Consonant and vowel production in the spontaneous speech productions of children with auditory brainstem implants

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Abstract

Auditory brainstem implantation provides hearing sensations in children and adults with anomalies of the auditory nerves. In children, perceptual benefits have been established, and research already demonstrated (limited) effects on children's speech production. The current study extends the literature by scrutinizing the phonological development of three children with ABI. Spontaneous speech samples were used to establish their phonemic inventories of vowels, word-initial consonants and word-final consonants, both independently of the target phoneme and relative to the target phoneme. The three children produced all vowels with longer device use and larger vocabulary size. Word-initial and word-final consonants appeared in the three children's spontaneous productions. However, the segmental accuracy was only moderate in the children's productions.

Keywords: auditory brainstem implantation; pediatric; phoneme inventory; consonants; vowels

Introduction

Approximately two out of 1,000 children are born with a hearing loss and half of them have a severe-to-profound hearing loss of more than 70 dB HL (decibels hearing level) which considerably restricts their speech and language development (De Raeve, 2016; Declau, Robillard, & Janssens de Varebeke, 2005; Korver et al., 2017). For children with a severe-to-profound hearing loss, implantable technologies can (partially) restore their hearing. Cochlear implants and auditory brainstem implants were initially designed and used for adults, but they are nowadays also commonly used as a therapeutic aid in the pediatric population (Moeller, 2006).

The type of implant, a cochlear implant (CI) or an auditory brainstem implant (ABI) is determined by the locus of the hearing deficit, but in the external part of a CI and an ABI environmental sounds are caught by a microphone and the acoustic signals are converted into a digital code in a processor. A cochlear implant bypasses absent or damaged hair cells in the cochlea by directly stimulating the auditory nerve through electrodes inserted in the cochlea. An auditory brainstem implant is used when the auditory deficit results from a damaged or absent auditory nerve, or when the cochlea is not suitable for inserting an electrode array (i.a. due to malformation or ossification). The auditory brainstem implant directly stimulates the cochlear nucleus on the brainstem, thus bypassing the entire cochlea and auditory nerve.

ABI in Children

In contrast to pediatric cochlear implantation and auditory brainstem implantation in adults, pediatric auditory brainstem implantation is a relatively recent innovation. In 2001, the first pediatric patients – a three- and a four-year-old – were implanted with an ABI in Europe (V. Colletti, Fiorino, Sacchetto, Miorelli, & Carner, 2001). A good decade later, the first clinical trials for children started in the U.S. as well (Puram and Lee, 2015). Before 2010, cochlear implantation was considered to be preferable over auditory brainstem implantation if the former was possible (Vincenti, Pasanisi, Guida, Di Trapani, & Sanna, 2008) and auditory brainstem implantation was sometimes presented as an option after CI failure (V. Colletti, Carner, Miorelli, Colletti, & Fiorino, 2004). But, in their consensus statement issued in 2016, Sennaroglu, Colletti, et al. (2016) recognized that some children who have good sound detection with CI, but who are low performers on language development, may well benefit from ABI implantation. Moreover, Friedman, Asfour, Shapiro, Thomas Roland, & Waltzman (2018) suggested that a CI and a contralateral ABI seem to synergize, although their study was only a first indication and more research was certainly needed. One of the cases presented in the current study, first received a CI and a few years later a contralateral ABI because his language benefits with the CI were very low.

Studies already showed the effectiveness of ABI implantation for speech perception. With extended ABI use, children can reach auditory thresholds of 30 to 60 dB hearing level (Sennaroglu, Colletti, et al., 2016). Besides sound awareness, children with ABI are able to identify sounds, syllables, phonetic contrasts, vowels and consonants (e.g. Sung et al., 2018) and most of them can reach CAP scores (Categories of Auditory Performance, Archbold, Lutman, & Marshall (1995)) of five (on a seven point scale), indicating that they can understand simple phrases without lip-reading (L. Colletti, Shannon, & Colletti, 2014; Sennaroglu, Sennaroglu, et al., 2016). Studies also pointed out that children with ABI perform better with earlier implantation, lower hearing thresholds after ABI implantation and when they have no additional disabilities (Aslan et al., 2020; Sennaroglu, Colletti, et al., 2016; Sennaroglu, Sennaroglu, et al., 2016; Sung, et al., 2018; van der Straaten et al., 2019). Moreover, Sung, et al. (2018) indicated that children with ABI's progress keeps continuing over at least five years. Similarly, the two children with ABI without additional disabilities in van der Straaten, et al. (2019) also kept increasing their perception skills over five years of device use.

For production, van der Straaten, et al. (2019) showed that children with ABI without additional disabilities generally have better expressive language skills as compared to children with ABI with additional disabilities. As a group, children with ABI appeared to perform on average as children with CI with additional disabilities. However, it needs to be indicated that most of these children with ABI had additional disabilities themselves. In addition, the two best performing children with ABI had no additional disabilities (and limited usage of sign language), and performed between the means of children with CI with and without disabilities with respect to expressive language (van der Straaten, et al., 2019).

Children with ABI without additional disabilities were shown to go through the main stages of spontaneous speech and language development: from first vocalizations, they started to babble with increasing age and device use, and later they also started to produce words (Faes, Boonen, & Gillis, 2019; Faes and Gillis, 2019a). Even though they expanded their word use substantially, after four years of hearing experience their lexicon size was still systematically lower when compared to peers with CI and peers with typical hearing (Faes and Gillis, 2019b).

Phonological development of children with ABI was addressed in only a few studies. Eisenberg et al. (2018) analyzed four children with ABI's word patterns, consonantal and vocalic features in a naming task. They found that children with ABI produced mono- and disyllabic words, with a syllable correspondence to the target between 40% and 100% after two years of ABI use. The children also started to produce consonants at word onset when the target word had a word-initial consonant. Most of the time, however, the consonant was inaccurate. Some children also started to use word-final consonants by two years of hearing age. All four children used at least nasals and liquids and half of them also the other consonant manners of articulation after two years of device use. With respect to place of articulation, all children produced front and mid consonants, and one child used back consonants. The accuracy of the back consonants of this child increased to 90% after three years of ABI use. Finally, all children used some full vowels in their speech production after two to three years of hearing age.

The phonological development of five children with ABI in a naming task was reported by Teagle, Henderson, He, Ewend, & Buchman (2018). One child only vocalized after two years of ABI use, i.e., did not use identifiable words. Another child produced only the labial, visible, sounds /p/, /b/ and /w/ word initially by three years of device use. The percentage of accuracy of the consonants' manner, place and voice features varied around 25%. A third child produced the labial plosives /p/ and /b/, the labial and coronal nasals /m/ and /n/ and central vowels. However, the percentage of accuracy of vowels was only 20%, and 4%, 6% and 0% for manner, place and voice of consonants. The other two children produced vowels and initial as well as final consonants where appropriate, though still often incorrectly. For one of these children, the consonant features manner, place and voice were correct in 25%, 21% and 20% of the productions by two years of device use. For the other child, percentages equaled 56%, 58% and 90% of the productions after three years of device use. The accuracy of vowel production was 17% and 53% for these children respectively. For the child followed three years after implantation, it was noticed that back and central vowels were developing, but only a limited number of front vowels was attested.

In these scientific reports, hearing-impaired children's language development is often described relative to their length of device use, also referred to as "hearing age". Hearing age is most often used rather than chronological age to track the development of children with ABI as well as that of children with CI, since the use of hearing age rules out a possible impact of different onsets of hearing, i.e., different chronological ages at which implantation took place. It has been shown that hearing age is a predictor of children with ABI's and CI's language development over the different language domains (e.g. Blamey et al., 2001; Blamey, Barry, & Jacq, 2001; Eriks-Brophy, Gibson, & Tucker, 2013; Faes and Gillis, 2019a; Schauwers, 2006; Szagun and Stumper, 2012). Hearing age, as opposed to chronological age, is thus a convenient yardstick used to measure children with hearing loss' development

Yet, language-intrinsic yardsticks have also been increasingly used in the literature on children with NH and CI. These language-intrinsic yardsticks, such as Mean Length of Utterance (Brown, 1973) or lexicon size (operationalized in terms of cumulative vocabulary), are a proxy for 'language age'. They have been used as an alternative to the time-based proxy's such as chronological age and hearing age. Lexicon size is a case in point. Stoel-Gammon (2011) convincingly demonstrated that lexical and phonological development are closely related to each other, or "commensurate" as she postulated (p. 15). For instance, intraword variability and syllable development were found to be more related to lexical age and lexicon size than to chronological age in children with NH (Sosa and Stoel-Gammon, 2006; van den Berg, 2012). In a similar vein, fricative production was predicted by lexicon size and not by chronological age in children with CI (Reidy, Beckman, Litovsky, & Edwards, 2015). For both groups of children (CI and NH), it was also shown that an increasing lexicon size predicted accurate phoneme production, for instance for fricatives (Faes and Gillis, 2016; Nicholson, Munson, Reidy, & Edwards, 2015; Reidy, et al., 2015). Given this close relationship between lexical and phonological development in children with NH and CI, lexicon size was used as a yardstick, in addition to hearing age, in the present study of children with ABI.

