Speech production accuracy of children with auditory brainstem implants: A comparison with peers with cochlear implants and typical hearing using Levenshtein Distance

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Abstract

Auditory brainstem implantation (ABI) is a recent innovation in pediatric hearing restoration in children with a sensorineural hearing impairment. Only limited information is available on the spontaneous speech development of severe-to-profound congenitally hearing impaired children who received an ABI. The purpose of the present study was to investigate longitudinally the accuracy of ABI children's word productions in spontaneous speech in comparison to the accuracy of children who received a cochlear implant and children with normal hearing.

The data of the present study consist of recordings of the spontaneous speech of the first three Dutch-speaking children living in Belgium who received an ABI. The children's utterances were phonemically transcribed and for each word the distance between the child's production and the standard adult phonemic transcription was computed using the Levenshtein Distance as a metric. The same procedure was applied to the longitudinal data of the children with CI and the normally hearing children.

The main result was that the Levenshtein Distance decreased in the three children with ABI but it remained significantly higher than that of children with typical hearing and cochlear implants matched on chronological age, hearing age and lexicon size. In other words, the phonemic accuracy increased in the children with ABI but stayed well below that of children without hearing loss and children with cochlear implants. Moreover, the analyses revealed considerable individual variation between the children with ABI.

Keywords: auditory brainstem implantation; pediatric; oral language, Levenshtein Distance, speech production

1. Introduction

Auditory brainstem implants (ABI) and cochlear implants (CI) are devices that have been developed relatively recently to help restore hearing in individuals with severe-to-profound sensorineural hearing loss. Sensorineural hearing loss can be the result of a defective cochlea, caused by absent or damaged hair cells in the cochlea, in which case a CI may be at least in part alleviate the hearing issue. But it can also result from the absence of the auditory nerve or from an ossified or malformed cochlea in which cases the insertion of a CI may be impossible. Then an ABI may be the only viable solution. At present a cochlear implant is the best solution for individuals with a well-functioning auditory nerve but with a malfunctioning cochlea permitting CI placement (Moeller, 2006).

The two devices are structurally similar: environmental sounds are captured by a microphone and converted into a digital code in a sound processor. The digital code is sent to the internal part of the device, which consists of a number of electrodes. At this point the two devices differ. The electrode array of a CI is inserted into the cochlea and directly stimulates the auditory nerves (Puram & Lee, 2015). The electrode array of the ABI is placed on the cochlear nucleus of the brainstem, thereby surpassing the cochlea in the inner ear as well as the auditory nerves connecting the inner ear with the brain. The different locus of placement of the electrodes has consequences for sound processing. Electric stimulation by the electrodes of a CI can be well targeted in the cochlea since the tonotopic organization of the cochlea is relatively circumscribed. In contrast, the hearing pathways of the brainstem are identified as unpredictable, which appears to make the ABI intervention less effective and more uncertain (Wong et al., 2019).

Auditory brainstem implants (ABI) were initially designed for adults suffering from hearing loss due to neurofibromatosis type 2 (NF2) (Edgerton et al., 1982). Gradually ABIs were also used in adults with other inner ear pathologies, such as cochlear nerve aplasia (Colletti et al., 2009; Puram & Lee, 2015). Since the beginning of this century, Colletti and colleagues (Colletti et al., 2001) have expanded the use of ABI to pediatric populations. Nowadays, children who are not eligible for cochlear implants (CI), due to for instance cochlear malformation or absence of auditory nerves, are candidates for an ABI. Still, ABI implantation is only recommended if the neural anatomy makes a CI impossible or after a period of CI use in which the child is showing little benefit of the implant (Buchman et al., 2011; Farhood et al., 2017; Hammes Ganguly et al., 2019). In that last case, the ABI is often implanted contralaterally. In addition, recent studies have shown that children with cochlear nerve deficiency seem to benefit from the combination CI and ABI as compared to only CI stimulation (Batuk et al., 2020; Friedman et al., 2018).

1.1. Children with ABI

Children with ABI develop sound awareness and speech perception skills after a varying period of ABI use. Some children are able to detect ambient sounds after two weeks of ABI use, whereas others need up to 18 months of ABI use (Teagle et al., 2018). Speech perception (and production skills as well) are more developed in children with ABI with lower hearing thresholds after surgery (Sennaroglu, Sennaroglu, et al., 2016), in children who are implanted earlier (Aslan et al., 2020) and in children with no additional disabilities (Colletti et al., 2014; Sennaroglu, Colletti, et al., 2016; van der Straaten et al., 2019). Only the so-called *good performers* are able to develop open set speech perception and to understand simple phrases without lip-reading (Aslan et al., 2020; Bayazit et al., 2014; Colletti et al., 2014; van der Straaten et al., 2019; Yucel et al., 2015). These *good performers* continue to improve their speech perception skills up to five years of device use (Sung et al., 2018; van der Straaten et al., 2019).

With open set speech perception, the better performing children with ABI are able to achieve speech production as well. Nevertheless, speech production appears to be difficult for children with ABI: they tend to be only intelligible for experienced and familiar listeners even after five to six years of ABI use (Sennaroglu, Sennaroglu, et al., 2016; van der Straaten et al., 2019).

Children with ABIs without additional disabilities have been found to follow the overall course of early spoken language development of children with typical, normal hearing (NH) and children with CI matched on hearing experience: from vocalizations, to babbling, and eventually to word use (Faes et al., 2019; Faes & Gillis, 2019a). However, their lexical expansion remained well below the abilities of children with CI and NH. Their vocabulary sizes fell below the 95% confidence intervals around the mean for children with NH and children with CI with a comparable hearing age (Faes & Gillis, 2019b).

As to phonological development, the better performing children with ABI have been shown to use basic word patterns and language ambient consonants and vowels with varying accuracy (Eisenberg et al., 2018; Faes & Gillis, 2020, 2021; Teagle et al., 2018). Their consonants showed a quite typical course of development: stops, nasals and glides (for manner of articulation) and labials and coronals (for place of articulation) appeared first in their speech productions (Eisenberg et al., 2018; Faes & Gillis, 2021; Teagle et al., 2018). Despite these more general patterns, a substantial amount of individual variation was observed, even in children with ABI with similar (early) age at implantation and similar hearing thresholds after implantation (Eisenberg et al., 2018; Faes & Gillis, 2020, 2021; Teagle et al., 2018). In addition, they expanded their phonological inventories considerably more slowly (especially for consonants) as compared to the reported pace of development of children with NH and CI in the literature (Faes & Gillis, 2021).

The phonological complexity of children with ABI's word productions (as measured by i.a. the number of phonemes and syllables of words, the pMLU of the target words, see below for further elaboration) fell out of the 95% confidence intervals of children with CI and NH with similar hearing experience (Faes & Gillis, 2020). Moreover, even though their attempted words were less complex as compared to these two reference groups, the accuracy of their actual word productions was not higher at similar hearing ages (Faes & Gillis, 2020). Rather, their speech production accuracy also fell in the lower ranges or even below the 95% confidence intervals of children with NH and children with CI (Faes & Gillis, 2020).

1.2. Measuring speech production accuracy

Two aspects of children with ABI's speech production accuracy have been studied: (1) speech production accuracy at the phoneme level (Faes & Gillis, 2021), and (2) speech production accuracy at the word level (Faes & Gillis, 2020). For the latter aspect, Ingram (2002)'s measures pMLU (phonological mean length of utterance) and PWP (proportion of whole-word proximity) were used. These measures are familiar from studies of NH and CI children's speech (e.g. Saaristo-Helin, 2009; Saaristo-Helin et al., 2006; Schauwers et al., 2008). Both measures focus on children's whole-word productions and quantify the number of segments in the child's word production and the number of correctly produced consonants (pMLU) and ratio of the child's pMLU relative to the pMLU of the adult target word that the child attempts to produce (PWP).

However, pMLU as a measure of speech accuracy raises a number of issues. First, the measure only takes consonantal accuracy into account and leaves the accuracy of vowels out of consideration. Secondly, pMLU is not a pure measure of speech accuracy. It is a composite measure because in computing pMLU, the length of the adult target word and the length of the child's rendition play a role in addition to the accuracy of the consonants in the child's rendition. This implies that two children's segmental accuracy can be on a par, but if one uses longer words than the other, pMLU will be higher for the latter (Saaristo-Helin et al., 2006). A second issue with pMLU concerns the implicit and unmotivated weighting of "speech errors", viewed as the deviation of the adult target (Faes et al., 2016). In computing pMLU (and PWP) deletions and substitutions of segments are taken into account, but insertions are not. Thus, surprisingly, insertions are apparently not considered to be deviations from the adult equivalent. In addition, deletions are weighted more heavily than substitutions because a deletion weighs on the length parameter while a substitution does not, which implies that pMLU values are higher for children who more often substitute than delete segments. These general considerations regarding the differential use of the three basic operations insertion, substitution and deletion cast some doubt on how pMLU and PWP as computed according to Ingrams's (2002) proposal, reflect speech accuracy in a valid way.

