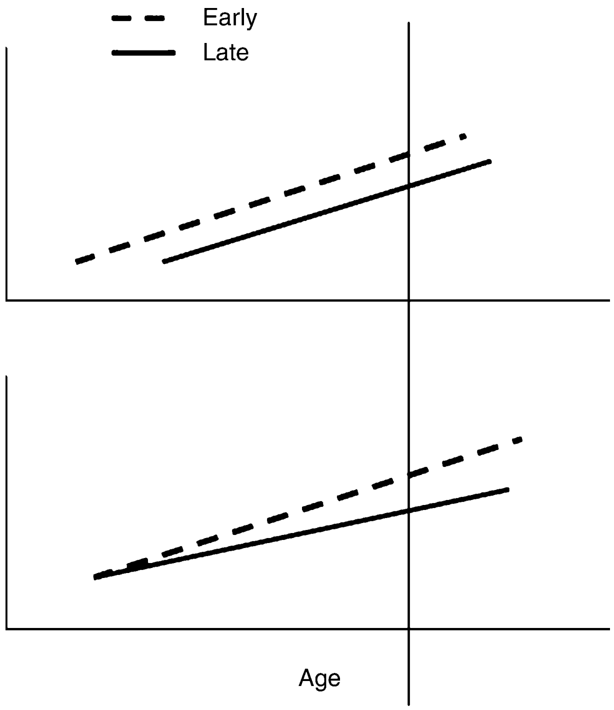

**Figure 2.** Two ways in which earlier implantation can result in better outcomes at a later time shown by the vertical line cutting across both graphs. In the top graph early implantation provides a benefit via influencing the intercept but does not affect growth rate. In the lower graph earlier implantation would provide a benefit via changing the rate of learning.

Within the literature on sensitive periods there are two parallel issues regarding constraints on speech and language development. The first issue concerns whether there is evidence that such constraints exist. In other words, are older learners less adept at speech and language learning than younger learners? We will show that the empirical evidence to date is largely in the affirmative. The second issue concerns the source of the constraints on development. It is with this issue that we will demonstrate the greatest amount of disagreement and, in some cases, a failure to specify the mechanism at all. In an attempt to organize this literature, within this paper we will distinguish between mechanisms that are *experience independent* and those that are *experience driven.*

### *Experience-independent mechanisms*

One of the early statements within the field concerning sensitive periods for speech and language development came from Eric Lenneberg (Lenneberg, 1967). Lenneberg proposed that speech and language were an outgrowth of particular biological characteristics of humans, which arose independently of the child's life experiences. Specifically, he proposed that there is a sensitive period for language development that terminated with the onset of puberty. His reasoning was based on studies of second-language (L2) learning, aphasia recovery, and poor speech and language growth in children with mental retardation demonstrating a termination in language-learning processes after the onset of puberty. The mechanism that drove this termination was a maturational brain process of lateralization of language processing to the left hemisphere. This maturational process was controlled by fundamental, chronological-age-dependent, experience-independent, biological growth processes. The timing of the opening and closing of the sensitive period for speech and language was not influenced by the speech-language exposure provided to the learner.

Lenneberg's thinking about the experience-independent mechanisms involved in language acquisition was clearly nativist. He assumed specific biological systems were involved in language and these systems constrained the acquisition process. The nativist perspective expressed by Lenneberg was not the same as the linguistic nativism espoused by Chomsky (for instance: Chomsky, 1986). Fundamental to Chomsky's thinking is that the acquisition of grammar involves a genetically determined, grammar-learning mechanism. Some accounts of Chomsky's theory assume that the grammatical knowledge contained in the mechanism is available to the child at birth (Crain & Pietroski, 2001). Whereas other accounts propose that the grammatical knowledge becomes available during childhood due to genetically controlled maturation (Borer & Wexler, 1987). In the case of Borer and Wexler's proposal several sensitive periods (timed by genetic expression) would have to be present. These sensitive periods would be responsible for placing certain knowledge online for learning. These accounts are less specific about the termination of a sensitive period for learning than Lenneberg's account. However, they could easily argue that at some point the language acquisition system becomes disassembled and any subsequent language learning relies on alternate mechanisms (Newport, 1990).

### *Evidence in favor of experience-independent mechanisms*

Lenneberg's hypothesis of a sensitive period for speech and language development has motivated research searching for evidence of sensitive periods in L2 learners and late-onset first language (L1) learners. In the subsequent pages, we will review this research and identify the primary issues that have emerged with these populations.

### Second language learning

Lenneberg's maturational hypothesis predicts that language proficiency during adulthood should be negatively correlated with the age at which L2 learning begins prior to puberty (i.e. before 15-years-old). It is further predicted that native language proficiency cannot be obtained when learning begins after puberty (Birdsong & Molis, 2001a). A sizable amount of this L2 literature examined the degree to which the age when an L2 learner begins learning the L2 is correlated with the degree to which native language users judge that the L2 learner has a foreign accent (Flege et al 1995; Krashen & Ladefoged, 1975). In the typical paradigm, adult immigrants' speech is first evaluated with regard to the presence of a non-native accent. These measures range from perceptual ratings to detailed acoustic analyses. These data are then related to the age at which the participant immigrated and used as a measure of the person's age at acquisition of the L2. In general, these studies showed that age at acquisition was related to having foreign-accented speech during adulthood. Adults exposed to the L2 in childhood were more likely to have native-like accents (Oyama, 1976; Scovel, 2000; Long, 1990; Patkowski, 1994).

