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Auditory brainstem implantation in children: the case of place of articulation

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Samenvatting

Deze studie onderzoekt de uitspraak van de articulatieplaats van spraakklanken in de spontane spraak van drie kinderen met een herstenstamimplantaat. Deze kinderen worden vergeleken met twee controlegroepen: kinderen met een cochleair implantaat en kinderen met een normaal gehoor. Het spraakmateriaal werd betrokken uit de spontane spraak tussen de kinderen en hun zorgverleners. Voor elke doelklank werd de plaats van articulatie gecodeerd en de plaats van articulatie zoals die door de kinderen werd gerealiseerd. Plaats van articulatie werd gecodeerd als labiaal, coronaal of dorsaal. De resultaten tonen aan dat "coronaal"het vaakst voorkwam in de eigen producties. Eén kind vormde hierop een uitzondering en had een voorkeur voor "labiaal". De labiale plaats van articulatie werd ook accurater uitgesproken dan de coronale plaats van articulatie. De dorsale plaats van articulatie was het minst accuraat. Kinderen met een hersenstamimplantaat waren het minst accuraat. Als de plaats van articulatie niet juist werd uitgesproken, dan werd de klank vaak weggelaten en niet vervangen door een klank met een andere plaats van articulatie. De algemene conclusie is dat kinderen met een hersenstamimplantaat wel degelijk baat hebben bij een implantaat, maar dat zij nog een hele weg af te leggen hebben om achterstand in te lopen. Het gebruik van gebarentaal is nuttig om de communicatie te ondersteunen.

Abstract

This study aimed to investigate the development of the production of place of articulation of three children with auditory brainstem implants (ABI) in spontaneous speech production. The main participants were three children implanted with an ABI. They were compared against two different control groups: children with a cochlear implant (CI) and children with normal hearing (NH). Data was obtained from spontaneous speech between the children and their caregivers. For each word production, the place of articulation of both the target word as the child's own production was identified. This was broadly identified in three categories: labial, coronal and dorsal. The analysis revealed

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that in general, the coronal place of articulation was most used in all children's own production, as well as in the target words, except for one child with ABI, who showed a preference for labials. In terms of accuracy, labial place of articulation was produced more accurately than the coronal place of articulation for all children. The dorsal place of articulation had very low accuracy probabilities. Children with ABI had the lowest accuracy rates. When the place of articulation was not correctly produced, they were often omitted instead of replaced by another place of articulation. It was concluded that the children with ABI benefit from their device, but still have a long way to go to catch up to their peers. It is suggested that sign language is needed to guarantee smooth communication.
Keywords: auditory brainstem implantation; pediatric; oral language, place of articulation; labial; coronal; dorsal

Introduction

This study reports on the development of place of articulation in three children with auditory brainstem implants (ABI), in comparison to a group of children with cochlear implants (CI) and a group of children with typical, normal hearing (NH).

In the past several decades, different techniques have been emerging to restore hearing capacity in patients with a severe-to-profound sensorineural hearing loss. The decision for one or the other therapeutic aid is usually determined by the type and/or locus of the hearing deficit. With respect to sensorineural hearing loss, there are two implantable aids: a CI and an ABI. With experience of adult patients, both techniques have been expanded to pediatric populations as well. CIs have been implanted in children in the last two decades of the previous century. In contrast, ABI has only been emerging in pediatric hearing restoration since the beginning of this century, with the first implantation in 2001 (Colletti et al., 2001).

A CI is used when the hearing loss results from absent or malformed hair cells in the cochlea, whereas an ABI is used when the hearing loss results from an absent auditory nerve or malformed or ossified cochlea, precluding a CI placement. Studies recommend ABI implantation only if CI placement is anatomically impossible or after a period of CI use with poor language outcomes (Batuk et al., 2020; Buchman et al., 2011; Farhood et al., 2017; Hammes Ganguly et al., 2019). The external part of both devices, ABI and CI, consists of a microphone that captures the environmental sounds and a processor that transforms them into a digital code. The internal part consists of an electrode array, but the placement of this array depends on the type of implant. In a CI, this electrode array is inserted into the cochlea, preserving the tonotopic organization of the cochlea and directly stimulating the auditory nerve. In an ABI, this electrode array is inserted directly onto the cochlear nucleus of the brainstem, bypassing the entire cochlea and the auditory nerve. In contrast to the CI – which maintains the tonotopic organization-, the organization of hearing pathways of the brainstem are unclear and unpredictable in ABI, which seems to have lower hearing benefits as a result (Long et al., 2005; Wong et al., 2019). Yet, some children wear both a CI and a contralateral ABI. The first research results seem to suggest that this CI-ABI combination enhances the effect of both implants (Batuk et al., 2020; Friedman et al., 2018), although clearly more research is needed.

Children with ABI

Children with a congenital severe-to-profound hearing loss reach hearing thresholds between 30 and 60 dB HL (decibels hearing level) after ABI implantation (Colletti et al., 2004; Sennaroglu, Colletti, et al., 2016; Teagle et al., 2018; Yucel et al., 2015). The ABI offers sound awareness, sound discrimination and identification of phonetic contrasts to these children. Research has pointed out that speech perception outcomes are better when children are implanted earlier (Aslan et al., 2020), when children have lower hearing thresholds after their ABI implantation (Sennaroglu, Sennaroglu, et al., 2016; Yucel et al., 2015), and when children have no additional disabilities (Colletti et al., 2014; van der Straaten et al., 2019). The children who meet these three specifications can at least understand easy phrases without the aid of lip reading. Nevertheless, there are also considerable individual differences in their open set speech perception outcomes, even when they met these specifications (Colletti et al., 2014; Colletti et al., 2004; Sennaroglu, Colletti, et al., 2016).

Children who achieve open speech perception (i.e., the children with low hearing thresholds after early implantation and without other disabilities) also develop speech production skills. This development follows the pathway of typical spoken language development, in the sense that these children develop vocalizations, babble, and start to produce words and sentences after a period of ABI experience (e.g. Bayazit et al., 2014; Faes & Gillis, 2018, 2019a, 2019b) as children with typical development. Nonetheless, the pace of development is very slow (Aslan et al., 2020; Eisenberg et al., 2018; Faes & Gillis, 2019b, 2021a; Teagle et al., 2018; van der Straaten et al., 2019) and there is considerable variation between the children with ABI. With increased hearing experience, children with ABI use basic word patterns (Eisenberg et al., 2018; Faes & Gillis, 2021b) in their increasing lexicon (Faes & Gillis, 2019b). In their speech production, language ambient phonemes and words appear after two to three years of device use, even though the accuracy of these phonemes and words is still low (Eisenberg et al., 2018; Faes, Gillis, et al., 2022; Faes & Gillis, 2021a; Teagle et al., 2018).

In sum, children with ABI with open set speech perception develop speech production, but this development is slow. When compared to children with cochlear implants (CI) – another group of children with congenital severe-to-profound hearing loss – and children with typical, normal hearing (NH), children with ABI clearly lag behind even after five to six years of device use. For instance, the best performing children with ABI have expressive language skills that are to be situated between those of children with CI with and without additional disabilities (van der Straaten et al., 2019). These best performing children with ABI were those early implanted children with low hearing thresholds and no additional disabilities. Going into detail, several aspects of lexical and phonological development of such best performing children with ABI lag behind those of children with CI and children with NH. For instance for lexical development, children with ABIs vocabulary sizes fall out of the lower border of the 95% confidence intervals of the children with CI and NH (Faes & Gillis, 2019b). For phonological development, the same is found for speech production accuracy and phonological complexity in speech: these fall out of the lower borders of the 95% confidence interval in children with CI and NH (Faes & Gillis, 2021b). In line with these results, the overall speech intelligibility of children with ABI was scored considerably lower than that of children with CI and NH, even after more than three years of device use (Faes, De Maeyer, et al., 2022). Overall, it takes children with ABI five to six years of device use in order to be intelligible for a familiar listener with or without lipreading (Aslan et al., 2020; Sennaroglu, Sennaroglu, et al., 2016; van der Straaten et al., 2019).

Effect of hearing loss on place of articulation

The important question is whether children with ABI reach similar spoken language proficiency as their CI or even NH peers. The current study will extend on the question by focusing on the phonemic accuracy of the children and specifically place of articulation. Phonemic accuracy is essential for children's speech intelligibility (Ingram, 2002). In general for children with NH, labial and coronal place of articulation are acquired before dorsal place of articulation (Beers, 1995). However, not much is known about the occurrence and the accuracy of place of articulation of children with ABI. One study has shown the consonant inventories of children with ABI (Faes & Gillis, 2021a), but here, the set off levels to include a certain consonant into a phonemic inventory were set at 2 occurrences and/or 50% or 75% accuracy rate. Even though this gives a good idea of the developmental trend, this does not give insight into the precise accuracy of production. Still, it seems that there was not much of a pattern to be found over the different children, rather all children showed highly individual patterns of in their developing phonemic inventory.