The Present Study: Phonemic Inventories

Up till now, few analyses of children with ABI's phonological development have appeared in the literature and the number of participants in each study is limited. But it may well be inferred from the reported cases that speech production accuracy developed very slowly in children with ABI. In this respect, Aslan, et al. (2020 : 11) concluded that "speech intelligibility [is] the most challenging skill to develop" for children with ABI. It has been shown that accurate phonemic production contributes largely to intelligible speech (Ingram, 2002). However, except for the studies of Eisenberg, et al. (2018) and Teagle, et al. (2018), no information on children with ABI's phonological development is available in the literature thus far. Both studies reported on the development of vowel and consonant features, but detailed information on the appearance and acquisition of each individual phoneme is still lacking. However, in the last five years, various studies pointed to the need of more basic, as well as clinical research in pediatric ABI implantation (Puram and Lee, 2015) beyond speech perception and communication (Asfour, Friedman, Shapiro, Roland, & Waltzman, 2018), in order to sort out the long term effectiveness of ABI (Shah, Kozin, Kaplan, & Lee, 2016) and to set up evidence-based therapy for children with ABI (Hammes Ganguly, Schrader, & Martinez, 2019). In the present study, we aim to expand Eisenberg, et al. (2018) and Teagle, et al. (2018)'s work by examining three children with ABI's spontaneous speech productions and describing aspects of their phonological development. Teagle, et al. (2018) pointed out that some of their tests for language development were not sensitive to the slow and subtle progress in children with ABI. The monthly follow-up design of spontaneous production presented here will enable to catch more fine-grained changes in the children's development.

The aim of the present study is to disentangle the phonological development of children with ABI. Following the established practices in the literature, two types of analyses will be performed: an independent or targetless phonemic analysis and a dependent or target phonemic analysis. A targetless phoneme inventory captures the phonemes present in the child's productions without reference to the adult targets. Thus, the phonemes occurring the child's spontaneous speech are added to the inventory irrespective of their accuracy. A target phoneme inventory, also called relational, compares the child's productions to the adult equivalents (Saaristo-Helin, 2009). By charting out the unfolding of the children's phoneme a longitudinal picture of their individual development is established. Moreover, a detailed comparison with children with NH and CI will lead to general trends and directions of phonemic development across individuals with ABI.

Method

Participants

This study reports on the phonemic development of three children with ABI. The pool of potential participants was fairly restricted, since only eight children were implanted with an ABI between 2015 and 2019 in Belgium. Two additional criteria further narrowed down the possible participants: (1) the children had to be raised in oral Dutch (i.e., only the northern part of Belgium, hence excluding French-speaking and German-speaking children), and (2) the absence of any patent additional health or developmental problems from their medical records. Individual information for the children is presented in Table 1 and below.

This study was approved by the Ethical Committee of the University of Antwerp (ESHW_16_29). All parents signed an informed consent for participation in the study.

ABI1 was diagnosed with a congenital sensorineural hearing loss as a result of the absence of the auditory nerves. She was implanted with an ABI (Med-El) at two years of age. The implant fitting took place two months later. Nine of the 12 electrodes could be activated. Her pure tone average (PTA) hearing thresholds evolved from 120 dB HL (decibel hearing level) before implantation to 37.5 dB HL two years after implantation. At four years and nine months of age, the child received a second ABI. ABI1 was raised in oral Dutch, supported with Flemish Sign Language. The data collection for this child started a year after implant fitting (age 3;02 – years;months) and stopped at age 5;07.

ABI2 was a female child with a congenital sensorineural hearing loss, also resulting from the absence of the auditory nerves. She received her ABI (Mel-El) at age 2;01. The implant was fitted two months later, and nine of the 12 electrodes could be activated. Her PTA hearing thresholds improved from 116 dB HL before implantation to 43 dB HL two years after implantation. The child was raised in oral Dutch, also supported with Flemish Sign Language. The data collection started two years after implantation (age 4;01) and went on for two years (age 6;03).

ABI3 was diagnosed with an auditory neuropathy. His congenital sensorineural hearing loss resulted in PTA hearing thresholds of 90 to 95 dB HL in his better (right) ear. The child was first implanted with a cochlear implant (CI) at eight months of age. Even though his PTA thresholds improved to 33 dB HL, there seemed to be little effect of the CI on the child's hearing and language development. Therefore, the child was implanted with a contralateral ABI at four years of age. Two months later, the implant was fitted, and all electrodes could be activated. ABI3 was raised in oral Dutch, supported by Flemish Sign Language. The data collection started two months before the ABI implantation (3;10) and lasted for a year and a half (until age 5;04).

The children with ABI received speech and language therapy at least once a week. In addition, speech and language training was also provided in their schools. The individual certified speech and language therapist treating each child determined the actual rehabilitation program. These services are reimbursed by the RIZIV - INAMI, the Belgian Sickness and Invalidity Institute.

-- Insert Table 1 here --

Data Collection and Transcription

The data collection consisted of monthly one-hour video recordings at the child's home. The recordings were unstructured and thus involved spontaneous interactions between the child and his/her caregiver(s). For ABI1 25 recordings were made and 24 recordings for ABI2. For ABI3 14 recordings were made, of which two before and 12 after ABI implantation, starting two months after the surgery. Between age 4;10 and 5;00, there were no recordings due to personal reasons.

All video recordings were transcribed using CHILDES' in CLAN according to the CHAT conventions (MacWhinney, 2000). Non-linguistic utterances, such as vegetative and distress sounds, were excluded from transcription. All other oral utterances were further transcribed orthographically and phonemically. The guidelines established by Vihman and McCune (1994) to distinguish the prelexical utterances from the lexical ones were followed. Utterances were identified as lexical, if they met a number of criteria corresponding to their shape (e.g., an exact match with a target word), their context of use (e.g., as judged by maternal identification of the word) and their relation to other vocalizations (e.g., appropriate use of the vocalization in plausible contexts only).

Lexical utterances were transcribed phonemically using DISC symbols, i.e., a computer phonetic alphabet consisting of distinct single ASCII characters adopted from CELEX (Baayen, Piepenbrock, & Gulikers, 1995). A phonemic transcription of the target word, i.e., the adult equivalent of the child's production, was added as well. The child's production and the target word were syllabified with stress marking. Both transcriptions were aligned at the phoneme level, with a PYTHON script incorporating a dynamic alignment algorithm based on ADAPT (Elfers, Van Bael, & Strik, 2005). The automatically generated alignments were verified manually and corrected if needed.

All transcriptions were made within the Dutch vowel and consonant system (Booij, 1995). In Table 2, an overview of the consonant system can be found. In Table 3, an overview is presented of the steady state vowels (excluding the diphthongs: /ɑu/, /ɛi/ and /œy/).

-- Insert Tables 2 and 3 here --

The reliability of the phonemic transcriptions was checked for approximately 15% of the data. For each child, a second transcriber retranscribed three transcription files, each representing a recording of approximately one hour. The files were selected in a random fashion. The interrater percentage of agreement in a phoneme-to-phoneme comparison equaled 79.90% (SD = 3.57). Split out, the percentage of agreement equaled 83.54% (SD = 4.72) for consonants and 72.52% (SD = 7.48) for vowels.

Data Analyses

Three phonemic inventories were constructed: the inventory of steady state vowels, word-initial consonants and word-final consonants. Each inventory was composed in two ways: (1) a targetless inventory and (2) a target inventory. When is a phoneme added to a phoneme inventory? A common practice is for a phoneme to be included in a targetless inventory when it appears at least twice in the transcript of a child at a particular age (among others: Bouchard, Le Normand, & Cohen, 2007; Chin, 2003; Iyer, Jung, & Ingram, 2017; Salas-Provance, Spencer, Nicholas, & Tobey, 2013; Serry and Blamey, 1999). In order to be also included into the target inventory, the phoneme needs to reach a particular level of accuracy as well (Saaristo-Helin, 2009). Whereas the literature generally agrees on the frequency criterion, the accuracy rate differs over studies. As an example, Serry and Blamey (1999) and Salas-Provance, et al. (2013) use a 50% accuracy criterion, whereas Beers (1995) and Smith, McGregor, & Demille (2006) use a 75% criterion. Since setting an accuracy boundary is relatively random, it was decided to construct an inventory for 50% accuracy and an inventory for 75% accuracy, and to trace the development of the inventories between those two thresholds.