If this constraint process were following the time course of a critical period we would predict that there should be a discontinuous relationship between age at acquisition and accented speech that follows the rapid ending of the critical period. Such a relationship would suggest that an L2 initiated 'before the window closed' would be much more native-like and L2 learning initiated 'after the window closed' would be highly non-native-like. Additionally a critical period account would argue that there should be few (if any) native-like speakers who began L2 learning after adolescence. Often the same data that showed an age-at-acquisition effect (i.e. later L2 learners are more likely to have accented speech than earlier L2 learners) failed to show any clear discontinuity in this relationship between accent and age of L2 learning. In other words, there was no evidence suggesting that unaccented speech was common up to a particular age, and then after that age accented speech was more likely (for instance see: Birdsong & Molis, 2001b; Flege, 1987; Flege et al, 1999; Bongaerts et al, 1997). Instead, in these studies, the age-at-acquisition effect was gradual and continuous; accented speech became more prominent as age-at-acquisition increased. It is also important to note that cases of adult onset in L2 learning resulting in an unaccented, spoken L2 were also reported. It thus appears that with regard to speech acquisition, *sensitive period* serves as a better description of the data than *critical period*.

Much of the literature on L2 critical/sensitive periods focused on phonological properties of speech. However in recent years, there has been an increased interest in morphosyntactic development in L2 learners as well. This research used a paradigm similar to the foreign accent research to evaluate age-at-acquisition effects with regard to morphosyntactic development. In particular, the research asked whether the L2 learners with later ages at acquisition were less skilled at grammaticality judgments than those L2 learners with earlier ages at acquisition. This question was posed by Johnson and Newport (1989) in a very influential paper. In their study Chinese and Korean adult speakers, who had immigrated to the U.S. at different ages, were tested on their ability to make grammaticality judgments of English. This study reported that participants who immigrated before the age of six years could make judgments similar to native speakers. Alternatively, the grammaticality judgments of the participants who arrived to the U.S. between the ages of six and 15 years were negatively correlated with their ages at acquisition and no correlation was found between age at acquisition after 15 years of age. The authors viewed these data as strong evidence of a sensitive period that was maturationally influenced. Other researchers have also found a negative correlation between age at acquisition and grammaticality judgments (Flege et al, 1999; Bialystok & Miller, 1999; Birdsong & Molis, 2001b), but as in the research on accent they did *not* find the discontinuity in this relationship that is indicative of a strong sensitive period. Thus, it seems that there is an age-at-acquisition effect for both speech and grammar. It seems explicitly to be an effect that suggests a gradual loss of learning facility, that is a sensitive period with a very broad shoulder, rather than an abrupt stop to learning associated with a critical period.

This age-at-acquisition effect was also examined with respect to semantics. Phonology and grammar are both language systems that are usually mastered by native speakers by the end of childhood, but semantic development appears to continue throughout life. Weber-Fox & Neville (1996), and Wartenburger and colleagues (2003) used brain imaging methods to demonstrate that although there is an age-at-acquisition effect for grammatical judgments, there is not one for semantic judgments. Thus, there may not be any form of a sensitive or critical period for such things as vocabulary development, or accuracy in judging non-meaningful (anomalous) sentences. It is reasonable to assume that lexical acquisition is not constrained because vocabulary continues to develop well into adulthood for L1 learners. These age-at-acquisition effects in phonology and grammar, but not in semantics, are quite consistent with the nativist theories derived from Chomsky. The innate knowledge that is proposed to be biologically based concerns grammar (including phonology), but not semantics.

On the surface, most of the research in L2 acquisition seems to be in agreement that there is an age-at-acquisition effect for language learning—at least within the domains of phonology and grammar. Moreover evidence supports a graded decline in language learning with an increase in age, and some retention of language ability well into adulthood.

### Late onset of first language learning

Although the sensitive period hypotheses make specific predictions with regard to L2 learning, L2 learning is a very particular type of speech and language learning problem. If the L2 research is reflective of a more general constraint on speech and language, then similar trends should also hold for L1 learning that begins later in childhood. There is a small body of research that provides additional insight into sensitive periods by examining individuals where the onset of the children's L1 was delayed. A small number of case reports of children who were extremely neglected make up much of this literature. As a result of their neglect these children were provided very little language experience until later childhood when they were taken into protective custody and provided with enriched language exposure (Curtiss, 1977; Itard, 1932; Zingg, 1940). Longitudinal follow-up studies of these children demonstrated that, after several years of language exposure, they were unable to achieve language abilities of adult, native speakers. Regrettably, interpreting these data from the perspective of finding a sensitive period is difficult. Documenting the status of these children and their environments prior to or during neglect is usually impossible, thus it is also unclear what their language status was at the time of neglect.

A less complex population of delayed L1 learners can be found within congenitally deaf adults who acquired American Sign Language (ASL) at some point in childhood. Often these adults are tested later in life for their proficiency in ASL as a measure of the effects of delayed L1 learning. Newport (1990) examined the ASL proficiency among three groups of congenitally deaf adults who had at least 30 years of ASL experience. Some of these individuals were native signers who were exposed to ASL from birth; some individuals acquired ASL when they attended a school for the deaf between the ages of six and seven years. The remaining individuals acquired ASL after the age of 12 years. Analyses of the production of sign morphology across the groups showed that ASL proficiency declined with age at acquisition. Similar findings were also reported by Mayberry (1993). Thus, the research suggested that L2 and late L1 learning are constrained such that native levels of mastery in phonology and grammar become less likely with older onsets of learning. These data are interpreted as providing evidence consistent with some type of developmentally sensitive mechanism. The specific nature of this mechanism however varies across researchers.