More research has been done on the performance of children with CI. Research to non-word repetition found that children with CI produced coronals with greater accuracy than labials and dorsals. They tended to replace labial and dorsal targets with coronals (Dillon, Cleary, et al., 2004; Dillon, Pisoni, et al., 2004; Moreno-Torres & Moruno-López, 2014). This result is consistent with the theory of Cummings et al. (2020), which states that the coronal place of articulation is the default place of articulation, and that the labial and dorsal place of articulation only appear with maturation and exposure to language. It is also possible that the poorer performance on labials is due to the absence of visual cues in the study design of these non-word repetition tasks, such as lip closure (Dillon, Pisoni, et al., 2004). Evidence for this can be found in research on children's use of consonants in spontaneous speech. Warner-Czyz and Davis (2008) showed that children with CI and NH differed on the frequency of consonants and consonant accuracy before the age of 24 months. Children with NH produced labial and coronal consonants with equal frequency, while children with CI produce more labials than coronals. Both groups produced dorsals the most infrequently. The children with NH produced consonants more accurately than children with CI. Children with CI used more omission, but their performance gradually increased over time. The finding that children with CI use more labial consonants than children with NH is not surprising. It is found that less proficient children with CI rely more on visual cues than auditory cues, and lipreading is even essential for proficient CI users (Huyse et al., 2013). Since the labial place of articulation is visually the most prominent, this would be easier to learn.

Because children with ABI are often implanted later in life than children with CI, sign language is an important part of their communication (Faes & Gillis, 2019a). It has been shown that hearing impaired children with a cochlear implant who are educated using both signed and spoken language, have poorer speech perception skills than hearing impaired children who have been educated using only spoken language (Bergeson et al., 2003). Furthermore, later implanted children with CI rely more on visual cues for speech perception than auditory cues (Bergeson et al., 2005). Likewise, for instance Schorr et al. (2005) and Most et al. (2009) showed that children with CI highly rely on visual cues in their speech perception, especially in challenging auditory conditions. Moreover, children with CI rely more on visual cues than NH-listeners do (Desai et al., 2008). So, it could be inferred that children with ABI, who also have poorer speech perception skills, also need more visual cues. As speech production depends on speech perception (Altvater-Mackensen & Fikkert, 2010; Jusczyk, 1992; Stoel-Gammon, 2011; Stoel-Gammon & Sosa, 2007), this could have consequences for their performance relating to place of articulation.

The present study

In the present study, the comparison between children with ABI and the control groups, viz. children with CI and children with NH, will be held against a language-intrinsic comparison measure, namely level of lexical development. More specifically, children with a similar amount of cumulative vocabulary in their spontaneous speech will be compared to one another. By using lexical development as a yardstick in the comparison, some age-related issues can be avoided. Children with ABI, as well as children with CI, have a delayed onset of hearing, so it seems inappropriate to compare them to children with NH on chronological age. Yet, a frequently used alternative option is to compare children in terms of hearing experience (see for instance Blamey, Barry, Bow, et al., 2001; Blamey, Barry, & Jacq, 2001; Eriks-Brophy et al., 2013; Faes & Gillis, 2019a; Schauwers, 2006; Szagun & Stumper, 2012). However, even in that case, there are issues with later implantation of the children with ABI as compared to the children with CI. In that case, the chronological age difference still has an influence, even in children with a similar amount of hearing experience, so that the use of hearing age as a comparative measure in this study also seems suboptimal. Therefore, lexical development was chosen as a language-intrinsic measure in the present study. This measure is increasingly being used to compare children with CI and ABI. Lexical development has been put forward in previous research as it has been shown to closely follow phonological development in children with CI and NH (e.g. Faes & Gillis, 2016; Smith et al., 2006; Sosa & Stoel-Gammon, 2012; van den Berg, 2012), and a similar trend seems to emerge in research involving children with ABI (Faes & Gillis, 2021a). In addition, lexical development is more related to phonological development than chronological age (van den Berg, 2012), so that it seems the least skewed measure of comparison.

Place of articulation is operationalized in three categories: labial, coronal and dorsal in line with Booij (1995)'s division of the place feature (Figure 2.3 on page 9 in Booij (1995). Also in Booij (1995), the Dutch consonant system is depicted: Labial consonants are bilabial and labio-dental consonants, coronals are alveolar and palatal consonants and dorsals are velar consonants. The distinction between these categories is one of the most common contrasts in different languages. In terms of token frequencies, coronal consonants appear the most frequently in Dutch (Luyckx et al., 2007).

Four research questions will be assessed in the present study:
(RQ1) Occurrence of the different places of articulation in target: how often are the three different places of articulation targeted by the children? What is the distribution in the target words?
(RQ2) Occurrence of the different places of articulation in replica: how often do children use the different places of articulation in their own productions – regardless their correctness?
(RQ3) Accuracy of place of articulation: how accurately is place of articulation produced by the children?
(RQ4) Error analyses: if the place of articulation was produced incorrectly, is it replaced or omitted? And, if it is replaced, which other place of articulation?

For each of these research questions, a comparison between each child with ABI and the control groups (children with CI and children with NH) will be carried out. As mentioned earlier, the comparison will be based on similar lexicon sizes. There are two possibilities with respect to the four research questions: (a) children with ABI produce place of articulation differently as compared to children with CI and children with NH, (b) children with ABI show a similar pattern in place of articulation as compared to children with CI and children with NH. With respect to the first possibility, there seem to be two valid hypotheses according to the literature.

A first possibility is that there is a difference in labial place of articulation in ABI children as compared to the control groups. For children with ABI, as well as children with CI, it has been shown that the speech signal provided by their device is degraded and more noisy than in normal hearing (Drennan & Rubinstein, 2008). The literature seems to indicate that the speech signal is even more degraded in ABI than in CI (Wong et al., 2019). In addition, children with ABI are generally implanted later than children with CI. So, sign language is more common in ABI children than in children with CI (and by extension also children with NH). This is due to their later implantation, the need for a different communication mode before implantation and the more degraded speech ABI signal, resulting in a greater need for supportive sign language for efficient communication. Since the labial place of articulation is visually the most salient and children with ABI are more used to pick up visual cues for speech perception, a more prominent role of labial consonants in children with ABI's speech productions is expected. In other words, it is expected that labials are more present in children with ABI's word productions (replica, RQ2), that they are more accurate in children with ABI (RQ3) and that they are used as an alternative in erroneous productions (RQ4). For the target words, RQ1, there might also be an effect of children with ABI targeting words with a labial place of articulation, because of their own increased attention for it. This result would be in line with the results of Warner-Czyz and Davis (2008) with respect to comparison CI-NH.

A second possibility is that children with ABI produce more and more accurate coronal place of articulation as compared to the control groups. In adult speech production, it is evident that the coronal place of articulation is the default place of articulation, also called underspecified place of articulation (see e.g. for an review in the introduction of Cummings et al., 2020). Cummings et al. (2020) proposed that acquiring place of articulation is a developmental process, in which first the default [coronal] is acquired, as it is the least complex. Later on, more complex – specified – place of articulation, i.e. labial and dorsal, appear as well. Cummings et al. (2020) indicated that time and, especially, exposure to language are needed to develop place of articulation. For instance, they suggested that four-to-six-year-old children with phonological disorders have less fine-grained phonological representations, as compared to a typically developing group of peers, resulting in a less mature stage of phonological acquisition, so that they had only acquired coronal place of articulation. Extrapolating this to children with ABI, a similar pattern may present itself. Due to a degraded speech signal, the phonological representations of children with ABI are highly likely the be less fine-grained than in children with CI and children with NH. Faes and Gillis (In press), for instance, showed significantly greater variability in word production in children with ABI than in children with CI, which can be explained by less-fine-grained phonological representations in the ABI group. In addition, children with ABI have had less exposure to language as compared to the control groups. As a result, it is possible that children with ABI are in an earlier stage of development like children with phonological disorders in Cummings et al. (2020). This would result in a more extended use of the coronal place of articulation in children's productions and error patterns as well as a more accurate production of this place of articulation. This result would be in line with Dillon, Cleary, et al. (2004); Dillon, Pisoni, et al. (2004); and Moreno-Torres and Moruno-Lopez (2014) for the CI – NH comparison.

Methods

Participants

The present study reports on the speech production of three children with ABI. In the period 2015 to 2019, only eight children received an ABI in Belgium. Inclusion criteria for the present study were: a congenital bilateral severe-to-profound hearing loss, no other health or developmental problems, growing up in a Dutch-speaking family and having completed at least one and a half years of follow-up. These three of children had been followed up longitudinally on a monthly basis. The study was approved by the Ethical Committee for the Social Sciences and Humanities of the University of Antwerp (EASHW_16_29) and all parents signed an informed consent.

