Consonant cluster production in children with cochlear implants : a comparison with normally hearing peers

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In early word productions, the same types of errors are manifest in children with cochlear implants (CI) as in their normally hearing (NH) peers with respect to consonant clusters. However, the incidence of those types and their longitudinal development has not been examined nor quantified in the literature thus far. Furthermore, studies on the spontaneous speech of Dutch-speaking children with CI are missing. Here we compare children with CI and NH children with respect to their use of word-initial two-consonant clusters and the frequency of each type of error. The spontaneous speech of 9 Dutch-speaking children with CI and an age-matched cohort of NH children was analysed from word-onset up to age seven. Results showed that accuracy and frequency of consonant clusters increases with age and that the age at implant activation is crucial in children with CI. Cross-sectional comparisons showed that some aspects of consonant cluster production in children with CI lag behind that of their NH peers, but that children with CI catch up by age five.

Introduction

For a couple of decades now, cochlear implantation has offered access to spoken language for congenitally deaf children. Even though the signal provided by a cochlear implant (henceforth: CI) is still degraded compared to the signal in normal hearing (Drennan & Rubinstein, 2008), a CI enables children with severe-to-profound hearing impairment to perceive speech after a period of auditory deprivation. After cochlear implantation children's speech perception has been shown to improve (Liu, Liu, Kirk, Zhang, Ge, Zheng, Liu, & Ni, 2015; Tyler, Fryauf-Bertschy, Kelsay, Gantz, Woodworth, & Parkinson, 1997). As a result of (improved) speech perception, cochlear implantation is also beneficial for speech production. For instance children with CI produce the same segments as children with normal hearing (NH) (Blamey, Barry, Bow, Sarant, Paatsch, & Wales, 2001; Chin,

2002; Serry & Blamey, 1999; Spencer & Guo, 2013). In addition, their articulation of vowels and singleton consonants improves after implantation (Blamey et al., 2001), although the fine phonetic details of their production remains deviant even after several years of device use (Verhoeven, Hide, De Maeyer, Gillis, & Gillis, 2016). In contrast with singleton consonants, the production of consonant clusters in children with CI has hardly been studied.

The present paper traces in detail the development of word-initial two consonant (CC) clusters longitudinally in the spontaneous speech of congenitally deaf Dutch-speaking children with CI, from their first appearance up to age seven. Several aspects of the development of CC clusters are quantified: their overall accuracy, the types of errors, and the precise development of cluster reduction (for a definition, see further). Our aims are twofold. The first aim is to trace the production of consonant clusters longitudinally in children with CI. Production is related to the children's chronological age and their age at implant activation. The second aim is to statistically compare the development of consonant clusters to that of NH peers between ages two and seven.

Word-initial consonant cluster production in NH children

In English-speaking NH children, word-initial (WI) consonant clusters emerge approximately around age 2;0 (McLeod, van Doorn, & Reed, 2001b). Initially, these productions are inaccurate, but they gradually become more accurate with age (Phoon, Maclagan, & Adbdullah, 2015). On the road to complete accuracy, three types of errors in the production of WI consonant clusters with two consonants (CC) are well attested across languages (e.g. Dutch: Fikkert, 1994; English: Greenlee, 1974; McLeod, van Doorn, & Reed, 2001a; McLeod et al., 2001b): (1) both consonants are deleted (complete deletion), (2) only one consonant is produced (cluster reduction), and (3) both consonants are produced, but one or both are produced inaccurately (cluster simplification). These three phenomena typically co-occur before fully accurate production (Chin, 2007; Fikkert, 1994; Jongstra, 2003; McLeod & Hewitt, 2008; McLeod et al., 2001a). In what follows, the different types of errors in NH children's speech are discussed.

Cluster deletion

Complete deletion of a CC cluster entails the deletion of both target consonants, i.e. the adult equivalent of the child's rendition, e.g. /blu/ (blue) produced as /u/. In the literature, complete deletion of WI consonant clusters is characterised as a rare phenomenon. For instance, in picture naming tasks involving English-speaking children (Chin & Dinnsen, 1992; Smit, 1993) and in the spontaneous speech of Dutch-speaking children (Fikkert, 1994), complete deletion of a consonant cluster is nearly absent. In contrast, cluster reduction and cluster simplification are common.

Cluster reduction

Consonant cluster reduction is the most frequently reported and attested type of errors in NH children (Dutch: Beers, 1992; English: Dodd, Holm, Hua, & Crosbie, 2003; Fikkert, 1994; Chinese: Hua & Dodd, 2000; McLeod et al., 2001a; see McLeod et al., 2001b for an overview). Cluster reduction is defined as the production of a singleton consonant instead of a consonant cluster (McLeod et al., 2001b). Two reduction patterns have been observed: (1) the singleton consonant is one of the target consonants, e.g. /pl/ rendered as /p/, and (2) the singleton consonant differs from the target consonants, e.g. /pl/ rendered as /b/.

The first reduction pattern (1) is explained by the sonority hypothesis (SH). The SH predicts reduction patterns based on the sonority of segments (Geirut, 1999; Jongstra, 2003; McLeod et al., 2001a, 2001b; Ohala, 1999; Wyllie-Smith, McLeod, & Ball, 2006). Segments are ordered from less to more sonorous according to the Sonority Sequencing Principle (Clements, 1990; Geirut, 1999; Ohala, 1999), which ranks plosives as the least sonorous segments and vowels as the most sonorous, as shown in (1):

(1) Plosives < Fricatives < Nasals < Liquids < Glides < Vowels
Least sonorous *Most sonorous*

The SH holds that when a cluster is reduced to a single consonant, the least sonorous consonant is preserved, resulting in a maximal sonority distance between the onset consonant and the (vocalic) nucleus. This regularity is in agreement with the universally preferred CV syllable: across languages, the preferred CV syllable exhibits a maximum rise in sonority between onset and nucleus

(Vennemann, 1988). Similarly, the SH predicts that the least sonorous consonant is preserved in initial cluster reduction, which results in a maximal contrast in sonority between the preserved consonant and the following vowel (Fikkert, 1994; Ohala, 1999). For instance, the SH predicts that when a plosive plus liquid cluster (e.g. /pl/) is reduced, the plosive (/p/) will be preserved. Even though there is ample evidence for adherence to the SH in, for instance, English-speaking NH children (Chin & Finnegan, 2002), Jongstra (2003) showed that in children acquiring Dutch there is considerable variation in the reduction patterns between children and even within the same child.

The second reduction pattern involves the production of a singleton consonant that differs from the two target consonants. The new consonant often combines features of both target consonants. This is called coalescence (Chin & Dinnsen, 1992; Dyson & Paden, 1983; McLeod et al., 2001a, 2001b). For instance, when *spider* /spaɪdər/ is produced as [faɪdər], the manner feature of /s/ merges with the place feature of /p/ to become the labial fricative [f]. Such instances of coalescence suggest that the child has at least some knowledge of the two target consonants (Chin & Dinnsen, 1992). This substitution pattern cannot, however, be explained by the SH (Wyllie-Smith et al., 2006).

Cluster simplification

Next to cluster reduction, cluster simplification is a common type of error in NH children's speech. In cluster simplification, a consonant cluster is produced, but at least one consonant deviates from the target (McLeod et al., 2001b), as in *frog* /frɔg/ produced as [fwɔg].