### *Experience-independent explanatory accounts for sensitive periods*

As we noted earlier in this paper, one dominant class of these mechanisms alter experience or cognitive/neurological systems that in turn affect language learning. We described the remaining class of mechanisms as experience-independent mechanisms. Such mechanisms may be characterized by a generalized loss of neural plasticity triggered by adolescence and the hormonal actions associated with pubescence as represented by Lenneberg (1967). Alternatively, the generalized loss may be more language-specific and genetically controlled by changes in a grammar learning module such as proposed by Boer and Wexler (1987). Regardless, these mechanisms share the property that some aspect of developmental biology triggers changes in the brain, but the timing of these triggers are not based on the prior history of learning. These accounts can therefore be viewed as involving some type of biological maturational mechanism.

Several researchers studying L2 acquisition proposed alternatives to maturational mechanisms. Researchers, who found age-at-aquisition effects in phonological and grammatical development, clearly express that they do not believe that there is a maturationally-based critical or sensitive period (Bialystok & Miller, 1999; Birdsong & Molis, 2001b; Flege, 1987; Flege et al, 1999). They instead argue that the decline in language learning facility (particularly with L2 learners) may relate to the confounds of one's educational level, involvement in an L1 speaking community after immigration, and motivation to learn the L2. In stark contrast with a maturational account, these researchers argue that there are no changes in the fundamental learning abilities of L2 learners. Rather they assume that the cultural setting for learning changes as the learner ages. In other words, older immigrants are more likely to seek companions who also speak their L1 rather than their L2, whereas younger immigrants are more likely to be assimilated into the L2 community.

Newport (1990) also hypothesized that non-maturational mechanisms may account for changes in non-language cognitive systems which could have deleterious effects on L2 learning. Elman (1993) also supported this hypothesis by demonstrating that language learning may benefit from restrictions on short-term memory at least in the early phases of learning. Thus a better memory system and the tendency to use explicit learning strategies in adults might yield a different and, possibly poorer, learner. These non-maturational mechanisms differ from the maturational accounts because they do not involve a biologically directed change in the neural system responsible for speech and language learning. Instead, the non-maturational mechanisms assume that the system remains open to learning. However, similar to the maturational mechanism, these non-maturational constraints are independent of the prior learning history of the language learner.

We will now turn to an alternate class of mechanisms, experience-dependent mechanisms. These mechanisms assume that developmental constraints arise from neural changes within the speech and language representational system due to learning.

### *Experience-dependent mechanisms*

Shortly before Lenneberg proposed a sensitive period for language, a series of papers were published in neurobiology by Hubel & Wiesel (1965; 1965; 1964; 1963). In these papers they demonstrated that kittens reared with normal visual experience resulted in each eye having sole access to alternating columns of neurons in layer IV of the visual cortex. However, this pattern is not found at birth. At birth both eyes synapse on *all* neurons in layer IV. In order to assure that a neuron is stimulated by experience coming from only one eye, a competitive process occurs in which activation and inhibitory activity results in an alternating pattern of connectivity between columns of neurons in layer IV and each eye. When kittens were reared with one eye closed for a period of time after birth, the occluded eye became essentially functionally blind. This blindness was due to the elimination of connections of the closed eye to layer IV and the lack of activity, thus an inability to compete for neuronal connectivity. Subsequent visual stimulation was not able to restore visual function. Therefore there seems to be a sensitive period for the development of binocular vision. These findings of Hubel and Wiesel are often used as the model of a maturationally-based sensitive period.

It is important to understand however, that the loss of binocular function did not arise simply because of the absence of input to the occluded eye. This is because occluding both eyes does not result in loss of binocular vision after the eyes are unoccluded (Cynader & Mitchell, 1980). Instead, it is necessary for one eye to have access to layer IV of the visual cortex while the other eye is denied access. In this way, it is the activity of the unoccluded eye that is responsible for capturing all of the connectivity in layer IV, to the detriment of the occluded eye. It seems therefore that the loss of binocular function is actually a product of the interaction of experience and brain-based learning processes. Hubel and Wiesel's work consequently illustrates an experience-dependent sensitive period as opposed to a maturationally-based sensitive period.

### *Evidence in favor of experience-dependent mechanisms*

Drawing on the work of Hubel and Wiesel and the field of neurobiology, researchers attempted to model sensitive periods in speech and language acquisition using *biologically oriented* connectionist models or neural networks (Christiansen & Chater, 2001; O'Reilly & Munakata, 2000). Neural networks are intended to model the activity of individual neurons (and/or groups of neurons) in the brain during learning. These neural network models are particularly useful for comparing the experience-independent and experience-based accounts of sensitive periods, because the network can be kept constant with regard to features affected by maturation, motivation, and amount of exposure. Once controlled, there should not be any patterns of learning suggestive of a sensitive period.

Using these learning networks, investigators examined whether features of sensitive periods may arise from the processes involved in learning (i.e. experience-dependent), rather than from processes external to learning (i.e. experience-independent). McClelland and colleagues (1999) used Hebbian learning to train networks and ask questions similar to those asked about adult, L2 learners and their L2 accents (Long, 1990; Oyama, 1976; Patkowski, 1994; Scovel, 2000). In particular, McClelland et al asked whether networks trained on one phonological system would be resistant to learning a new phonological system—just as researchers observed with regard to adults and their non-native accents. In their study, they trained half of the networks to discriminate speech simulations that fell within the semivowel space represented by the two English phonemes /r/ and /l/. The remaining networks were trained *not* to discriminate the two phonemes, but rather perceive a single blended speech category as in Japanese. The 'English trained' networks developed separate phonemic categories for /r/ and /l/ and the 'Japanese trained' networks acquired a single phoneme representation. Most importantly however, networks trained with the Japanese blended category were resistant to later learning of the English distinction. Thus these data suggested that the networks demonstrated a sensitive period for phoneme perception as a result of the networks' experiences, despite the fact that no maturational process was applied to the network.