ABI1 and ABI2 were born with a sensorineural hearing loss, due to the absence of their auditory nerves. Their pure tone average (PTA) hearing thresholds before implantation were 120 dB HL and 116 dB HL respectively. Both children were implanted around their second birthday (24 months and 25 months of age), with a Med-El ABI (Synchrony and Concerto respectively). Two months after surgery, the ABI was fitted. In both children nine of the 12 electrodes were activated. Two years after ABI surgery, pure tone average thresholds had improved to 37.5 dB HL and 43 dB HL. ABI1 was bilaterally implanted, this child received a second, contralateral ABI at four years and nine months of age. Longitudinal monthly data collection started about one year after implantation for ABI1 and two years after implantation for ABI2 and lasted more than two years in both children. To be precise, data collection for ABI1 started when the child had three years and two months of age and continued up till the age of five years and seven months. The data collection of ABI2 started at four years and one months of age and continued up till six years and three months of age. Both children were raised with oral communication, supported by Flemish Sign Language. The amount of sign language in the input was larger for ABI1 than for ABI2.

ABI3 first received a CI at eight months of age, due to a severe-to-profound hearing loss after a diagnosis of auditory neuropathy. The child's PTA hearing threshold was 92.5 dB HL in the better, CI-implanted ear. With CI, the mean PTA improved to 33 dB HL. Nevertheless, language and communication skills did not develop well. Therefore, a contralateral ABI was implanted at the age of four. Two months after implantation, all electrodes could be fitted. The data collection for this child started two months before ABI implantation (at three years and ten months of age) and went on for one year and a half, up till five years and four months of age. ABI3 was also raised in oral Dutch, supported by Flemish Sign Language (similar amount of sign language input as ABI1).

Two control groups were included in the study: (a) children with a cochlear implant, and (b) children with typical hearing. Nine children with CI participated in the study as a first control group (Table 1). These children were born with a sensorineural hearing loss with no other health or developmental problems. Their sensorineural hearing loss was associated to underlying pathologies different from those in ABI children, causing deficits in their cochlea. The mean PTA before implantation was 112.56 dB HL. All children were implanted well before their second birthday, with a range of 5 to 20 months and a mean implantation age of one year (SD = 5 months). After implantation, the mean PTA hearing threshold was 32.22 dB HL at the age of two. Six children received a bilateral implant at a later age (Table 1). All children were raised in spoken Dutch, with only a limited number of lexical signs in support. Longitudinal monthly data collection started after implant fitting and went on for 30 months after implantation (and yearly thereafter).

Thirty children with NH were selected as a second control group. These children had no reported health, hearing, or developmental problems. All children were raised in spoken Dutch and were followed monthly between six months and two years of age.

Data collection and transcription

Monthly spontaneous video recordings were made at the children's home, capturing spontaneous conversations between the children and their caregiver(s). These video recordings were entirely unstructured (participants were free to do whatever they wanted), so that they resembled daily life interactions. All recordings lasted about one hour. For the control groups, these one-hour video recordings were reduced to 20-minute selections, to keep transcription time within reasonable limits. For detailed information, see Molemans (2011),

Table 1: Individual characteristics of children with CI

ID	Gender	PTA unaided (dB HL)	PTA CI (dB HL) (age 2;00)	Age CI implantation	Age second CI
CI1	F	120	48	1;01	6;03
CI2	F	120	30	0;07	4;08
CI3	F	115	33	0;10	5;10
CI4	M	113	48	1;06	-
CI5	M	93	38	1;05	6;04
CI6	M	120	53	0;09	-
CI7	F	117	42	0;05	1;03
CI8	F	112	38	1;07	-
CI9	F	103	28	0;08	1;11

dB HL = decibel Hearing Level. Ages are presented in years;months. - = no second CI.

Schauwers (2006), van den Berg (2012) and Van Severen (2012). Because of the smaller number of children in the ABI group, ABI video recordings were transcribed entirely.

The video recordings were transcribed in CHILDES' CLAN following the CHAT conventions (MacWhinney, 2000). All children's lexical productions were transcribed orthographically and phonemically. In addition, a phonemic transcription of the target word was added to these transcriptions, using the Flemish pronunciation database Fonilex (Mertens, 2001). For the ABI group, interrater reliability equalled 79.90% (SD = 3.57) in a phoneme-to-phoneme comparison. For the CI and NH group, interrater reliability for consonant place of articulation was 82.90% and 81.14% respectively (for more information on data reliability assesment, see methods sections of Faes, 2017; Molemans, 2011; Schauwers, 2006; van den Berg, 2012; Van Severen, 2012).

Data analyses and statistical approach

The cumulative vocabulary was counted for each child in each group. That is, in the transcription of the first speech sample of a child, all distinct word types were tallied, constituting the vocabulary count at this point. Then, in the transcription of consecutive speech samples, the vocabulary size was increased each time a new distinct word type appeared in the transcription. For ABI1, the cumulative vocabulary size went up to 450 word types, for ABI2 it varied between 50 and 650 word types and for ABI3 up to 350 word types. In order to match the data, only CI and NH files with corresponding cumulative vocabulary counts were selected in the analyses.

For each word production, the place of articulation of both the target word and the child's own production (henceforth replica) was identified for singleton consonants in the target. Place of articulation was broadly classified in three categories: labial, coronal or dorsal. With respect to children's replicas, a fourth option 'omitted' was added if the child did not produce the target phoneme. For instance, for the target word /buk/ *boek* (Eng. book) with a replica /tu./ (with the dot representing an omitted phoneme) the places of articulation for the target /b/ and /k/ were determined (labial and dorsal) as well as the places of articulation for the child's production, i.e. the replica /t/ and /./ (coronal and omitted).

The four research questions were investigated in the following way:
(1) Occurrence of the different places of articulation in targets: how often are the three different places of articulation targeted by the children? What is the distribution in the target words?
(2) Occurrence of the different places of articulation in replicas: how often do children use the different places of articulation in their own productions - regardless their correctness?
(3) Accuracy of places of articulation: how accurately are the places of articulation produced by the children?
(4) Error analyses: if production of place of articulation incorrect, is it replaced or omitted? And, if it is replaced, by which other place of articulation?

For research questions (1), (2) and (4), multinomial logistic regression analysis was carried out in R using the multinom function from *nnet* package (Venables & Ripley, 2002). The fixed effects in each of these models were Hearing status (CI and NH) and the effect of cumulative vocabulary. Interactions between these effects were considered as well. For research question (3), a binomial generalized logistic regression was used (glm). The fixed effects were Hearing status (CI and NH), cumulative vocabulary, place of articulation in the target (PoA_Target) and the interaction between Hearing status and place of articulation in the target (PoA_Target). The intercept was set at a cumulative vocabulary size of 100 word tokens for all analyses. For sake of clarity, the log odds from the models were retransformed to probabilities in the figures.

Results

Frequency distribution in children's speech

In order to study the occurrence of the different places of articulation in children's productions, two analyses were carried out. A frequency distribution was drawn with respect to the three places of articulation in children's target words (labial, coronal, and dorsal) and a frequency distribution was drawn for the places of articulation in their own productions, i.e. replicas (labial, coronal, dorsal, and omitted). The results of these analyses can be found in Figures 1 and 2 respectively and Tables A1 and A2 in the Appendix.

In the target words of all children (ABI1, ABI2, CI and NH), except ABI3, the coronal place of articulation is the most likely, followed by the labial place of articulation and the dorsal one. For ABI3, however, the labial place of articulation occurs most frequently in the target, even though there is a decrease with increasing lexicon size. These patterns can be clearly observed in Figure 1, and the differences between the places of articulation for each (group of) child(ren) are significant, as shown in Table A1 in the Appendix. The comparison of each

ABI child to the children with CI and NH indicates that children with CI and children with NH show a smaller preference for one place of articulation, in contrast to ABI1 and ABI2 who have a stronger preference for the coronal place of articulation, and ABI3 labial place of articulation in their target words.