Consonant cluster production in children with CI

Few studies have investigated the production of clusters in children with CI. Moreover, their scope is often restricted: they either report on only one aspect of consonant cluster production, or they do not provide a longitudinal and quantified developmental picture. More specifically, some studies only analyse cluster accuracy without further analysing the types of errors (Fulcher, Baker, Purcell, & Munro, 2014; Von Mentzer, Lyxell, Sahlén, Dahlström, Lindgren, Ors, Kallioinen, Engström, & Uhlén, 2015). Other studies are limited to a single aspect of cluster production, such as cluster

reduction (Baudonck, Dhooge, D'haeseleer, & Van Lierde, 2010; Flipsen & Parker, 2008), without considering other types of errors.

A second strand of research addresses children's rendition of clusters at one particular point in their development without considering longitudinal development (Baudonck et al., 2010; Chin & Finnegan, 2002; Fulcher et al., 2014; Von Mentzer et al., 2015). Alternatively, some studies provide an extensive qualitative overview of the types of consonant clusters produced by children with CI and frame their development theoretically (Adi-Bensaid & Ben-David, 2010; Chin & Finnegan, 2002), but do not report development quantitatively.

To date, the only study on Dutch-speaking children with CI is Baudonck et al. (2010), who report that consonant cluster reduction occurs at a mean age of 9;0 (range 5;4 – 13;7). No further information is available on Dutch-speaking children with CI thus far. The present paper provides a detailed, longitudinal and quantitative study of consonant cluster production in children with CI acquiring Dutch as their native language. Since the same types of errors have been observed across languages, we expect to find similar patterns in children acquiring Dutch, though particular language-specific effects may be evident (Yavas, 2013).

Adi-Bensaid and Ben-David (2010) and Chin and Finnegan (2002) provide detailed, qualitative analyses of children with CI acquiring Hebrew and English respectively. They show that complete deletion of consonant clusters is rare in Hebrew children between 2;0 and 4;5 (Adi-Bensaid & Ben-David, 2010) and even absent in English at age 9;9 (Chin & Finnegan, 2002). Two patterns of consonant cluster reduction are commonly reported: (1) reduction to a singleton consonant that is part of the target cluster, and (2) reduction to another singleton consonant. With respect to the first pattern (1), Hebrew-speaking children with CI preserve the second consonant, except when it is liquid (Adi-Bensaid & Ben-David, 2010), whereas English-speaking children with CI adhere to the sonority hypothesis by producing the least sonorous segment (Chin, 2006; Chin & Finnegan, 2002). With respect to the second reduction pattern (2), Adi-Bensaid and Ben-David (2010) claim that coalescence only rarely occurs in Hebrew-speaking children with CI. Finally, regarding cluster simplification, Chin and Finnegan (2002) show that 34% of the target clusters were simplified by English-speaking children with CI at a mean age of 9;9.

These studies give an interesting overview of consonant cluster production. However, it should be noted that in Adi-Bensaid and Ben-David (2010) and in Chin and Finnegan (2002) a picture-naming task was used. How well do these findings generalize from a fairly controlled task to spontaneous speech in naturalistic interactions? Children's speech production has been shown to contain fewer errors in single-word tasks than in connected speech (Healy & Madison, 1987), hence the results of such studies may well overestimate children's accuracy in naturalistic spontaneous speech. To the best of our knowledge, only Flipsen and Parker (2008) and Fulcher et al. (2014) have collected spontaneous speech samples of English-speaking children with CI in their studies of CC clusters, but they only reported on consonant cluster reduction and consonant cluster accuracy respectively. In the present study the accuracy of consonant cluster production and various error patterns in children's spontaneous speech will be analysed.

Moreover, Adi-Bensaid and Ben-David (2010) and Chin and Finnegan (2002) present a qualitative overview of consonant cluster production in children with CI, but they do not provide information about the incidence of consonant clusters in children with CI, about the likelihood or the relative incidence of the different types of errors, and the like. Thus, even though the literature has provided extensive qualitative overviews (with examples), a quantified picture of consonant cluster production in children with CI is still lacking. Our goal is to quantify the incidence of accurate production, the incidence of the various types and subtypes of errors.

In the literature on children with CI, often only one point in development is considered (Baudonck et al., 2010; Chin & Finnegan, 2002; Fulcher et al., 2014; Von Mentzer et al., 2015). Such a snapshot leaves longer term developmental patterns unrevealed and leaves unanswered the question of whether children with CI ultimately reach a level of accuracy comparable to their NH peers.

A notable exception is Flipsen and Parker (2008), who did collect longitudinal speech samples of English-speaking children with CI. They report that consonant cluster reduction does not decrease between the (mean) ages five and seven. Information about other aspects of consonant cluster production is not provided. For Hebrew, Adi-Bensaid and Ben-David (2010) adopted a longitudinal approach as well, but the effect of age is not quantified. Instead, the authors focussed on the different

types of errors in consonant cluster production over the entire study period (word onset – the age of seven). Even though they provide an order in which particular types of errors appear, no precise information about their incidence relative to the children's age is provided. Flipsen and Parker (2008, p. 341) note that a primary question in language acquisition research is: "What occurs at what age?". It is surprising that the precise quantitative development with age has not been considered for children with CI. The present paper expands previous work by studying the production of consonant clusters longitudinally. Age will be entered as a predictor in the statistical analysis of each aspect of consonant cluster production.

In children with CI, not only the child's chronological age is shown to affect language development, but also the age at implant activation, which is usually one or two months after surgery took place. Providing access to sound early in life, and thus early activation and fitting of the implant, is shown to be beneficial for grammatical development (Boons, De Raeve, Langereis, Peeraer, Wouters, & Van Wieringen, 2013; Nikolopoulos, Dyar, Archbold, & O'Donoghue, 2004), speech production (Leigh, Detmman, Dowell, & Briggs, 2013), speech production accuracy (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Schauwers, Taelman, Gillis, & Govaerts, 2008; van den Berg, 2012), and various other aspects of language development. At present, no information about the effect of age at implantation on consonant cluster production is available in the literature, and we aim to address this gap.

The current study

The current study has two goals: (a) to trace the development of consonant cluster production in the spontaneous speech of Dutch-speaking children with CI longitudinally, and (b) to compare this development to that of NH age-matched peers. Regarding the first research goal (a), it is as yet unclear if the age at implant activation and maturation with age significantly affect consonant cluster production in children with CI. Regarding the second research goal (b), it remains to be seen if children with CI differ significantly from their NH peers on the incidence of consonant clusters, the incidence of the different types of errors, and the incidence of the different patterns in consonant

cluster reduction. A detailed quantitative analysis of consonant cluster production is provided for both research goals: the likelihood of consonant clusters is considered, as well as their accuracy and the likelihood of the different types of errors, i.e. complete deletion of the consonant cluster, consonant cluster reduction and consonant cluster simplification. In addition, the different patterns of consonant cluster reduction are examined: do children reduce more often to a consonant that is one of the target consonants? If so, to what extent does the sonority hypothesis explain which consonant is preserved? If not, to what extent does coalescence account for the non-target consonant that is produced?

Method

Participants

Two groups participated in this study: children with CI and NH children. All were monolingual Dutch-speakers and lived in Flanders, i.e. the northern Dutch-speaking part of Belgium.

The first part of the data consists of longitudinal data of nine children with CI. In Table 1, details of the children with CI are shown. The data were obtained monthly from the month of implant activation up to age 2;6, and after that yearly between 3;0 and 7;0. All children had a congenital profound hearing loss. The causes of deafness were genetic (S1 – S2, S4 – S7 and S9), a cytomegalovirus infection (S3) and unknown (S8). Before implantation, the mean Pure Tone Average (PTA) threshold was 112.56 dBHL (SD = 9.12) in the better ear. Each child received a Nucleus-24 multichannel implant. The mean age at implantation was 1;0 (SD = 0;5) and mean age at implant activation was 1;2 (SD = 0;5). At 5;0, the mean PTA had improved to 32.33 dBHL (SD = 7.11). Six children received a second implant during data collection. The children with CI were raised in an oral communication setting and used only a limited amount of lexical signs. No other patent cognitive or developmental problems were reported during data collection.