The composition of phonological inventories is influenced by the size of the speech sample. Yet, We believe we have a unique sample of children with ABI with no additional disabilities, followed longitudinally on a monthly basis over – on average – two years, and tracking their spontaneous speech development, so we opted to use the yardsticks used in the literature thus far. As described above, these yardsticks are a frequency limit of at least two productions for the targetless inventory, and in addition an accuracy criterion (50%, 75%) for the target inventory.

The phoneme inventories were related to both hearing age and cumulative vocabulary of the children. Hearing age, or length of device use, is highly frequently used in studies on language development after cochlear or auditory brainstem implantation (e.g., Blamey, Barry,

& Jacq, 2001; Caselli, Rinaldi, Varuzza, Giuliani, & Burdo, 2012; Ertmer and Goffman, 2011; Faes and Gillis, 2018; Fagan and Pisoni, 2010; Schramm, Bohnert, & Keilmann, 2010; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tomblin, Spencer, & Lu, 2008). In addition, length of device use is shown to impact the language development of children with CI and ABI (Faes and Gillis, 2019a; Gillis, 2017; Szagun and Stumper, 2012). But, research in children with NH and CI has also shown that phonological development is closely related to lexical development (Faes and Gillis, 2016; Reidy, et al., 2015; Santos and Sosa, 2015; Smith, et al., 2006; Sosa and Stoel-Gammon, 2012; van den Berg, 2012). Therefore, lexical age (in terms of cumulative vocabulary) was also included as a proxy for children with ABI's phonological development.

Hearing age was defined as the number of months after ABI implantation. The negative hearing ages for ABI3 represented the child's language development with only a CI. Cumulative vocabulary was a proxy for the lexical diversity for each child. Cumulative vocabulary was measured by counting the number of distinctive word types in the transcription file of the first recording and by adding the number of new word types in each consecutive file (e.g. Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Rowe, Raudenbush, & Goldin-Meadow, 2012; Vanormelingen, De Maeyer, & Gillis, 2016). In this study, the raw data of cumulative vocabulary counts were used. In Faes and Gillis (2019b) an in-depth analyses of the (cumulative) vocabulary development of ABI1 and ABI2 were presented.

Results

Phoneme inventories in the three children with ABI

Figures 1 – 3 present the targetless and 50% target phoneme inventories relative to hearing age for vowels, word-initial (WI) consonants and word-final (WF) consonants respectively.

The upper limit of the y-axis represents the total amount of phonemes in the Dutch vowel and consonant inventories.

It appears that in all the phoneme inventories of the three children with ABI, the targetless inventories are larger than the target inventories, except for the vowel inventories of ABI2, which end up with the same number of vowels. All children acquire the entire vowel inventory in a targetless condition, but only ABI2 does also acquire the entire vowel inventory in a target 50% condition. For instance, at 28 months of hearing age, ABI2 has acquired all 13 steady state vowels in the target condition (50%), whereas ABI1 has only acquired nine of them. So, there seems to be a considerable individual variation between the children.

Turning to consonants, the interindividual variation is even more outspoken. For word-initial (WI) and word-final (WF) consonants in a targetless inventory, ABI2 acquired already 21 WI and 15 WF consonants after 28 months of hearing age, whereas ABI1, for instance, acquired only 14 WI and 12 WF consonants with an added year of hearing age as compared to ABI2 (i.e. by 40 months of hearing age). For ABI3, 15 WI and 11 WF consonants were acquired by 16 months of ABI use, but with more than four years of CI use. A similar picture can be derived from the target inventories (50%) in Figures 2 and 3. Over the entire period, ABI1 acquired seven WI consonants and one WF consonant; ABI3 acquired nine WI and three WF consonants, but ABI2 acquired 16 WI and eight WF consonants.

So there are large differences in the phoneme inventories between the three children with ABI when matched on hearing age. Yet, at similar hearing ages, the cumulative vocabulary size of the children with ABI differs tremendously as well (see Figure 4). For instance for ABI1 and ABI2, the difference in lexicon size is about 100 word types at all matched hearing ages. This lexical ‘age’ difference might impact the phonological development of children with ABI, because of the close link between lexical and phonological development (Stoel-

Gammon, 2011). Indeed, when their cumulative was approximately 100 words, the target vowel inventory (50% criterion) of ABI1 contained 9 vowels, that of ABI2 12 vowels, and that of ABI3 7 vowels.

Given the considerable interindividual variation between the three children with ABI on all aspects described above, their development will be discussed in more detail in an individual manner in the next paragraphs.

-- *Insert Figures 1 – 4 here* –

Vowels

The acquisition of vowels is displayed in Table 4. For ABI1, three phonemes reached a frequency of 2 productions (targetless inventory) at a very small vocabulary size: the central low vowel /a/ and the front mid vowels /e, y/. Before the cumulative vocabulary size reached 100 word types, the child had acquired also almost all other vowels, except for the front mid vowel /Y/, which was acquired by a cumulative vocabulary of almost 200 word types and a hearing age of 32 months. The order of acquisition of the other vowels is as follows: /ɑ, i/, then /ə ø o/, followed by /ɔ/, followed by /ɛ, u/ and finally the vowel /ɪ/.

In the target inventory, three vowels were acquired with a very small cumulative vocabulary size of four words (14 months of hearing age): /a, e, y/. Before the cumulative vocabulary sizes had increased to 50 word types, the front mid vowel /i/ was acquired at 16 months of hearing age and the back mid vowel /o/ at 18 months of hearing age. By 23 months of hearing age and a cumulative vocabulary size of 50 word types, the central and low vowel /ɑ/ was acquired as well as the back and mid vowel /ɔ/. Between a cumulative vocabulary size of 50 and 100 word types, the high back vowel /u/ was acquired at 27 months of hearing age and the schwa (mid central /ə/) at 28 months of hearing age. One month later, also the front mid vowel /ɪ/ were acquired with a cumulative vocabulary size of approximately 130 word types. By 37 months of hearing age (cumulative vocabulary size of 280 words), also the front mid vowel /ø/ were acquired in the 50% target inventory.

Setting the accuracy criterion for inclusion in the target inventory to 75% instead of 50%, the size of the inventory dramatically diminished. Five vowels remained acquired at the same hearing ages: /a/ and /e/ at 24 months of hearing age, /i/ and /o/ at 16 and 18 months of hearing age and /ø/ at 37 months of hearing age. However, two vowels were acquired at a later hearing age and with a larger cumulative vocabulary size: /ɔ/ one month later than in a 50% target criterion, and /ɑ/ only at 36 months of hearing age (i.e. 13 months later) and with a cumulative vocabulary size above 300 word types. Moreover, four vowels were not marked as acquired the 75% target inventory: /y/, /u/, /ə/ and /ɪ/.

-- *Insert Table 4 here –*

For ABI2, the targetless and target vowel acquisition are represented in Table 4. In the targetless inventory, ABI2 had acquired all vowels already at the first datapoint (24 months of hearing age), except the front mid vowels /Y, ø/. The front mid vowel /Y/ was acquired at a cumulative vocabulary size of approximately 100 words. It seems very plausible that ABI2 has acquired some of these vowels already at an earlier point in development – before the recordings had started, i.e., at a lower hearing age and with a lower cumulative vocabulary size. As her hearing age increased and as the cumulative vocabulary expanded to above 200 word types, also the front mid vowel /ø/ appeared in ABI2’s targetless vowel inventory.

In a 50% target inventory, ABI2 had acquired all Dutch vowels at 24 months of hearing age, except the front mid vowels /Y, ø/. The front vowel /Y/ was acquired one month later.

The front vowel /ø/ was acquired at 28 months of hearing age, when the cumulative vocabulary size approximated 230 word types. When the accuracy criterion was set at 75%, a few changes appeared: the front mid vowel /ɛ/ was acquired at 26 months of hearing age instead of at 24 months of hearing age, when the cumulative vocabulary surpassed 150 word types. The front mid vowel /ø/ was not acquired at all with the 75% accuracy criterion.

The vowel inventory of ABI3 is also shown in Table 4. For the targetless inventory, the child had acquired the following vowels after approximately three years of CI use, i.e., before ABI mplantation: /ə, a, ɑ, e, ɛ, ɪ, u, y, Y, o/. Before ABI implantation, ABI3 had also acquired some vowels in the target inventory: /ə, a, ɑ, e, u, y/ when the 50% criterion was applied, and /a, e, u, y/ when the 75% criterion was applied.