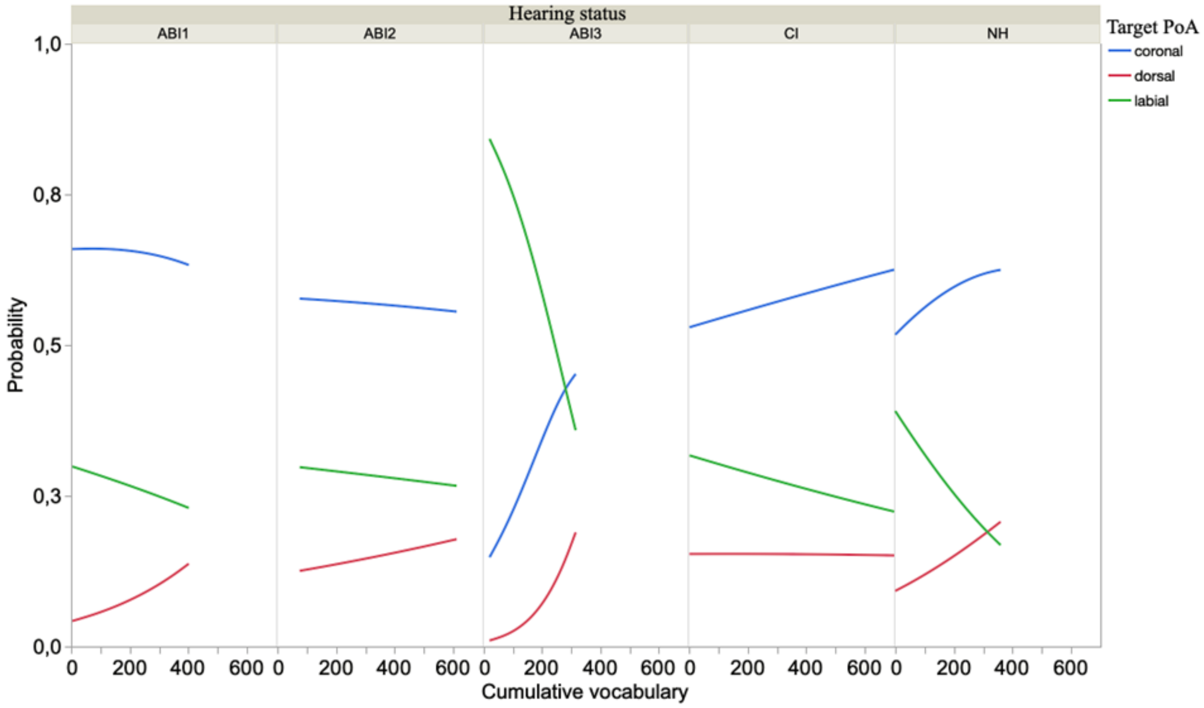

Figure 1: Frequency distribution in the targets - predicted probabilities

In children's own productions, there were four options in terms of place of articulation: labial, coronal, dorsal and omitted. In omission, no consonants were produced by the children, so the place of articulation could not be identified.

In all (groups of) children, the dorsal place of articulation is significantly less frequent than labial, coronal and omitted place of articulation (Table A2, Figure 2). For ABI1, ABI2 and the children with CI and NH, the coronal place of articulation is the most likely in children's own productions. The coronal place of articulation is significantly more frequent than labial and dorsal for ABI1 and ABI2. For children with CI and NH, these effects are significantly less pronounced, as can be seen in Figure 2 and the different main effects of Hearing status in Table A2 in the Appendix. When taking into account the omitted consonants as a place of articulation, ABI2 seems to follow the trend seen in children with CI and NH: coronal > labial > omitted > dorsal. The difference between the labial and omitted place of articulation is significant in ABI2, indicating that ABI2 was less likely to omit a consonant than to produce a labial consonant. This pattern is identical for the children with CI and NH, but it is significantly less pronounced (Table A2 in the Appendix). In contrast, ABI2 omitted consonants significantly more often than producing a labial consonant, whereas the opposite is true for children with CI and NH (Figure 2, Table A2).

As in the target, ABI3's most frequent place of articulation in the child's own productions is labial, which is significantly more frequent than the other places of articulation at a lexicon size of 100 word types (table A2). This effect decreases with increasing lexicon size.

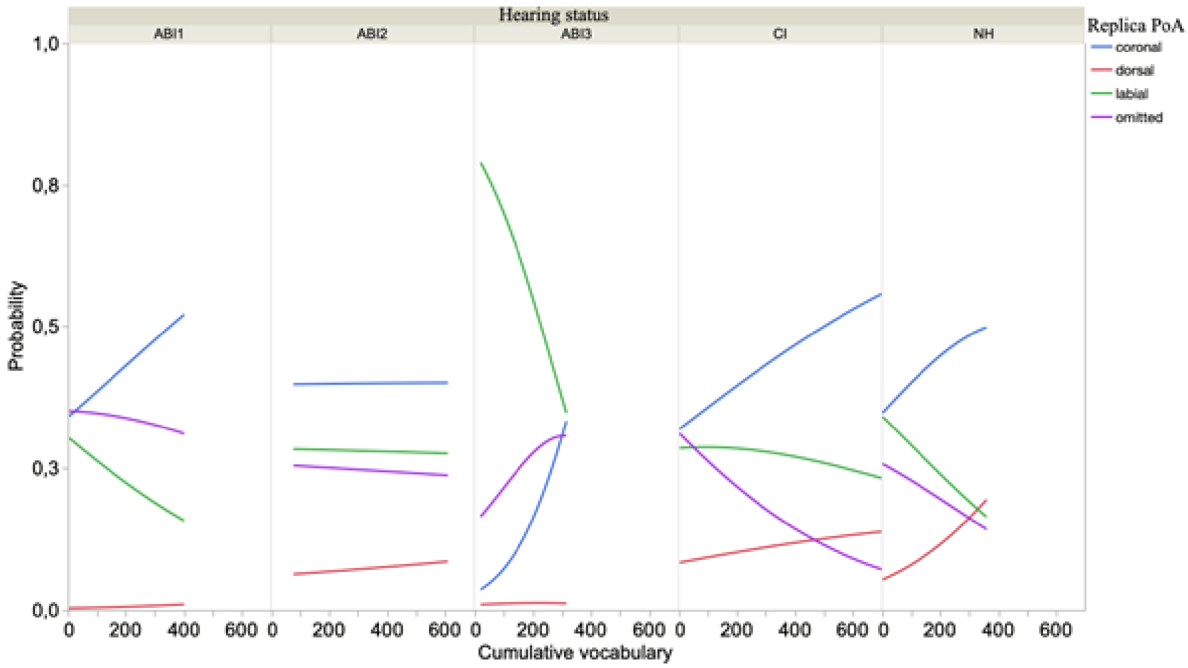

Figure 2: Frequency distribution in the replicas - predicted probabilities

Accuracy of place of articulation

The accuracy of the different places of articulation for each child with ABI and the control groups CI and NH are shown in Figure 3 and Table A3 in the Appendix. For all children with ABI, the labial place of articulation is produced significantly more accurately than the coronal and dorsal place of articulation, and the coronal place of articulation is produced significantly more accurately than the dorsal place of articulation. Overall, production accuracy increased significantly with increasing lexicon size, even though differences are represented in Figure 3 with respect to the different places of articulation. For each place of articulation, ABI2 is outperforming the other two ABI children and the difference becomes especially clear in the least accurately produced place of articulation, i.e., dorsal place of articulation. When comparing the children with ABI to one another in Figure 3, the difference in accuracy between the labial and coronal place of articulation is the least pronounced in ABI1 and the most pronounced in ABI3 (still, the differences remain significant for both children, see Table 2 in the Appendix). Yet, the difference between the labial and dorsal place of articulation as well as the coronal and dorsal place of articulation is the least outspoken in ABI2 (but still significant), whereas ABI1 and ABI3 show significant drops in accuracy rate for the dorsal place of articulation (Table A3 in the Appendix).

For children with CI and children with NH, the same trend is visible: the labial place of articulation is significantly more accurately produced than the coronal place of articulation, which is, in turn, significantly more accurately produced than the dorsal place of articulation. However, as can be derived from the interaction effects in Table A3 in the Appendix (PoA_Target x Hearing status) and as illustrated in Figure 3, the differences are significantly smaller in these children with CI and NH.

When comparing the children with ABI to the children with CI and NH, ABI children's production is significantly less accurate for all places of articulation. The difference with the children with CI and NH is smallest for the labial place of articulation, and most outspoken for the dorsal place of articulation. In this respect, ABI2 is most similar to CI and NH when compared to the other two ABI children.