Table 1. Characteristics of the CI group

ID	PTA unaided	PTA CI	Age 1st CI	Age activation	Age 2nd CI	Age first

				1e CI		word
S1	120	35	1;1	1;3	6;3	1;8
S2	120	27	0;7	0;8	4;8	1;4
S3	115	25	0;10	1;0	5;10	1;8
S4	113	42	1;6	1;7	-	1;8
S5	93	32	1;5	1;6	6;4	1;6
S6	120	37	0;9	0;10	-	1;4
S7	117	23	0;5	0;6	1;3	1;3
S8	112	42	1;7	1;9	-	1;11
S9	103	28	0;9	0;10	1;11	1;3
Mean	*112.56*	*32.33*	*1;0*	*1;2*	*4;6*	*1;6*
SD	*9.12*	*7.11*	*0;5*	*0;5*	*2;3*	*0;3*

PTA = Pure Tone Average in dBHL
Ages are represented in years;months
- = no second implant

The data of the control group of NH children are cross-sectional, including a total of 53 children: 11 two-year-olds (mean = 2;0, SD = 0;1), 9 three-year-olds (mean = 3;0, SD = 0;1), 12 four-year-olds (mean = 4;0, SD = 0;1), 11 five-year-olds (mean = 5;0, SD = 0;1), 11 six-year-olds (mean = 6;0, SD = 0;3) and 10 seven-years-olds (mean = 6;11, SD = 0;2). The children in this cross-sectional corpus participated only once.

Procedure

The data consisted of video recordings of 60 to 90 minutes of spontaneous interactions between the child and a primary caregiver at the child's home. The caregivers were asked to act as in a normal play situation with their child. The interactions consisted of playing, picture book reading, and routine activities such as meals, bathing, etc. Hence, the data collection was not specifically designed to elicit the production of consonant clusters. After each recording, a 20-min selection of the complete interactions was made, excluding long pauses, noisy passages, etc. This was done in order to keep transcription time within reasonable limits (Molemans, 2011; Schauwers, 2006; van den Berg, 2012; Van Severen, 2012).

Each 20-min selection was transcribed in CHILDES' CLAN according to the CHAT conventions (MacWhinney, 2000). The children's productions were transcribed orthographically and

phonemically based on the video recordings. Phonemic transcriptions were made in DISC format with stress marks. Phonemic transcriptions of the target words, i.e. the adult equivalent of the children's renditions, were added automatically using the lexical database Fonilex, which is 'a pronunciation database containing the phonetic transcription of the most frequent word forms of Dutch as spoken in Flanders' (Mertens, 2001). The orthographic transcription of each word in the transcription was looked up in Fonilex and the corresponding standard phonemic transcription was selected and inserted in the transcription files. The standard phonemic transcriptions were verified manually with respect to well-known phenomena of spontaneous spoken Dutch, such as the deletion of final /n/ after schwa (e.g., zeggen 'to say' /zɛɣə(n)/), and the deletion of final /t/ (e.g., in the demonstrative dat 'that' /dɑ(t)/) (Booij, 1995; Ernestus, 2000). After the target words were added, the child's productions were automatically aligned with the target transcriptions at the phoneme level by means of a dynamic alignment algorithm based on ADAPT (Elffers, Van Bael, & Strik, 2005). The alignments were verified manually and corrected if needed.

The reliability of the phonemic transcriptions of consonants was assessed measuring a percentage of agreement for 10% of the 20-minute selections. In addition, Kappa scores were calculated in order to consider the possible influence of chance (Cucchiarini, 1996). For the NH speech samples, the interrater reliability was 70.43% (Kappa K = 0.74) and intrarater reliability 84.17% (K = 0.83) for the full code (segment-to-segment comparisons of consonants). These Kappa scores can be interpreted as *substantial* agreement (Kappa between 0.61 and 0.80) and *almost perfect* agreement (Kappa between 0.81 and 1.00) (Landis & Koch, 1977). Percentages of agreement for manner of articulation and place of articulation were also calculated. The percentages were 81.03% (K = 0.74) and 81.14% (K = 0.71) for interrater reliability and 91.72% (K = 0.89) and 92.08% (K = 0.88) for intrarater reliability respectively. For the CI corpus, only interrater reliability was checked and equalled 84.03% (K = 0.77) for the full code (segment-to-segment comparisons of consonants). The percentages of agreement for consonant manner and consonant place were 85.70% (K = 0.79) and 82.90% (K = 0.76). More detailed information about the data collection and transcription and the reliability assessment, including the research protocols, can be found in Molemans (2011), Schauwers (2006), van den Berg (2012) and Van Severen (2012).

Amount of data

Table 2 displays an overview of the total number of word tokens in the children's speech as well as the incidence of consonant clusters in the targets, i.e. the adult equivalents of the child's renditions. The total number of word tokens was 109,995, i.e. words with empty, singleton and complex onsets (CI: 64,035 word tokens, NH: 45,960 word tokens). In 7.87% of all word tokens, a word initial consonant cluster appeared in the adult form of the child's actual production: 8.13% in the CI corpus and 7.50% in the NH corpus. Three-element (CCC) clusters represented only 2.90% of all WI consonant clusters (2.61% and 3.34% for the CI group and the NH group respectively), and are not analysed.

Table 2. The distribution of consonant clusters in the targets of children's productions

		All children	CI corpus	NH corpus
Total number of word tokens		109,995	64,035	45,960
Number of word tokens with WI consonant cluster	*All consonant clusters*	8656	5209	3447
	CC clusters	8405	5073	3332
	CCC clusters	251	136	115

In Dutch WI CC clusters, two combinations of consonants are possible: obstruent plus obstruent and obstruent plus sonorant (Booij, 1995). In (2) examples of the combinatorial subtypes are presented:

(2)

Obstruent + obstruent	
(2a) fricative + stop	*stop* /stop/ (Eng.: stop), *spelen* /spelən/ (to play)
(2b) fricative + fricative	s*chool* /sχol/ (school), *sfeer* /sfer/ (ambiance)
(2c) stop + fricative	*pseudo* /psœdo/ (pseudo)
Obstruent + sonorant	
(2d) stop + nasal	*knippen* /knIpən/ (to cut)
(2e) stop + liquid	*broer* /brur/ (brother), *klas* /klɑs/ (classroom)
(2f) stop + glide	*kwaad* /kwat/ (angry)
(2g) fricative + nasal	*snoep* /snup/ (sweets, candy)
(2h) fricative + liquid	*slang* /slɑŋ/ (snake), *vriend* /vrint/ (friend)

(2i) fricative + glide *zwart* /zwɑrt/ (black)

Data analyses

Seven aspects of CC cluster production were studied:

(1) In order to compute the incidence of CC clusters, a list of all children's word productions and their targets, i.e. adult equivalents, was retrieved from the corpus. The onset of each word production of a child, irrespective of the number of consonants in the target word, was identified as (a) empty, (b) singleton consonant, (c) CC cluster. The likelihood of CC clusters in children's productions was estimated relative to empty and singleton onsets.