But in addition to these general considerations concerning the use of the basic operations in computing pMLU (and PWP), another problem turns up. Accuracy is usually calculated by comparing a child's word production with the adult equivalent of that word in the standard language. The standard language pronunciation is usually taken from a lexical database such as CELEX for Dutch, English or German (Baayen et al., 1995). That standard adult form is compared to the child's actually produced form segment by segment and deviations reduce the accuracy of the child's production. But should every deviation weight as heavily as any other? Does each insertion, substitution or deletion render the child's form equally distant from the adult form? Probably not because the speech that a child actually hears may deviate from the standard form represented in a lexical database (as represented by CELEX or FONILEX, see the method section). For instance, in colloquial Belgian Dutch the monophthongization of the diphthong /ɛi/ occurs very frequently, even though this is not accepted as standard, formal language. In contrast, substituting this diphthong by, e.g., the back low monophthong /a/ is very exceptional (Kloots et al., 2003; Swerts et al., 2003). Hence, the former substitutions are closer to the adult example form and even coincide with the colloquial variants than the latter. Another example, in spoken Dutch, deletion of a final /n/ preceded by schwa, as in [bɑlɔnə] for /bɑlɔnən/ (*Eng. balloons*) is also particularly frequent. Or inserting /ə/ in a consonant cluster consisting of a liquid followed by a non-coronal obstruent as in *melk* /mɛlək/ (*Eng. milk*) instead of /mɛlk/ or *werp* /wɛrəp/ (*Eng. throw*) instead of /wɛrp/, is also a common phenomenon in colloquial speech (Kloots et al., 2002, 2004). Thus, children hearing colloquial Dutch may easily pick up those forms, and thus show deviations from the adult, formal standard, which, in fact, do occur in spontaneous colloquial speech. In other words, the examples show that some deviations of the adult standard are quite common in colloquial speech, and, hence, result in deviations that should weigh less heavily than others. Faes et al. (2016) suggested to take the frequency of such deviations into account in the computation of phonemic accuracy at the word level, by using Levenshtein Distance.

Levenshtein Distance (LD) is a metric for computing the difference between two-character strings, which is well-known from computer science and bioinformatics, where it is used to measure the difference between character strings or to assess the (mis)match of DNA strings. LD was introduced by Nerbonne and Heeringa (1997) in dialectology to measure the distance between various dialects. In the present study LD is used to measure the difference between an adult target word and the child's production of that word. Essentially, LD measures the minimal edit distance between two strings of characters by applying single character edits to one string in order to arrive at the other string. The permitted single character edits are insertions, substitutions and deletions (Heeringa, 2004; Nerbonne & Heeringa, 2010; Wieling et al., 2011). For instance, if a child produces the adult target *boek* /buk/ (*Eng. book*) as [bu], one single edit suffices to arrive from the adult target to the child's form, viz. the deletion of the final /k/. The final LD is the sum of all edit operations needed to transform the adult word into the child's production. The logic of applying LD to a child's rendition of an adult word is that the fewer edit operations are required, the closer the child's rendition is to the adult word. Moreover, it can be assumed that LD is a proxy of the intelligibility of speech: the larger the distance from adult speech, the less intelligible the children's speech will be. Indeed, Sanders & Chin (2009) showed that distance between word productions of children with CI and the adult targets measured by LD correlated with intelligibility judgments of naïve listeners.

In computing LD, each edit operation can be assigned a "cost" or a "weight". These weights can be defined a priori using, for instance, phonological features so that substituting a voiced segment by an unvoiced one has a different weight than substituting a voiced labial by a voiced coronal (as in the pairs /buk/-/puk/ versus /buk-duk/). Changing the feature voice of a consonant, as in substituting a voiced segment by its unvoiced counterpart (as in /b/-/p/), can arguably be considered to have a lower cost than changing the place feature of that consonant, as in changing the articulation from labial to coronal (as in /b/-/d/). But deciding on the exact weight differences appears to be rather hazardous (Sanders & Chin, 2009; Wieling et al., 2012). For this reason, Wieling et al. (2012) proposed a dynamic LD procedure to derive the weights or costs of edit operations on empirical grounds. The model was adapted by Faes et al. (2016) to comparisons of children's word productions with their adult targets and to compute the LD between the two. The starting point of that procedure is a model of adult spoken language as represented in a corpus of child directed speech. From that model weights or costs can be derived for particular edit operations. For instance, some phonemes typically appear more frequently than others and some phonemic variations are more frequent in spontaneous speech than others (e.g., the deletion of /n/ after schwa at the end of words, as in

/etə/ instead of /etən/ *eten* (*Eng. eat*), or the substitution of a tense vowel by its lax counterpart in unstressed position, such as the tense /a/ in /vɪla/ *villa* (*Eng. villa*) which is frequently replaced by lax /ɑ/). These frequency differences can be taken into account in computing the distance between the adult model and a child's production of that word. The exact weight of the final /n/ deletion depends on particular aspects of its frequency distribution in the adult model and will most probably differ from a deletion of word-internal /n/, which is far less frequent. Consequently, deleting the first /n/ in /tenən/ *tenen* (*Eng. toes*) will carry a larger weight than deleting the final /n/. The specifics of the dynamic LD calculation will be presented in the Method section.

1.3.Aims of the present study

The aim of the present study was to investigate the speech accuracy of three Dutch-speaking children who received an auditory brainstem implant in Flanders (Belgium). The longitudinal speech data were compared with similar data collections of children with normal hearing (N=30) and children with severe-to-profound hearing impairment who received a cochlear implant (N=9). In the literature, in-depth longitudinal analyses of children with ABI are currently still rare. Moreover, the monthly approach that was adopted in this study (see methods), allows to track very subtle changes in the children with ABI's development. For instance, Teagle et al. (2018) pointed out that their six-month interval testing was not sensitive enough for tracking the small changes in children with ABI's language development. In addition, this study adopts a triple-case approach for the three children with ABI, since Nagels et al. (2020) accentuated the need to study individual patterns in the language development of heterogeneous clinical groups such as children with CI. Since children with ABI represent an even more diverse group, this approach was applied in this study as well.

The focus of the study was on the accuracy of their spoken words, as opposed to previous research in which the accuracy of the individual segments (vowels, word-initial and word-final consonants) was investigated (Faes & Gillis 2021). Word accuracy was defined in terms of how closely the children's word productions approximated the adults' targets. More precisely, for each child's word production the Levenshtein Distance (LD) was computed with the adult target production taking into account the frequency distribution of substitution, deletion and insertion patterns in child-directed adult speech. This metric adds to the body of knowledge of children with ABI's accuracy in production by its sensitiveness as opposed to studies using e.g. pMLU (Faes & Gillis, 2020). Hence the overarching research question was: how distant were the children with ABI's word productions from their adult equivalent and how did that distance develop, both in comparison to children with CI and in comparison to children with NH? It was expected that all the children's accuracy would increase, irrespective of the dimension relative to which development was measured.

Development was operationalized in three different ways. First, the three ABI children were compared with the children with CI relative to their chronological age (comparable longitudinal data of children with NH were lacking). It was expected that children with ABI's word productions would be less accurate because at the same chronological age ABI children had considerably less hearing experience due to their later access to ambient sound.

Secondly, the three children with ABI were compared to the other two groups relative to their hearing age. It was expected that, everything else being equal, children with ABI and children with CI would be equally accurate in their word production. However, since the age at device placement was later for children with ABI this factor was expected to be in their disfavor, hence causing lower accuracy.

Thirdly, the three children with ABI were compared with the children with CI and children with NH at similar levels of lexical development, and more precisely at similar levels of cumulative vocabulary. It was expected that putting the children on a par relative to a linguistic yardstick, contrary to the extralinguistic yardsticks chronological age and hearing age, would show the impact of their different hearing statuses in the clearest way. In other words, by leveling the children with ABI with children with CI and children with NH with similar vocabulary sizes, it is expected to get around the intrinsic variation found in children of similar ages and hearing ages (e.g. Duchesne et al., 2009; Leonard et al., 1980; Vihman et al., 1986). Moreover, the CI and NH literature has suggested that phonological development (and thus speech accuracy) is more closely related to lexical development than to (chronological) age (e.g. Faes & Gillis, 2016; Reidy et al., 2015; Santos & Sosa, 2015; Sosa & Stoel-Gammon, 2012; van den Berg, 2012).