After two months of ABI use, when the cumulative vocabulary size varied between 50 and 100 word types, the front high vowel /i/ was included in the targetless inventory. After three months of device use, the mid vowels /ɔ, ø/ (front, back) reached a targetless condition as well.

After ABI implantation, ABI3 acquired some vowels in the target inventory when the 50% criterion was applied. With two months of hearing age, the front and mid vowel /ɪ/ was acquired. When the cumulative vocabulary surpassed 100 words, the high front vowel /i/ was acquired at six months of hearing age. When the cumulative vocabulary increased to more than 200 word types, also the mid front vowel /ø/ was acquired, i.e., at nine months of hearing age. When the accuracy rate was set to 75%, ABI3 had acquired no vowels after ABI implantation.

Word-initial Consonants

The acquisition of word-initial consonants is displayed in Table 5 for all three children with ABI. In ABI1's targetless word-initial consonant inventory, the glides /j, w/ and the nasal /n/ appeared first, at a cumulative vocabulary size of only four word types. Before the cumulative vocabulary size reached 50 word types, also the plosives appeared: the labial plosives /b/ and /p/ appeared by respectively 16 and 18 months of hearing age, and by 21 months of hearing age, also the voiced coronal plosive /d/. After two years of hearing age, the voiceless coronal plosive /t/ was acquired as well as the labial nasal /m/. By 32 months of hearing age and a cumulative vocabulary size of 200 word types, the first fricative appeared, the voiceless labial /f/, as well as the coronal liquid /l/. Five to six months later, when the cumulative vocabulary size had increased to above 250 word types, the glottal /h/ appeared in the inventory as well as two dorsals, first the plosive /k/ and the following month the dorsal nasal /ŋ/. Finally, also the voiced labial fricative /v/ had appeared at least two times in the child's productions by 40 months of hearing age and a cumulative vocabulary size of 350 word types.

With respect to the target inventory, the dorsal glide /j/ was acquired with a 50% accuracy rate at 14 months of hearing age. In the three consecutive months, also the plosives /d/, /b/ and /p/ were acquired. When the cumulative vocabulary reached 100 word types, also the nasal /m/ and the plosive /t/ were acquired. Finally, at 32 months of hearing age and a cumulative vocabulary size of 200 word types, also the nasal /n/ was acquired with 50% accuracy. If the accuracy criterion was increased to 75%, only four phonemes were marked as acquired: /j/ was acquired at 14 months of hearing age, /b/ at 17 months, /t/ at 34 months, and /p/ at 37 months of hearing age. The cumulative vocabulary was well over 200 words at that point.

-- Insert Table 5 here –

At the first data point, i.e. after two years of hearing age, ABI2 had acquired already most word-initial consonants of the Dutch consonant inventory in the targetless condition: /b, d, ɣ, h, j, k, l, m, n, p, r, s, t, v, w, z/. In terms of place of articulation, all labials were acquired, except for the voiceless fricative /f/, which appeared two months later, when the cumulative vocabulary size surpassed 150 word types. All coronals were acquired as well, except for the fricative /ʃ/, which appeared after 28 months of hearing age and at a cumulative vocabulary size of above 200 word types. Only half of the dorsals were acquired. The dorsal fricative / χ / was acquired after 25 months of hearing age, with a cumulative vocabulary size of just above 100 word types. The dorsal /ɣ/ appeared after 26 months of hearing age, when the cumulative vocabulary size exceeded 150 word types. The nasal dorsal /ŋ/ appeared simultaneously with the fricative /ʃ/, after 28 months of hearing age.

At 24 months of hearing age, already twelve consonants were acquired in word onset in the target inventory: /b ɣ h j k m n p s t v w/. One month later, when the cumulative vocabulary had increased above 100 word types, the coronal fricative /z/ was acquired with a 50% criterion. When the cumulative vocabulary size was near 200 word types, also the coronal plosive /d/ was acquired. Finally, at 29 months of hearing age and with a cumulative vocabulary size above 250 word types, two fricatives were acquired provided the 50% criterion: the labial /f/ and the coronal /ʃ/. When the accuracy rate was increased to 75%, the inventory at 24 months of hearing age looked the same except for the /h/, which was not acquired over the entire period studied, and /s/, which was acquired at 28 months of hearing age. The /d/ and / ʃ/ disappeared from the inventory and were thus not acquired with an accuracy of 75%. The labial fricative /f/ was acquired somewhat later, at 34 months of hearing age and with a cumulative vocabulary size above 300 word types.

Before ABI implantation, ABI3 had acquired already the plosives /p, b, t, d, k/, the nasal /m/, the glide /w/ and the /h/ in the targetless condition. In terms of place of articulation, these word-initial consonants were all labial or coronal (and the glottal /h/), except for the dorsal plosive /k/. In a target inventory, ABI3 had acquired the plosive /k/ before ABI implantation in a 50% criterion, but not when the accuracy criterion was 75%. Regardless of the accuracy criterion, the nasal /m/, plosives /p/ and /t/ and the glide /w/ are all acquired before ABI implantation as well.

Two months after ABI implantation, the dorsal glide /j/ appeared in ABI3's targetless inventory. His cumulative vocabulary size reaches almost 100 word types. Five and seven months after ABI implantation, the coronal fricative /ʃ/ and the coronal nasal /n/ appeared (with cumulative vocabulary sizes of 125 and 170 word types respectively). After 14 and 15 months of hearing age, and with a cumulative vocabulary size between 250 and 300 word types, also the dorsal fricative / χ / appeared, as well as the fricatives /f, v, s/ (labial and coronal).

In the target inventory (50% criterion) the glottal /h/ and the fricative /s/ were acquired after three months of device use. With seven months of device use and a cumulative vocabulary near 170 word types, also the fricative /v/ was acquired in the target inventory. By 13 months of hearing age and a cumulative vocabulary size of approximately 250 words, also the nasal /n/ was acquired in the target inventory with a 50% criterion. When increasing the accuracy criterion to 75%, no word-initial consonant was acquired after ABI implantation, except for the nasal /n/ at 16 months of hearing age and with a cumulative vocabulary size of more than 300 word types.

Word-final Consonants

In Table 6, the targetless and the target word-final consonant acquisition of the children with ABI are displayed. In the targetless inventory of ABI1, the glottal /h/ was the first to appear after 18 months of hearing age and a cumulative vocabulary size of 35 word types. Between 24 and 30 months of hearing age, four word-final consonants appeared: first the labial glide /w/, then the dorsal glide /j/ as well as the coronal fricative /ʃ/ and somewhat later also the dorsal fricative / χ /. The cumulative vocabulary size increased from 50 to 100 word types in that period of time. When the cumulative vocabulary size had increased to 150 word types, the coronal nasal /n/ and the coronal plosive /t/ were acquired, at 31 months of hearing age. One month later, the cumulative vocabulary increased to 200 word types, and two voiceless labials appeared: the fricative /f/ and the plosive /p/. At 37 months of hearing age and a cumulative vocabulary size of 280 word types, the dorsal nasal /ŋ/ appeared. Two months later, and with a cumulative vocabulary size surpassing 300 word types, also the coronal fricative /s/ was acquired.

The word-final target inventory of ABI1 was limited to the labial glide /w/ at 20 months of hearing age, and only when considering the 50% criterion. No word-final consonant were acquired with the accuracy criterion set at 75%.

-- *Insert Table 6 here –*

At the first data point, i.e. after two years of hearing age, ten word-final consonants were already acquired by ABI2 in the targetless inventory: /k, l, m, n, p, r, s, t, w, χ /. Two months later, also the labial plosive /b/, the labial fricative /f/ and the dorsal glide /j/ were acquired. The cumulative vocabulary size exceeded 150 word types at this point. When the cumulative vocabulary size further increased to more than 200 word types, three other word-final consonants appeared. At 28 months of hearing age, two fricatives entered the inventory: the glottal /h/ and the coronal /ʃ/. At 29 months of hearing age, also the dorsal nasal /ŋ/ reached the targetless condition.

Word finally, the target inventory (50% criterion) consisted of – surprisingly – the liquid /l/ and the glide /w/ at 24 months of hearing age. The two consecutive months, when the cumulative vocabulary increased to between 100 and 150 word types, also the labial plosive /p/, the coronal glide /j/ and the dorsal fricative /χ/ were acquired. When the cumulative vocabulary size increased above 200 words, the fricative /s/ and the nasal /m/ were acquired at 28 and 29 months of hearing age. At 35 months of hearing age and with a cumulative vocabulary size well above 300 word types. When the accuracy rate was increased to 75%, only the liquid /l/ and the glides /j/ and /w/ were acquired at 24 months, 26 months and 28 months of hearing age respectively.