(2) The likelihood of accurately produced CC clusters was estimated. In this analysis, only those word productions with CC clusters in the onset of the adult form were considered. The child's rendition was compared to the target CC cluster and classified as correct/incorrect. After this second layer in the analyses, inaccurately produced CC clusters were further analysed.

(3) The likelihood of complete deletion of the CC cluster within the subset of inaccurately produced CC clusters was estimated.

(4) The likelihood of CC cluster reduction was estimated and compared to the likelihood of CC cluster simplification. In this analysis, only inaccurately produced CC clusters that were not entirely deleted were considered. Children's renditions that comprised only one consonant were labelled *CC cluster reduction*, renditions with 2 consonants *CC cluster simplification.* After this fourth aspect, we further investigated those CC clusters that were labelled *CC cluster reduction.*

(5) The likelihood of cluster reduction to one of the target consonants was estimated. If the singleton rendition was a consonant that also occurs in the target cluster, the rendition was labelled *reduction to one of the target consonants*, otherwise it was labelled *no reduction to one of the target consonants.*

(6) The likelihood of adherence to the sonority hypothesis was estimated when the reduction was labelled *reduction to the one of the target consonants.*

(7) The likelihood of coalescence was estimated when the reduction was labelled *no reduction to the one of the target consonants.*

Statistical analyses

All statistical analyses were done in R (R Core Team, 2013) by means of logistic regressions in multilevel models (Baayen, 2008; Woltman, Feldstain, MacKay, & Rocchi, 2012). Our data are hierarchically structured: utterances are nested in individual children at different ages. Multilevel models take this variation into account. Multilevel models consist of two parts: a random part and a fixed part. The random part of the model considers the nesting of variables in the data, whereas the fixed part includes the predicting variables. In R, the estimates and standard errors (SE) of logistic regressions are computed in logits. Logits can easily be converted to probabilities in two steps. First, logits are converted to odds using an exponential function (step 1 in equation (A)). Second, the odds are converted to probabilities using the formula in step 2 of equation (A):

(A) S*tep 1:* $\text{odds} = e^{logit}$

Step 2: $p = \frac{odds}{(1-odds)}$

The analyses are presented in two steps: (1) a longitudinal analysis of children with CI and (2) cross-sectional comparisons between NH children and children with CI. For the longitudinal analysis of children with CI (1), all available data of children with CI were used: the monthly data from word onset (median = 1;6, range 1;3–1;11) up to age 2;6 and the yearly data of those children between ages 3;0 and 7;0. For these analyses, the random part of the multilevel models of each analysis included random intercepts and random slopes to model the variation between children and ages. The fixed part, i.e. the predicting variables, was composed in an incremental way. A particular predictor was added to the model and an ANOVA was used to test whether the resulting model had a significantly better model fit compared to the previous model, i.e., the model without that particular predictor. If the resulting model had a better model fit, the predicting variable was preserved in the model – even if the variable itself was not significant. The predicting variables included in each of the longitudinal analyses of children with CI were chronological age in months (Age, centred at 24 months of age) and the age at implant activation (CIactivation). Quadratic and cubic age effects

(Age^2, Age^3) and interactions between Age and CIactivation were tested as well. Only the best fitting model is reported.

The cross-sectional analyses (2) were performed in order to compare the development of consonant clusters in children with CI and their NH age-matched peers. For these cross-sectional comparisons, the data of the CI group were split, as no longitudinal data were available for the NH children. It would be incorrect to include the cross-sectional data of all NH children in one model with the longitudinal data of the CI group. NH children and children with CI were matched and compared at ages 2;0 (range 1;11–2;1), 3;0 (2;10–3;4), 4;0 (3;9–4;3), 5;0 (4;11–5;3), 6;0 (5;7–6;6) and 7;0 (6;10–7;4). In each analysis, a random intercept was included in the multilevel model, taking the variation between children into account in the random part of the multilevel model, and the predicting variable (the fixed part of the multilevel model) was HearingStatus (NH vs. CI).

Results

Longitudinal analyses of children with CI

This section presents the longitudinal development of WI CC clusters of children with CI relative to their chronological age (Age) and the age at implant activation (CIactivation). The tables represent the best fitting models expressed in logits.

The likelihood of CC clusters and the likelihood of accurate CC clusters

Table 3 presents the fixed effect results of the best fitting models for the likelihood of CC clusters and the likelihood of accurate CC clusters in the productions of children with CI.

The likelihood of words with CC clusters is significantly lower than the likelihood of words with empty and singleton onsets (intercept $p < 0.001$). At the intercept (i.e. 24 months of age), the likelihood of a CC cluster is 2.08%. Table 3 also displays a significant effect of Age ($p < 0.001$), showing that the likelihood of CC clusters increases as children get older. The quadratic effect of age (Age^2) is also significant ($p < 0.001$). In Figure 1, the effects of Age and Age^2 are plotted: there is an increase with age (Age), but this increase becomes less steep from approximately 36 months of age

(Age^2) onwards. Finally, Table 3 shows that the effect of CIactivation is not significant ($p > 0.05$), indicating that the likelihood of CC clusters is not statistically different in children with CI with different ages at implantation.

Table 3 also shows the likelihood of accurate CC clusters as compared to that of inaccurate CC clusters. The intercept is not significant ($p > 0.05$), which means that the likelihood of accurately produced CC clusters is not significantly lower or higher as compared to that of inaccurately produced CC clusters. At 24 months of age, the likelihood of an accurately produced CC cluster is 46.01%. There is a significant effect of Age ($p < 0.01$): as shown in Figure 2, the likelihood of accurately produced CC clusters increases with age. There is no significant quadratic effect of Age^2, nor did this effect improve the model fit, therefore it is not included in the model. Next, there is a significant effect of CIactivation ($p < 0.001$), indicating that the likelihood of an accurately produced CC cluster is lower in children with CI with later implant activation. In addition, the significant interaction between CIactivation and Age ($p < 0.001$) shows that the increase of the likelihood of accurately produced CC clusters is steeper in children with CI with later implant activation. Thus, they are catching up on the likelihood of accurate CC clusters.

Table 3. Fixed effect results of the likelihood of CC clusters and the likelihood of accurate CC clusters

	Likelihood of consonant clusters	Likelihood of accurate consonant clusters
	Estimate (SE)	*Estimate (SE)*
Intercept	- 3.85 (0.30) ***	- 0.16 (1.11)
Age	0.12 (0.01) ***	0.09 (0.03) **
Age^2	-0.01 (< 0.01) ***	
CIactivation	-0.03 (0.02)	-0.27 (0.08) ***
CIactivation x Age		0.01 (< 0.01) ***
$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***		

