The Basis for Language Acquisition: Congenitally Deaf Infants Discriminate Vowel Length in the First Months after Cochlear Implantation

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Abstract

■ One main incentive for supplying hearing impaired children with a cochlear implant is the prospect of oral language acquisition. Only scarce knowledge exists, however, of what congenitally deaf children actually perceive when receiving their first auditory input, and specifically what speech-relevant features they are able to extract from the new modality. We therefore presented congenitally deaf infants and young children implanted before the age of 4 years with an oddball paradigm of long and short vowel variants of the syllable /ba/. We measured the EEG in regular intervals to study their discriminative ability starting with the first activation of the implant up to 8 months later. We were thus able to time-track the emerging ability to differentiate one of the most basic linguistic features that bears semantic differentiation and helps in word segmentation, namely, vowel length. Results show that already 2 months after the first auditory input, but not directly after implant activation, these early implanted children differentiate between long and short syllables. Surprisingly, after only 4 months of hearing experience, the ERPs have reached the same properties as those of the normal hearing control group, demonstrating the plasticity of the brain with respect to the new modality. We thus show that a simple but linguistically highly relevant feature such as vowel length reaches age-appropriate electrophysiological levels as fast as 4 months after the first acoustic stimulation, providing an important basis for further language acquisition. ■

INTRODUCTION

Individuals with a profound sensory hearing loss (>90 dB) are able to (re)gain access to hearing via a cochlear implant (CI). This neuroprosthesis bypasses the dysfunctioning inner ear by delivering the sound of an external microphone directly to the auditory nerve via electric stimulation. For postlingually deafened adults, the implantation promises the restoration of hearing and communication. For children with a congenital or early acquired hearing deficit, it enables access to auditory stimulation in the vital phases of synaptogenesis, thus allowing the development of auditory cortical functions and opening the prospect of oral communication.

But how do implanted children successfully master language acquisition while facing the challenge of an auditory input diminished in spectral features and dynamics? There are three conceivable main scenarios:

(1) After the implantation, the development of acoustic discrimination takes place as if the implanted infant was newborn and presented with the first linguistic stimuli.
(2) Development is slowed down. This is either because of the degraded input the implant offers and/or due to the prolonged period of deafness in which the auditory system has developed unfavorably and the possibility of other modalities taking over the auditory areas.
(3) Development is faster. The infant can compensate lost time with her/his otherwise normally maturing cognitive abilities so that s/he has a more advanced starting point than a newborn.

Assessing what infants actually perceive with the implant and, thus, answering the above question are a challenging task usually limited to observation. Even for professional therapists, it can be difficult to extract which auditory features are processed. These features are difficult to tease apart in a nontalking infant to begin with and she/he might not show its discriminative abilities behaviorally, because an infant's behavior is highly susceptible to her current mood, attentiveness, and general alertness. Also, many congenitally deaf children still need to develop auditory attention after the prolonged period of deafness and do not react despite a perceived input. Therefore, an objective measurement evaluating what aspects of the input are processed is needed—ideally a measurement of the neural responses directly. Whereas fMRI is not an option due to the implant, EEG has multiple benefits. It offers near-online tracking of the neuronal population's response, is noninvasive, and has already

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been used for studying auditory perception both in children and in adult CI users.

Although a number of EEG studies exist for adult CI users with postlingual hearing loss (Hahne, Wolf, Müller, Mürbe, & Friederici, 2012; Timm et al., 2012; Sandmann et al., 2010; Lonka et al., 2004; Kraus, McGee, et al., 1993), only few studies address implantees at child age with congenital deafness. Even less studies consider children in the critical age of language acquisition. We therefore aimed to investigate how the processing of the prerequisites of language acquisition evolves in infants and young children during the first months of auditory input and compare these results to normal hearing peers.

Prerequisites for Language Acquisition—Choice of Stimulus

One crucial step in language acquisition is the ability to segment the continuous stream of speech into words and their subunits. Segmentation is aided by extracting auditory cues, like vowel lengthening, stress patterns, and phonotactics (valid phoneme combinations) that may signal the onset and offset of a word.

Infants that demonstrate an altered processing of these basic linguistic features are likely to be diagnosed later with dyslexia or specific language impairment (Chobert, François, Habib, & Besson, 2012; Friedrich, Herold, & Friederici, 2009; Friedrich, Weber, & Friederici, 2004; Benasich & Tallal, 2002; Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999). This supports the theory that language impairments can arise from a deficient processing of relevant auditory features at early stages of speech development (Tallal & Piercy, 1974, 1975; for a review, see also Kujala, 2007).

These findings have direct implications for children with a CI. The altered acoustic input raises the possibility that critical linguistic features are not perceived sufficiently for successful speech segmentation, in consequence hindering further language development (Kujala, 2007). Indeed, some implanted children do not show the expected progress in language acquisition despite the absence of any additional neurological impairment. This leads to the question, what early implanted children can actually perceive with an implant in the first months and, specifically, what resources they have to extract linguistically essential features from incoming speech to begin with.

The study focuses on vowel length as one of the most elementary auditory features with linguistic relevance. In German and other languages, lengthening of the vowel in a syllable can alter the semantics of a word (German: "Kahn" (barge) vs. "kann" (can), English: "keen" vs. "kin"). It can also mark syllable stress, which is yet another feature that helps infants in extracting linguistic units from a continuous stream of speech (see above). Vowel length is thus a very simple and at the same time elementary acoustic feature to test. Normal hearing children are able to perceive differences in vowel length from very early on: Neonates (Leppänen, Pihko, Eklund, & Lyytinen, 1999; Pihko et al., 1999) and 2-month-old infants (Friederici, Friedrich, & Weber, 2002) already display a positive mismatch response toward deviant vowel lengths. An explicit familiarization during pregnancy with syllables differing in vowel length actually alters the discriminative responses measured after birth (Partanen et al., 2013), thus demonstrating that the sensitivity already develops in utero. Acoustic experience influences the sensitivity toward vowel length differences also in later life time. Eight- to 10-year-old children with no prior musical education show an enhanced mismatch response after a year of musical training (Chobert, François, Velay, & Besson, 2014).

MMN—Choice of Paradigm

Auditory perception and specifically the ability to discriminate certain acoustic features like vowel length can be studied particularly well using the MMN. The MMN is an electrophysiological component that is elicited whenever a stimulus deviates from a regular auditory pattern. It is typically described in the difference wave resulting from subtracting the standard stimulus from the deviating stimulus. For adults, the MMN emerges in the difference wave as a negative deflection with a frontocentral distribution. It peaks around 200 msec after stimulus onset depending on stimulus properties with stimulus length and/or complexity increasing the latency of the component. The MMN can be elicited by all kinds of acoustic deviations including frequency, duration, and intensity of an acoustic signal as well as deviations of more complex properties like change of phoneme type, length of a syllable, or auditory patterns and even complex rule deviations (for a review of the characteristics of the MMN, see Kujala, Tervaniemi, & Schröger, 2007; Näätänen, Paavilainen, Rinne, & Alho, 2007).

The fact that the MMN can only be elicited when the deviation is actually perceived by the auditory system makes it an ideal component to study the perceptual abilities of hearing-impaired adults after cochlear implantation (e.g., Timm et al., 2012; Sandmann et al., 2010; Lonka et al., 2004; Wable, van den Abbeele, Gallégo, & Frachet, 2000; Ponton & Don, 1995; Kraus, Micco, et al., 1993). Although the elicitation of the MMN depends on the actual perception of the deviation, the stimuli themselves don't have to be attended. This in turn makes the MMN ideal for investigating the processing of tones and phonemes in infants (He, Hotson, & Trainor, 2007; Friederici et al., 2002) or even neonates and preterms (Ceponiene et al., 2002; Cheour-Luhtanen et al., 1996). The objective assessment of discriminative abilities is helpful in a number of situations where self-report is biased or unreliable, but it is particularly valuable when studying infants who lack self-report altogether and thus cannot communicate what acoustic features they perceive and how they perceive them. The lack of studies addressing the perceptual abilities of infants and young children with an implant is thus remarkable, considering their model character for studying the effects of a late hearing onset on language acquisition.