The fundamental feature of these connectionist models is that as the network learns, the connections among nodes become committed (or biased) toward 'perceiving' and 'responding' to experience in ways that make learning new, alternate response modes more difficult. Within these networks nodes (simulated neurons or constellations of neurons) can participate in multiple activation patterns, thus new learning competes against already existing learned tendencies among nodes in the network. This competition occurs because in addition to the presence of connections that provide activating signals, there are inhibitory connections. Patterns of activating connections that become enhanced through learning then inhibit alternate patterns of activation. Thus, patterns of responses among nodes are pushed toward previously learned patterns of responses and away from alternate new responses. This biasing is increased by a property of these networks, which dictates that the initial weight changes during early learning increase or decrease in larger increments, whereas weight changes during later learning occur in smaller increments. In other words, experience has a greater impact on an untrained 'young' network as compared to the same experience on an 'older' trained network. This biasing feature supports previous research conducted with people who have aphasia showing that words learned earlier in life are more resistant to loss and are more easily accessed in naming tasks as compared to words learned later (Ellis & Lambon-Ralph, 2000). This process by which initial learning leads to a constraint on later learning is termed *entrenchment*. Munakata & Pfaffly (2004) and Seidenberg & Zevin (2006) have shown that entrenchment can explain many of the late-onset, L2 learning inefficiencies such as those reported by Johnson & Newport (1989).

Entrenchment produces many of the terminal features of a sensitive period without requiring maturational processes; however it has one important difference from what would occur from a maturational constraint. In theory, an experienced-dependent constraint should still allow a learner to be able to learn phonetic contrasts that are not present in one's native language. Whereas non-native phonetic contrasts, that are perceptually similar to native contrasts, should be difficult to learn and interfere with previous perceptual learning. An experience-independent account of sensitive periods would not predict this difference since the non-native contrasts should no longer be available for language use outside of the sensitive period. Several researchers (Best et al, 1988b; Kuhl, 2000; Guion et al, 2000; Frieda et al, 1999) have shown, however, that adults are often better at discriminating non-native phonetic contrasts when they differ substantially from phonemes of their native language. Adults are poorer at discriminating when the phonetic contrasts are similar to phonetic contrasts of their native language. For instance Best and colleagues (1988a) showed that adult, native English speakers retained the ability to make fine, perceptual discriminations across a continuum of Zulu clicks. Alternatively, native Zulu speakers and speakers of other click languages perceived the continuum categorically. A connectionist perspective would predict the findings of Best and colleagues because the perceptual space occupied by the Zulu click continuum does not overlap with the English, phonetic space in the English speakers. Rather the Zulu perceptual space remains uncommitted in the English speakers, due to the absence of experience listening to Zulu clicks. Therefore, we would predict that English speakers should be able to learn to discriminate Zulu clicks more adeptly than speakers of click languages other than Zulu, because the non-Zulu click learning will constrain Zulu learning. In contrast an experience-independent, maturational account would assume that even the uncommitted perceptual space of the English speakers should be closed to learning and all speakers, regardless of prior experience with the spoken language, would fail to learn how to discriminate the Zulu clicks.

So far the experience-dependent processes we have considered are those involved in learning, therefore they involve changes in neural connectivity. In this regard, the mechanisms we describe are very similar to what Greenough et al (1987) described as *experience-dependent* processes; indeed, this is where we first noted the term. According to these authors, experience dependency provides the organism with the capacity to learn about specific environments and the responses needed for these environments. Experience-dependent plasticity involves Hebbian learning systems, such as those emulated in connectionist models, which construct new synapses based on experience. Thus, activity can result in new connectivity via experience-dependent processes. Greenough proposed that this experience-dependent system is likely to be found in brain systems that serve highly culturally and experientially varied stimuli and responses—such as language learning.

There seems to be little doubt that learning a language in later childhood or adulthood is difficult and is unlikely to result in mastery. Why exactly this seems to be the case remains an open question. As we suggested, it is important not to equate the same type of developmental constraint on speech and language with a particular mechanism such as a maturational mechanism. Evidence that children are more adept at speech and language during one period of development than another can be explained by several different mechanisms. It is the current, unresolved status of these different sensitive periods hypotheses that makes pediatric implantation particularly intriguing for research in speech and language development. Accordingly, we now will turn to the following questions: Are there developmental constraints on speech and language development? If so, how might we test whether these constraints arise from experience-dependent or independent sources?