2. Method

2.1. Participants

Three children with ABI participated in the present study and their speech production was compared to that of children with typical hearing and children with cochlear implants. All the children were raised in monolingual Dutch speaking homes by parents with self-reported normal hearing and from a mid-to-high socio-economic background. This study was approved by the Ethical Committee for the Social Sciences and Humanities of the University of Antwerp (EASHW_16_29). A written informed consent was signed by all the parents.

Eight children received an ABI in Belgium between 2015 and 2019. For the present study, children meeting two criteria were selected: (a) raised in Dutch, which is only spoken in the northern part of Belgium (Flanders), and (b) no patent developmental or health problems. This resulted in three participating families, henceforth ABI1, ABI2, and ABI3.

ABI1 and ABI2 had a congenital severe-to-profound hearing loss of 120 and 116 dB HL respectively resulting from the absence of the auditory nerves. The children were implanted with an ABI (Med-El) at 2;00 and 2;01 respectively. Nine out of 12 electrodes could be activated at the first fitting two months after surgery. The pure tone average (PTA) hearing thresholds improved to 37.5 dB HL and 43 dB HL two years after implantation. At 4;09 ABI1 was bilaterally implanted, ABI2 was not. ABI1 and ABI2 were raised in oral Dutch, supported with Flemish Sign Language. Data of ABI1 were collected monthly from 3;02 until 5;07. Data of ABI2 were collected monthly from 4;01 up till 6;03.

ABI3 was first implanted with a CI in the right ear at eight months of age, after a diagnosis of auditory neuropathy. The child's PTA hearing thresholds equaled 90 to 95 dB HL in the right (and better) ear. Even though the aided PTA levels improved to 33 dB HL, the effect of the CI on language and hearing development was limited. Therefore, a contralateral ABI (Med-El) was implanted at four years of age. Two months after the surgery, the implant was fitted, and all 12 electrodes could be activated. ABI3 was raised in oral Dutch, supported by Flemish Sign Language. Data were collected monthly from two months before the ABI surgery (3;10) until 5;04.

Two control groups were included in the study: children with cochlear implants (CI) and children with typical hearing (NH), all growing up in Flanders as well. For none of these children, additional health, motor or developmental problems were reported during data collection. The first control group comprised nine congenitally hearing-impaired children with CI (Table 1). All children had a severe-to-profound hearing loss detected virtually at birth by universal hearing-screening with otoacoustic measurements. The mean age at implantation was one year (SD = 5 months). The mean PTA of 112.56 dB HL before implantation (SD = 9.12) improved to 32.22 dB HL (SD = 7.11) at two years of age. Six children received a second CI at a later age (Table 1). All children were raised in oral Dutch by their hearing parents and only a limited number of lexical signs were used in support. The children were of mid-to-high Socio-Economic Status. Data collection started immediately after implant fitting, continued monthly up to 30 months thereafter and yearly up to seven years of age afterwards. Further details of the data collection and processing are provided in Schauwers (2006) and Molemans (2011).

The second control group consisted of 30 monolingual children with typical, normal hearing (NH). The children were included showed no health or developmental problems, no (history of) hearing problems, and no repeated scores less than percentile 1 on the N-CDI (Zink & Lejaegere, 2002). The parents were also monolingual, had self-reported normal hearing, and spoke Standard Dutch to their child. Furthermore, they could be categorized as mid-to-high Socio-Economic Status (mhSES). These children were also followed longitudinally with monthly observation sessions between six and 24 months of age. This corpus is further described in Molemans (2011), Van Severen (2012) and van den Berg (2012).

Insert Table 1 here.

2.2. Data collection and transcription

Spontaneous interactions between each child and his/her caregivers (henceforth: adults) were video recorded monthly, resulting in longitudinal data for all children. The recordings lasted approximately one hour. This resulted in 25 recordings for ABI1, 25 recordings for ABI2 and 14 recordings for ABI3. For the children with CI, the mean number of recordings was 24.56 (SD = 2.78, range 21 – 30). For each child with NH (N = 30), 18 recordings were made between 6 and 24 months of age, meaning that none of the children with NH missed a single monthly recording.

All recordings were transcribed in CHILDES' CLAN according to the CHAT conventions (MacWhinney, 2000). The children's and adults' lexical productions were transcribed orthographically and phonemically. All productions were transcribed in two layers: a phonemic transcription of the actual child's production or a phonemic transcription of the adult's production, and a phonemic transcription of the corresponding target word, representing the standard adult equivalent and its pronunciation. These target words were identified using the criteria of Vihman and McCune (1994). The target pronunciation was retrieved from the phonetic dictionary Fonilex (Mertens, 2001), i.e. a lexicon of Dutch words and their standard Flemish pronunciation. Subsequently, the transcription of the actual productions (both for the children and the adults) and the target words were aligned at the phoneme level, using a dynamic alignment procedure based on ADAPT (Elfers et al., 2005). The alignments were verified manually and corrected if needed.

Transcription reliability of the actual child productions was checked for 10% of each of the groups (ABI, CI, NH). For the ABI group, interrater reliability equaled 80.05% in a phoneme-to-phoneme comparison. Agreement on consonant manner and place and vowel place and height equaled 81.63% for the CI group and 78.77% for the NH group.

2.3. Data analyses

2.3.1. Levenshtein Distance (LD)

Production accuracy is assessed by determining the Levenshtein distance (LD) between the child's production of a particular word and the standard adult form of that word. LD is a commonly used technique to measure the distance between two character strings. In the present study the first character string is the phonemic transcription of the adult word and the second string is the phonemic transcription of child's rendition of that word. For instance, the child produced the wordform [bu] as a rendition of the adult standard form *boek* [buk] (*Eng. book*). The LD is defined as the minimal edit distance between the two character strings. The LD uses the single character editing operations insertion, deletion and substitution, and determines the minimal set of those edit operations to arrive at the second string starting from the first one. For instance, [bu] can be derived from [buk] by applying a single edit: deletion of the final [k]. Hence the LD distance equals one, provided that the "cost" for each edit equals one, and zero if no edits are required. The LD between [mu] and [buk] equals two: the substitution of the initial [b] by [m] and the deletion of the final [m]. The LD distance is the sum of the costs of the edit operations. Thus, in this example, it is assumed that the distance between [bu] and [buk] is smaller than the one between [mu] and [bum]. The application of the minimal set of edits to [bum] results in the alignment of the two strings in example (1). In the examples a dot is used as a representation of an empty symbol. In both cases the final [k] is deleted, and hence replaced by a dot in the child's rendition.

(1)	Adult target	b u k	b u k
	Child rendition	b u .	m u .

For aligning the character strings and determining the LD, the algorithm developed by Wagner and Fisher (1974) was implemented in a bottom-up dynamic programming framework. It should be noted that determining the minimal edit distance, maximizes the number of matches between both strings, and minimizes the number of mismatches. Following a recommendation of Wieling and colleagues (Wieling et al., 2012; Wieling et al., 2009), the LD was enriched with a linguistic constraint in the alignment procedure: vowels could only be aligned with vowels and consonants with consonants. This constraint ensures that alignments obey a linguistically motivated logic beyond the mere mechanical alignment of symbols.

The "cost" of the edit operations or the "weight" of the deviations from the adult standard received some attention in the literature (e.g. Bailey & Hahn, 2005). The issue has various facets. For instance, does a child's deletion (e.g., [bu] for [buk]) result in a variant that is equally distant from the adult standard form as a variant with a substitution (e.g., [muk] for [buk])? At least according to the basic version of LD both forms are at the same distance (a single edit). Or is one substitution equally distant from the standard form as any other substitution? In the present study, the dynamic cost model developed by Wieling et al. (2012); Wieling et al. (2009) is used. In that model, the LD costs are estimated from an adult language model of spontaneous speech. Also in adult spontaneous speech, deviations from the standard pronunciation occur, such as the deletion of word final /n/ after a schwa, as in /wɛrkən/ *werken* (*Eng. work*) pronounced as [wɛrkə] instead of [wɛrkən] or the production of the lax vowel [ɑ] instead of the tense vowel [a] in /vɪla/ *villa* (*Eng. villa*) pronounced as [vɪlɑ]. The frequency of such deviations is estimated from the transcribed adult speech in our corpora of spontaneous infant directed speech and then applied in the computation of LD. In this way, the similarity of segments is arrived at in a data-driven way. More specifically, pointwise mutual information (PMI) is used to estimate the association strength between segments. PMI is computed according to the formula in (2):

(2) $$PMI(x,y) = log_2 \left(\frac{p(x,y)}{p(x)p(y)}\right)$$

In which x and y represent two segments, p(x) and p(y) represent their respective frequencies relative to the total number of segments in the corpus, and p(x,y) represents the cooccurrence of the segments x and y at the same position in two aligned transcriptions of the corpus.