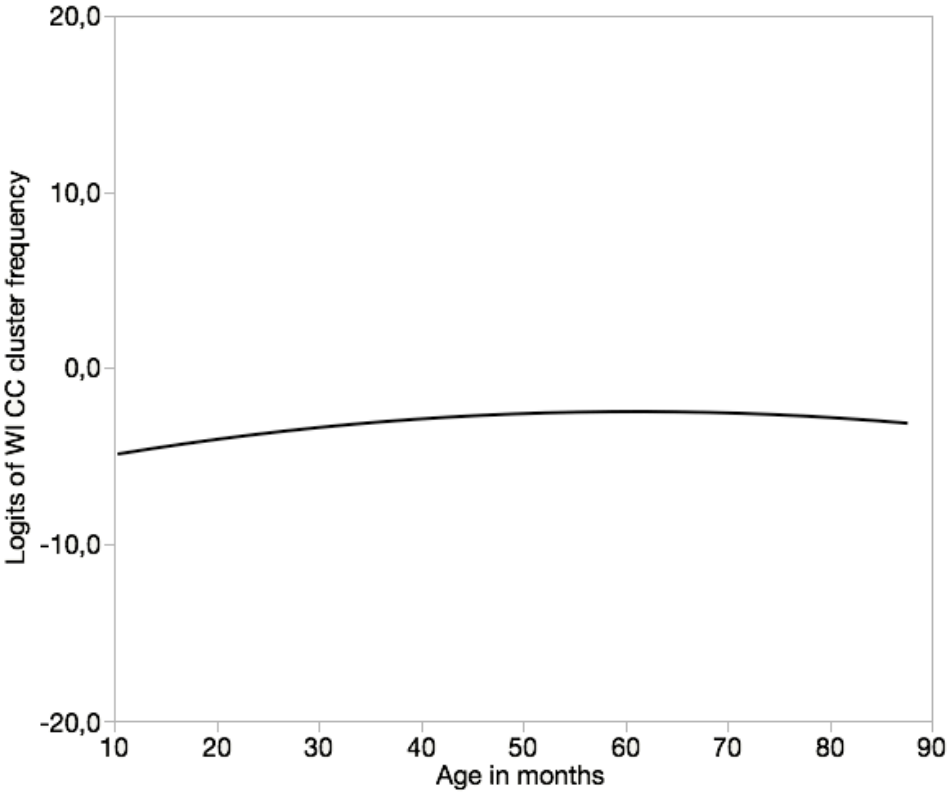

Figure 1. Development of the likelihood of CC clusters (expressed in logits)

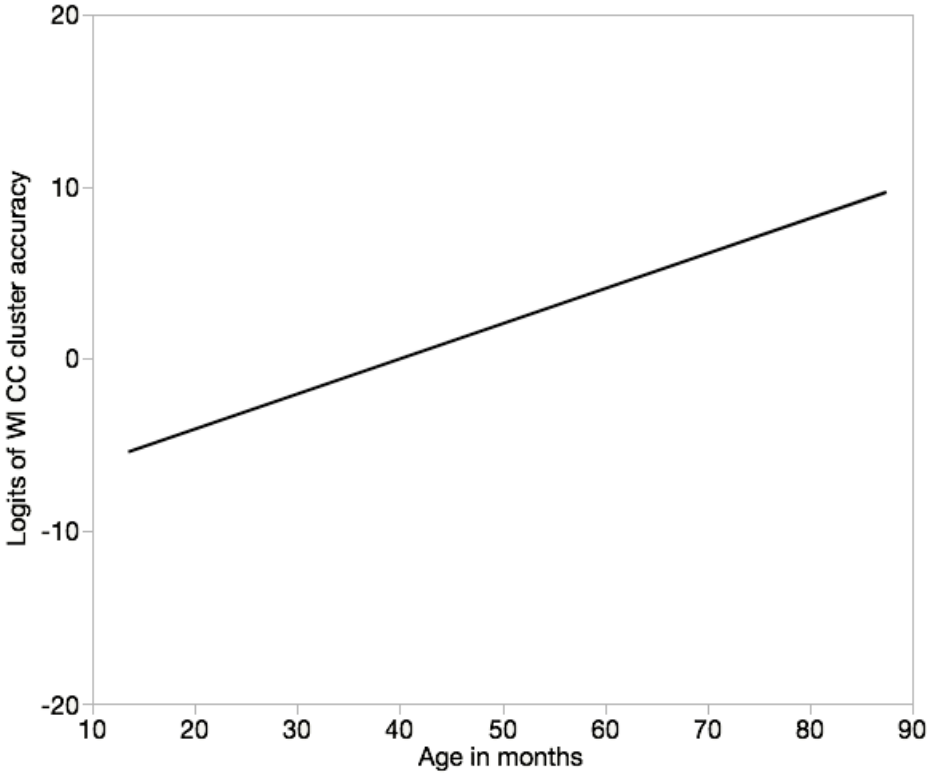

Figure 2. Development of the likelihood of accurate CC clusters (expressed in logits)

Types of errors: the likelihood of complete deletion, reduction and simplification

This section reports on the development of inaccurately produced CC clusters. The fixed effect results of the best fitting models are displayed in Table 4, expressed in logits. In figure 5, the development of the likelihood of each type of errors is displayed.

The left panel of Table 4 shows the likelihood of complete deletion of the CC clusters. The negative intercept shows that CC clusters are significantly less likely to be completely deleted than to be either reduced or simplified ($p < 0.001$). At 24 months of age, the likelihood of complete deletion of the CC cluster is 4.15%. There is a significant decrease with age (Age and Age^2, $p < 0.001$), as also shown in Figure 3. The significant effect of CIactivation ($p < 0.001$) indicates that the likelihood of complete deletion of the CC cluster is higher in children with CI with later implant activation. In addition, the decrease of complete deletion of CC clusters with age is less steep in children with CI with later implant activation (interaction between Age and CIactivation, $p < 0.001$).

When CC clusters are not entirely deleted, they can either be reduced or simplified. The right panel of Table 4 displays the likelihood of cluster reduction as compared to that of cluster simplification. The likelihood of cluster reduction is significantly higher than that of cluster simplification (intercept $p < 0.001$). At 24 months of age, the likelihood of cluster reduction is 88.29%, and evidently the likelihood of cluster simplification is 11.71%. There are significant age effects (Age, Age^2 and Age^3) that can be inferred from Figure 4: the likelihood of cluster reduction decreases with age (and thus cluster simplification increases). However, this decrease levels out by approximately 70 months of age. Finally, there is a significant effect of CIactivation ($p < 0.001$), which indicates that the likelihood of cluster reduction is higher in children with CI with later implant activation. There was no significant interaction between Age and CIactivation nor did this interaction improve the model fit. Therefore it is left out of the best fitting model reported in Table 4. However, the lack of an interaction between Age and CIactivation shows that children with CI with later implant activation are not catching up with their CI peers with earlier implant activation as to the likelihood of cluster reduction versus cluster simplification.

Table 4. Fixed effect results of the likelihood of CC cluster deletion and CC cluster reduction

	Likelihood of complete cluster deletion	Likelihood of cluster reduction

		(vs. simplification)
	Estimate (SE)	*Estimate (SE)*
Intercept	- 3.14 (< 0.01) ***	2.02 (0.01) ***
Age	- 0.20 (0.06) ***	-0.20 (0.01) ***
Age^2	-0.01 (< 0.01) ***	< -0.01 (0.01) **
Age^3		< 0.01 (< 0.01) ***
CIactivation	0.05 (< 0.01) ***	0.13 (0.01) ***
CIactivation x Age	0.01 (< 0.01) ***	
p ≤ 0.05*, p ≤ 0.01**, p ≤ 0.001***		