ABI3 acquired the glides /w/ and /j/ and the labial nasal /m/ in a targetless condition with only CI, i.e., before ABI implantation. In the target inventory ABI3 acquired the labial nasal /m/ in the target inventory before ABI implantation, under the 50% as well as the 75% accuracy criterion. The labial glide /w/ was acquired as well, but only in the target inventory with a 50% accuracy criterion.

When the cumulative vocabulary size surpassed 100 word types, other word-final consonants appeared in the child's targetless inventory. The coronal fricative /s/ appeared after five months of hearing age and a cumulative vocabulary size of 125 word types. The labial plosive /p/ and the dorsal nasal /ŋ/ appeared one month later, with a cumulative vocabulary size of 150 word types. By seven months of hearing age (and a cumulative vocabulary size of 170 word types), also the coronal plosive /t/ appeared in the targetless inventory. At nine months of hearing age, when the cumulative vocabulary size exceeded 200 word types, the glottal /h/ was acquired, as well as the coronal fricative /ʃ/ and the coronal nasal /n/. Finally, after 13 months of hearing age, also the dorsal fricative / χ / was acquired in a targetless condition. The cumulative vocabulary size reached almost 250 word types at this point.

After ABI implantation, ABI3 acquired only the glide /j/ in the word-final target inventory. The cumulative vocabulary size at this point was 150 word types. The phoneme was acquired both under the 50% criterion as well as under the 75% criterion.

Discussion

The present study addressed the question: which phonemes do congenitally hearing-impaired children acquire after pediatric auditory brainstem implantation? Phonemic analyses of three children's spontaneous speech were presented. Their targetless and target phoneme inventories were constructed of their steady state vowels, word-initial and word-final consonants relative to their hearing age and their vocabulary development. It was found that with increasing cumulative vocabulary size and with higher hearing age, targetless and target inventories expanded in all three children. In all categories, but especially for the word-initial and word-final consonants, there was a considerable difference in the amount of phonemes considered to be *acquired* between the targetless phoneme inventory and the target phoneme inventory, even when this last one was constructed with a 50% accuracy rate. As expected, when the target phoneme inventory was constructed with a 75% criterion for accuracy, the inventory was considerably smaller than when it was constructed with a 50% criterion for accuracy. For the target phoneme inventory, the production accuracy was fairly modest, even after 16 to 50 months of device experience and a cumulative vocabulary of more than 300 word types.

Phonemic Inventories of Children with ABI

All vowels were acquired in the targetless criterion for the three children with ABI. Two years after implantation, ABI2 has acquired nearly all vowels in both target inventories (50% and 75%) as well. For the other two children, fewer vowels appeared in their target inventories. With respect to targetless acquisition, it seems that the children with ABI in this study were performing better than the children in Eisenberg, et al. (2018), since they reported the presence of only *some* full vowels after two to three years of ABI use. For ABI2, most of the vowels were already present in her repertoire by the beginning of data collection, i.e. two years after implantation. To get an idea of the vowel development of ABI2 before the start of our data collection, the data of the other children with ABI are highly informative, though that does not mean that their courses of development were the same by default.

A consistent pattern in the two children with ABI showed that the front and central corners of the Dutch vocal triangle (/i/ and /a/) were acquired well before the back one (/u/) in both the targetless and the target inventories. In terms of vowel backness, there was not really a pattern in the children's course of development. This interindividual variation contrasts to Teagle, et al. (2018)'s results of their best performing child, who produced central and back vowels, but little front vowels. In our three cases, there was no such limited amount of front vowels. However, there seemed to be an effect of vowel height: mid vowels appeared later in the targetless inventory of all children with ABI, as it is also the case for children with typical hearing (Beers, 1995). This suggests that children seem to explore the extreme sides of the vowel space, before filling in the gaps between those extremes. The accuracy of vowel production was moderate, as can be inferred from the many vowels, especially back and mid ones, that disappeared from children with ABI's inventories when the accuracy criterion was raised from 50% to 75%. In the literature, Teagle, et al. (2018) reported that the best performing children had accuracy rates in vowels of 17% after two years of device use and

53% after three years of device use. Given the fact that they did not differentiate between the vowels, it is difficult to compare their results to ours.

As to consonants, all children produced at least some word-initial and word-final consonants, be it often incorrectly, already in the first data points. Relative to the development reported by Eisenberg, et al. (2018) and Teagle, et al. (2018) the results reported in the present study revealed a more intricate and advanced picture of the children's development. Whereas Eisenberg, et al. (2018) reported some word-final consonants only after two years of device use, we observed word-final consonants much earlier. This difference might be a methodological effect: whereas Eisenberg and colleagues used a naming task, with a fairly limited amount of tokens, we investigated spontaneous speech samples with a larger amount of words.

The three children with ABI seemed to follow the course of consonantal development of children with typical hearing (e.g. Beers, 1995; Fikkert and Altvater-Mackensen, 2013; Van Severen, 2012; Van Severen, Van den Berg, Molemans, & Gillis, 2012) and children with cochlear implants (e.g. Schauwers, Taelman, Gillis, & Govaerts, 2008; Serry and Blamey, 1999; Spencer and Guo, 2013; Wiggin, Sedey, Awad, Bogle, & Yoshinaga-Itano, 2013). In the targetless and both target inventories, stops, nasals and glides (with respect to manner of articulation) and labial and coronal consonants (with respect to place of articulation) were acquired mostly before liquids and fricatives and before dorsal consonants. The first dorsals to appear were glides and stops, the first fricatives were labial and coronal. With respect to voicing, it is interesting to note that ABI3's stops in the target inventory were all voiceless, whereas the other two children with ABI acquired both voiced and voiceless stops. However, the voiced stop /d/ was also acquired much later than other stops in ABI2 as well. In contrast to the other children with ABI and the typical course of development observed in children with CI and NH, the consonantal acquisition of ABI1 did not follow any specific order word-finally: with longer device use and an extended vocabulary size, fricatives, nasals and stops seemed to appear without an apparent order.

In Eisenberg, et al. (2018) two out of four children produced nasals and liquids, and the other two children all consonant manners of articulation after two years of ABI use, regardless of word position. In our study, ABI1 and ABI2 produced all consonant manners of articulation by that time as well word-initially, and ABI3 produced all consonant manners of articulation except for liquids word initially. Also, the word-initial consonant inventories were larger than the word-final ones for all children with ABI, especially with respect to the target inventories. Similar findings have been found for children with CI (e.g., Ertmer, Kloiber, Jung, Kirleis, & Bradford, 2012). For place of articulation, Eisenberg, et al. (2018) reported that all children produced labial and coronal consonants, but only one child also dorsal consonants. Even though the children in the present study produced all places of articulation, we also noticed a clear advantage of labial and coronal word-initial and word-final consonants.

The production accuracy of the word-initial and word-final consonants was fairly modest. In none of the children, all consonants (word-initial and word-final) were acquired when the accuracy criterion was set at 50%. If the accuracy criterion was increased, a lot of consonants disappeared from the inventory, especially in ABI1 and ABI3, and more dramatically for the word-final consonants as compared to the word-initial consonants. Word-finally, ABI1 and ABI3 acquired only one consonant after ABI implantation in their target inventory. With the observed accuracy percentages, phoneme-to-phoneme comparisons in the present study seem to be well in agreement with the results of Teagle, et al. (2018): their best performing child produced all consonant features with about 60% accuracy after three years of device use.

Overall, the present study showed that the children with ABI make a clear development with longer device use and lexical expansion. But their development was very slow in comparison to children with NH and CI. For instance in a sample of 30 children with NH, Van Severen (2012) showed that 90% of them acquired approximately ten word-initial consonants in their targetless inventory by two years of age, which equals two years of hearing age. In comparison, ABI1 has acquired ten word-initial consonants at 32 months of hearing age. After two years of device use, ABI2 seemed to approximate the children with NH at two years of age, even though this child was four years old at that moment. ABI3 acquired ten word-initial consonants after more than four years of CI use, including three months of ABI use. For target inventories (75%), Beers (1995) showed that children with NH acquired approximately 9 syllable-initial consonants by two years of age. As for the targetless inventories, only ABI2 seemed to be able to reach this amount of initial consonants by the same hearing experience of two years, be it that the child was two years older in terms of chronological age.