In practice, the starting point of the construction of the cost model is the transcription of the adults' speech in the three corpora used in the present study. For each adult utterance, a standard phonemic representation was extracted from the FONILEX lexical database (henceforth: the target) and a transcription of the actual production (henceforth: the rendition) was made. These two transcriptions were lined up at the segmental level. An example is provided in (3) for the Dutch noun *villa* (*Eng. villa*):

(3) Target: vɪla

Rendition: vɪlɑ

PMI is computed for all segments in the corpus, which means that for all pairs of segments in the aligned transcriptions, PMI is computed. Thus, for the target /a/ in (3) the PMI is computed for all the segments it is paired with, including the segment /ɑ/. In practice, the (log of) the probability of /a/ being paired with [ɑ] is estimated relative to all occurrences of /a/ in the corpus of child directed speech. But also the cooccurrence of target /a/ with [ɑ], with [ə], and possibly with other vowels are taken into account. Since /a/ paired with [a] occurs much more frequently than the pairing of /a/ with /ɑ/, which in its turn is more frequent than the pairing of /a/ with [ə], this will be reflected in the PMI values. Consequently, when these PMI values are used as weights in calculating LD, /vɪlɑ/ will be at a closer distance from /vɪla/ than /vɪlə/.

In sum, very frequent deviations in adult language (such as substituting /a/ by /ɑ/ or deleting word final /n/) are less heavily sanctioned (i.e., receive a lower LD cost) than highly infrequent ones (like replacing /b/ by /r/) when evaluating the children's deviations. Lower LD scores represent child productions that are closer to the target equivalent, indicating a higher phonemic accuracy. More elaborate examples including attached weightings are provided in Faes et al. (2016).

The technical details of the algorithm used in the present study are further discussed in Wieling et al. (2012) and further refinements to adapt the algorithm to the child language corpora are elaborated on in Faes et al. (2016).

2.3.2. Data matching

The three children with ABI were analyzed separately. Each child was compared to children with CI and children with NH, based on three different measures of comparison: (a) their chronological age, (b) their hearing age, i.e. the duration of device use for the children with ABI and CI. For children with NH, chronological age and hearing age were identical. And (c) their cumulative vocabulary as a measure for "lexical age". Cumulative vocabulary was computed as the number of distinct word forms in the child's first data point (i.e., the first chronologically ordered recording) and increased with each new distinct word type that appeared at the following data points.

The precise matching of the data was done based on the specific ranges covered for each child with ABI on each measure of comparison. The overview in Table 2 shows, for instance, that ABI1 was compared with the CI children from 38 to 67 months of age. But since the data of the NH children only ranged from 6 to 24 months, a comparison of ABI1 with NH children could not be made. The same holds for ABI2 and ABI3 for the same reason: the onset of their recordings also started well beyond the age where the recordings of the NH children stopped, viz. at 24 months. For hearing age, all comparisons could be made, except for ABI2 for whom there was no match with the NH children's recordings. A further restriction followed from the characteristics of the data: target words with more than 4 syllables and/or more than 10 segments were excluded from the datasets, since such target words occurred only in the production of the children with CI and the children with NH and not in the lexicon of the children with ABI.

Insert Table 2 here.

2.4. Statistical approach

All statistical analyses were performed in R (R Core Team, 2013), using multilevel modeling. Multilevel models consist of two parts: a random part, which takes into account the individual variation in the data (Baayen, 2008; Woltman et al., 2012), and a fixed part, which includes the independent variables. In all models, random intercepts for child and random slopes for the measure of comparison (Age, HearingAge, CumulativeVocabulary) were included in order to model the inter-subject variation. LD was set as the dependent variable in all models. The independent variables were Corpus (CI, NH or both, depending on the data that could be matched) and the measure of comparison (Age, HearingAge or CumulativeVocabulary). Three models were run for each child with ABI (ABI1, ABI2, ABI3), resulting in a total of nine models. The intercept was set at the start of the ABI data. So, for ABI1 and ABI2, the intercepts were equivalent to their age, hearing age and cumulative vocabulary at the first data point (see Table 2). For ABI3, the intercepts were at the first data point after ABI implantation (viz. age 50 months, hearing age 2 months and a cumulative vocabulary of 62 word types).

3. Results

In Figures 1 – 3, the observed data for each child with ABI are plotted as well as the matched data of children with CI and, if available, children with NH. The statistical analyses are presented in tables 3 – 5.

3.1. ABI1

The LD of ABI1, plotted in Figure 1, decreases very slightly in all three comparisons. With increasing age (per month), hearing age (per month) and cumulative vocabulary (per word), overall the LD decreases with 0.11, 0.10 and 0.01 respectively ($p<0.001$ in all analyses, Table 3). For all measures of comparison, LD of children with CI is considerably lower than that of

ABI1 (Figure 1). These differences were also significant: the LD of children with CI is 4.00, 3.68 and 3.21 lower for age, hearing age and cumulative vocabulary respectively ($p<0.001$ in all analyses, Table 3). LD remains equally distant between ABI1 and children with CI with increasing chronological age (Figure 1 and interaction effect Age*Corpus CI: -0.03, $p>0.05$, Table 3), whereas the difference becomes smaller when compared on hearing age and cumulative vocabulary (Figure 1 and HearingAge*Corpus CI: 0.06, $p<0.001$, and Figure 1 CumulativeVocabulary*Corpus CI: 0.01, $p<0.001$, Table 3).

Figure 1 shows that the LD of children with NH is lower than the LD of ABI1 for hearing age and cumulative vocabulary (no matched data for chronological age). For hearing age, this difference equals 1.86 at the intercept ($p<0.05$, Table 3), and remains stable with increasing hearing age, as shown in Figure 1 and by a non-significant interaction HearingAge*Corpus NH ($p>0.05$, Table 3). For cumulative vocabulary, the LD is 2.24 lower than in ABI1 at the intercept ($p<0.01$, Table 3), but this difference diminishes very slightly with increasing cumulative vocabulary, as shown in Figure 1 and by a significant interaction CumulativeVocabulary*Corpus NH (0.002, $p<0.05$, Table 3).

Insert Figure 1 here.

Insert Table 3 here.

3.2. ABI2

The LD of ABI2 (Figure 2) changes little with increasing age, hearing age and cumulative vocabulary. Accordingly, there is no significant effect of Age, HearingAge or CumulativeVocabulary ($p>0.05$ in all analyses, Table 4). In addition, Figure 2 shows that ABI2 and children with CI have a similar LD at all intercepts. However, with increasing age, hearing age and cumulative vocabulary, the difference between ABI2 and children with CI enlarges (Figure 2). These observations are confirmed by inferential statistics. There is no significant difference at intercept: the LD of children with CI is 0.56; 0.76 and 0.09 lower (p>0.05) than that of ABI2 when comparing on Age, HearingAge and CumulativeVocabulary respectively. However, there are significant interactions (p<0.001 in all analyses), indicating a significantly different development with increasing age, hearing age and cumulative vocabulary size between ABI2 and the children with CI.

Matched data for children with NH were only available for cumulative vocabulary. Analogous to children with CI, the difference between ABI2 and children with NH at the intercept is limited and not significant, with even a higher LD for children with NH (0.48, p>0.05, Table 4). But, also similar to the comparison with children with CI, the LD decreases more significantly in children with NH (-0.004, p<0.001, Table 4) than in ABI2 (Figure 2).

Insert Figure 2 here.

Insert Table 4 here.

3.3. ABI3

The LD of ABI3 seems to remain quite stable over age, hearing age and cumulative vocabulary (Figure 3), as also shown by the non-significant effects of Age, HearingAge and CumulativeVocabulary (p>0.05 in all analyses, Table 5). The LD of children with CI is lower than that of ABI3 compared on chronological age: the difference is 2.39 (p<0.001) and the effect is stable over age (non-significant interaction, p>0.05). For hearing age, children with CI have a similar LD at the intercept as ABI3. Inferential statistics confirm a non-significant difference of 0.57 between children with CI and ABI3 (p>0.05). Nevertheless, the decrease of LD is more outspoken in children with CI than in ABI3 as can be derived from Figure 3. This is also confirmed by a significant interaction HearingAge*Corpus CI (p<0.001): the decrease of LD in ABI3 is -0.02, whereas that of children with CI is -0.14. For lexical age, the LD of children with CI is similar than that of ABI3 at the intercept (difference of 0.92, p>0.05). Even though Figure 3 indicates a steeper decrease of LD in children with CI than in ABI3, their development does not differ significantly as indicated by a non-significant interaction CumulativeVocabulary*Corpus CI (p>0.05).