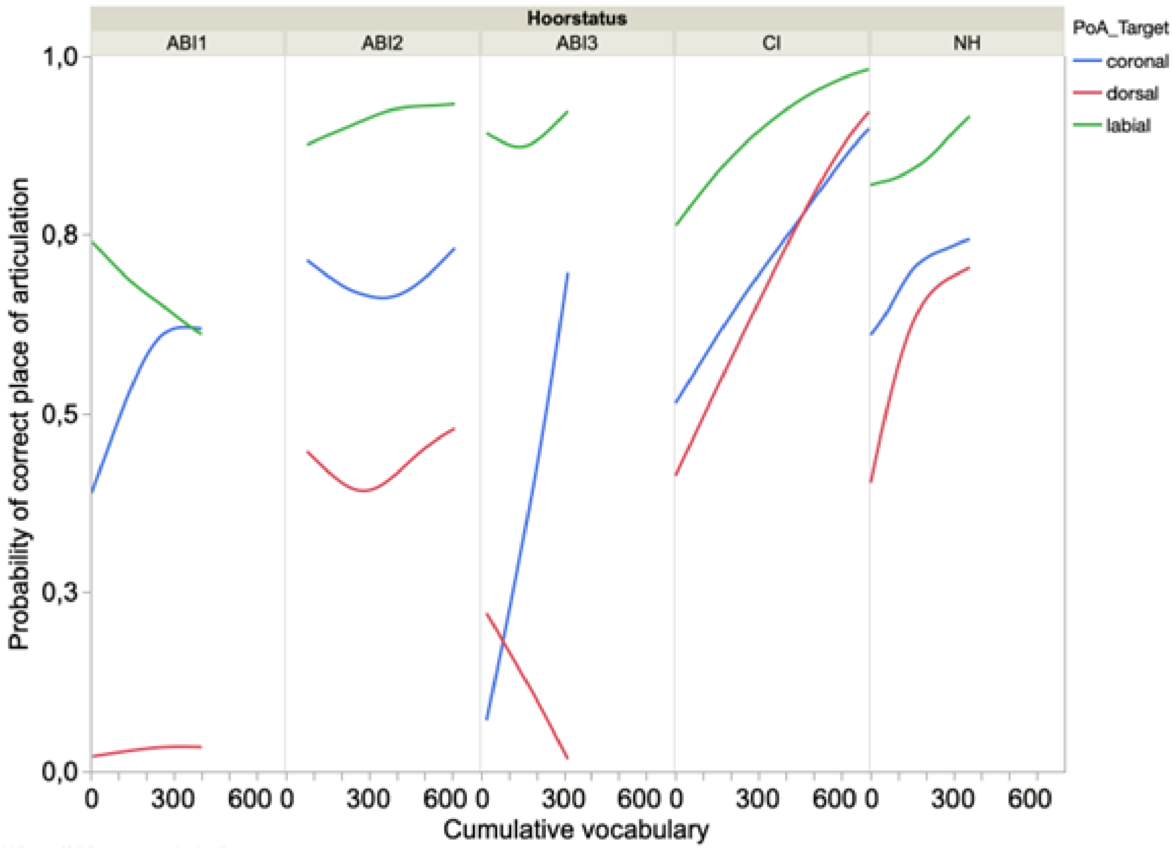

Figure 3: Probability of accurate production of place of articulation – observed values

Error analyses

Figure 4 represents the predicted error patterns for each ABI child and the control groups (CI and NH). For each target place of articulation produced incorrectly, the predicted development of erroneous place of articulation is displayed. The statistical analyses can be found in tables A4 – A6 in the Appendix. Overall, incorrect production of a place of articulation mostly involved omission of the consonant without replacing it by another place of articulation. This can be clearly seen in Figure 4 and is confirmed in the statistical analyses in Tables A4 - A6 in the Appendix.

For all ABI children as well as the children with CI and NH, an incorrectly produced labial consonant is more likely to be omitted than to be replaced by a coronal or a dorsal consonant (all significant, except for the coronal - omitted comparison in ABI1, Table A4 in the Appendix). ABI1 shows a somewhat different pattern in that coronal consonants appear more frequently to replace incorrect labials than they are omitted, even to a significantly greater extent than children with CI and children with NH.

Dorsal consonants appear very infrequently instead of labial ones in the error analyses. This difference is significant for all children (Table A4 in the Appendix), but the effect is significantly less pronounced in children with CI and children with NH (Table A4 in the Appendix) as compared to the children with ABI.

When comparing the ABI children to one another, Figure 4 indicates that ABI3 omitted the most frequently when labial place of articulation was produced incorrectly. ABI2, instead, seems to approach the trend in children with CI and NH the most. For instance, for the coronal - dorsal comparison in ABI2, there was no significant difference between ABI2 and the children with CI and NH (Table A4 in the Appendix).

When coronal place of articulation was not produced correctly, the consonant was significantly more often omitted than it was replaced by a labial or dorsal consonant (Table A5). Overall, the trend is highly similar in all children with ABI and children with CI and children with NH. However, statistical analyses showed that the effect is significantly less pronounced in children with CI and children with NH as compared to ABI1, ABI2 and ABI3 (please see Table A5 in the Appendix for the details).

When the consonant was replaced, it was significantly more often replaced by a labial consonant than by a dorsal one in ABI1, ABI2 and ABI3 (Table A5 in the Appendix). For ABI1, the effect is more pronounced than in children with CI (on the edge of significance, $p = 0.0487$) and children with NH (significant). For ABI2 and ABI3, the effect is more pronounced than in children with CI (significant), but less pronounced than in children with NH (only significant for ABI3). These differences can probably be explained by the higher omission rates in the children with ABI.

If a dorsal consonant was produced incorrectly in terms of place of articulation, it is significantly more likely that the consonant was omitted than it was replaced by a labial or a coronal consonant (Table A6 in the Appendix) in all children with ABI, CI and NH. Nevertheless, the effect is significantly less pronounced in children with CI and NH. To conclude, if the consonant was replaced, it was significantly more often replaced by a coronal consonant than a labial consonant for ABI1, ABI2 and the children with CI and NH. ABI3 showed a somewhat different pattern, in the sense that it was more likely that this child used a labial consonant than a coronal one in the very first word productions. Nevertheless, with increasing vocabulary size, this effect is reversed into the same trend as that was seen in all other children. At 100 word tokens, this is already significant (Table A6).

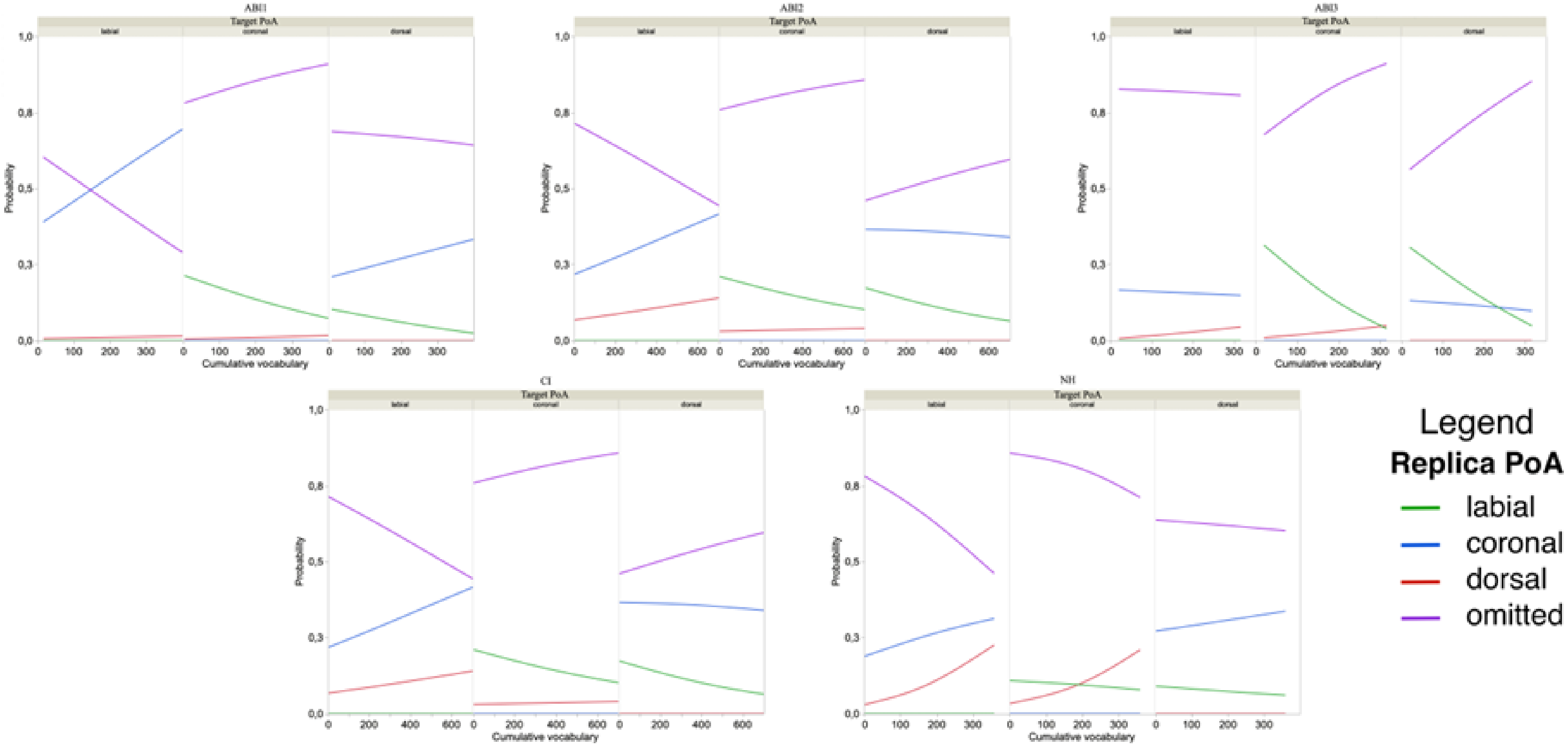

Figure 4: Predicted probability of the error patterns for all groups of children

Discussion

In this study, the production of place of articulation in spontaneous speech in three children with ABI were examined in comparison to two different control groups, i.e. children with CI and children with NH. This study used three general categories defining place of articulation: labial, coronal and dorsal. The place of articulation was identified for consonants in both the target word and the child's own production. Overall, the coronal place of articulation was the most frequently used in all children's (ABI, CI and NH) own productions as well as in the target words, except for ABI3, who showed a preference for labials (RQ1, RQ2). However, in terms of accuracy (RQ3), the labial place of articulation was more accurately produced than the coronal place of articulation by all children, and the dorsal place of articulation had a very low accuracy. In the error analyses (RQ4), it was shown that all places of articulation were most frequently omitted when they were produced incorrectly. If not omitted, the coronal place of articulation appeared as erroneous place of articulation.