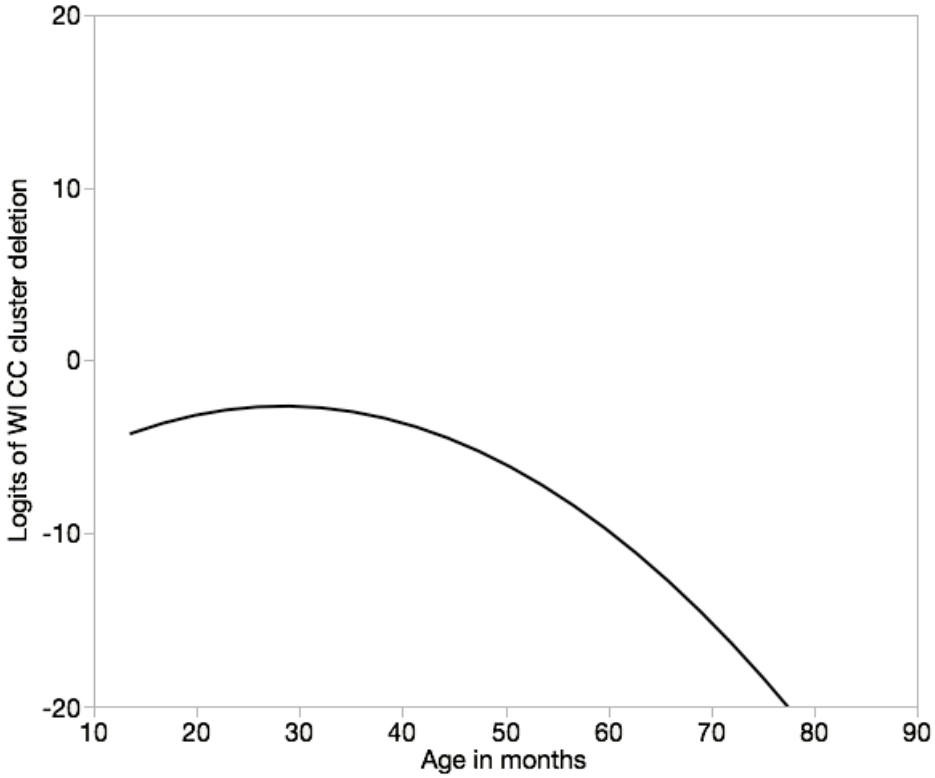

Figure 3. Development of the likelihood of CC cluster deletion (expressed in logits)

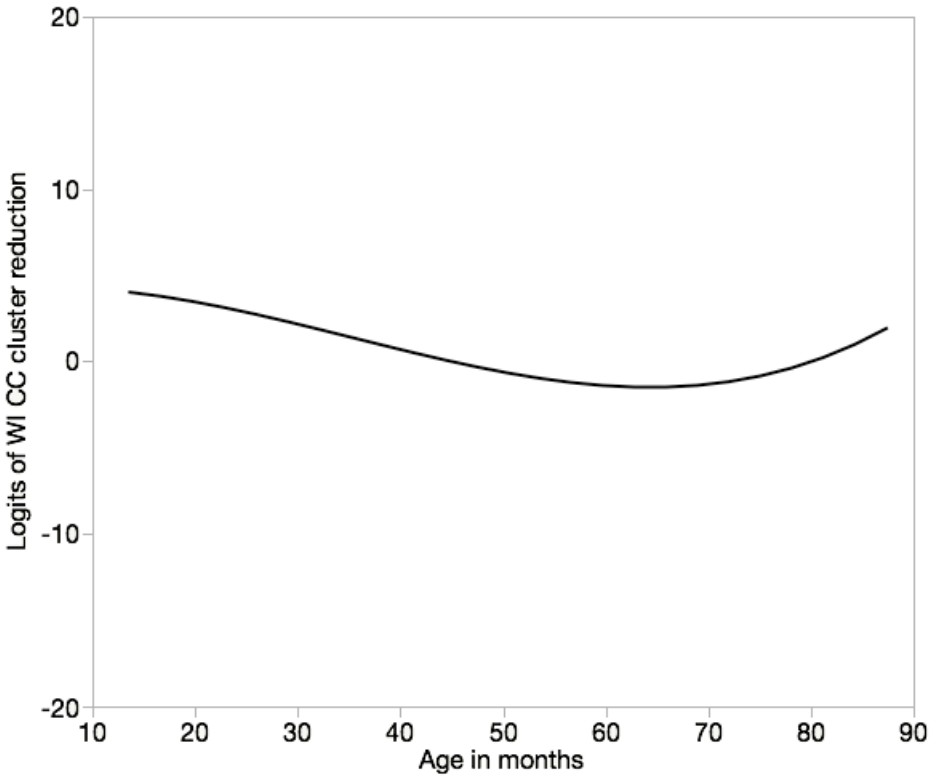

Figure 4. Development of the likelihood of CC cluster reduction (vs. cluster simplification) (expressed in logits)

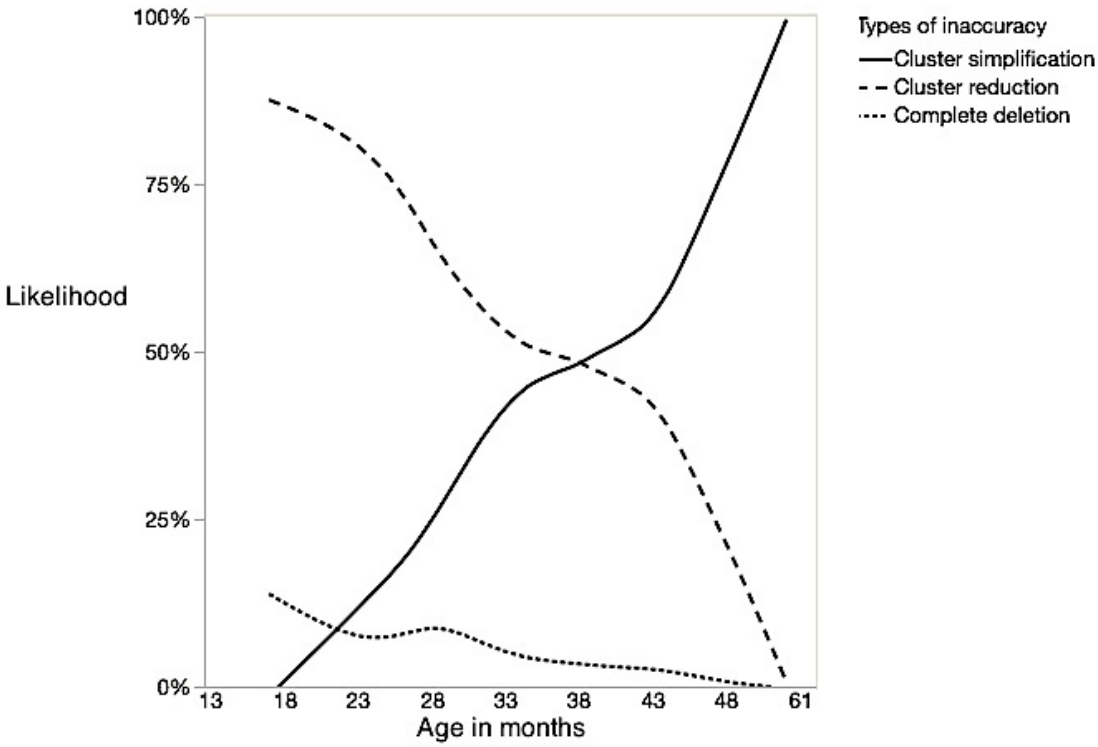

Figure 5. Development of the likelihood of the three types of errors in children with CI

Reduction processes

This section presents the development of cluster reduction in more detail. The fixed effect results of the best fitting models – expressed in logits – are shown in Table 5. We discuss, first, the likelihood of reduction to one of the target consonants, secondly, the likelihood of adherence to the sonority hypothesis and, thirdly, the likelihood of coalescence.