The few existing MMN studies on acoustic discrimination in implanted children are summarized in Table 1. The first thing to note is that an MMN elicitation is possible and even reaches properties of normal hearing controls in some of the studies (Watson, Titterington, Henry, & Toner, 2007; Ponton et al., 2000). Auditory discrimination abilities include basic auditory signal properties like frequency, pulse length, or intensity as well as linguistic features like vowel or consonant type. Second, with exception of Liang et al. (2014), all studies involve older children or adolescents after a prolonged period of hearing experience with a CI. Notably, onset and duration of hearing loss also vary greatly, yet both have a huge impact on auditory development: The later the hearing loss and the earlier the implantation, the shorter the auditory deprivation during crucial phases of neural development with its potential negative consequences (Kral & Sharma, 2012). In addition, if the hearing loss is acquired postlingually, language performance after implantation tends to be substantially better: Not only did the auditory system have more years to mature normally, it also learned to discriminate and categorize fine acoustic structures of language. Postlingually deafened individuals have already acquired phoneme categorization and learned the concept of morphemes, two linguistic elements that are an acoustic challenge to all implant users.

The MMN results of children so far are thus referring to performance after some years of hearing experience and partially with a normally developed auditory system in the first years of life. But how about auditory discrimination abilities right after implantation? Liang et al. (2014) studied young children with a prelingual but otherwise unclear onset of deafness by presenting pitch deviants in the first 6 months after implant activation. Although the participants were drug sedated with chloral hydrate and thus asleep, an increase of MMN incidence was observable over the first months of implant use. An equivalent study for linguistic stimuli with preferably awake, unsedated children is missing.

Type of MMN: Comparison within or across Blocks?

An additional point to be considered is that there are several ways of obtaining the difference wave, each having different implications. Already early studies of the MMN (e.g., Kraus, McGee, et al., 1993; Kraus, McGee, Sharma, Carrell, & Nicol, 1992) advocate the comparison of physically identical stimuli in the difference wave, for example, stimulus A in a deviant condition versus the same stimulus A in a standard condition. This should reflect the detection of a deviant on the cognitive level as compared to a change of ERPs merely due to differences in physical properties of the stimulus per se (see also, e.g., Ceponiene et al., 2002, for a different attempt to address the same issue).

In our study, we thus differentiate between both (a) the difference wave resulting from contrasting different stimuli within one block and (b) the difference wave resulting from contrasting the deviant stimulus of one block with its physically identical counterpart of the another block where it is presented as a standard stimulus. In this article, we will call the negative peak of the difference wave "within-block MMN" and "across-block MMN," respectively. Whereas the within-block MMN could simply emerge from the difference in physical properties reflected in the ERPs, the across-block MMN reflects a cognitive process as it requires a concept of "deviant" and "standard" in order to appear. Obviously, a "deviant"/"standard" signature can also exist in the local context of one block—context does matter after all (see also Sussman, Chen, Sussman-Fort, & Dinces, 2014). The point is rather that one should be aware that the obtained within-block MMN might be originating mainly from inherent differences in the physical properties of the stimuli rather than from processes comparing the stimuli. The two effects might not be able to be told apart without a control condition (e.g., a control block with an equiprobable or exclusive presentation of the deviant or two blocks were the deviant/standard role of the stimuli is reversed). We will demonstrate the effect this has on MMN evaluation by analyzing both types of MMN. There may be sensible reasons for both kinds of difference wave. Results of studies can only be compared, though, when knowing on which processes the obtained difference wave taps.

Summarizing, there is a great lack of research on the acoustic discriminative abilities of congenitally deaf children, in particular during their first months of acoustic input. Thus, one of the most fascinating aspects of auditory development with a CI remains practically unknown: the development of auditory processing in response to the very first input, and specifically to speech-relevant features, while all other systems have matured normally. We therefore examine in the following how acoustic discrimination of vowel length develops during the first 8 months after implant activation in congenitally deaf infants and young children who are in the sensitive phase of language acquisition.

METHODS

Participants

Children with CIs

Nineteen children with congenital bilateral deafness participated in the study. Bilateral deafness was confirmed by pedaudiologic assessment, consisting of a negative brain stem electric response audiometry and subjective audiometry, and was complemented by the reports of family and specialized therapists. After a period of bilateral hearing

Table 1. Existing Studies Investigating Acoustic Discrimination in CI Children Using the MMN

Study	*No. of Patients*	*Age at Hearing Loss*	*Age at Implantation*	*Age at Measurement*	*Duration of Implant Use*	*Stimuli*	*Results*	*Type of MMN*[a]
Kileny et al., 1997	n = 14	Not stated	ca. 3–9 years	4–12 years	0.7–7.0 years	1) **Intensity**: 75 dB vs. 90 dB 2) **Frequency**: 1500 Hz vs. 3000 Hz 3) **Vowel type**: /heed/ vs. /who'd/	MMN elicited in all subjects for all stimulus types. Negative correlation for MMN latency in frequency, condition, and language score	Within-block MMN
Ponton et al., 2000	n = 12	3 congenital, others: identification up to 5.1 years	Not stated	6–18 years	Not stated	**Click and pulse trains** (10 clicks/pulses per trains vs. 1–9 clicks/pulses per train)	MMN development similar to normal hearing peers	Across-block MMN
Singh et al., 2004	n = 35	14 congenital, 7 prelingual, 2 postlingual	2–15 years	7–17 years	1–10 years	**Consonant type**: /da/ vs. /ba/, duration: 275 msec, ISI: 1000 msec	MMN visible in 10 of 35 subjects (of which 5 congenital). Positive correlation of MMN presence with language score	Across-block MMN
Watson et al., 2007	n = 15	14 congenital, 1 early acquired	2.7–6.0 years	7–13 years	3.9–7.9 years	**Pitch**: 500 Hz vs. 2500 Hz, duration: 50 msec, ISI: 900 msec	MMN for the low frequency deviant in all subjects. MMN of implanted children similar to normal hearing controls	Across-block MMN
Liang et al., 2014	n = 18 (sedated)	Identified at 0.4–4.1 years	1.3–6.1	1–6 years	0.0–0.6 years	**Pitch**: 1000 Hz vs. 1500 Hz, duration: 50 msec, ISI: 550 msec	MMN incidence increases with duration of implant use (none at M0, 17/18 at M6), latency decreases with time	Within-block MMN

[a] For the definition of "Within-block MMN" and "Across-block MMN," see the section titled: Type of MMN: Comparison within or across Blocks?