Frequency of place of articulation in target and replica (RQ1 + RQ2)

With respect to children's target words and their own productions (replica), the results indicate that coronals were most frequent in all children, except for ABI3, who used more labials. The rank order between the three places of articulation was identical for ABI1, ABI2, children with CI and NH, i.e. coronals were more frequent than labials and dorsals. However, the differences are significantly smaller in children with CI and NH children in both targets and replicas. In other words, dorsals and labials appear more frequently in children with CI and children with NH than in ABI1 and ABI2. When comparing them to one another, ABI2 is approaching the probability levels of CI and NH more than ABI1.

These results complement the results of e.g. Beers (1995) for NH children, as well as Dillon, Cleary, et al. (2004); Dillon, Pisoni, et al. (2004) and Moreno-Torres and Moruno-Lopez (2014) for the CI – NH comparison: they found that coronals were more accurately produced than labials and dorsals in a non-word repetition task. In the present study, coronals were not produced more *accurately*, but more *frequently* and this was also clear for the children with CI and NH. This contrasts with the findings of Warner-Czyz and Davis (2008) who found that children with CI used more labials and children with NH used an equal proportion of labials and coronals.

The frequent occurrence of the coronal place of articulation in children's speech is not so surprising. In adult spoken Dutch, these sounds appear the most frequently as well (Luyckx et al., 2007). Thus, children hear more examples of coronal sounds, which could help with the acquisition. In addition, the labial and coronal place of articulation are generally acquired by children with NH before dorsal place of articulation (e.g. Beers, 1995). This high rate of coronal place of articulation fits also in the theory of Cummings et al. (2020). They stated, in line with the literature, that coronal place of articulation is the most frequent in languages, and that labial and dorsal place of articulation appear only with maturation and language exposure. In that sense, they suggested that children with phonological disorder, who are assumed to have less fine-grained phonological representations, are in an earlier stage of the developmental process, and have greater preference for coronals. In a similar vein, the preference for coronals and the smaller number of dorsals and labials in ABI children seems to suggest that they are in an earlier stage of speech development similar to children with phonological disorder in Cummings et al. (2020). ABI children have had less language exposure than the control groups. In addition, the speech signal provided by their implant is poor (Wong et al., 2019), so it is very likely that their phonological representations are less fine-grained as well. That would explain their delayed development.

Accuracy and error patterns (RQ3 + RQ4)

The coronal place of articulation appeared most frequently in children's spontaneous speech productions as well as their target words. Surprisingly, it was not the most accurately produced place of articulation. Instead, the labial place of articulation was significantly more often produced correctly than the coronal and dorsal place of articulation in all children. The effect is bigger in ABI children. When comparing the children with ABI to one another, the effect is the most pronounced in ABI1 and ABI3. ABI2 is approaching the levels of children with CI and NH to a greater extent, even though the difference is still significant. ABI1, on the other hand, showed the lowest accuracy rates overall, when taking all places of articulation into account. These findings, i.e. higher accuracy rates for labial consonants, are in line with those of Warner-Czyz and Davis (2008) with respect to children with CI as compared to children with NH: also in their study, labial consonants were produced more correctly by both groups of children as compared to other places of articulation.

This high likelihood of accurate labial production is inconsistent with Cummings et al. (2020). There are different ways to explain the high accuracy of labial sounds. In the first instance it is clear that labials are visually more salient than coronals and dorsals. As a result, it is likely that children learn to produce labials correctly more easily. As the effect is the most prominent in children with ABI, their exposure to sign language might be a contributing factor. Children with ABI are not only raised in spoken Dutch but receive a great amount of sign language input in order to communicate before and after implantation. Therefore, they have greater attention for cues this may result in more correct labials. This is supported by the fact that the effect is most prominent in ABI1 and ABI3, the two children with ABI most exposed to sign language. These children produce labials quite accurately, but have very low accuracy for the other two places of articulation, with a particularly low accuracy in dorsals.

Besides the factors mentioned above, it is possible that the inaccuracies in the production of labials and dorsals in children with ABI may have to be accounted for by a more limited set of word templates than children with CI and NH because of the later onset of hearing and the degraded speech signal. Vihman and Croft (2007) proposed a radical template phonology, in which they assume that children have so-called word templates, which are based on their own productions in the babbling period (vocal motor schemes) and the input they receive. In speech production, children adapt their word production to the word templates they have acquired. For instance, if a Dutch-speaking child has a word template /pV/, the child would produce /pu/ for /blum/ *bloem* (Eng. *flower*) and /pe/ for /spel/ *speel* (Eng. *to play*) and /ber/ *beer* (Eng. *teddy bear*) in order to produce the word in accordance to the acquired word template (Faes & Gillis, In press). This may well have an impact on the accuracy of place of articulation. Since ABI children have delayed and degraded auditory input as well as a less extensive babbling phase, it is likely that they have a smaller number of word templates. As a result, matching word productions to the few templates available, automatically increases the likelihood of inaccuracies in the production of consonants in general, as compared to children with CI and children with NH. With respect to children with ABI, the nature of their word templates remains an open question. Is it especially with labial consonants, given their high accuracy rate, or rather coronal consonants, given their frequency in target and replica (own production). In fact, the results of RQ1 and RQ2 and the results of RQ3 are somewhat contradictory. Yet, it is unclear how these differences are best explained, or which factors contribute to these effects. For instance, if it is sign language exposure, we would expect that labials appear more frequently in replicas. If it is a less developed phonology (in line with Cummings et al. (2020)), resulting in more use of the coronal place of articulation, coronal place of articulation would be expected to be pronounced the most accurately as well. It is open for future research to further disentangle these possibilities.

It should be pointed out that more accurate production of the labial place of articulation in all children was not reflected in the error patterns. Incorrectly produced consonants were most likely to be omitted by the ABI children. Although this effect was also noticeable in the control groups, it was significantly less outspoken. In other words, children with ABI and - to a lesser extent also - children with CI and NH, rather omit the consonant if they could not produce place of articulation correctly instead of producing it erroneously. This effect was also found in Warner-Czyz and Davis (2008) with respect to children with CI as compared to NH peers. In their study, children with CI omitted consonants with all places of articulation, whereas children with NH omitted especially labial and dorsal consonants, but no coronals – these were replaced. In other words, the CI group avoided complex phonology for a longer period than children with NH did. A similar finding was found for morphology: Szagun (2002) reported that CI children rather omit for instance articles and noun plurals instead of producing these morphological elements incorrectly. Children with NH, however, use nouns plurals and articles, but often incorrectly. Children with CI thus avoid using complex morphology initially, but they improve and catch up with children with NH with increasing hearing experience (Faes et al., 2015; Hammer, 2010). A similar trend seems to appear with the phonological development for especially children with ABI. They show an avoidance of complex phonology, mainly with respect to dorsal place of articulation, but also for labial and coronal place of articulation. So they rather omit a consonant than producing it incorrectly in terms of place of articulation. In this respect, it seems that children with ABI are avoiding complex phonology for an even longer time than children with CI (as compared to their NH peers in Warner-Czyz and Davis (2008)).

Individual variation

The children with ABI showed considerable individual variation, especially ABI3 showed a number of different patterns, while ABI1 and ABI2 were more similar. For instance, ABI3 used more labials than other places of articulation in both the target words as the replicas and that labials appear initially more often to replace erroneous dorsals. One of the factors that can contribute to this different pattern in ABI is probably to be found in the child's etiology. In contrast to ABI1 and ABI2, ABI3 wears both a CI and an ABI. In addition, ABI3 had different inner ear pathology leading to ABI implantation as compared to ABI1 and ABI2, which also resulted in later ABI implantation by the age of four after an unsuccessful CI period. CI implantation was no option for ABI1 and ABI2, so they received their ABI as early as their second birthday. It might be the case that these differences have led to another trend in ABI3's phonological development of place of articulation. In addition, the child received the ABI implant two years later than the other two children with ABI as the CI seemed not to have the desired effect, so the child and family relied on sign language much longer and more extensively. This might have caused the child's sensitivity for visual cues in the oral speech signal, leading to a general preference for the most salient place of articulation, viz. labial.