### *Speech and language outcomes of children with cochlear implants*

Within the past 15 years several researchers documented clear advantages of earlier implantation on speech and language development. In an early study (Osberger et al, 1993), the speech production outcomes of children implanted after the age of 10 years were found to be poorer than those outcomes of children implanted at a younger age. Shortly thereafter, Tye-Murray and colleagues (1995) compared pediatric cochlear-implant users' scores from a variety of speech production tasks and found that children implanted before the age of five years had significantly more accurate speech production than those children implanted after the age of five years. Likewise Miyamoto and colleagues (Miyamoto et al, 1997) showed similar results with regard to the intelligibility of speech produced by children who used cochlear implants. Later, Connor and colleagues, (Connor et al, 2000) performed a growth curve analysis on children's consonant production accuracy, subsequent to implantation, and found better speech sound production outcomes for those children implanted at younger ages than those implanted at older ages. Connor noted that the children implanted at earlier ages also typically had devices with newer technology; therefore this could account for some of the benefits of earlier implantation noted in her study. These speech production data demonstrating a benefit of earlier implantation also paralleled work examining speech perception in children with cochlear implants (Harrison et al, 2005; Meyer et al, 1995; Fryauf-Bertschy et al, 1997; Kirk et al, 2002b; Miyamoto et al, 1997; El-Hakim et al, 2002; Dawson et al, 1992; Nikolopoulos et al, 1999; Snik et al, 1997).

These findings of better outcomes with younger ages at implantation are not limited to speech perception and production. Connor and colleagues' (Connor et al, 2000) study using growth curve analysis revealed that steeper rates of expressive and receptive vocabulary growth were associated with earlier implantation. Similar findings were also reported by Kirk and colleagues (Kirk et al, 2002a) who reported that language growth was greater in children implanted before three years of age than for children implanted after three years of age. Hammes and colleagues (2002) obtained data that further supported the idea that early implantation yields spoken language benefits. They conducted a retrospective study of 47 pediatric, cochlear-implant recipients evaluated on several spoken language measures. These children all received their implants before the age of four years. After looking at the plotted data, the authors noted that the 10 children implanted before the age of 18 months consistently demonstrated rates of language growth similar to their normal hearing peers, and four children had acquired spoken language skills within six months of their chronological ages. Recently, Nicholas & Geers (2006) reported that among a group of 3.5-year-old children implanted between the ages of one and three years, that age at implantation was negatively correlated with standardized language measures. In this case, age at implantation was confounded with length of implant use which was positively correlated with language outcome.

From the literature reviewed above, you will note that many studies have demonstrated an affect of a child's age at implantation; however it is important to note that not all studies demonstrate a *benefit* from earlier implantation. Geers (2004) studied a large group of children implanted during their preschool years. These children were examined with respect to their speech, language, and reading achievement when they were between eight and nine years of age. Unlike many of the other aforementioned studies, they did not find age-at-implantation effects with respect to these areas of development. Geers speculated that the absence of an age-at-implantation effect may have been due to two factors: (1) these children were implanted after a sensitive period that might exist from birth to two years of age; or (2) the devices these children were using were not providing sufficient auditory benefit. Still, it remains unclear as to why no effect was found in Geers' study because both of these factors were present in the other studies that *did* find an age-at-implantation effect.

*Sensitive periods and pediatric cochlear implantation*

The motivation for most of the aforementioned research comes from the need for parents and clinicians to make an informed decision regarding timing of implantation. From that research came support for the notion that 'the earlier the better' when considering the speech and language benefits of pediatric cochlear implantation, but in most of these studies the concept of a sensitive period was not specifically mentioned. A majority of the research, however, did pose the question, 'Is there a time point before which implantation is more likely to result in good outcomes, and after which poor outcomes are more likely?' This is a question that is analogous to the one asked by L2 researchers with respect to whether a discontinuity in the age of L2 learning existed. Thus by posing this question the field of pediatric cochlear implantation proposed a hypothesis that a sensitive period may exist with regard to children's sensitivity to spoken language input. As we will show, the search for the point in development where this discontinuity resides has not been successful in the field of implantation, just as it has not been successful in the field of L2 learning.

Harrison et al (2005) recently used regression-based analyses of the relationship between age at implantation and changes in speech recognition to explore this issue. In each of the speech recognition tasks they noted an age-at-implantation at which point an improvement in the child's speech recognition skills was no longer found. The age associated with this discontinuity varied according to the task used to measure speech recognition, thus Harrison and colleagues could not arrive at a single age that defined a terminus of a sensitive period for implantation. As well, Tomblin and colleagues (Tomblin et al, 2005) did not find evidence of a discontinuity in the relationship between age of implantation and language growth in their recent study. Rather they showed that there seemed to be a general decline in language-learning rates associated with later ages at implantation. In their study the researchers performed a growth curve analysis on the expressive language development of children who received their implants between one and 3.5 years of age. The data showed a consistent pattern of steeper growth rates associated with earlier implantation. This benefit of earlier implantation appeared to be continuously graded from one year of age on (some evidence that this benefit might extend even earlier comes from the reports of Miyamoto and colleagues (Miyamoto et al, 2003) where the two-year-old language outcomes of a child implanted at the age of six months was shown to be similar to levels typically achieved by five-year-olds implanted two years earlier). These findings don't particularly fit a standard sensitive period because they do not really suggest a point when the system opens, or a point where the learning system is relatively stable with regard to its sensitivity to input. Instead it is noted that more efficient learning is suggested with younger ages. These data also suggest that the age-of-implantation effect extends well below the cut-off ages for a critical or sensitive period in L2 learners.

*Toward mechanisms behind age-at-implantation benefits*

When we began to consider the literature evaluating age-at-implantation, our goal was to relate it to the literature on sensitive periods and ultimately reveal the mechanisms behind the age-at-implantation effect. This age-at-implantation literature has shown that there is an advantage to earlier implantation across measures of speech recognition, speech production, and higher level language learning. However, we need to consider what exactly is driving the age-of-implantation effect.