Matching data for ABI3 with children with NH were available for hearing age and cumulative vocabulary. Figure 3 indicates a higher LD in children with NH than in ABI3 at the intercept, but this difference is not significant (p>0.05 in all analyses, Table 5). Yet, the decrease of LD is significantly more outspoken for children with NH than for ABI3 for hearing age and cumulative vocabulary. This effect was only significant for HearingAge (p<0.05, Table 5), but not for CumulativeVocabulary (p>0.05, Table 5). With prolonged observations of children with NH, this would probably result in lower LD values in children with NH than in ABI3, especially when compared on hearing age.

Insert Figure 3 here.

Insert Table 5 here.

3.4. Examples of LD in children with ABI

In Figures 4 – 6, the development of LD for three target words is displayed, one for each child with ABI, based on the children's hearing age in months. In Figure 4, the development of the Dutch target word *groen* /ɣrun/ (*Eng. green*) is shown for ABI1; in Figure 5, the development of the Dutch target word *groot* /ɣrot/ *(Eng. big, large)* is displayed for ABI2, and in Figure 6, the development of the Dutch target word *drie* /dri/ *(Eng. three)* is presented for ABI3. As can be derived from the figures, only ABI2 reaches a LD of zero, as the child's production is phonemically adult-like. For the other children, no accurate production of the target words was reached and consequently the LD remains higher than zero at the end of the data collection.

The higher the LD, the more distant the child's production from the adult target, including a weighting of speech errors, so that infrequent and more severe deviations from the target receive higher LD costs than frequent, less severe ones. For instance, for ABI1, the LD approaches a score of four between 20 and 35 months of hearing age, when child productions were only accurate with respect to the vowel in *groen* /ɣrun/ (/mu/ and /bu/). However, there is a little dip in the curve with a lower LD, when the child produces the target word *groen* /ɣrun/ as /ɣuf/, in which both the word initial consonant and the vowel were accurate. By 40 months of hearing age, the child produces the target word as /ɣu/ with a deletion of the /r/ and /n/, yielding a LD of three.

Also for ABI2, the vowel was produced accurately over the entire period studied for the target word *groot* /ɣrot/ (*Eng. big, large*). The LD decreases gradually as the child produces more segments of the target word correctly: from the vowel and /r/ in /kro/ to /xo/ with only the vowel correct, but with the word initial consonant related much more closely to the target. In both case the place of articulation coincides with the target (target /ɣ/ versus /k/ and /x/ in the child's form). Moreover, devoicing of initial /ɣ/, yielding /x/, actually occurs relatively often in spoken standard Dutch (Booij, 1995; Van de Velde et al., 1997). The LD further decreases as also the word final consonant was produced correctly by the child (/xot/), to a final zero score of LD, indicating an – indeed – correct production (/ɣrot/).

For ABI3, the production of the target word *drie* /dri/ (*Eng. three*) does not reach a correct pronunciation in the period studied. The child's production by 9 months of hearing age (/d@/) is the furthest away from the target, since only the word initial consonant was correct, but the vowel was not and a word final consonant was inserted whereas the target had no word final consonant. The variants /hɪ/, /vɪ/, and /pɪ/) show a substitution of the lax vowel /ɪ/ for the tense counterpart /i/, but the initial consonant cluster in the target is reduced, and the consonants the child produces remain relatively far from the targets /d/ and /r/, which results in a still elevated LD. But the substitution of the cluster /dr/ by /h/ is more deviant than the substitution by /v/ or /p/, as the LD is higher in the child's production (/hi/). The lowest LD is reached by 15 months of hearing age, with only the deletion of the /r/ in the child's production (/di/).

Insert Figures 4, 5 and 6 here.

4. Discussion

The aim of the present research was to investigate the phonemic accuracy of three children with ABI's spontaneous speech productions in comparison to that of children with CI and NH. The results revealed three main findings: (1) the phonemic accuracy of the three children with ABI increased over time, since the LD between the children's productions and the adult equivalents decreased. Thus, their productions became more adult-like, irrespective of the axis of comparison: chronological age, hearing age, and lexicon size. With increasing age, increasing device use and increasing cumulative vocabulary the gap between the ABI children's productions and their adult equivalents narrowed down. But the increase of phonemic accuracy was only a trend, which was only significant for ABI1 and not for the other two children. (2) Throughout the period studied, children with CI's speech production was more accurate than that of the three children with ABI. (3) In the case where the collected corpus permitted a comparison, the phonemic accuracy of children with NH was significantly higher than that of the three children with ABI, except when ABI3 and children with NH were matched on cumulative vocabulary size.

The accuracy of the ABI children's speech production was studied relative to their chronological age, their hearing age and their lexical age. As the children grew older, an increase of their accuracy was expected. However, only a significant development towards more accurate speech was found for ABI1, and with progressing chronological age there was no significant increase for the two other children with ABI. Similarly for hearing age: with more hearing experience, ABI1's accuracy increased significantly, but a comparable development was not found for ABI2 and ABI3. These findings suggest that ABI implantation may lead up to a plateau in some children's speech accuracy beyond which they do not seem to make any further progress, at least not in the time window investigated in the present study. For ABI1 a significant improvement was noted in the early stages (up to approximately hearing age 43 months), which levelled out afterwards. Even with the bilateral implant, ABI1 did not seem to show any progress in speech production accuracy. Since the second ABI was only fitted for about six months, it might be that a beneficial effect of bilateral implantation appeared beyond the data available in this study. But for the two other children there was no significant effect of increasing hearing experience on their speech accuracy. This was particularly striking for ABI2: device use up to 50 months did not result in a significant decrease of LD.

The comparison relative to lexical age adds to this tentative conclusion that learning more words seems to have a positive effect on speech accuracy, but there seems to be a limit to it. For lexical age, measured in terms of cumulative vocabulary, the phonemic accuracy increased up to approximately 350 word types in ABI1, but there was no effect of increased cumulative vocabulary in ABI2, whose lexicon size was much larger, namely up to more than 600 words. Similarly for ABI3: acquiring more words did not significantly affect his speech accuracy. In contrast, for instance Faes et al. (2016) showed a gradual decrease of Levenshtein Distance, and thus an increase in speech accuracy, up till five years of age in children with CI and in children NH. In more detailed analyses, for instance Ferguson and Farwell (1975) have shown a u-shaped learning curve for children with NH with respect to production accuracy. Children set off producing their words highly accurately. However, as the size of their lexicon increases, production accuracy appears to diminish. With development, however, their production becomes (more and more) accurate again.

In comparison to children with CI, the LD of the speech production of ABI1, ABI2 and ABI3 is higher at intercept and/or with development. Thus, the children with ABI produce their words less accurately than children with CI with similar chronological ages, hearing ages and cumulative vocabulary sizes. An explanation of this divergence in accuracy relative to chronological age may be found in the different ages at implantation. On average children with ABI are older than children with CI when they receive their device. In the present study, the children with CI received their implant on average around their first birthday while the children with ABI were at least two years of age (ABI1 and ABI2) and four years of age (ABI3). Is this difference of at least one year between the ages at implantation critical? If it were not, then it was to be expected that at similar hearing ages, the performance of children with CI and children with ABI would have been similar. But that does not appear to be the case: children with ABI still lag behind children with CI in accuracy at comparable hearing ages. This seems to point at the importance of early implantation and, hence, the importance of the chronological age at implantation. Indeed, the literature suggests that implantation during the first year of life is the key factor for success in spoken language development. Crucial for children with CI to be able to catch up with their typically developing peers' language abilities is the timing of the CI intervention. It has been argued that "missing out on input in the first year of life is associated with a decline in neural plasticity that has long term effects" (Kral & Sharma, 2012; Levine et al., 2016, p. e59). Since children with ABI typically receive their device at a later age, they are not exposed to the same influence of the linguistic and social environment and do seem to miss out on some critical aspects of it. As a consequence, implantation at a later age does not lead to their catching up on their peers with CI: at similar hearing ages, children with ABI are not on a par with children with CI regarding the accuracy of their spontaneous speech production. In other words, in the children with ABI who participated in the present study, it is not the case that the development of their speech accuracy simply started a bit later due to their later implantation. The pace of their development is slower in comparison with children with CI. Moreover, their development does not only appear to be slower, as the accuracy of children with CI appears to be increasing, the accuracy of children with ABI appears to stagnate in the age range considered in the present study. The slower development of children with ABI has been reported in the literature by i.a. van der Straaten et al. (2018), who found that, on average, children with ABIs without additional disabilities did not only develop slower, but even after five to six years of device use their performance was at similar levels as children with CIs with additional disabilities.