Table 2. Details for Implanted Children Entering the Final Analysis

Patient	*Sex*	*Mode*	*Implant*	*Processor*	*Manufacturer*	*Age at Activation (in months)*
1	m	Simultaneous bilateral	Sonata	Opus2	MED-EL[a]	11
2	f	Simultaneous bilateral	CI512	CP810	Cochlear[b]	12
3	f	Sequential bilateral	CI422	CP810	Cochlear	12/16
4	m	Sequential bilateral	Concerto	Opus2	MED-EL	12/17
5	f	Simultaneous bilateral	CI512	CP810	Cochlear	13
6	f	Simultaneous bilateral	Concerto	Opus2	MED-EL	13
7	f	Sequential bilateral	Concerto	Opus2	MED-EL	13/19
8	m	Simultaneous bilateral	CI512	CP810	Cochlear	15
9	f	Simultaneous bilateral	CI512	CP810	Cochlear	16
10	m	Simultaneous bilateral	Concerto	Opus2	MED-EL	16
11	f	Simultaneous bilateral	CI512	CP810	Cochlear	17
12	m	Sequential bilateral	Concerto	Opus2	MED-EL	18/26
13	m	Simultaneous bilateral	CI512	CP810	Cochlear	20
14	m	Simultaneous bilateral	CI512	CP810	Cochlear	21
15	m	Simultaneous bilateral	CI512	CP810	Cochlear	22
16	m	Simultaneous bilateral	CI512	CP810	Cochlear	36
17	f	Simultaneous bilateral	CI512	CP810	Cochlear	45

[a] MED-EL Elektromedizinische Geräte Gesellschaft m.b.H., Innsbruck, Austria.

[b] Cochlear Ltd., Sydney, Australia.

aid use remained without benefit, cochlear implantation was performed on both ears.

Two children had to be excluded from further analysis because of excessive artifacts. The remaining 17 children received bilateral CIs, 13 in a simultaneous surgical intervention and 4 sequentially (see demographic details in Table 2). After implantation, all children entered the rehabilitation program at the Saxonian Cochlear Implant Center, University Hospital Dresden, Dresden, Germany. There they received a bimonthly fitting of the speech processor and multidisciplinary speech and language therapy for up to 3 years. The first activation occurred 1 month postsurgically during a 5-day rehabilitation stay. Age at first activation of the implant ranged from 11 to 45 months (M = 18 months, SD = 9 months, *Median* = 16 months). After implant activation, parents are instructed to have the child wear the speech processor daily for as many waking hours as possible.

The EEG recordings of this study were performed at the following time points of their regular rehabilitation stay: preoperatively as a baseline condition (Mpre), in the week of initial activation (M0) and after 2 (M2), 4 (M4), 6 (M6), and 8 (M8) months of implant use. Not all of the recordings could be obtained for each child due to illness or restlessness of the child (see Table 3 for eventual number of children per group).

Normal Hearing Controls

Two control groups of normal hearing (NH) full-term children were measured at the Max Planck Institute for Cognitive and Brain Sciences in Leipzig, Germany. The first group NH1 (n = 12) matched the CI children of group Mpre in age and gender at the time point of measurement (6 girls, age range = 11–36 months, *Median* = 11 months, SD = 8.47). Likewise the second group NH2 (n = 13) matched age and gender of the implanted children included in M4 (6 girls, age range = 15–48 months, *Median* = 19 months, SD = 9.36).

For all children, informed consent was signed by a parent or a person having the custody for the child, and the following procedures were approved by the local ethics committee (Medical Faculty Carl Gustav Carus of the Technische Universität Dresden).

Table 3. Groups According to Duration of Implant Use

	Mpre	*M0*	*M2*	*M4*	*M6*	*M8*
	$n = 7$	$n = 7$	$n = 9$	$n = 11$	$n = 11$	$n = 6$
Range	11–36	12–21	14–46	15–48	16–50	18–52
Median	11	16	18	20	23	19.5

Age in months.

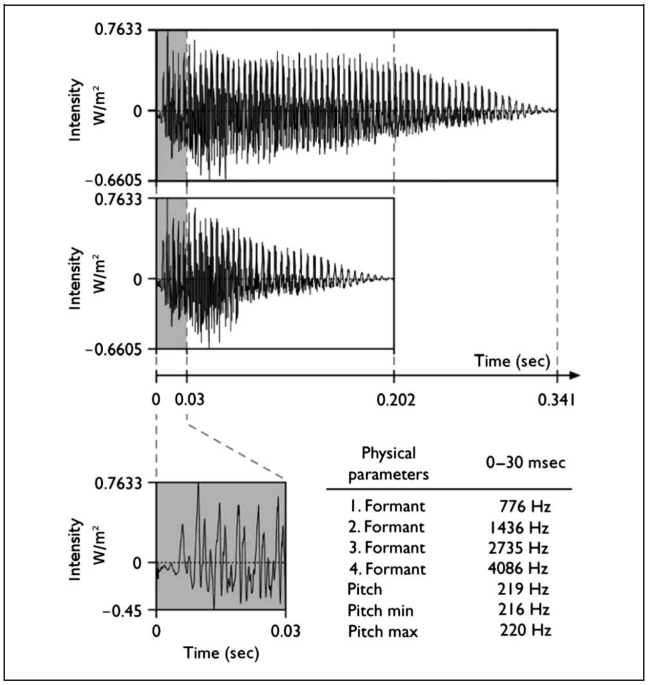


Figure 1. Syllable /ba/ with long and short vowel. Adapted from “Neural manifestation of cognitive and precognitive mismatch detection in early infancy,” by Friederici et al. (2002, p. 1252). Copyright 2015 by Wolters Kluwer Health. Adapted with permission.

Stimuli and Procedure

Stimuli and paradigm originate from the study of Friederici et al. (2002; see Figure 1). In a random oddball paradigm, the syllable /ba/ was presented either with a short and/or with a lengthened vowel (total syllable length of 202 and 341 msec). In one of two blocks, the short syllable was the standard stimulus (frequency of 5/6) and the long syllable the deviant stimulus (1/6) and vice versa. The order of the two blocks was pseudorandomized across an individual’s session and across all participants. Deviants were separated by two to seven standard stimuli. Each block contained 600 trials with an ISI of 855 msec. Stimuli were presented at 65 dB with the software Presentation (NeuroBehavioral Systems, Albany, CA). During the auditory stimulation via loudspeakers, children were sitting awake on their parent’s lap watching a silent animated movie or being silently entertained with books, puppets, etc., by one of the experimenters.

EEG Recording

Data were obtained continuously with Ag–AgCl^{-} electrodes positioned according to the International 10–20 System in an elastic electrode cap (EasyCap, GmbH, Herrsching, Germany). Nine scalp sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) and the left and right mastoid were recorded. An EOG was obtained from two horizontal electrodes at the outer canthi of the left and right eye and from a vertical electrode above the right eye. An additional vertical electrode was recorded below the right eye whenever possible. It was omitted if otherwise the child would not have tolerated the EEG measurement. The signal was sampled at 500 Hz and amplified with a PORTI-32/MREFA (Twente Medical Systems, Oldenzaal, The Netherlands) with electrode Cz as online reference.

Data were offline referenced to the average of both mastoids. Sometimes the implant or the transmitter coil of the speech processor would hinder an optimal positioning of one of the mastoid electrodes. In that case, the other mastoid electrode served as single reference. A band-pass filter of 1–15 Hz reduced slow drifts and muscle artifacts. Trials with the signal at the midline electrodes (Fz, Cz, Pz) or eye electrodes exceeding 80 μV within a 200-msec sliding window were rejected. A subsequent correction of eye blinks and eye movements was applied (EEP 3.2.1, developed by the CBS MPI, Leipzig, Germany, and distributed by ANT Neuro, Enschede, The Netherlands). The standard trial immediately following a deviant trial was removed from analysis. Each session had a minimum of 50% accepted trials of each condition, that is, ≥50 trials in the two deviant conditions and ≥200 trials in the two standard conditions. Only two sessions did not meet this criterion, one belonging to the group of M2 and one to M6. In both sessions, the block with the short deviant and long standard stimuli had to be discarded due to motion artifacts. The data of the block with sufficient trials was then used only for the within-block comparison of the long deviant versus short standard stimulus. Mean number of accepted trials can be found in Table 4. Averaging occurred from −200 to 600 msec with reference to stimulus onset. The −200 to 0 msec range served for baseline correction.