We previously noted (Tomblin et al, 2005) that differences in outcomes associated with a child's age at implantation can be due to two different causes. One effect of variation resulting from differing ages at implantation is that earlier implantation reduces the duration of deafness and increases the duration of auditory/spoken language exposure. Therefore, if we assume that exposure to auditory/spoken language is effective in facilitating speech and language development; then an increase in exposure is surely beneficial. It is likely that an increase in exposure will yield better outcomes and produce evidence for a positive age-at-implantation effect on speech and language development. The simple explanation for this however is that earlier implantation reduces the amount of delay in the onset of development. Such an explanation actually does not support the contention that there is a sensitive period because it does not show that the later implantation results in less efficiency in learning. If a sensitive period is present, it is necessary to show that the rate of learning changes despite constant exposure.

The growth curve methods employed by Conner et al (2000) and Tomblin et al (2005) attempted to show that the rate of learning changes despite a constant exposure. Additionally, these studies provided evidence that speech and language learning rates for children who received cochlear implants were greater for those who were implanted at earlier ages. These data would seem to support some type of mechanism underlying the age-at-implantation effect that alters learning efficiency due to the timing of the onset of exposure. However, before we fully accept this conclusion, we need to acknowledge that even in these studies, that demonstrated improved learning rates, there was no direct control of the spoken language experience provided to the children. Both of these studies were measuring the speech and language learning products of the children's daily communication experiences. Scarr & McCartney (1983) noted several years ago that individuals create their own environments. Thus, we need to recognize that children implanted at later ages may engage in different kinds of interaction patterns with their caregivers than children who are implanted at younger ages. After all, the parents and children who are implanted later in life have a very different communication history than those children implanted earlier in life. This issue is analogous to the explanation of an age-at-implantation effect in L2 learners where children entering a new language society participate differently and often times more fully in that society than older individuals entering that society. One way to overcome the confound of differing language environments in studies testing for sensitive periods, either among L2 learners or children receiving implants, is to conduct studies wherein spoken language exposure is controlled. Then researchers can examine the learning product resulting from a controlled input. We recently conducted such a preliminary study aimed at testing for an age-at-implantation effect using a novel word learning task based on the earlier work of Dollaghan (1985).

## Novel word learning and an age-at-implantation effect: A pilot study

### *Participants*

Fourteen children with cochlear implants (mean age = 3.62 years, SD = 1.18 years) and 14 children with normal hearing (mean age = 3.36 years, SD = 1.14 years) participated in this study. All the children were learning English as their primary language, although a number of the children with cochlear implants had varying competency in manually coded English. The children with cochlear implants were all participants in an ongoing longitudinal study at the Department of Otolaryngology in the University of Iowa Hospitals and Clinics, where they were seen during their regularly scheduled appointments. The normal-hearing children were recruited from the local community.

### *Stimuli*

The spoken words to be learned in the task were: *koob* (/kub/), *dat* (/dæt/), and *sachoon* (/səʃun/).

The novel referents used were nine abstract pieces of hardware made from metal and plastic, each with a distinctive shape. All of the novel objects were selected for their low codability, based on the fact that several normal adults were unable to label them. Three objects were used in each trial of the experiment, as the novel referent and the two novel foils. The objects used as the novel referents varied across children, with the stipulation that no child was introduced to two novel referents of the same color. This stipulation was included to maximize the differences in the objects used as novel referents, and reduce the chances of confusion across trials.

### *Procedure*

Each child was tested individually by the examiner in a quiet room. A row of objects was placed on the table in front of the child. Two of the objects were familiar (a pen and a fork), and one of was unfamiliar (e.g. a caster). Three hiding places (a box, a bowl, and a piece of wrapping paper) were also placed on the table in front of the child. The child was introduced to a hungry puppet named Jonah, and the examiner explained that everyone was going to play a 'hiding game'. The child's goal was to hide objects from Jonah so that he could not eat the objects.

The examiner then told the child to hide the fork in one of the hiding places (e.g. under the bowl) and the pen in another. When the unfamiliar object was the only remaining object in sight, the examiner told the child to hide it in the final hiding place using the novel name (e.g. "Hide the *koob* under the box"). The novel word was only spoken once; if the child requested clarification or did not respond, the examiner said, "You hide it", until the child did so. Significant gestural and tactile support (e.g. pointing to the desired location, guiding their hands to the objects to be hidden) was provided to children during this task to enable them to experience initial success.

#### COMPREHENSION TASK

After all of the objects were hidden, the hiding places were removed. Next, two additional, unfamiliar objects were placed on the table next to the three objects that were previously hidden. At this time, the child was asked to feed the puppet the objects he requested. The puppet first asked for the fork, to give the child initial success with this task. Next, the puppet asked for the *koob*, and finally the pen. The child was then required to select the novel object from an array consisting of a familiar object (the fork), two completely unfamiliar objects, and the newly-introduced unfamiliar object, which the child had previously encountered one time (the koob). The word *koob* was spoken only once, and the child was encouraged to guess what the puppet wanted if she expressed confusion or asked for clarification. No feedback was provided regarding whether or not the child's response was correct.

#### PRODUCTION TASK

The child was next asked to label the pen, fork, and *koob* as each object was held up in turn and the examiner asked, "What's this? What is its name?" If the child did not respond, she was encouraged to guess until a label was attempted or the child refused to respond. Responses were scored as correct if they were recognizable efforts to produce the novel word, where two of its three phonemes were produced in the correct order. Other attempts at a label included recognizable real words and phrases (e.g. 'thingy') and unrecognizable sequences of phonemes. All verbalized responses were phonetically transcribed by the examiner during the test session. Of interest was how much phonetic information about the novel word children were able to store after hearing the novel word only twice.