The results of present study suggest that hearing experience as measured by the children's (hearing) ages is not a decisive factor in an explanation of the ABI children's lower accuracy in comparison with children with CI. But even at a comparative level of linguistic development, as measured by their cumulative vocabulary, ABI children's accuracy is significantly lower as that of the children with CI. A factor that should be considered in this respect is the nature of the device. The electrodes of CIs are implanted along the tonotopical arrangement of the cochlea, whereas the electrodes of the ABI are arranged on the cochlear nucleus of the brainstem. The tonotopical organization of the cochlea is relatively well-known whereas that of the cochlear nucleus is nearly unknown (Long et al., 2005) or at least unpredictable (Wong et al., 2019). This implies according to Aslan et al. (2020) that when an ABI is placed on the surface of the cochlear nucleus, the temporal and spectral resolution of the transmitted signal is virtually unknown. This may explain why the auditory information transmitted by a CI is sufficient for children to eventually acquire speech accuracy comparable to that of NH children, while in the case of ABI users the information is insufficient to reach accuracy levels comparable to those of children with CI and NH. It can be inferred from the literature that further research leading to technological breakthroughs and refinement of surgical procedures and techniques are required in this area.

The speech production of children with NH was found to be more accurate than that of ABI1, ABI2 and ABI3 at intercept and/or with development, in comparisons on hearing age and lexical age. This finding replicates those of a previous report on the same cohort of children in which the pMLU measures were used (Faes & Gillis, 2020). But there seems to be one exception: no significant difference was found in the comparison of ABI3 with NH children matched on cumulative vocabulary size. This finding seems to be surprising at first sight. However, there are a number of factors that may explain ABI3's accuracy levels. First of all, ABI3 is the only child with ABI in this study who is also wearing a CI which he received at the age of eight months. Friedman et al. (2018) and Batuk et al. (2020) showed that an ABI and a contralateral CI reinforce one another, which may explain why ABI3 attains such remarkable speech accuracy in comparison to NH children matched on lexical age. Nevertheless, there is still a difference between ABI3 and the children with CI. Moreover, ABI3 received an ABI because of the limited benefits with CI. This implies, at least, that the issue of ABI with a contralateral CI and the effects of this combination on children's language and speech should be further investigated.

A second plausible explanation may be found in the chronological age difference between the NH children and ABI3 at comparable lexical ages. The data on ABI3 are from an age range between four and six years of age, while with a similar cumulative vocabulary of 300 words or less, the NH children were two years old or younger. Children gain considerably more motoric control over their articulators with age, resulting in enhanced articulatory accuracy (MacNeilage et al., 2000; Snow & Ertmer, 2009). In that sense, it is reasonable to assume that the children with NH, no older than two years, do not outperform a four-to-six-year-old (ABI3), even though the lexical ages were matched. However, also this explanation remains speculative since the precise relationship between speech accuracy and motor control is not really clear.

A third reason why ABI3's accuracy is similar that of the NH children matched on cumulative vocabulary may be found in the fact that ABI3 has another underlying pathology as compared to the other two children with ABI. The diagnosis for ABI3 mentions auditory neuropathy, while the two other children's auditory nerves are lacking. At present it is unclear if there is a causal relationship between the children's speech production and their underlying conditions. This issue certainly needs further investigation since in the case of children with a cochlear deficiency who received a CI, the etiology appears to play a role since children with a genetic cause of their deafness appear to have better prospects than children with a viral cause such as a cytomegalovirus (CMV) infection.

5. Conclusion

ABI implantation is a recent development in pediatric hearing restoration. The effect of the implant on children's early language acquisition and speech development is still largely uncharted territory. Moreover, since the number of cases is still relatively small, studies of ABI children's speech development are restricted to small number of participants. This makes the generalizability of the findings difficult. In addition, the condition of these children is characterized by many factors that throw up fundamental questions regarding the role of audition in speech production. For instance, an intriguing finding in the present and in previous studies is the difference between children with a single ABI and those with a contralateral CI. Or the effect of different etiologies on children's speech production and the further prospects of their language development.

The children with ABI in the present study can be considered to be good performers. They have no additional needs, were early implanted and have relatively low hearing thresholds after implantation. The speech production of children with those characteristics has been shown to be more accurate than that of children with ABI with additional developmental and/or health problems, who lag behind on speech perception and production (e.g. van der Straaten et al., 2019).

Considerable variation was observed between the three children. On the one hand, this may be explained by this study's restraints: the limited number of participants and the different age and hearing age ranges of the children. On the other hand, the interindividual variation, which cannot be explained by factors such as the presence of additional disabilities, has also been observed in the literature and future research will need to disentangle factors affecting this variation (e.g. Aslan et al., 2020; Faes & Gillis, 2021; Teagle et al., 2018). The present study has shown the benefits of ABI implantation on speech production in all three children. Still, their performance was well below that of children with CI and children with NH, pointing to the need of additional support such as sign language for smooth communication (Hall et al., 2019).

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Tables

Table 1. Individual data of the children with cochlear implants

ID	Gender	PTA unaided (dB HL)	PTA CI (dB HL) (at age two)	Age CI implantation	Age second CI
CI1	F	120	48	13.49	75.00
CI2	F	120	30	6.69	56.00
CI3	F	115	33	10.00	70.00
CI4	M	113	48	18.16	-
CI5	M	93	38	16.89	76.00
CI6	M	120	53	8.76	-
CI7	F	117	42	5.16	15.00
CI8	F	112	38	19.46	-
CI9	F	103	28	8.69	23.00
Mean		*113.00*	*40.10*	*12.05*	*52.50*
SD		*8.72*	*8.24*	*4.96*	*27.03*

CI = cochlear implant
PTA = Pure Tone Average hearing threshold
dB HL = decibels Hearing Level
Ages are presented in months
- = no second CI

Table 2. Matched CI and NH data for each child with ABI

	Chronological age			Hearing age			Cumulative vocabulary		
	Child with ABI (months)	Match with children with CI possible?	Match with children with NH possible?	Child with ABI (months)	Match with children with CI possible?	Match with children with NH possible?	Child with ABI (word types)	Match with children with CI possible?	Match with children with NH possible?
ABI1	38 – 67	yes	no	14 - 43	yes	yes	4 - 397	yes	yes
ABI2	49 - 75	yes	no	24 - 50	yes	no	79 - 618	yes	yes
ABI3	46 - 64	yes	no	-2 – 16 [a]	yes	yes	17 - 303	yes	yes

[a] *Hearing age is computed from the moment of ABI activation. For ABI3, some data before ABI surgery were available as well.*
CI = cochlear implant, NH = normal hearing, ABI = auditory brainstem implant

Table 3. Fixed effect results of ABI1

	Chronological age (Age)				Hearing age (HearingAge)				Lexical age (CumulativeVocabulary)			
	Estimate	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*
Intercept (ABI1)	6.45	0.68	9.54	p<0.001	6.06	0.91	6.67	p<0.001	6.18	0.76	8.14	p<0.001
Measure of comparison (Age, HearingAge, CumulativeVocabulary)	-0.11	0.02	-4.81	p<0.001	-0.10	0.01	-8.33	p<0.001	-0.01	0.00 [a]	-6.80	p<0.001
Corpus CI	-4.00	0.67	-6.00	p<0.001	-3.68	0.95	-3.86	p<0.001	-3.21	0.6379	-4.04	p<0.001
Measure of comparison * Corpus CI	-0.03	0.04	-0.78	p=0.433	0.06	0.01	4.61	p<0.001	0.01	0.00 [a]	4.45	p<0.001
Corpus NH					-1.89	0.92	-2.04	p<0.05	-2.24	0.77	-2.91	p<0.01
Measure of comparison * Corpus NH					-0.02	0.02	-1.56	p=0.119	0.00 [a]	0.00 [a]	2.26	p<0.05

[a] 0.00 indicates an estimate (or SD) lower than 0.01

Table 4. Fixed effect results of ABI2

	Chronological age (Age)				Hearing age (HearingAge)				Lexical age (CumulativeVocabulary)			
	Estimate	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*
Intercept (ABI2)	2.71	0.55	4.92	p<0.001	2.87	0.53	5.46	p<0.001	2.93	0.87	3.35	p<0.001
Measure of comparison (Age, HearingAge, CumulativeVocabulary)	0.02	0.02	1.30	p=0.193	0.00 [a]	0.00 [a]	0.22	p=0.826	0.00 [a]	0.00 [a]	0.45	p=0.652
Corpus CI	-0.56	0.55	-1.02	p=0.309	-0.76	0.56	-1.37	p=0.172	-0.09	0.92	-0.11	p=0.915
Measure of comparison * Corpus CI	-0.23	0.02	-9.54	p<0.001	-0.07	0.00 [a]	-11.97	p<0.001	- 0.00 [a]	0.00 [a]	-4.32	p<0.001
Corpus NH									0.48	0.89	0.54	p=0.592
Measure of comparison * Corpus NH									-0.00 [a]	0.00 [a]	-4.63	p<0.001