For children with CI, Chin and Pisoni (2000) showed in a case study that the consonant and vowel targetless inventories were almost complete by two years of device use. In a similar vein, also Barry, Blamey, & Fletcher (2006) showed a rapid increase of vowel acquisition in Cantonese-speaking children with CI. Within the first two years of device use, these children acquired on average 12 vowels in a targetless condition. Likewise, Serry and Blamey (1999) showed that all children acquired all 12 English steady state vowels by one year of device use in a targetless inventory and by three years of device use in a 50% target inventory. In both inventories (targetless and target), ABI2 and ABI3 approximated the complete vowel inventory by two years of device use, i.e. one year of device use longer than the children with CI. For ABI1, it even takes three years of device use.

As to consonants, the most recent literature on children with CI suggested that they acquire on average 16 to 18 consonants (regardless of word-position) by two years of device use (Sundarrajan, Tobey, Nicholas, & Geers, 2020). By four years of device use, most children with CI had acquired all but four consonants in their targetless inventory (Wiggin, et al., 2013). Split out for word-position, Spencer and Guo (2013) found the largest increase between two and three years of CI use: from six to 13 word-initial consonants and from two to 13 word-final consonants in a targetless condition. For the children with ABI in this study, considerable differences were observed. Word-initially, ABI1 acquired only eight consonants by two years of device use, whereas ABI2 already acquired 16 consonants word-initially. Word-finally, ABI1 acquired only two targetless consonants after two years of device use, ABI2 10 consonants within that same period of device use, but ABI3 acquired already 10 consonants word-finally after nine months of ABI use, but including more than four years of CI use. Thus, only ABI2 seems to approach the levels of children with CI in a targetless condition.

In Serry and Blamey (1999), most of the children 8 consonants by two years of device use in a 50% target inventory, regardless of word position. For the 50% target inventory, ABI2 and ABI3 seemed to reach similar levels by two years of device use, but only word initially. But, with an added year and a half of hearing experience as compared to the children with CI, ABI1 did not yet reach this point of 8 consonants: the child still had 7 word-initial consonants in the target inventory after three and a half years of device use. Turning to the 75% accuracy criterion, the children with CI in Ertmer, et al. (2012) performed extremely well: they acquired 10 word-initial and six word-final consonants by three years of age, which matches with approximately 18 months of device use, and an additional eight word-initial and five word-final consonants two years later. In contrast, the children with ABI in this study acquired very few consonants in the 75% criterion, even after several years of device use, and almost none of the word-final consonants. The best performing child in this study, ABI2, acquired 11 word-initial consonants after almost two-and-a-half years of device use in the 75% criterion, as compared to 18 word-initial consonants after a similar amount of device use for the children in Ertmer, et al. (2012). Word-finally, ABI2 acquired only three consonants after two-and-a-half years of device use in a 75% criterion, as compared to the 11 consonants acquired by the children in Ertmer, et al. (2012). The other two children with ABI in this study acquired not more than five word-initial (ABI1 four, ABI3 five) and two word-final consonants in a 75% criterion (ABI1 none, ABI3 two). More consonants appeared when the accuracy criterion was lowered to 50% (especially in word-initial position), but still a big difference was noted when comparing with hearing age-matched children with CI.

Implications, Limitations and Future Research

In this study, a first detailed overview of three children with ABI's phonemic productions in spontaneous speech was presented. It also gave a first, highly requested (Hammes Ganguly, et al., 2019), indication for speech and language therapists to start from. For instance, our results revealed that production accuracy is far more affected than the variety of different consonants and vowels produced in spontaneous production. The children with ABI produced a substantial amount of phonemes of the ambient language, but the accuracy of production was fairly moderate. Moreover, there seemed to be a strong influence of longer device use and vocabulary size on the children's articulatory development. For children with ABI, it has already been shown that speech perception and speech production are positively impacted by longer device use (e.g. L. Colletti, et al., 2014; Eisenberg, et al., 2018; Sennaroglu, Colletti, et al., 2016; Sennaroglu, Sennaroglu, et al., 2016). The effect of longer device use has also been observed for children with CI (Gillis, 2017). Even though the progress with longer hearing experience seems to be more slowly in children with ABI, prolonged learning continued over at least five years of ABI use (e.g. Eisenberg, et al., 2018; Hammes Ganguly, et al., 2019; Sung, et al., 2018).

Speech and language therapy could also start from the apparent synergy between vocabulary development and phonological development of children with ABI. Even though more research is needed for the ABI population, similar observations have already been made in the literature for children with typical hearing (Santos and Sosa, 2015; Stoel-Gammon, 2011; van den Berg, 2012) and children with cochlear implants (Faes and Gillis, 2016; Reidy, et al., 2015).

One of the limitations of the present study was the number of participants: only three cases with ABI could be presented. In addition, there was only some overlap between the hearing ages of the children and a considerable interindividual variation was observed. The children with ABI in this study had no additional disabilities and two of them have a relatively early age at implantation as compared to the literature. In that sense, the children in the present study are in a very advantageous position to develop oral language skills. It has already been shown that perceptional benefits after ABI implantation are stronger in children without additional disabilities and earlier implant age (Aslan, et al., 2020; Sennaroglu, Colletti, et al., 2016; Sennaroglu, Sennaroglu, et al., 2016; Sung, et al., 2018; van der Straaten, et al., 2019). Similar trends for speech production are found (van der Straaten, et al., 2019). The progress showed by the three children with ABI in the present paper must therefore be interpreted in the light of the differences between ABI populations and not be generalized to the entire ABI population by default.

One child in our cohort was first implanted with a CI and received a contralateral ABI at four years of age. With only the CI, the child's language development stayed well below the general expectations of children with CI. It is not unusual for children to receive a CI first and then an ABI (Batuk et al., 2020; Buchman et al., 2011; Sennaroglu, Colletti, et al., 2016). Recently, Friedman, et al. (2018) and Batuk, et al. (2020) indicated that an ABI and a CI may ally fairly well. The child reported on in the present study seems seemed to have a little advantage over ABI1 after a comparable amount of ABI device use. Nevertheless, a CI implantation would have not been suitable for ABI1, since this child had no auditory nerve at all. This shows, again, that the population of children with ABI is characterized by a lot of individual differences in terms of their specific conditions, which makes great caution in interpreting and generalizing the results individual cases.

To conclude, ABI implantation seems to provide ample information for the children to progress to spontaneous articulatory production. All three children produced all vowels after some time of ABI use and with extension of their cumulative vocabulary size. Also word-initial and, to a lesser extent, word-final consonants appear in the children's spontaneous productions. There was a considerable amount of variation between the children, especially with respect to the order of vowel acquisition. For consonants, the children seem to follow a more typical course of development, in the sense that stops, glides and nasals are acquired earlier than liquids and fricatives and that labials and coronals are acquired earlier than dorsals. But, the accuracy in the children's phoneme productions was fairly modest. Even though our results suggest clear benefits from the implant on spoken language, the development is slow and it takes several years of device use to acquire the language ambient phonemes. Therefore, we expect children with ABI to still rely on sign language in their daily life as well.

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Tables.

Table 1. Overview of the children with ABI

	PTA unaided (dB HL)	PTA with ABI (dB HL)	Age at ABI surgery (years;months)	Age at ABI fitting (years;months)	Age at start of data collection (years;months)	Duration of data collection (in months)
ABI1	120	37.5 *	2;00	2;02	3;02	29
ABI2	116	43 *	2;01	2;02	4;01	26
ABI3	90 – 95	33 **	4;00 CI at 0;08	4;01	3;10	18

* After two years of ABI use; ** with CI

PTA = Pure Tone Average, in decibels hearing level (dB HL)

Table 2. The Dutch consonant system.

	Labial	**Coronal**	**Dorsal**	**Glottal**
Plosive	p, b*	t, d*	k, g*	
Fricative	f, v*	s, z*	χ, ɣ*	h*
		ʃ, ʒ*		
Nasal	m	N	ŋ+	
Liquid		l, r		
Glide	w		j	

Voiceless, voiced

* = cannot occur in word-final position

\+ = cannot occur in word-initial position

Table 3. The Dutch vowel system.

	Front	**Central**	**Back**
High	i y		u
Mid	ɪ e ɛ ø Y	ə	o ɔ
Low		a	ɑ

Table 4. Vowel inventories of the children with ABI – targetless and target inventories.