The differences with children with CI and children with NH remained obvious and significant even with increasing vocabulary size. Regarding the children with ABI, ABI2 was approaching the children with CI and the children with NH the most, even though these differences were also mostly significant. This is entirely in line with other research on the same children with ABI, CI and NH, in which ABI2 was also approaching the control groups with respect to for instance intraword variability (Faes & Gillis, In press), speech intelligibly (Faes, De Maeyer, et al., 2022), and phonemic accuracy (Faes & Gillis, 2021b). Yet, as stated in these studies, it is still unclear which factors are contributing to the better performance of ABI2 as compared to ABI1 overall. In the literature, factors such as hearing experience, age at implantation, absence of additional disabilities and lower hearing thresholds after implantation have been identified to explain individual differences between children with ABI. However, all these factors are identical in ABI1 and ABI2: they were both implanted by their second birthday and thus have a similar amount of hearing experience, none of them have additional disabilities and their hearing thresholds are also quite similar after implantation. So, further research on factors contributing to successful ABI use is desireable. This would be extremely useful in speech and language therapy applications for children with ABI (Hammes Ganguly et al., 2019).

Although place of articulation production of ABI2 is similar the children with CI and NH and shows similar trends, some caution should be taken with these results. In this study, lexical age has been used as a comparative measure between children with ABI and the controls. Although this seems a highly reasonable approach (viz., the close relationship between lexical and phonological development), this measure is not ideal either. The matching on lexicon size might have been the most optimistic measure, because when considering the hearing ages or chronological ages of the children, the differences with between children with ABI and children with NH and CI would increase even more. For instance, the children with NH in this study were not older than two years of age and were matched with children with ABI between three and six with similar lexicon sizes, which is considerably older in terms of chronological age. It seems very unlikely that a three-to-six-year-old child with NH performs in a similar vein as the current results for children with ABI. The same holds for children with CI: they were somewhat older in terms of chronological age as compared to the children with NH to reach the same lexicon sizes, but they were still younger than children with ABI at that point. In addition, they have had less hearing experience as well (fewer length of device use) (Faes & Gillis, 2019b). So, even though ABI2 seem to approach the trends visible the children with CI and the children with NH, there is still an enormous difference with respect to the children's chronological and hearing age. For ABI1 and ABI3, these effects are even bigger.

Conclusion

This study has shown that most children, except one child with ABI, used the coronal place of articulation the most frequently. This child with ABI most frequently used labials. However, all children produced labial place of articulation more accurately than the coronal place of articulation. Thus there was a difference between frequency and accuracy. Overall, the children with ABI performed the worst in terms of accuracy rates. It can be concluded that even though the children with ABI clearly benefit from their implant to develop spontaneous speech. However, there is still a long way to go for these children: they lag considerably behind their peers with CI and NH in speech production and speech production accuracy. Given these poor accuracy rates, it is reasonable that these children are lowly intelligible as well, as these aspects are closely related to one another (see e.g. Ingram, 2002). Therefore, it seems highly recommended for children with ABI and their environment to not only rely on oral communication. A valid option is for instance sign language use to guarantee efficient communication in this population, but choices need to be made according to the individual child's needs.

In-depth research disentangling the contributing factors for successful ABI use is desireable, both on a linguistic level to guide speech and language therapy (Hammes Ganguly et al., 2019) as on a medical level – for instance the precise placement and understanding of the possible tonotopic organization of the cochlear nucleus of the brainstem

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Appendix

Table A1: Statistical analyses for target place of articulation: likelihood of labial place of articulation (vs. coronal, vs. dorsal) and coronal place of articulation (vs. dorsal)

	ABI1			**ABI2**			**ABI2**		
Labial vs. Coronal	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*
Intercept	0.85	0.06	<0.0001	0.42	0.01	<0.0001	-0.05	0.01	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.1130	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001
Hearing status CI	-0.43	0.07	<0.0001	0.04	0.01	0.0103	0.47	0.02	<0.0001
Hearing status NH	-0.29	0.06	<0.0001	0.14	0.01	<0.0001	0.62	0.02	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001	<0.01	<0.01	0.4928
Labial vs. Dorsal									
Intercept	-1.61	0.13	<0.0001	-0.46	0.01	<0.0001	-1.29	0.03	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001
Hearing status CI	0.82	0.13	<0.0001	-0.13	0.02	<0.0001	0.48	0.04	<0.0001
Hearing status NH	0.62	0.13	<0.0001	-0.33	0.02	<0.0001	0.30	0.04	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.1344	<0.01	<0.01	<0.0001	<0.01	<0.01	0.4592
Coronal vs. Dorsal									
Intercept	-2.46	0.12	<0.0001	-1.07	0.01	<0.0001	-1.24	0.03	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.0001	<-0.01	<0.01	<0.0001
Hearing status CI	1.25	0.12	<0.0001	-0.17	0.02	<0.0001	<0.01	0.04	0.8700
Hearing status NH	0.91	0.12	<0.0001	-0.48	0.02	<0.0001	-0.31	0.04	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	<0.0001	<-0.01	<0.01	<0.0001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0107	<0.01	<0.01	<0.0001	<0.01	<0.01	0.7172

Cumulative vocabulary is centered at 100 word tokens

Table A2: Statistical analyses for replica place of articulation: likelihood of labial place of articulation (vs. coronal, vs. dorsal, vs. omitted), coronal place of articulation (vs. dorsal, vs. omitted) and dorsal place of articulation (vs. omitted)

	ABI1			**ABI2**			**ABI2**		
Labial vs. Coronal	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*
Intercept	0.38	0.07	<0.0001	0.18	0.01	<0.001	-0.47	0.02	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	-0.34	0.07	<0.0001	-0.11	<0.01	<0.001	0.51	0.03	<0.0001
Hearing status NH	-0.06	0.07	0.4334	0.14	<0.01	<0.001	0.80	0.02	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0380	<0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.4048	<0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Labial vs. Dorsal									
Intercept	-4.07	0.01	<0.0001	-1.02	0.02	<0.001	-1.68	0.05	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	2.75	0.02	<0.0001	-0.30	0.03	<0.001	0.35	0.06	<0.0001
Hearing status NH	2.78	0.02	<0.0001	-0.26	0.02	<0.001	0.39	0.05	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0008	<-0.01	<0.01	0.0709	<-0.01	<0.01	0.0458
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.1386	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Coronal vs. Dorsal									
Intercept	-4.45	0.01	<0.0001	-1.21	0.02	<0.001	-1.21	0.06	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.0291	<0.01	<0.01	<0.001	<-0.01	<0.01	0.0049
Hearing status CI	3.09	0.02	<0.0001	-0.19	0.02	<0.001	-0.16	0.06	0.0073
Hearing status NH	2.84	0.02	<0.0001	-0.40	0.02	<0.001	-0.41	0.06	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0155	<-0.01	<0.01	<0.001	<0.01	<0.01	0.0146
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.2747	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Labial vs. Omitted									
Intercept	0.28	0.07	<0.0001	-0.15	0.01	<0.001	-0.41	0.01	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.0004	<-0.01	<0.01	0.0016	<0.01	<0.01	<0.0001
Hearing status CI	-0.52	0.08	<0.0001	-0.09	0.02	<0.001	0.19	0.02	<0.0001
Hearing status NH	-0.52	0.07	<0.0001	-0.10	0.01	<0.001	0.17	0.02	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	<0.0001	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0172	<0.01	<0.01	<0.001	<-0.01	<0.01	0.0005
Coronal vs. Omitted									
Intercept -0.10	0.07	0.1134	-0.33	0.01	<0.001	0.07	0.02	0.0056	
cumulative vocabulary	<-0.01	<0.01	<0.0001	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Hearing status CI	-0.19	0.07	0.0065	0.02	0.02	0.1392	-0.32	0.03	<0.0001
Hearing status NH	-0.46	0.07	<0.0001	-0.23	0.01	<0.001	-0.63	0.03	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0001	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0002	<-0.01	<0.01	<0.001	<0.01	<0.01	0.1458
Dorsal vs. Omitted									
Intercept	4.34	0.04	<0.0001	0.88	0.02	<0.001	1.27	0.05	<0.0001
Cumulative vocabulary	<-0.01	<0.01	0.0001	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Hearing status CI	-3.28	0.05	<0.0001	0.21	0.03	<0.001	-0.16	0.06	0.0055
Hearing status NH	-3.30	0.04	<0.0001	0.17	0.02	<0.001	-0.23	0.06	<0.0001
Cumulative vocabulary * Hearing status CI	<0.01	<0.01	0.4697	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0088	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001