Table 5 shows the likelihood of reduction to one of the target consonants. The intercept is not statistically significant ($p > 0.05$), meaning that the likelihood of reducing a cluster to a target consonant is not significantly more or less likely than that of reducing it to another consonant (62.48%). However, the significant effect of Age ($p < 0.05$) suggests that the likelihood of reducing a CC cluster to one of the target consonants increases. Figure 6 shows that this increase is quite small. Moreover, there is a significant effect of CIactivation ($p < 0.05$), indicating that the likelihood of reduction to one of the target consonants is lower in children with CI with later implant activation. Including the interaction between Age and CIactivation did not improve the model fit and is therefore left out. The lack of a significant interaction indicates, however, that children with CI with later implant activation are not catching up with their earlier implanted peers.

When CC clusters are reduced to a consonant that is part of the target cluster, the sonority hypothesis (SH) predicts that children preserve the least sonorous consonant in word onset position. Table 5 shows the likelihood of adherence to the SH as compared to no adherence. At 24 months of age, the likelihood of adherence to the SH is 95.35% (intercept $p < 0.001$), which is significantly higher than the likelihood of non-adherence (4.65%). No effect of Age ($p > 0.05$) nor CIactivation ($p > 0.05$) are found, showing that the likelihood of adherence to the SH remains stable over time (Figure 7) and is similar in all children with CI, regardless of their age at implant activation.

When CC clusters are not reduced to a consonant that is part of the target cluster, the consonant that is produced often combines features of both target consonants. Table 5 shows the analysis of the likelihood of coalescence. The intercept is significant ($p < 0.05$): at 24 months of age, the likelihood of coalescence is 86.99%, which approaches a ceiling level. There is no statistically significant effect of Age ($p < 0.05$), indicating that the likelihood of coalescence remains relatively stable, as can be

seen in Figure 8. Finally, the effect of CIactivation is significant ($p < 0.05$), showing that the likelihood of coalescence is significantly lower in children with CI with later implant activation.

Table 5. Fixed effect results of the likelihood of the different reduction processes

	Likelihood of reduction to one of the target consonants	Likelihood of adherence to the sonority hypothesis	Likelihood of coalescence
	Estimate (SE)	*Estimate (SE)*	*Estimate (SE)*
Intercept	0.51 (0.53)	3.02 (0.83) ***	1.90 (0.88) *
Age	0.06 (0.03)	- 0.06 (0.04) *	0.04 (0.05)
CIactivation	-0.07 (0.03) *	- 0.05 (0.05)	- 0.16 (0.06) *
$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***			

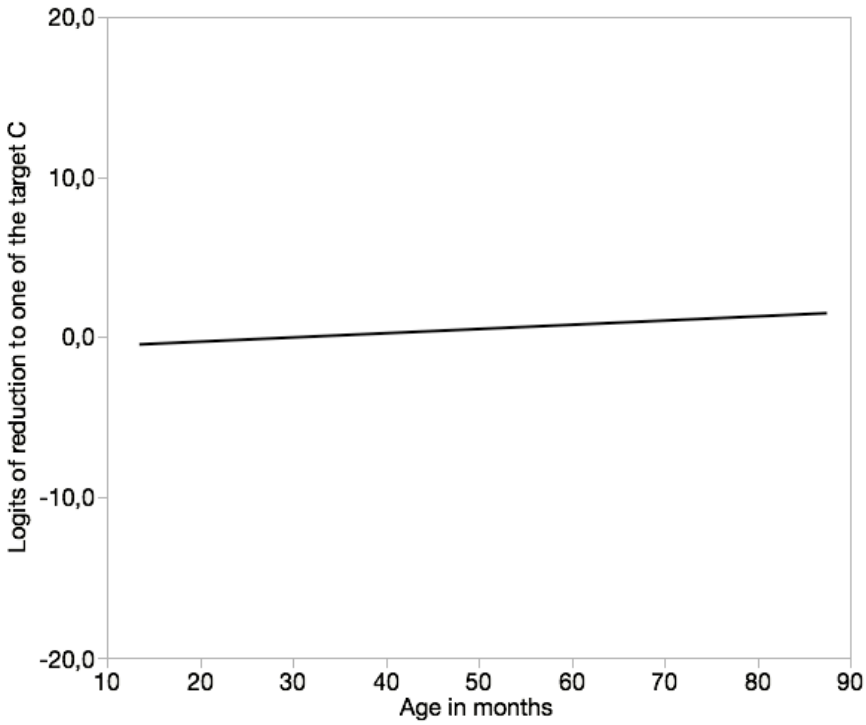

Figure 6. Development of the likelihood of CC cluster reduction: reduction to one of the target consonants (expressed in logits)

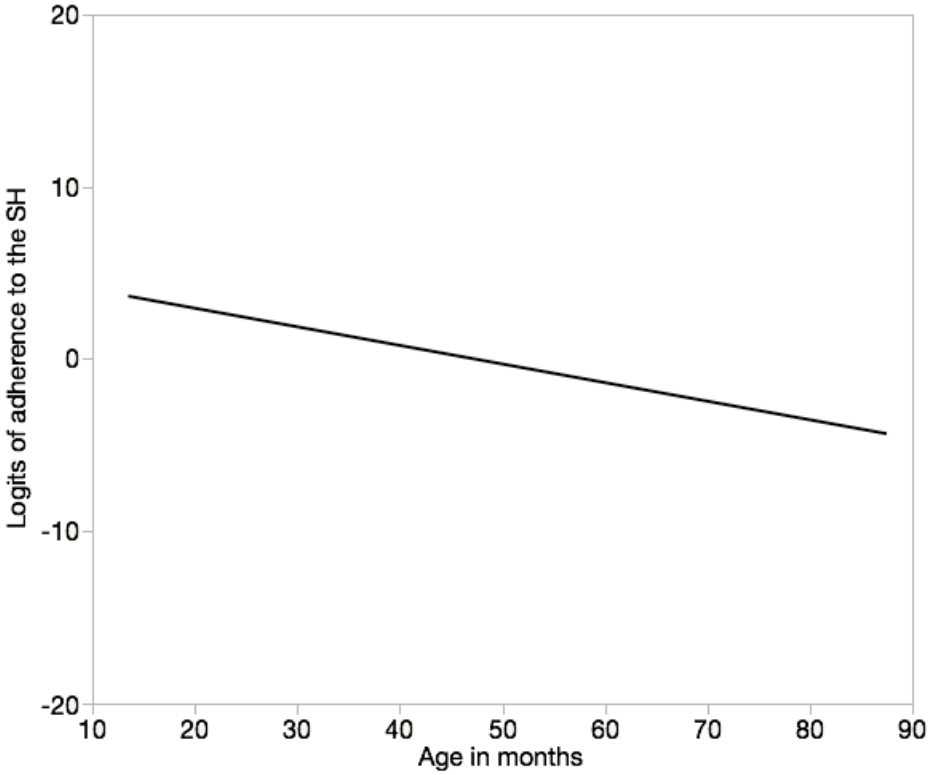

Figure 7. Development of the likelihood of CC cluster reduction: adherence to the sonority hypothesis (expressed in logits)