Hearing age (months)	Cumulative vocabulary (word types)			Vowel inventories																	
				Targetless						Target											
				ABI1		ABI2		ABI3		ABI1				ABI2				ABI3			
	ABI1	ABI2	ABI3							50%		75%		50%		75%		50%		75%	
				V	#	V	#	V	#	V	#	V	#	V	#	V	#	V	#	V	#
-2			20					ə a ɑ e ɛ ɪ u y ʏ	9									ə ɑ u y	4	u y	2
-1			48					o	10									a e	6	a e	4
0																					
1																					
2			70					i	11									ɪ	7		
3			90					ɔ ø	13												
4			97																		
5			126																		
6			150															i	8		
7			171																		
8			182																		
9			207															ø	9		
10																					
11																					
12																					
13			242																		
14	4		279	a e y	3					a e y	3	a e	2								
15	8		296																		
16	16		315	ɑ i	5					i	4	i	3								
17																					

18	35		ə ø o	8				o	5	o	4					
19	35															
20	41															
21	45		ɔ	9												
22																
23	49							ɑ ɔ	7							
24	52	76			ə a ɑ e ɛ ɪ i ɔ o u y	11				ɔ	5	ə a ɑ e ɛ ɪ i ɔ o u y	11	ə a ɑ e ɪ i ɔ o u y	10	
25	60	118			Y	12						Y	12	Y	11	
26	73	159	ɛ u	11										ɛ	12	
27	78	183						u	8							
28	100	228	ɪ	12	ø	13		ə	9			ø	13			
29	132	262						ɪ	10							
30		275														
31	164	291														
32	199	304	Y	13												
33	218	318														
34	232	327														
35	239	339														
36		355														
37	279	366						ø	11	ø	6					
38	306	394								ɑ	7					
39	324	401														
40	349	411														
41	379															
42		447														
43	401															
44		472														

45	513						
46	553						
47	562						
48							
49	577						
50	611						
V = vowel phoneme in the inventory # = cumulative number of phonemes in the inventory							

Table 5. Word-initial inventories of the children with ABI – targetless and target inventories.

Hearing age (months)	Cumulative vocabulary (word types)			Word-initial inventories																	
				Targetless						Target											
				ABI1		ABI2		ABI3		ABI1				ABI2				ABI3			
										50%		75%		50%		75%		50%		75%	
	ABI1	ABI2	ABI3	WI C	#	WI C	#	WI C	#	WI C	#	WI C	#	WI C	#	WI C	#	WI C	#	WI C	#
-2			20					b h k p t	5									k	1		
-1			48					d m w	8									m p t w	5	m p t w	4
0																					
1																					
2			70																		
3			90					j	9									h s	7		
4			97																		
5			126					ʃ	10												
6			150																		
7			171					n	11									v	8		

8			182																		
9			207																		
10																					
11																					
12																					
13			242															n	9		
14	4		279	j n w	3			χ	12	j	1	j	1								
15	8		296					f s v	15	d	2										
16	16		315	b	4					b	3									n	5
17												b	2								
18	35			p	5					p	4										
19	35																				
20	41																				
21	45			d	6																
22																					
23	49																				
24	52	76				b d ɣ h j k l m n p r s t v w z	16							b ɣ h j k m n p s t v w	12	b ɣ j k m n p t v w	10				
25	60	118				χ	17							z	13						
26	73	159		m t	8	f g	19														
27	78	183												d	14						
28	100	228				ŋ ʃ	21			m t	6					s	11				
29	132	262												f ʃ	16						
30		275																			
31	164	291																			
32	199	304		f l	10					n	7										
33	218	318																			

34	232	327					t	3	f	12	
35	239	339									
36		355									
37	279	366	h k	12			p	4			
38	306	394	ŋ	13							
39	324	401									
40	349	411	v	14							
41	379										
42		447									
43	401										
44		472									
45		513									
46		553									
47		562									
48											
49		577									
50		611									

WI C = word-initial consonant phoneme in the inventory
= cumulative number of phonemes in the inventory

Table 6. Word-final inventories of the children with ABI – targetless and target inventories.

Hearing age (months)	Cumulative vocabulary (word types)			Word-final inventories																	
				Targetless						Target											
	ABI1	ABI2	ABI3	ABI1		ABI2		ABI3		ABI1				ABI2				ABI3			
										50%		75%		50%		75%		50%		75%	
				WF C	#	WF C	#	WF C	#	WF C	#	WF C	#	WF C	#	WF C	#	WF C	#	WF C	#
-2			20					m w	2									m	1	m	1
-1			48					j	3									w	2		
0																					
1																					
2			70																		
3			90																		
4			97																		
5			126					s	4												
6			150					ŋ p	6									j	3	j	2
7			171					t	7												
8			182																		
9			207					h n ʃ	10												
10																					
11																					
12																					
13			242					χ	11												
14	4		279	h	1																
15	8		296																		
16	16		315																		
17																					
18	35																				
19	35																				

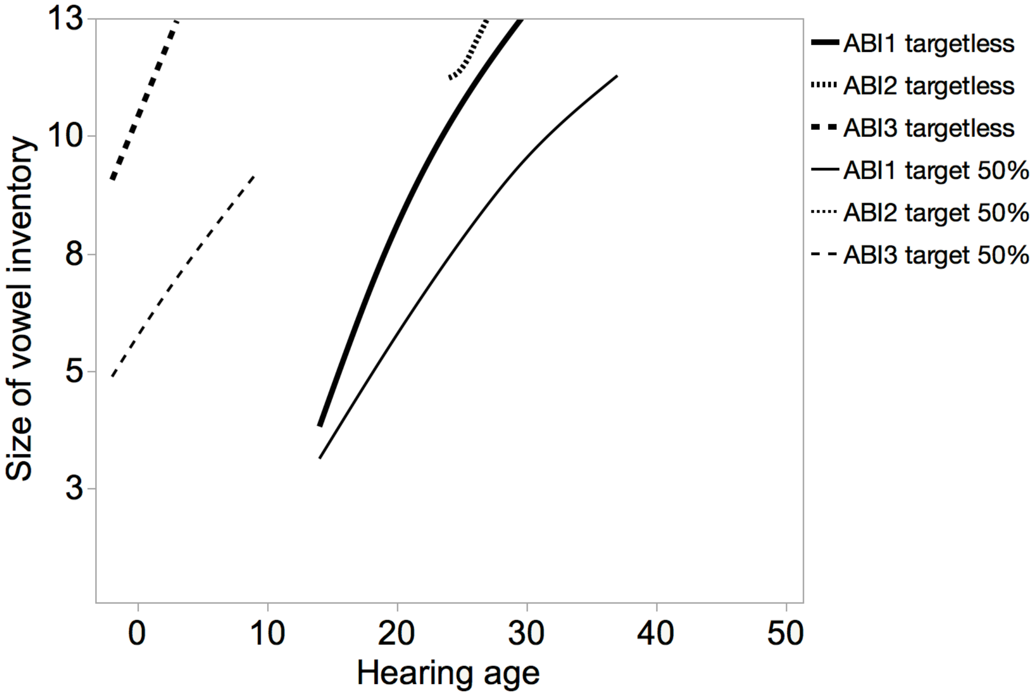
20	41							w	1					
21	45													
22														
23	49													
24	52	76	w	2	k l m n p r s t w χ	10				l w	2	l	1	
25	60	118								p	3			
26	73	159	j ʃ	4	b f j	13				j χ	5	j	2	
27	78	183										w	3	
28	100	228	χ	5	h ʃ	15				s	6			
29	132	262			ŋ	16				m	7			
30		275												
31	164	291	n t	7										
32	199	304	f p	9										
33	218	318												
34	232	327	m	10										
35	239	339												
36		355												
37	279	366	ŋ	11										
38	306	394												
39	324	401	s	12										
40	349	411												
41	379													
42		447												
43	401													
44		472												
45		513												
46		553												
47		562												

48							
49	577						
50	611						

WF C = word-final consonant phoneme in the inventory
= cumulative number of phonemes in the inventory

Figures.

Figure 1. Targetless and target (50%) vowel inventories relative to hearing age.



Note: the target inventory of ABI2 is equally large as the targetless one. As a result, the two lines presenting the development of ABI2 overlap entirely.

Figure 2. Targetless and target (50%) word-initial (WI) consonant inventories relative to hearing age.