Data Analysis

Each deviant condition was compared to (a) the standard condition of the same block (“within-block MMN”) and (b) the standard condition with the same physical

Table 4. Number of Accepted Trial per Group and Condition (Mean and *SD*)

	Long Deviant	*Long Standard*	*Short Deviant*	*Short Standard*
Mpre	78 (15)	283 (45)	76 (11)	309 (60)
M0	78 (13)	319 (62)	80 (17)	304 (43)
M2	77 (18)	288 (93)	72 (23)	313 (69)
M4	82 (11)	331 (37)	82 (9)	331 (50)
M6	80 (11)	332 (27)	84 (7)	308 (47)
M8	83 (12)	315 (46)	81 (10)	331 (66)
NH1	77 (12)	305 (44)	81 (9)	318 (37)
NH2	90 (11)	363 (27)	90 (8)	355 (30)

properties ("across-block MMN"), resulting in four comparisons: long deviant–short standard (LD-SS), long deviant–long standard (LD-LS), short deviant–long standard (SD-LS), and short deviant–short standard (SD-SS). The difference wave was calculated by subtracting the standard stimulus from the deviant stimulus. Each window of analysis was chosen such that it included the relevant peak of every group (Mpre–M8) and preferably the peak of the control groups as well. As the MMN is reported to have a latency of about 150–250 msec in adults (Näätänen et al., 2007) and children tend to have greater latencies than adults, we considered those peaks as relevant for mismatch investigation that had a latency greater than 150 msec. The longitudinal data of the implanted children were statistically analyzed by applying a linear mixed effect model with R and the lme4 package (Bates, Mächler, Bolker, & Walker, 2014; R Core Team, 2014) to account for missing values in the longitudinal data sets. Analysis was performed separately for each stimulus pair and time window with Stimulus (deviant vs. standard), Duration of implant use (Mpre, M0, M2, M4, M6, M8), and Electrode (Fz, Cz, Pz) as fixed effects and Subject as random effect. Each analysis model was optimized using backward elimination. For each control group, time window, and stimulus pair, a repeated-measure ANOVA with Stimulus and Electrode as factors was performed. All post hoc multiple comparisons are reported with Tukey-corrected p values, and significance level was set to $\alpha = 0.05$.

RESULTS

Within-block Mismatch: Long Deviant–Short Standard

CI Children

The difference wave resulting from subtracting the short standard syllable from the co-occurring long deviant syllable shows a clear pattern of a negative peak emerging over time (Figure 2). Duration of implant use × Stimulus

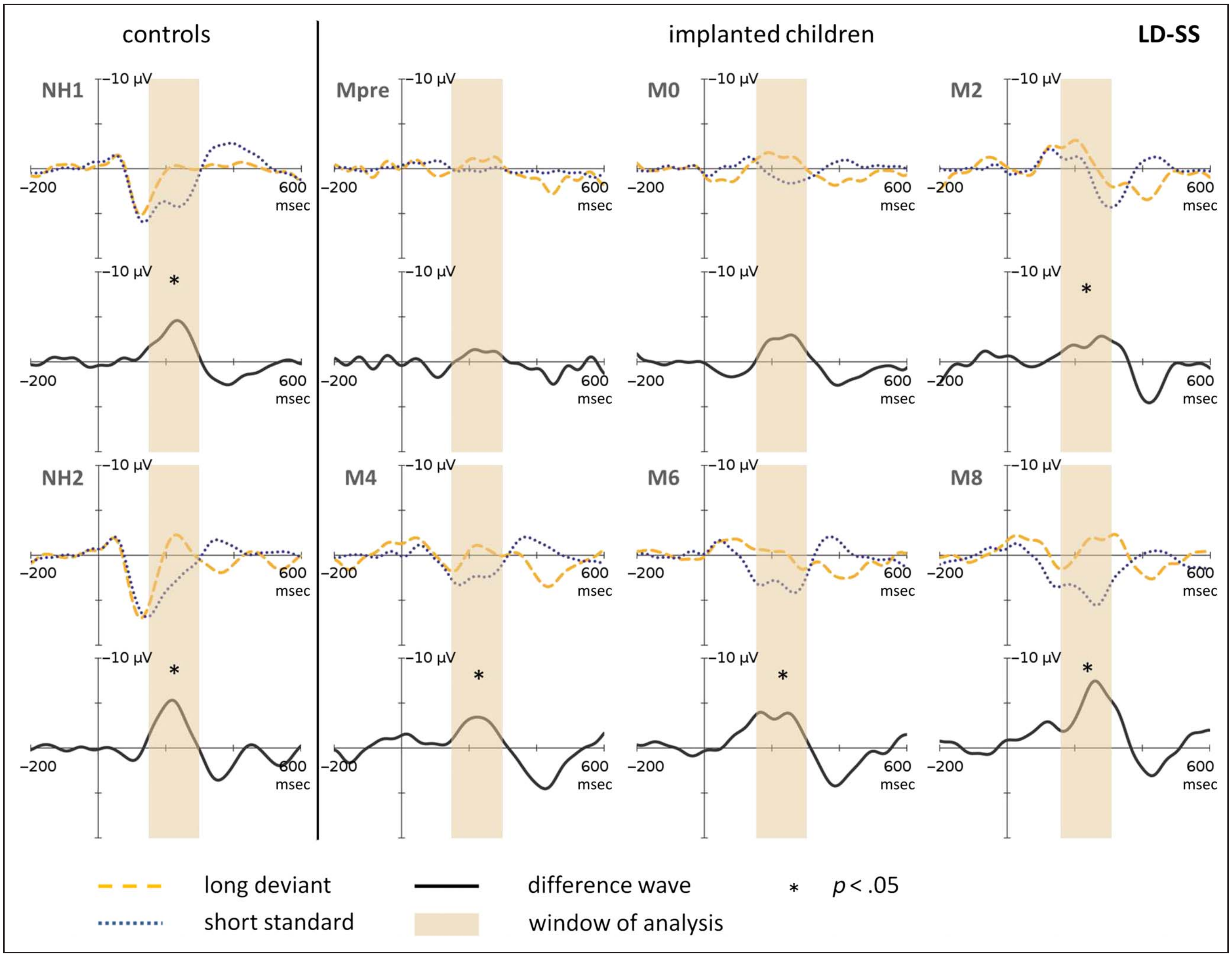
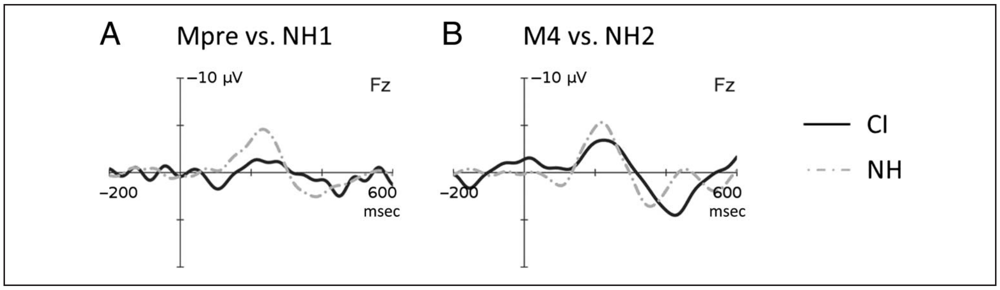


Figure 2. ERPs and difference wave of the stimuli presented in the same block: long deviant and short standard syllable at electrode Fz. Right side: Implanted children from before the implantation (Mpre) up to 8 months after activation (M8). Left side: Control groups NH1 and NH2 age-matched to Mpre and M4, respectively.