Cumulative vocabulary is centered at 100 word tokens

Table A3: Statistical analyses of production accuracy

	ABI1			ABI2			ABI2		
Labial vs. Coronal, Labial vs. Dorsal	*Estimate*	*std. Error*	*p*	*Estimate*	*std. Error*	*p*	*Estimate*	*std. Error*	*p*
Intercept (labial)	0.22	0.06	<0.0001	1.76	0.05	<0.001	1.73	0.06	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	1.32	0.07	<0.0001	-0.15	0.05	0.0045	-0.23	0.06	0.0003
Hearing status NH	1.34	0.07	<0.0001	-0.20	0.05	0.0001	-0.17	0.06	0.0072
PoA_Target coronal	-0.28	0.07	<0.0001	-1.66	0.05	<0.001	-2.12	0.08	<0.0001
PoA_Target dorsal	-4.14	0.27	<0.0001	-2.81	0.06	<0.001	-5.20	0.22	<0.0001
PoA_Target coronal * Hearing status CI	-0.95	0.08	<0.0001	0.37	0.06	<0.001	0.93	0.08	<0.0001
PoA_Target dorsal * Hearing status CI	2.63	0.27	<0.0001	1.37	0.07	<0.001	3.67	0.23	<0.0001
PoA_Target coronal * Hearing status NH	-0.63	0.08	<0.0001	0.74	0.05	<0.001	1.20	0.08	<0.0001
PoA_Target dorsal * Hearing status NH	2.82	0.27	<0.0001	1.49	0.07	<0.001	3.85	0.22	<0.0001
Coronal vs. Dorsal									
Intercept (coronal)	-0.06	0.04	<0.0001	0.11	0.02	<0.001	-0.39	0.05	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	0.36	0.04	<0.0001	0.22	0.02	<0.001	0.70	0.05	<0.0001
Hearing status NH	0.71	0.04	<0.0001	0.56	0.02	<0.001	1.04	0.05	<0.0001
PoA_Target dorsal	-3.86	0.27	<0.0001	-1.13	0.04	<0.001	-3.08	0.22	<0.0001
PoA_Target dorsal * Hearing status CI	3.58	0.27	<0.0001	1.00	0.05	<0.001	2.74	0.22	<0.0001
PoA_Target dorsal * Hearing status NH	3.45	0.27	<0.0001	0.73	0.05	<0.001	2.65	0.22	<0.0001

Cumulative vocabulary is centered at 100 word tokens

Table A4: Error patterns when labial place of articulation was produced incorrectly

	ABI1			**ABI2**			**ABI2**		
Coronal vs. Dorsal	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*
Intercept	-13.23	0.5	<0.0001	-1.05	0.12	<0.001	-1.02	0.16	<0.0001
Cumulative vocabulary	0.03	<0.01	<0.0001	<0.01	<0.01	0.0780	<-0.01	<0.01	0.9624
Hearing status CI	11.80	0.10	<0.0001	-0.18	0.15	0.2149	-0.45	0.19	0.0161
Hearing status NH	11.97	0.08	<0.0001	-0.21	0.14	0.1232	-0.24	0.17	0.1604
Cumulative vocabulary * Hearing status CI	-0.03	<0.01	<0.0001	<-0.01	<0.01	0.7562	<0.01	<0.01	0.0265
Cumulative vocabulary * Hearing status NH	-0.03	<0.01	<0.0001	<0.01	<0.01	0.1532	<0.01	<0.01	0.2927
Coronal vs. Omitted									
Intercept	0.17	0.20	0.4058	0.80	0.06	<0.001	1.18	0.07	<0.0001
Cumulative vocabulary	<-0.01	<0.01	<0.0001	<-0.01	<0.01	<0.001	<-0.01	<0.01	<0.0001
Hearing status CI	0.94	0.21	<0.0001	0.25	0.08	0.0011	-0.08	0.09	0.3379
Hearing status NH	1.00	0.21	<0.0001	0.37	0.07	<0.001	-0.02	0.08	0.8425
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.6499	<-0.01	<0.01	0.0589	<0.01	<0.01	0.1027
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.1285	<-0.01	<0.01	<0.001	<-0.01	<0.01	0.2659
Omitted vs. Dorsal									
Intercept	-13.40	0.05	<0.0001	-1.85	0.11	<0.001	-2.21	0.14	<0.0001
Cumulative vocabulary	0.04	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	10.86	0.09	<0.0001	-0.43	0.14	0.0020	-0.37	0.17	0.0333
Hearing status NH	10.97	0.07	<0.0001	-0.58	0.13	<0.001	-0.22	0.15	0.1515
Cumulative vocabulary * Hearing status CI	-0.03	<0.01	<0.0001	<0.01	<0.01	0.4194	<0.01	<0.01	0.1251
Cumulative vocabulary * Hearing status NH	-0.03	<0.01	<0.0001	<0.01	<0.01	<0.001	<0.01	<0.01	0.0938

Cumulative vocabulary is centered at 100 word tokens

Table A5: Error patterns when coronal place of articulation was produced incorrectly

	ABI1			**ABI2**			**ABI2**		
Labial vs. Dorsal	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*
Intercept	-2.64	0.46	<0.0001	-0.61	0.05	<0.001	-1.15	0.11	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.2853	<0.01	<0.01	<0.001	<0.01	<0.01	<0.0001
Hearing status CI	0.93	0.47	0.0487	-1.21	0.08	<0.001	-0.52	0.13	<0.0001
Hearing status NH	2.10	0.46	<0.0001	0.06	0.06	0.3234	0.61	0.12	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.3644	<0.01	<0.01	0.0980	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.1415	<0.01	<0.01	<0.001	<0.01	<0.01	0.0394
Labial vs. Omitted									
Intercept	1.57	0.13	<0.0001	1.41	0.03	<0.001	1.24	0.04	<0.0001
Cumulative vocabulary	<0.01	<0.01	<0.0001	<0.01	<0.01	0.0583	<0.01	<0.01	0.0006
Hearing status CI	-0.21	0.14	0.1261	-0.06	0.04	0.1404	0.17	0.05	0.0004
Hearing status NH	0.53	0.13	<0.0001	0.69	0.04	<0.001	0.86	0.05	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0320	<0.01	<0.01	<0.001	<-0.01	<0.01	0.0031
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0017	<0.01	<0.01	0.6448	<-0.01	<0.01	0.0180
Omitted vs. Dorsal									
Intercept	-4.21	0.45	<0.0001	-2.02	0.04	<0.001	-2.39	0.11	<0.0001
Cumulative vocabulary	<-0.01	<0.01	0.8636	<0.01	<0.01	<0.001	<0.01	<0.01	0.0011
Hearing status CI	1.13	0.46	0.0132	-1.15	0.07	<0.001	-0.69	0.12	<0.0001
Hearing status NH	1.56	0.45	0.0005	-1.63	0.05	<0.001	-2.25	0.11	0.0266
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.8105	<-0.01	<0.01	0.0116	<-0.01	<0.01	0.0008
Cumulative vocabulary * Hearing status NH	<0.01	<0.01	0.0085	<0.01	<0.01	<0.001	<0.01	<0.01	0.0003

Cumulative vocabulary is centered at 100 word tokens

Table A6: Error patterns when dorsal place of articulation was produced incorrectly

	ABI1			**ABI2**			**ABI2**		
Labial vs. Coronal	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*	*coeff*	*stdv*	*p*
Intercept	-2.64	0.46	<0.0001	-0.61	0.05	<0.001	-1.15	0.11	<0.0001
Intercept	0.89	0.40	0.0269	1.18	0.04	<0.001	0.49	0.08	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.0035	<0.01	<0.01	0.5475	<0.01	<0.01	0.0108
Hearing status CI	-0.06	0.41	0.8918	-0.32	0.06	<0.001	0.27	0.10	0.0003
Hearing status NH	0.42	0.41	0.3014	0.12	0.06	0.0482	0.83	0.10	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0417	<0.01	<0.01	0.0070	<-0.01	<0.01	0.1793
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0134	<0.01	<0.01	0.5067	<-0.01	<0.01	0.5245
Labial vs. Omitted									
Intercept	1.97	0.36	<0.0001	2.02	0.04	<0.001	0.77	0.08	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.0188	<0.01	<0.01	0.2564	<0.01	<0.01	<0.0001
Hearing status CI	-0.72	0.37	0.0516	-0.83	0.06	<0.001	0.51	0.10	<0.0001
Hearing status NH	0.05	0.37	0.8866	<0.01	0.06	0.9444	1.26	0.10	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.0607	<0.01	<0.01	0.020	<-0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.1176	<0.01	<0.01	0.0868	<-0.01	<0.01	0.0002
Omitted vs. Coronal									
Intercept	-1.08	0.24	<0.0001	-0.84	0.05	<0.001	-0.29	0.08	<0.0001
Cumulative vocabulary	<0.01	<0.01	0.1563	<-0.01	<0.01	0.4630	<-0.01	<0.01	<0.0001
Hearing status CI	0.67	0.25	0.0076	0.51	0.06	<0.001	-0.14	0.09	0.1389
Hearing status NH	0.37	0.25	0.1346	0.12	0.06	0.0421	-0.43	0.09	<0.0001
Cumulative vocabulary * Hearing status CI	<-0.01	<0.01	0.5963	<-0.01	<0.01	0.6982	<0.01	<0.01	<0.0001
Cumulative vocabulary * Hearing status NH	<-0.01	<0.01	0.0505	<-0.01	<0.01	0.0991	<0.01	<0.01	<0.0001

Cumulative vocabulary is centered at 100 word tokens