#### RECOGNITION TASK

If the child did not produce a recognizable attempt at the novel word during the production task, the recognition task was administered. The child was asked to identify the correct label for the novel object and she was given three choices provided by the examiner. The order of the correct versus incorrect choices varied across the three trials. For the word *koob*, the options included a phonetically similar foil (*soob*) and a phonetically dissimilar foil (*teed*). The examiner showed the child the koob and said, "I'll say three things, and you tell me what this is. Is it a koob, is it a soob, or is it a teed?" The child's response was phonetically transcribed. The intent of this task was to determine if children who had given an incorrect label could recognize the correct one when given choices, as well as to determine if those children who had been unable to attempt a label on their own could nonetheless identify it.

#### LOCATION TASK

At this point, the three hiding places were replaced in their original locations, and the child was shown the novel object and asked where it was hidden during the hiding game. The purpose of this task was to investigate if the child had stored some non-linguistic information about the context in which the word was first encountered.

### SECOND AND THIRD TRIALS

The second and third trials of the experiment differed from the first in terms of the novel words used and the objects presented. The second trial used a spoon and a ball as the familiar objects, while the third trial used a toothbrush and a crayon. The second trial used the word *dat* to refer to the novel referent, and the words *gat* and *fape* as foils. The third trial used the word *sachoon* to refer to the novel referent, and the words *rackel* and *pieden* as foils. In the production task for the word *sachoon*, a response was scored as correct if it included three of the five phonemes in correct order. During the experiment the child's responses were scored according to Dollaghan (1987).

## *Results*

### FAST MAPPING SCORES

It is clear that the children with normal hearing were better able to complete each task than the children with cochlear implants. In order to compare the novel-word learning performance of the children with cochlear implants and those with normal hearing, each child's *fast mapping* ability was assessed. *Fast mapping* is a term referring to the mental process during which a child is able to learn a novel label, for a novel object, after very limited exposure to the novel label. A score was calculated for each child as a measure of his or her fast mapping ability. These fast mapping scores were calculated by giving children one point each for correct performance on the following tasks: comprehension, production, and recognition. The exposure and location tasks were not included in the fast mapping score because they were judged to measure skills different from those required for fast mapping (i.e. inference and non-verbal memory). An individual child could get credit for production or recognition. The child could not receive credit for both because the recognition task was not administered to children who succeeded at the production task. Thus, an individual child's fast mapping score could range from zero to six when all three trials were included.

Both groups of children achieved a nearly full range of fast mapping scores. The children with cochlear implants had scores ranging from zero to six, while those with normal hearing had scores ranging from one to six. However, as shown in Figure 3, the children with normal hearing demonstrated higher scores on average than the children with cochlear implants. Children with normal hearing achieved an average fast mapping score of 3.86 (SD = 1.70), while those with cochlear implants achieved an average fast mapping score of 2.00 (SD = 2.04). This difference was statistically significant [$t$ (26) = −2.62, $p$ = 0.01]. Thus the data show that children with cochlear implants, as a group, have poorer fast mapping abilities than age mates with normal hearing.

### FAST MAPPING AND CHRONOLOGICAL AGE

Although the groups were similar in chronological age, the children within each group varied with regard to their chronological age. We would expect that older hearing children would learn more in this task than younger children, but it is more difficult to predict how chronological age would be associated with learning among the children with implants. Therefore we inspected the relationship between chronological age and fast mapping performance. These relationships are shown in Figure 4. As shown, chronological age was associated with fast mapping to a similar degree for both groups. The correlation between these two variables for the group of children was moderate and significant [$r$ (28) = .40, $p$ = 0.03]. Additionally, we see that this relationship was similar for both groups.

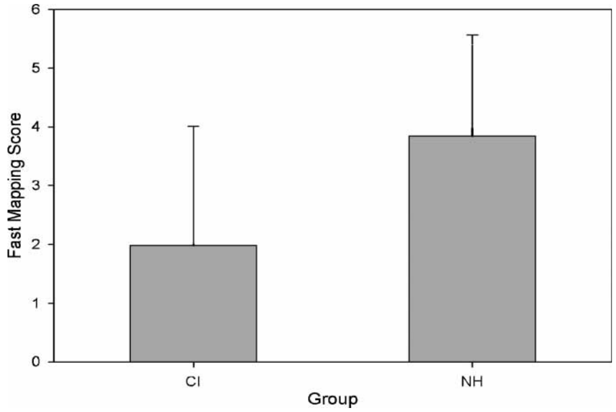

**Figure 3.** Mean and standard deviations for fast mapping scores for children with cochlear implants (CI) and children with normal hearing (NH).

### FAST-MAPPING AND AGE AT IMPLANTATION

The children with cochlear implants also differed with respect to their ages at implantation. The prior analysis demonstrated that fast mapping was related to chronological age, and age at implantation was negatively correlated with chronological age. Therefore, we first partialed out chronological age from the fast

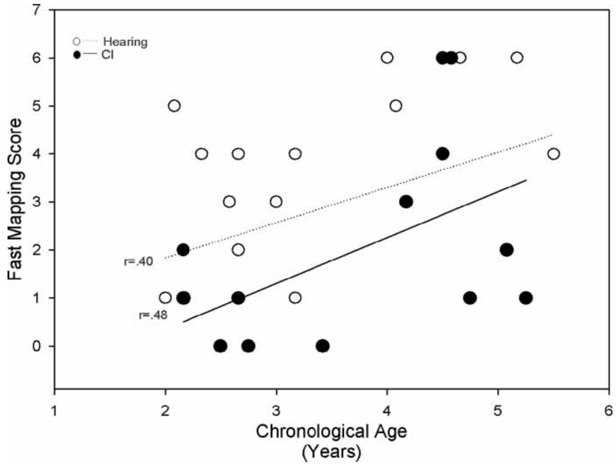

**Figure 4.** The association of fast mapping performance with chronological age for children with normal hearing (open circles) and children with cochlear implants (filled circles). Linear regression lines and Pearson correlations are shown for the hearing (light doted line) and the children with cochlear implants (dark doted line).