Figure 3. Comparison of the difference wave (long deviant–short standard) of the implanted children (solid line) (A) before the implantation and (B) with 4 months of hearing experience with their respective control group (dash-dotted line) at electrode Fz.



is significant in the time window 150–300 msec [$F(5, 268) = 3.37, p = .006$], post hoc analysis confirming a significant difference between the long deviant and the short standard stimulus at M2, M4, M6, and M8 [M2: $t(268) = 2.01, p = .046$; M4: $t(268) = 4.69, p < .001$; M6: $t(268) = 3.19, p = .002$; M8: $t(268) = 4.57, p < .001$]. There was also a marginally significant interaction of Stimulus × Electrode [$F(2, 268) = 3.01, p = .05$) with the difference between the stimuli being largest on electrode Fz [$t(268) = 5.58, p < .001$] compared to Cz [$t(268) = 2.96, p = .003$] and Pz [$t(268) = 2.35, p = .02$]. Latencies of the significant negative deflection at Fz are M2: 280 msec, M4: 220 msec, M6: 248 msec, and M8: 260 msec.

Normal Hearing Children

The two control groups display a similar negative peak in the difference wave (NH1: 232 msec; NH2: 220 msec). In both groups the syllables differ significantly in the time window of 150–300 msec [NH1: $F(1, 66) = 10.39, p = .002$; NH2: $F(1, 72) = 9.47, p = .003$].

Comparing the implanted children to their respective control group shows that by 4 months of implant use the difference wave pattern is remarkably similar to that of normal hearing peers (Figure 3B). An ANOVA over Group (M4 vs. NH2) and Stimulus at electrode Fz finds no significant difference between the implanted children and the control group [$F(1, 44) = 0.72, p = .4$].

Within-block Mismatch: Short Deviant–Long Standard

CI Children

Contrasting the stimuli of the other block reveals the opposite pattern. Rather than one prominent negativity there is an emerging positive deflection flanked by two negative peaks (Figure 4). Their respective peak latencies in the grand average were 160, 268, and 412 msec. Time windows of analysis were 120–220 and 370–440 msec for the negative peaks and 230–340 msec for the positive peak. The positivity only showed a main effect for Electrode [$F(2, 268) = 3.14, p = .04$] with Fz being more positive than Pz [$t(268) = 2.45, p = .04$] and a marginal significance for the main effect of Stimulus [$F(1, 268) = 3.47, p = .06$]. Of the negativities, the second showed a marginally significant interaction between Duration of implant use and Stimulus [$F(5, 260) = 2.14, p = .06$]. M2 [$t(260) = 2.41, p = .02$]. Post hoc analysis revealed that the difference between the short deviant and the long standard syllable was only significant for M8 [$t(260) = 2.10, p = .04$], but not for any other group.

The analysis was also performed without Mpre, because the early broad negativity in Mpre for the short deviant might be an unresolved artifact, although it is driven by infants for whom the diagnosis of congenital deafness was clear and thus highly unlikely to be an auditory response. The implant as artifact source is also improbable, because nothing similar is observable in the other conditions. Ocular artifacts have been corrected and are thus also ruled out. Excluding Mpre from the statistical analysis only changed the results for the positivity. The analysis revealed an interaction between Stimulus and Electrode [$F(2, 226) = 3.39, p = .03$] with the difference between the syllables being highly significant at Fz [$t(226) = 3.391, p < .001$) but not at the other electrodes.

Normal Hearing Children

Like the CI children, the control groups show the same pattern of reversed polarity, namely the difference wave displaying a prominent positive peak. The difference wave shows a positive deflection (NH1: 228 msec; NH2: 236 msec) flanked by a small negative peak (NH1: 164 msec; NH2: 152 msec) and a larger negative deflection (NH1: 352 msec; NH2: 348 msec). Time windows of analysis are 120–200 and 300–420 msec for the negative peaks and 170–280 msec for the positivity.

For the time window of the positivity, both groups have a significant main effect of Stimulus [NH1: $F(1, 66) = 14.10, p < .001$; NH2: $F(1, 72) = 32.704, p < .001$] and NH1 an additional main effect of Electrode [$F(2, 66) = 5.47, p = .006$] with Fz being more positive than PZ [$t(66) = 3.27, p = .005$].

For the time window 120–200 msec NH1 shows a main effect for Stimulus [$F(1, 66) = 4.61, p = .04$], whereas NH2 shows only a marginal effect [$F(1, 72) = 3.40, p = .07$]. Both control groups exhibit a main effect for Electrode [NH1: $F(2, 66) = 10.97, p < .001$;

NH2: $F(2, 72) = 8.82, p < .001$] with Fz and Cz being more positive than Pz [NH1: Fz–Pz: $t(66) = 4.49, p < .001$; Cz–Pz: $t(66) = 3.39, p = .003$; NH2: Fz–Pz: $t(72) = 3.93, p < .001$; Cz–Pz: $t(72) = 3.24, p = .005$]. There is no effect for either group in the time window of the second negativity.

Across-block Mismatch: Long Deviant–Long Standard

CI Children

Here the same physical stimulus is compared across blocks, that is, the ERPs of the long syllable being the deviant as opposed to being the standard condition were contrasted (Figure 5). The window of analysis was placed around the negativity peaking at 204 msec, thus set to 120–260 msec. The interaction of Duration of implant use × Stimulus was significant [$F(5, 260) = 2.71, p = .02$], with long stimulus as deviant being more negative than in the standard condition in M4 [$t(260) = 3.28, p = .001$] and M8 [$t(260) = 3.01, p = .003$].

Normal Hearing Children

Both of the two negative peaks (NH1: 152 and 344 msec; NH2: 184 and 324 msec) were tested for significance in the time windows 120–260 and 280–380 msec. None of the factors showed a significant difference in either window.

Across-block Mismatch: Short Deviant–Short Standard

CI Children

Comparing the physically identical short syllable in the deviant and the standard condition (Figure 6) reveals a main effect in the time window 140–240 msec for Stimulus [$F(1, 253) = 5.87, p = .02$], although the polarity of