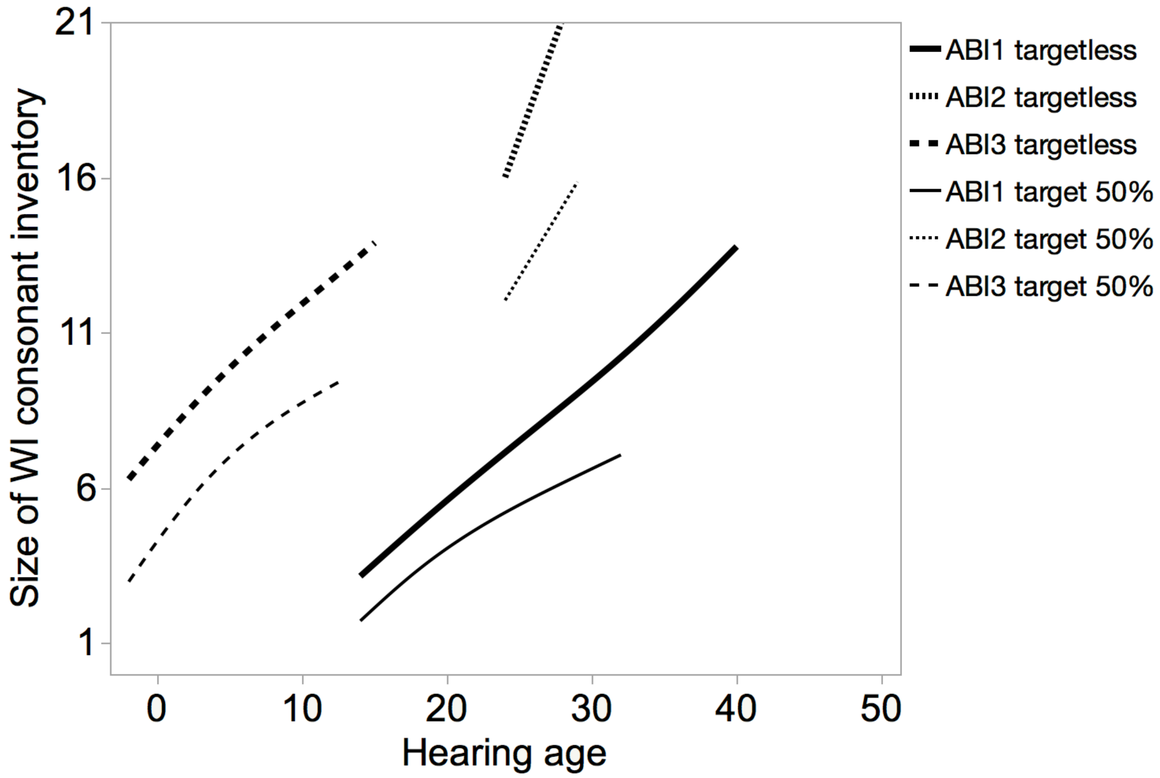
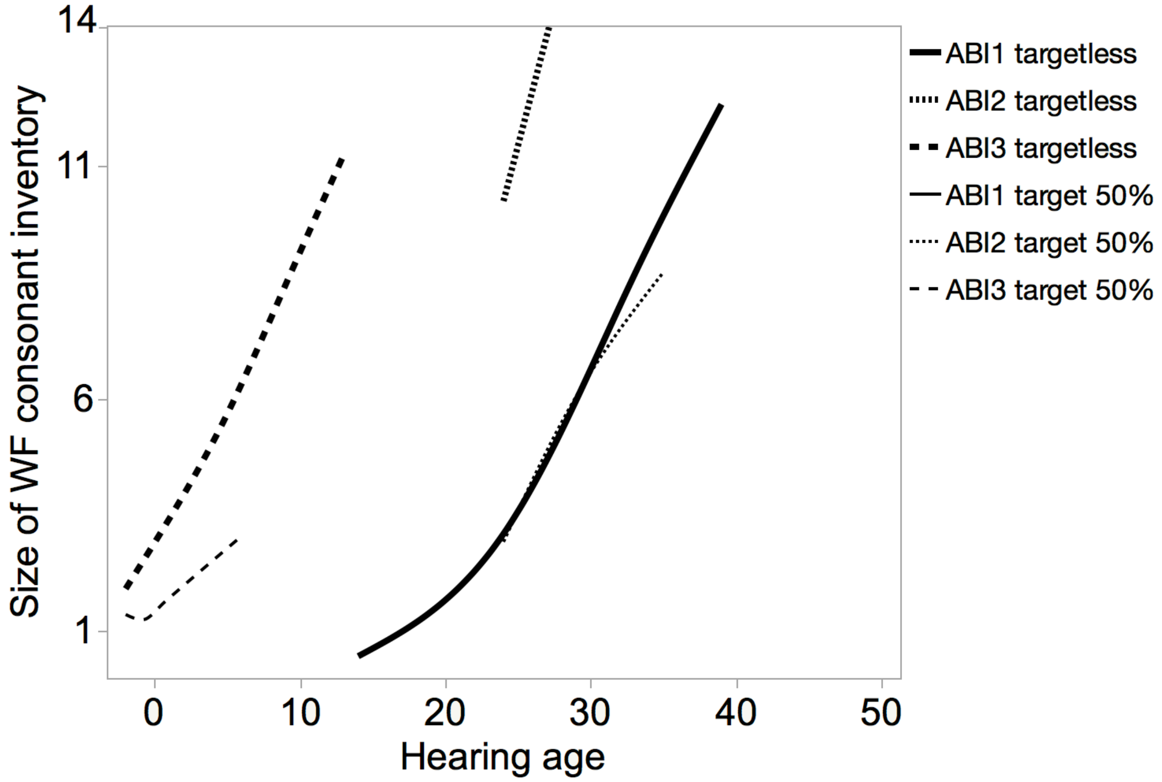


Figure 3. Targetless and target (50%) word-final (WF) consonant inventories relative to hearing age.



Note: the WF target consonant inventory of ABI1 includes only one phoneme. This is not shown on the figure.

Figure 4. Lexical development relative to hearing age.

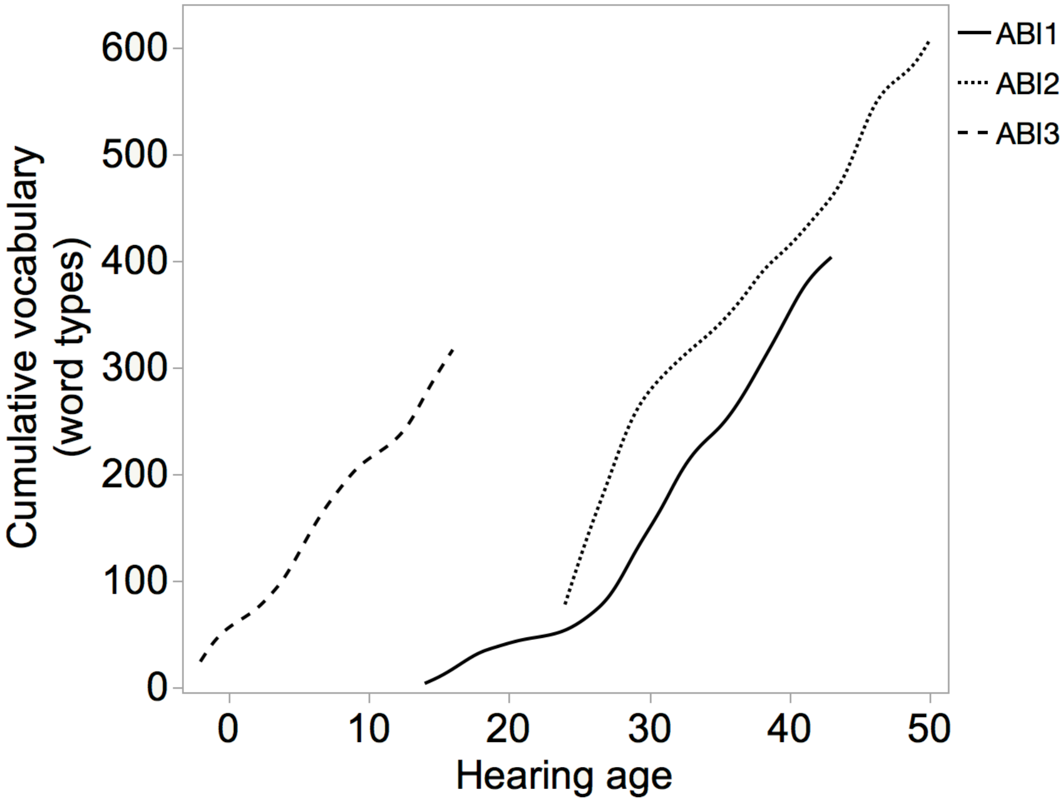


Figure captions.

Figure 1. Targetless and target (50%) vowel inventories relative to hearing age.

Figure 2. Targetless and target (50%) word-initial (WI) consonant inventories relative to hearing age.

Figure 3. Targetless and target (50%) word-final (WF) consonant inventories relative to hearing age.

Figure 4. Lexical development relative to hearing age.