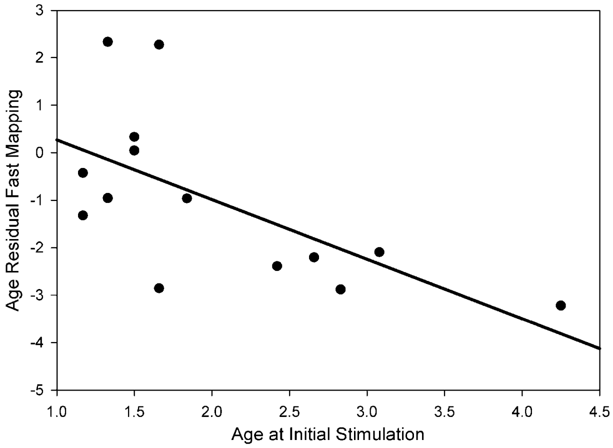

**Figure 5.** The association of age at initial stimulation for the children with cochlear implants and their fast mapping score with chronological age partialed out.

mapping scores and then performed a correlation on residual of this regression to evaluate the association of fast mapping and age at implantation, independent of chronological age. Figure 5 shows the resulting relationship. It can be seen that age of implantation was negatively associated with better fast mapping [$r$ (14) = −.63, $p$ = 0.01].

*Implications of fast mapping for sensitive periods*

The data from this novel word learning study add to the existing body of evidence regarding an advantage for speech and language learning deriving from earlier implantation. In this case, the data show greater efficiency in learning resulting from earlier listening experience. In the present study, all children received the same amount, and type, of spoken language exposure to the novel words. Therefore these results support the idea that the source of this benefit is likely to be some property of the learner, rather than the environment. Thus, we can at least begin to exclude those mechanisms that concern differences in the learning environment. Also, the nature of the benefit is similar to that shown for many of the other age-at-implantation effects. There is a continuous gain in learning efficiency with decrements in children's ages at implantation down to the minimum one year of age. Thus at this point, the data don't reveal a period of development before which earlier implantation no longer demonstrates benefits for speech, language, and listening development. The onset of any sensitive period is either during infancy or possibly *in utero*. Alternatively, there is no classic critical period.

To date, the data from this study and others within the field of pediatric cochlear implantation do not provide us with much insight into the nature of the mechanism. On the surface, these data could be used to argue that there is an experience-independent, maturationally-based sensitive period for fast mapping and possibly word learning in general. However, this would need to be reconciled with the fact that the hearing children (as well as the children using cochlear implants) became better fast mappers as they grew older. From an experience-dependent perspective it could be argued that the children who were implanted earlier in life had a longer language learning history, therefore they came in to the task as more sophisticated learners. Samuelson & Smith (1998) data support this idea and they have argued that later word learning processes in toddlers are influenced by prior word learning. In light of this, we need to consider whether the benefits of earlier implantation on this word learning task are the result of greater word learning skills being brought into the task. As it turns out, there was a moderate, but non-significant, negative correlation between the children's ages at implantation and lengths of implant use [$r$ (14) = −.44, $p$ = .11]. However when we partialed out length of use from the fast mapping score, and looked at the partial correlation of age-at-implantation and fast mapping, we found that there was no longer a meaningful or significant relationship between age at implantation and fast mapping [$r$ (14) = −.11, $p$ = .79]. The sample size in this pilot study is too small to appropriately control all of the important variables that would ideally be managed simultaneously. Consequently, these data need to be interpreted cautiously. These data however, may suggest that the age-at-implantation effect in this study derive from the benefits of greater language learning experience that has a positive transfer to this novel word learning task. Note that this kind of experience-dependent effect is opposite from that discussed in the L2 learning literature. There, learning L1 is viewed as having a negative impact on L2 learning. In the novel word learning task, although the stimuli were novel words the phonological properties were still English. The phonological properties of the novel words, along with more advanced word-learning strategies in general, may have allowed greater language experience to have a facilitative effect in the present study.

## Conclusions

It should be apparent from the review of literature provided here, that the concept of sensitive and critical periods is still emerging. In particular with respect to how the concept is defined and how it applies to speech and language development. There seems to be a substantial amount of evidence that learners do not retain equal sensitivity to speech and language input. The mechanisms proposed to account for this change in learning ability, however, still remain open to debate. Neurobiological evidence and computational modeling show that these mechanisms are experience-dependent. Specifically, sensory experience and the brain's response to this experience appear to play a prominent role in producing sensitive periods. It is in this regard that cochlear implantation, and the natural manipulation in timing of delivery of sensory experience, provides an opportunity to further explore the mechanisms underlying sensitive periods. Furthermore, the field of pediatric cochlear implantation could use such knowledge to inform clinical practice and address many of the challenges that arise with patient care, particularly those where several confounding variables are likely to be present.

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