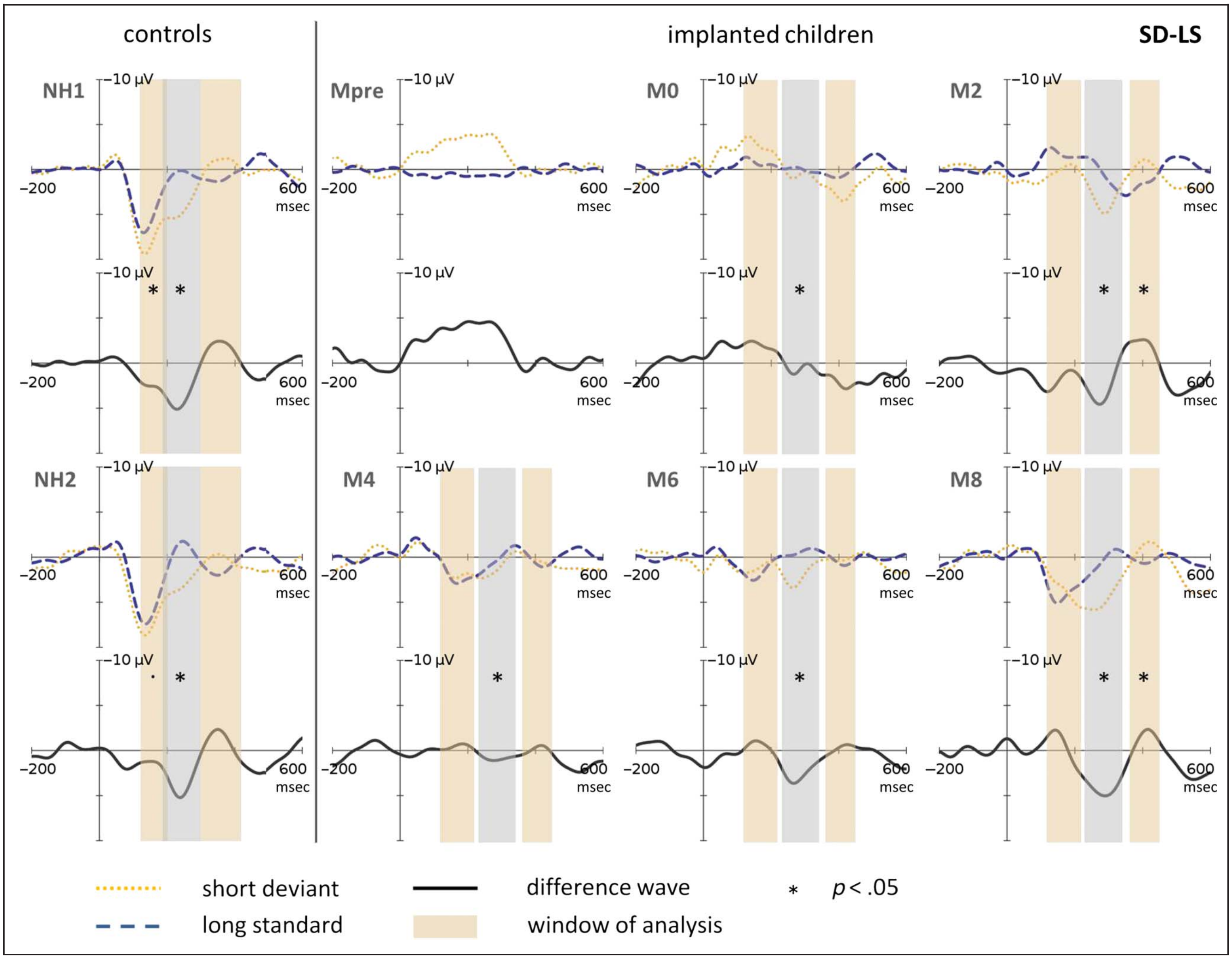


Figure 4. ERPs and difference waves of the stimuli presented in the same block: short deviant syllable versus the long standard syllable at electrode Fz for implanted and normal hearing children. Significances are shown for the analysis in which Mpre was not included.

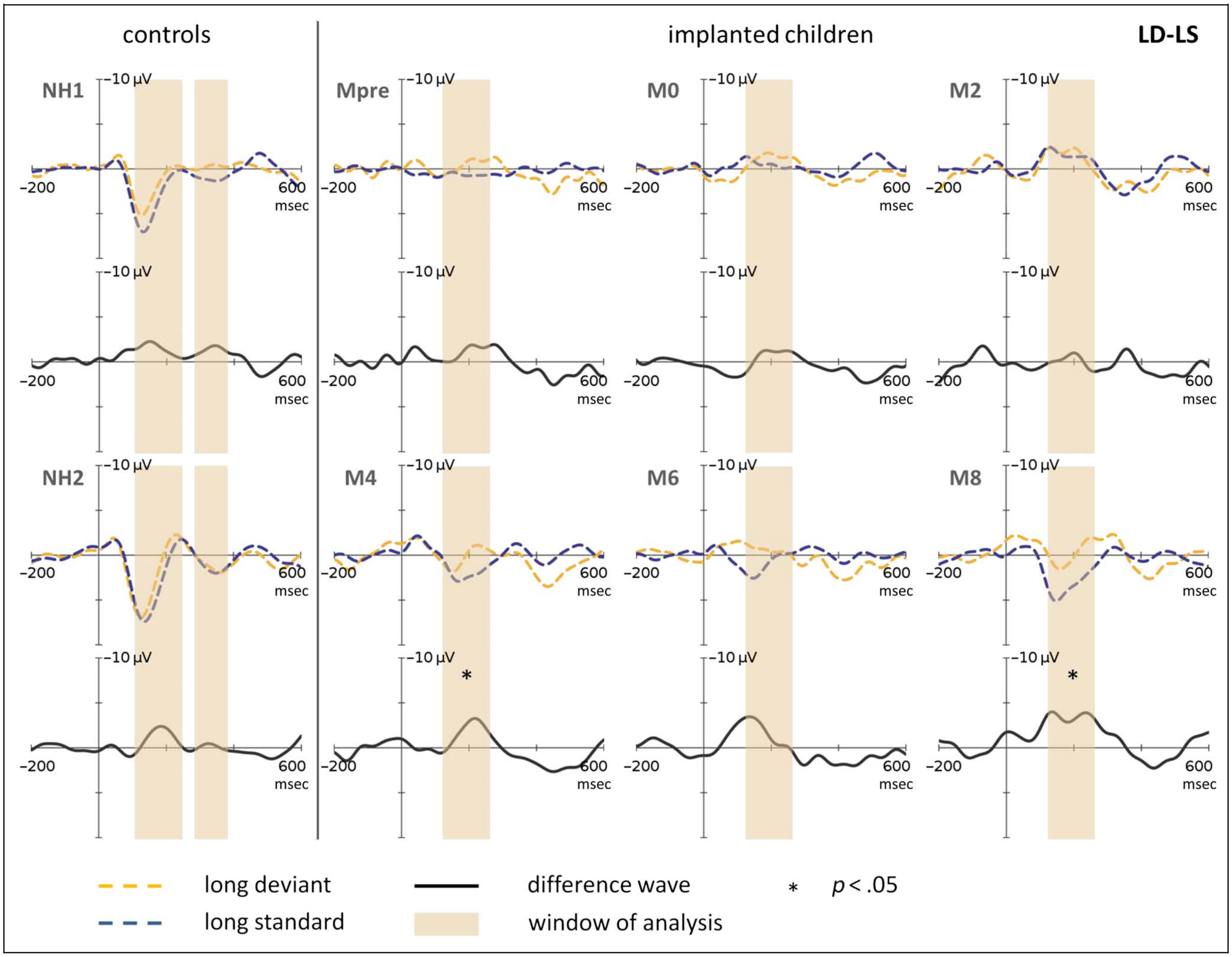


Figure 5. ERPs and difference waves of the physically identically stimuli: long deviant syllable versus the long standard syllable at electrode Fz for implanted and normal hearing children.

the peak is inconsistent: It is negative in all groups but M8. In the grand average without M8 the negativity peaks at 184 msec, whereas the positive peak of M8 lies at 212 msec.

When Mpre is excluded from statistical analysis due to the suspected artifact in condition SD, we still find a main effect for stimulus [$F(1, 224) = 6.21, p = .01$]—the deviant stimulus being more negative than the standard stimulus (peak of difference wave at 188 msec)—and the additional main effects of electrode [$F(2, 224) = 9.17, p < .001$] and duration of implant use [$F(4, 224) = 11.04, p < .001$]. A closer analysis reveals that the amplitude at electrode Pz is smaller than at Fz and Cz [$t(224) = 4.26, p < .001$ and $t(224) = 2.53, p = .03$, respectively]. The amplitudes of group M0 are significantly smaller than those of M4 [$t(235) = -5.26, p < .001$], M6 [$t(235) = -5.0, p < .001$] or M8 [$t(235) = -6.02, p < .001$] and the amplitudes of M2 are significantly smaller than those of M8 [$t(235) = -3.87, p = .001$].