[a] 0.00 indicates an estimate (or SD) lower than 0.01

Table 5. Fixed effect results of ABI3

	Chronological age (Age)				Hearing age (HearingAge)				Lexical age (CumulativeVocabulary)			
	Estimate	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*	*Estimate*	*SD*	*T-value*	*P-value*
Intercept (ABI3)	3.63	0.59	6.11	p<0.001	3.60	1.14	3.17	p<0.01	3.76	0.72	5.24	p<0.001
Measure of comparison (Age, HearingAge, CumulativeVocabulary)	-0.03	0.02	-1.52	p=0.129	-0.02	0.02	-1.63	p=0.104	-0.00 [a]	0.00 [a]	-1.41	p=0.158
Corpus CI	-2.39	0.62	-3.81	p<0.001	0.57	1.21	0.47	p=0.940	-0.92	0.75	-1.22	p=0.221
Measure of comparison * Corpus CI	-0.04	0.03	-1.48	p=0.140	-0.12	0.02	-5.25	p<0.001	-0.00 [a]	0.00 [a]	-0.15	p=0.881
Corpus NH					2.80	1.53	1.82	p=0.068	-0.14	0.73	-0.19	p=0.846
Measure of comparison * Corpus NH					-0.16	0.08	-2.08	p<0.05	-0.00 [a]	0.00 [a]	-1.75	p=0.081

[a] 0.00 indicates an estimate (or SD) lower than 0.01

Figures

Figure 1. Levenshtein distance results of ABI1 in comparison to children with cochlear implants (CI) and children with normal hearing (NH) – Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

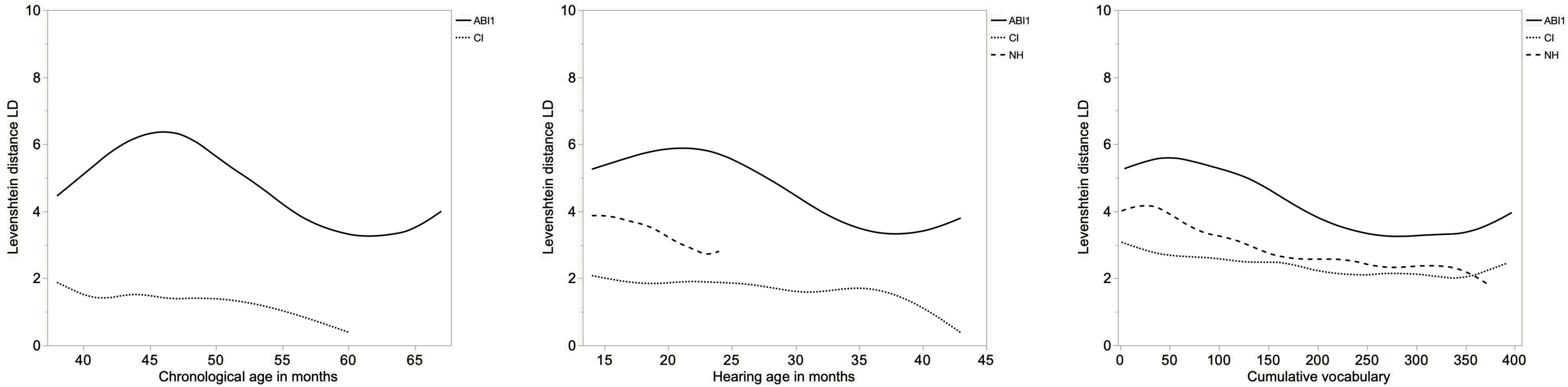

Figure 2. Levenshtein distance results of ABI2 in comparison to children with cochlear implants (CI) and children with normal hearing (NH) – Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

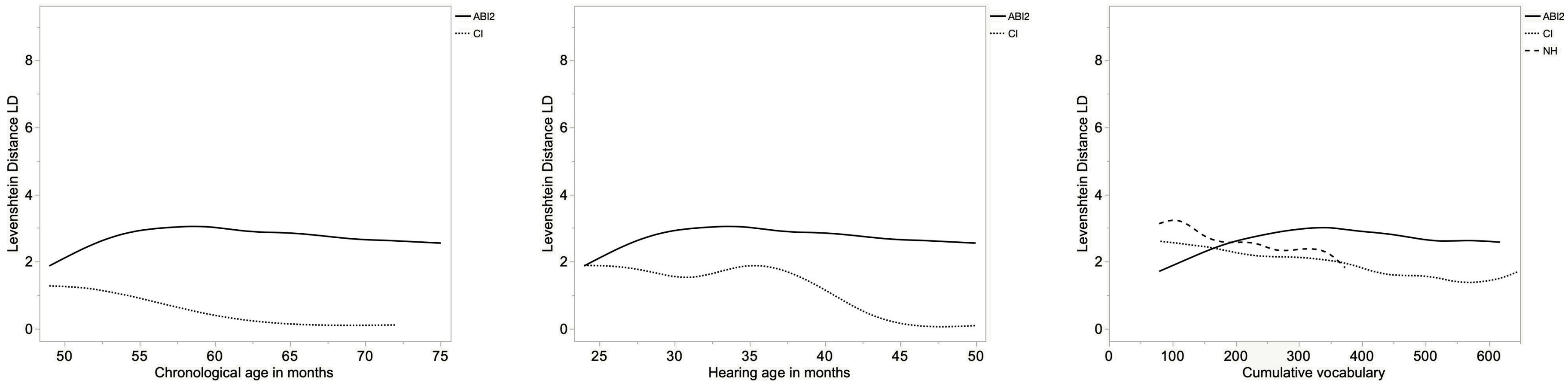

Figure 3. Levenshtein distance results of ABI3 in comparison to children with cochlear implants (CI) and children with normal hearing (NH)– Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

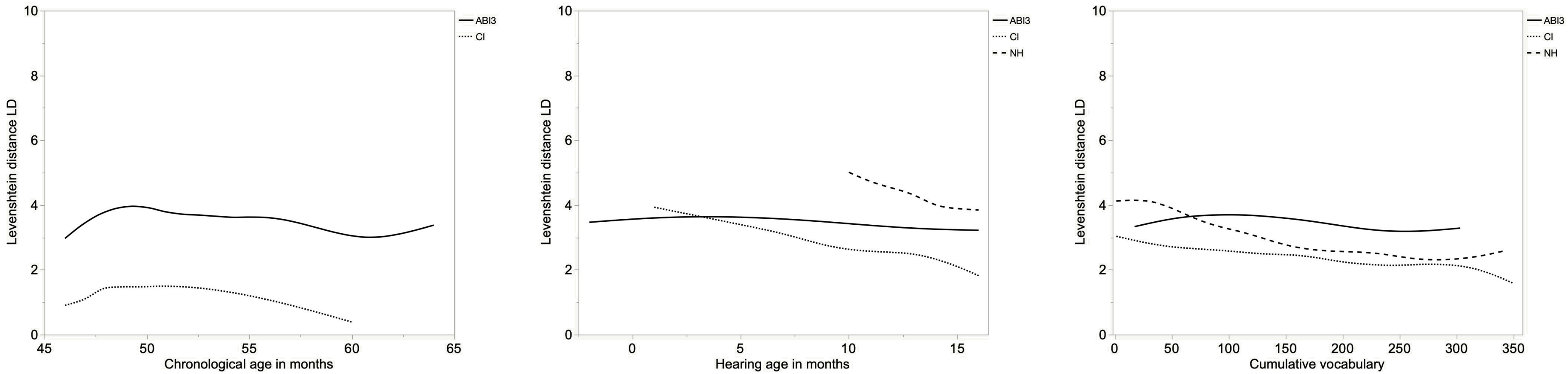

Figure 4. Example of development of Levenshtein distance for ABI1 for targetword groen *(green)*