Normal Hearing Children

Similar to the long stimulus, both control groups show no differentiation between the short syllable as deviant and as standard stimulus (small negative peak: NH1: 180 msec, NH2: 204 msec; second negative peak: NH1: 276 msec, NH2: 288 msec; time windows: 150–230 and 230–330 msec) except for a marginal significance in NH1 for the first time window [$F(1, 66) = 3.30, p = .07$].

DISCUSSION

The aim of this study was to assess the auditory discriminative abilities of congenitally deaf children after implantation with a CI and how these abilities evolve within the first months of hearing. We specifically tested features that are relevant for oral language acquisition, that is, vowel duration in syllables. To our knowledge, this is the first study monitoring the developing ability to discriminate linguistic features in early implanted congenitally deaf children over the first months of implant use.

Our results show that already 2 months after their first hearing experience with the implant children are differentiating syllables differing in vowel length, as can be seen in the within-block MMN difference waves of LD-SS and SD-LS. Notably, the implanted children reach age-appropriate values only 4 months after their first auditory input for the contrast of LD-SS. This is remarkable, considering that being congenitally deaf they are lagging behind at least 1 year from their age peers in terms of hearing experience.

The first appearance of a within-block MMN at 2 months of implant use for LD-SS and its growing robustness over time is in line with the observations of Liang et al. (2014), who identify only one participant with a within-block MMN for pitch deviants at 1 month after implantation, but already 16 participants with an MMN 3 months after implantation. Apparently, the auditory system needs around 2 months to adapt to the new input and to process acoustic differences cortically, irrespective of whether this difference concerns basic signal properties like pitch or the slightly more complex feature of a syllable's vowel length.

But is the observed effect really a within-block MMN or simply an effect of the physical difference in length? If the effect originates mainly from the physical difference of the stimuli reflected in the ERPs, it should switch polarity when subtracted for the reverse condition. That is, if the stimulus being deviant/standard plays only a minor role in the ERPs and the effect rather results from subtracting a short from a long stimulus, subtracting a long from a short stimulus should result in an effect with reversed polarity.[1] This is exactly what we observe: In the difference wave of LD-SS, there is an emerging negativity that becomes significant with hearing experience and is also prominent in the normal hearing controls. In the difference wave of SD-LS, however, there is a positivity that emerges over time and reaches significance in both the

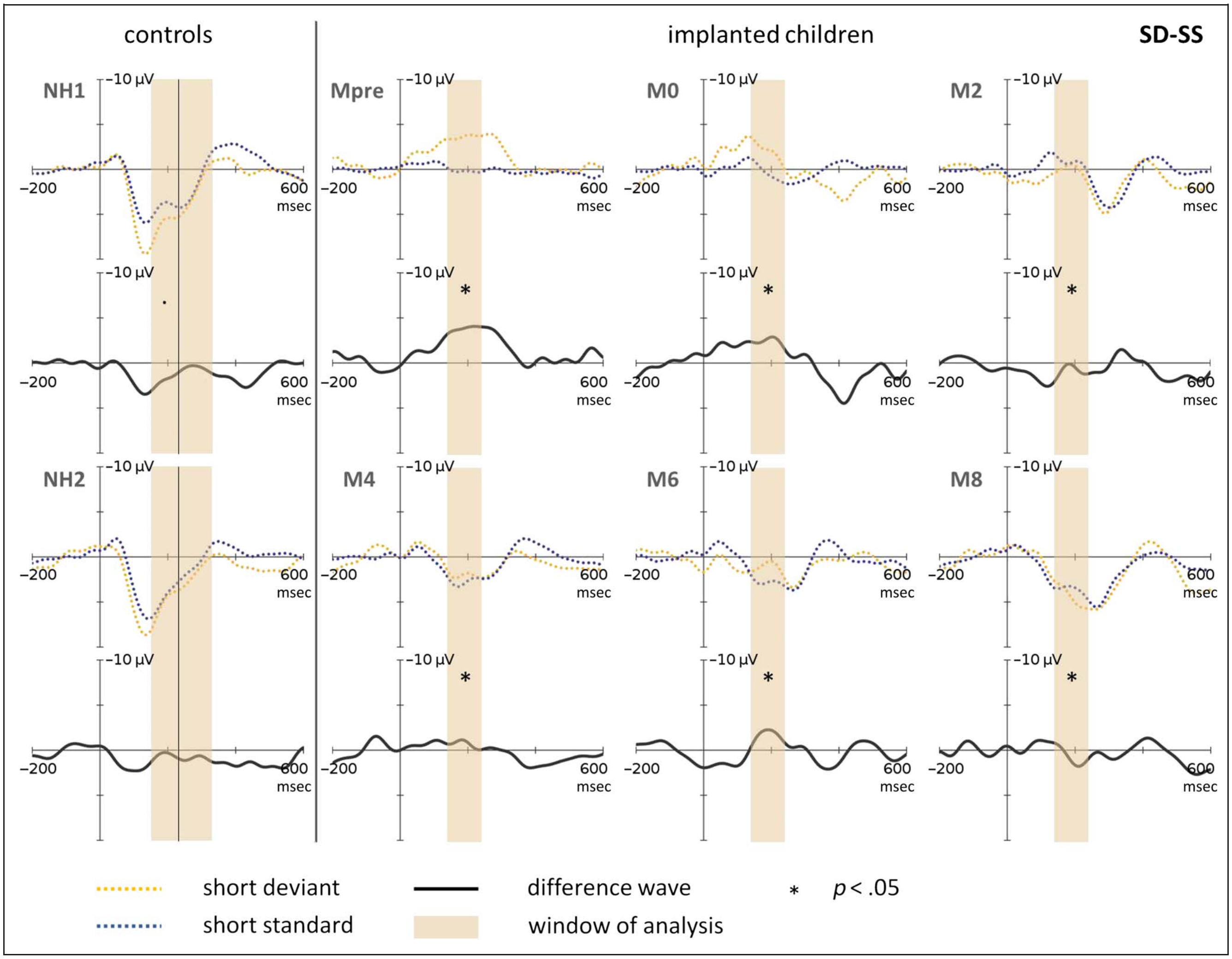


Figure 6. ERPs and difference waves of the physically identical stimuli: short deviant syllable versus the short standard syllable at electrode Fz for implanted and normal hearing children.

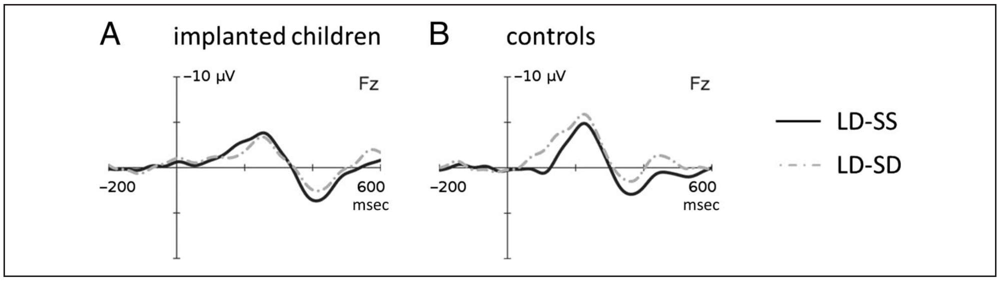


Figure 7. Visualizing the effect of physical properties in the difference wave. The difference wave of LD-SD in both groups (dash-dotted line) is strikingly similar to the difference wave of LD-SS (solid line) strongly suggesting that the amplitude pattern of LD-SS is mainly driven by differences in the domain of physical properties (i.e., stimulus length). (A) Averaged data of M0–M8 (i.e., after implantation). (B) Average over all controls.

implanted children and the controls. The physical difference thus seems to contribute largely to effects in the difference wave. To test how much it actually contributes, we also looked at the difference wave of LD-SD. Here, we should get the pure effect of physical difference: LD and SD are both deviating stimuli, differing only in length. Figure 7 shows the difference wave of LD-SD practically mirroring that of LD-SS, thus suggesting that any effect of the LD-SS contrast is mainly due to the difference in physical properties.

With the LD-SS and SD-LS contrasts showing so little of a cognitive mismatch in the local context of a presentation block, the inconsistent results for the across-block MMN are less surprising. For the long stimulus (LD-LS), the implanted children do show a significant negativity 4 and 8 months after implant activation, but the effect is missing in the control data. For the short stimulus (SD-SS), there is a main effect for stimulus for the implanted children, but a closer look at the ERPs shows that it is not a consistent effect developing over time. Again there is no MMN observable in the control group. It is striking that the normal hearing children do not show any effect for either stimulus, which raises the question whether there are either developmental or paradigm features that prohibit an across-block mismatch elicitation in our study.

Developmental changes in the polarity of the mismatch response are described among others by Mueller, Friederici, and Männel (2012), contrasting earlier articles that report the MMN to be stable both intraindividually (Kraus, McGee, et al., 1993; Kraus et al., 1992) as well as during development (Cheour, Korpilahti, Martynova, & Lang, 2001). If the ERPs to vowel length also undergo a developmental change from a positive to a negative mismatch response, it could be that in our control groups of mixed age, and thus mixed hearing experience, the response was simply cancelled out. Separating all control participants according to age, however, found no polarity shift. Another explanation might be that the ISI of the paradigm was too long to elicit an MMN. Most other child studies reporting a mismatch response with syllable length employ shorter ISIs (Lovio et al., 2009; Jansson-Verkasalo et al., 2003; Korpilahti, Krause, Holopainen, & Lang, 2001), but there are also studies that report an MMN for phoneme or pitch deviants with similar or larger ISIs (Bishop, Hardiman, & Barry, 2011; Watson et al., 2007; Singh, Liasis, Rajput, Towell, & Luxon, 2004; Cheour-Luhtanen et al., 1995; Kraus, McGee, et al., 1993) and one that finds stronger effects with an ISI of 855 msec in contrast to an ISI of 425 msec (Leppänen et al., 1999).

MMN: Differentiation on the Physiological versus the Cognitive Level

Many child studies claiming to observe an MMN are in fact contrasting physically different stimuli as we did for the LD-SS or SD-LS comparison. As we pointed out earlier, this contrast may merely reflect a different physiological processing of the two physically differing syllables, whereas the MMN is defined to reflect a cognitive process with an actual recognition of the deviance.

Albeit stimuli varying in length could be more affected (Jacobsen & Schröger, 2003), the little exercise above suggests that any study focusing on the MMN should at least double check: Is the assumed effect elicited by a true cognitive mismatch detection (within-block or across-block) or can it be traced down to lower-level processing of differing physical properties? The discussion above should make clear that a careful consideration of what is actually compared is necessary when studying the MMN.

Revisiting child MMN literature with that in mind, only a few actually study an across-block MMN (e.g., Leppänen et al., 2004; Ceponiene et al., 2002; Friederici et al., 2002; Cheour et al., 1998; Kraus, McGee, et al., 1993; Kraus et al., 1992). Most other studies, including those with varying stimulus length, only consider differences obtained within the same block (Chobert et al., 2012; Lovio et al., 2009; Shankarnarayan & Maruthy, 2007; Jansson-Verkasalo et al., 2003; Cheour, Kushnerenko, Ceponiene, Fellman, & Näätänen, 2002; Korpilahti et al., 2001; Leppänen et al., 1999; Pihko et al., 1999). Adult studies are more likely to include a control condition, most probably because it is demanding to run two blocks with the fidgety subjects of child studies to ensure that at least one of the stimuli is presented in a deviant and a standard condition.

With only a handful of studies that have a stimulus pair that differs in physical length as well as an across-block MMN contrast (Watson et al., 2007; Singh et al., 2004; Cheour et al., 1998; Leppänen, Eklund, & Lyytinen, 1997; McGee, Kraus, & Nicol, 1997; Kraus, McGee, et al., 1993; Kraus et al., 1992), it is hard to say, whether any of our paradigm features (e.g., stimulus properties, filtering properties, subject age) is responsible for the lack of a genuine across-block MMN in our control groups. However, finding that stimuli are processed differently based on their physical properties (length) is a valuable insight all by itself where hearing disabled groups like CI children are concerned.

Developmental Trajectory after Implantation

To answer our initial question of which developmental trajectory congenitally deaf children might follow after a cochlear implantation, more studies will be needed to cover the full range of linguistic development. For one of the elementary prerequisites of language acquisition—vowel length discrimination—we can conclude that a hearing experience of approximately 2 months is needed for discrimination to occur and 4 months to reach age-appropriate values. That means that after a brief period of adaptation to the new modality, development progresses at full speed. Implanted children therefore do not start like newborns who demonstrate tone duration discrimination already at birth (Cheour et al., 2002). Keeping in mind, though, the enormous head start of normal hearing children with processing of auditory input starting by the end of the second trimester of pregnancy (Moore & Linthicum, 2007) and duration features being one of the first available, the progress of the implanted children is most remarkably fast.

Summary

Our study demonstrated that features essential for language acquisition, like vowel length of syllables, are available to congenitally deaf children already 2 months after first activation of the implant. Moreover, the ability to discriminate syllable length reaches age-appropriate values only 4 months after the first auditory input. Early implanted children thus quickly catch up on basic auditory elements of language, thereby making up for their lesser hearing experience.

We further critically discussed methods of assessing the MMN and concluded that studies focusing on the MMN should always consider whether their claimed effect is an across-block MMN or rather the detection of a differentiated encoding of physical properties.

Outlook

Data sufficient for an individual analysis is extremely difficult to obtain for this agile age group, and longitudinal designs without the occasional missing session are even more difficult to obtain from a clinical population with its limited number of subjects. Nevertheless, further efforts to time-track the individual and group development of such language-specific auditory features and how it correlates with later language acquisition would be of great interest for theoretical and practical reasons. On the one hand, it would give insight to the time course of complex information processing in a sensory modality that has not been stimulated during an extended period of crucial development. On the other hand, knowing where the developmental trajectory of children with successful language acquisition diverges from those with poor language acquisition would help placing specialized therapeutic intervention in the critical period.

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Note

1. Let **A** stand for the long stimulus, **B** for the short stimulus, * for the deviant, and ** for the standard stimulus, such that, for example, **A*** represents a long deviant stimulus. If the effect originates mainly from the physical difference long versus short, instead of whether the stimulus appears as a deviant or a standard, then the difference wave of **A*–B**** should have the opposite polarity from **B*–A****: We could neglect the notion of deviant or standard, thus having **A–B** versus **B–A**, which are opposite in polarity due to the mathematical principle of **A–B = −(B–A)**. If, on the other hand, the difference between deviant and standard is the main source of the effect, **A*–B**** and **B*–A**** could be reduced to *–** and *–**, which are equivalent in polarity. Of course, with the variable nature of ERPs and some influence a stimulus being deviant or standard, we shall not find a strict reversal when comparing LD-SS **(A*–B**)** to SD-LS **(B*–A**)** nor a strict equivalence between LD-LS **(A*–A**)** and SD-SS **(B*–B**).**

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