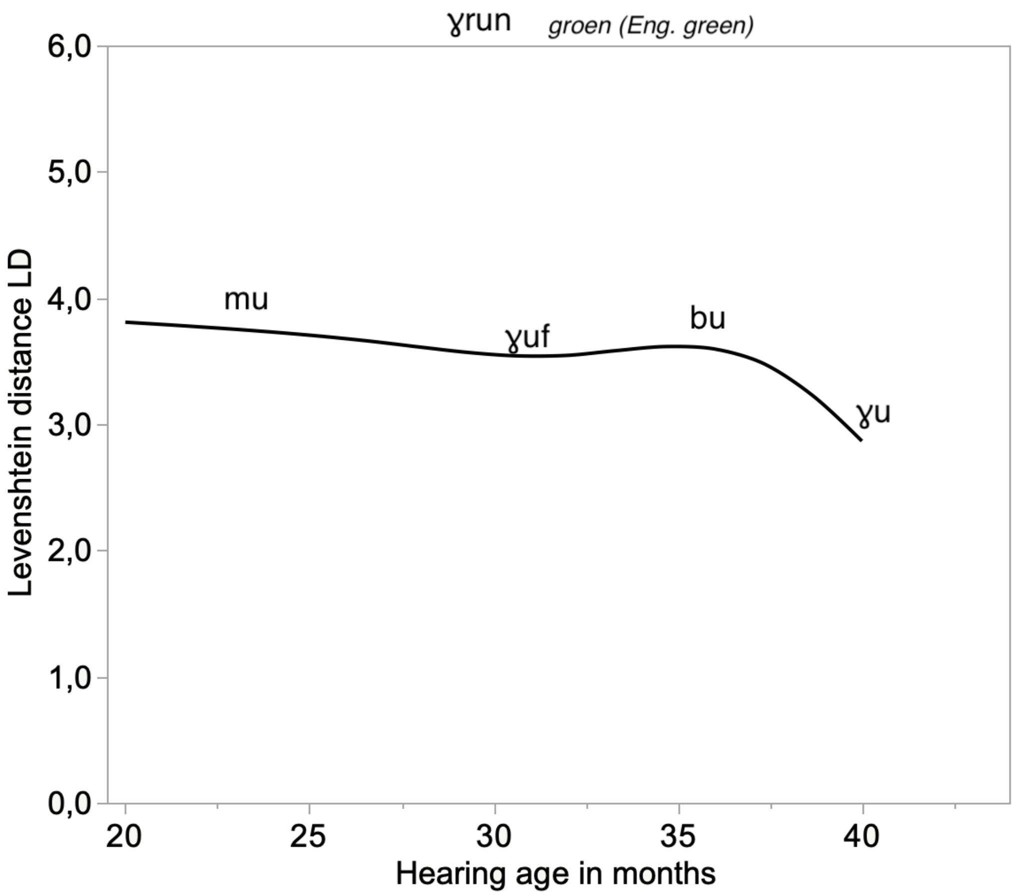

Figure 5. Example of development of Levenshtein distance for ABI2 for targetword *groot* *(big, large)*

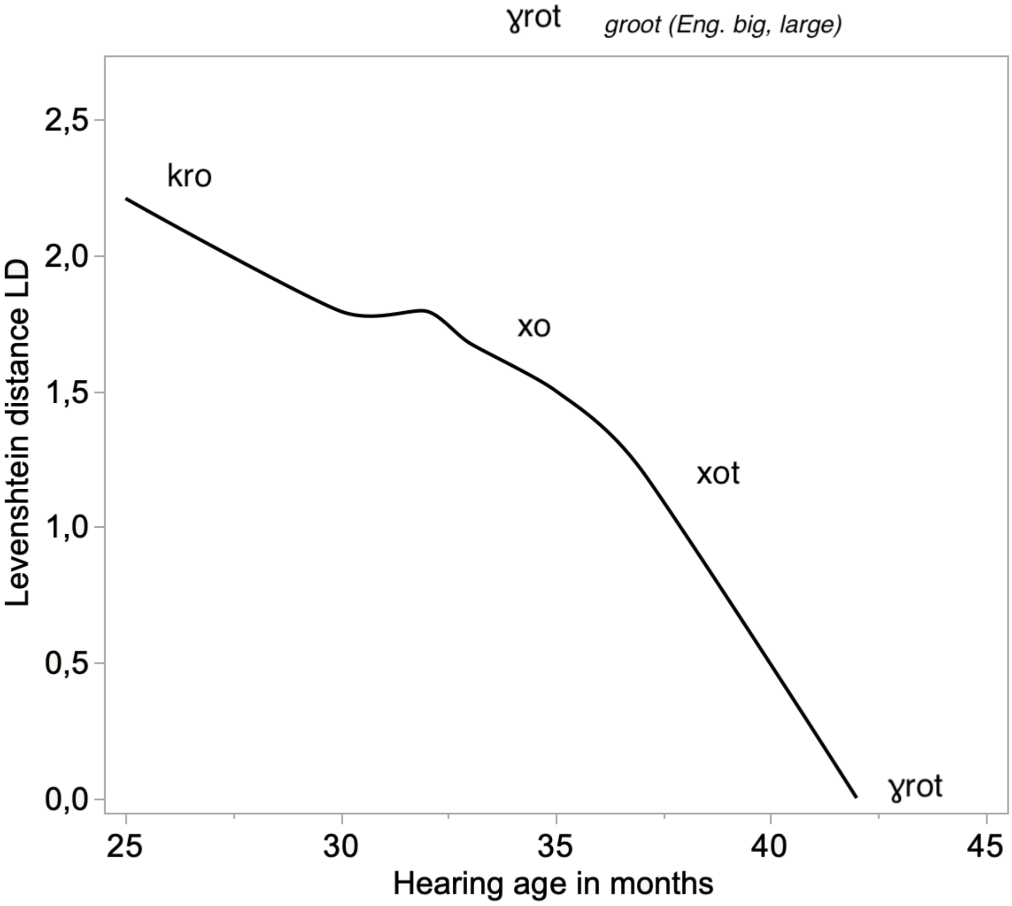

Figure 6. Example of development of Levenshtein distance for ABI3 for targetword *drie (three)*

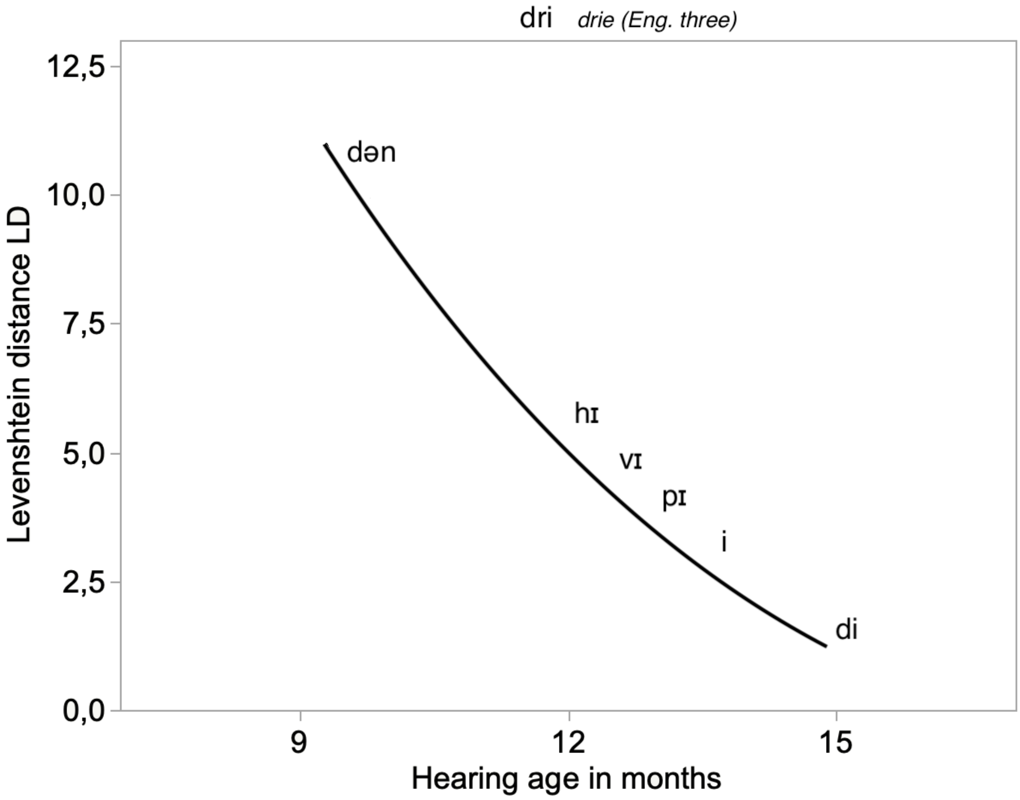

Figure Legends

Figure 1. Levenshtein distance results of ABI1 in comparison to children with cochlear implants (CI) and children with normal hearing (NH) – Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

Figure 2. Levenshtein distance results of ABI2 in comparison to children with cochlear implants (CI) and children with normal hearing (NH) – Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

Figure 3. Levenshtein distance results of ABI3 in comparison to children with cochlear implants (CI) and children with normal hearing (NH) – Comparisons on chronological age, hearing age and lexical age (cumulative vocabulary) – observed data

Figure 4. Example of development of Levenshtein distance for ABI1 for targetword *groen (green)*

Figure 5. Example of development of Levenshtein distance for ABI2 for targetword *groot (big, large)*

Figure 6. Example of development of Levenshtein distance for ABI3 for targetword *drie (three)*