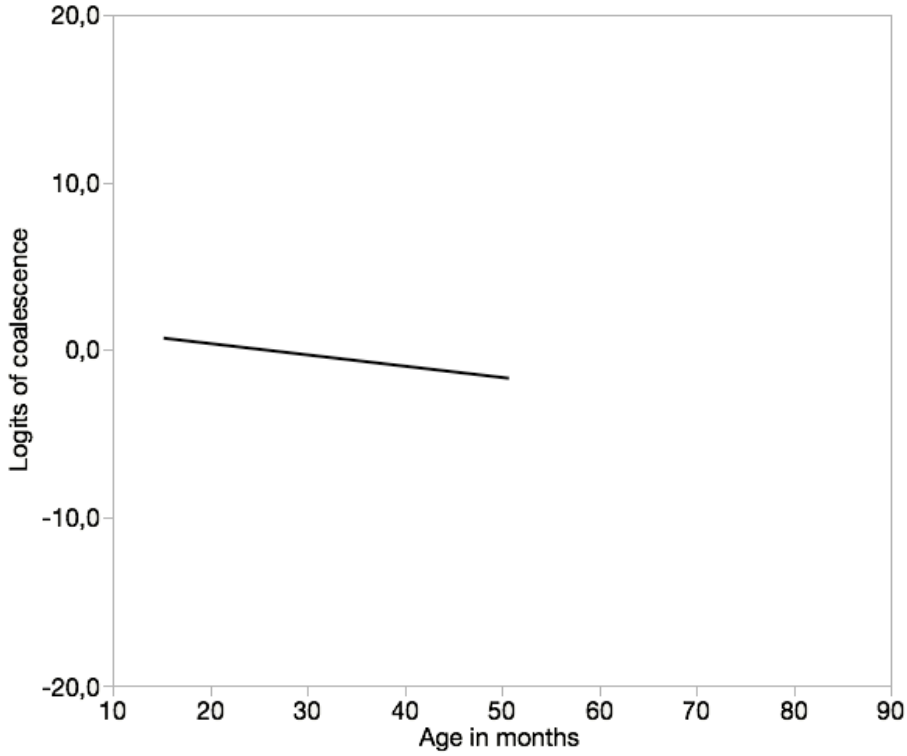

Figure 8. Development of the likelihood of CC cluster reduction: coalescence (expressed in logits)

(coalescence was no longer evident after 50 months of age)

Comparisons between children with CI and NH children

This section provides the results of the cross-sectional comparisons between children with CI and NH children, between ages 2;0 and 7;0. The tables exhibit the fixed effect results for the predicting variable HearingStatus, expressed in logits. In these cross-sectional comparisons the effect of Hearing status is considered at each age. This implies that no interactions between Hearing status and Age can be considered, as each analysis gives an indication for a particular age.

The likelihood of CC clusters and the likelihood of accurate CC clusters

Table 6 presents the cross-sectional comparisons between NH children and children with CI for the likelihood of CC clusters and the likelihood of accurate CC clusters.

Table 6 and Figure 9 show no significant differences between both groups of children ($p > 0.05$) as to the likelihood of CC clusters. However, the likelihood of *accurate* CC clusters reveals significant differences between the two groups, as can be inferred from Table 6 and Figure 10. The effect of HearingStatus is significant at ages 2;0, 3;0 and 4;0 ($p < 0.001$, $p < 0.05$ and $p < 0.001$), meaning that the likelihood of producing a CC cluster accurately is significantly higher in NH children than in children with CI at these ages. At age 2;0, the likelihood is 8.71% in NH children and only 3.52% in children with CI, at age 3;0, the likelihood is 73.31% and 33.84% respectively and at age 4;0, the likelihood is 91.68% and 67.48% respectively. From age 5;0 onwards, there are no longer significant group differences, because accuracy reaches ceiling percentages in both groups of children (99.55%).

Table 6. Fixed effect results of the cross-sectional comparisons between NH and CI: likelihood of CC clusters and the likelihood of accurate CC clusters

	2;0	3;0	4;0	5;0	6;0	7;0
	Estimate (SE)	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*
The likelihood of consonant clusters						
Intercept	-3.97 (0.35)***	-2.99 (0.16)***	-2.53 (0.11)***	-2.56 (0.16)***	-2.74 (0.10)***	-2.84 (0.11)***

HearingStatus [NH]	0.56 (0.45)	0.06 (0.24)	-0.14 (0.15)	0.11 (0.22)	0.10 (0.13)	0.08 (0.14)
The likelihood of accurate consonant clusters						
Intercept	-3.31 (<0.01)***	-0.67 (0.39)	0.73 (0.35)*	5.39 (0.94)***	*No inaccurate clusters in CI. Intercept NH: 3.73 (0.27)******	5.99 (1.10)***
HearingStatus [NH]	0.96 (<0.01)***	1.63 (0.59)*	1.67 (0.48)***	-1.87 (0.99)	0.10 (0.13)	-2.07 (1.14)
$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$*** CI is the reference category						

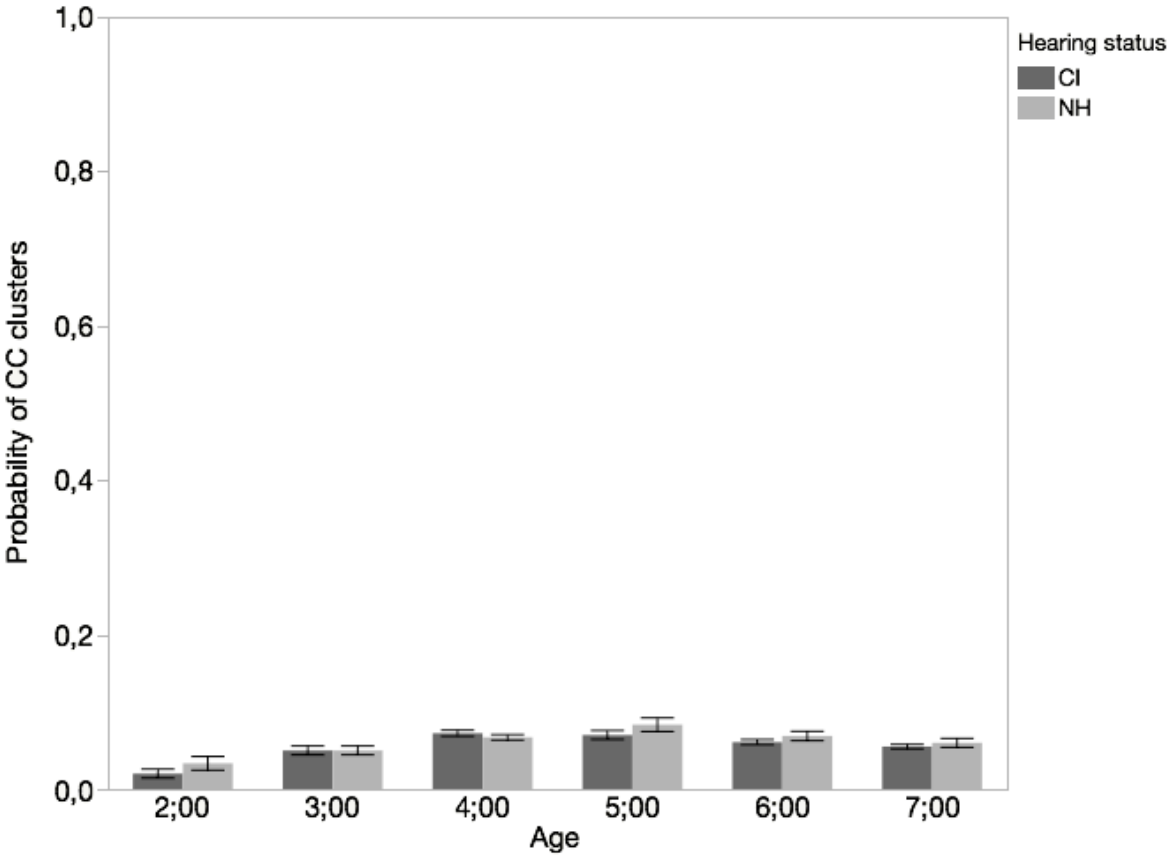

Figure 9. Probability of CC clusters in NH children and children with CI (predicted values)

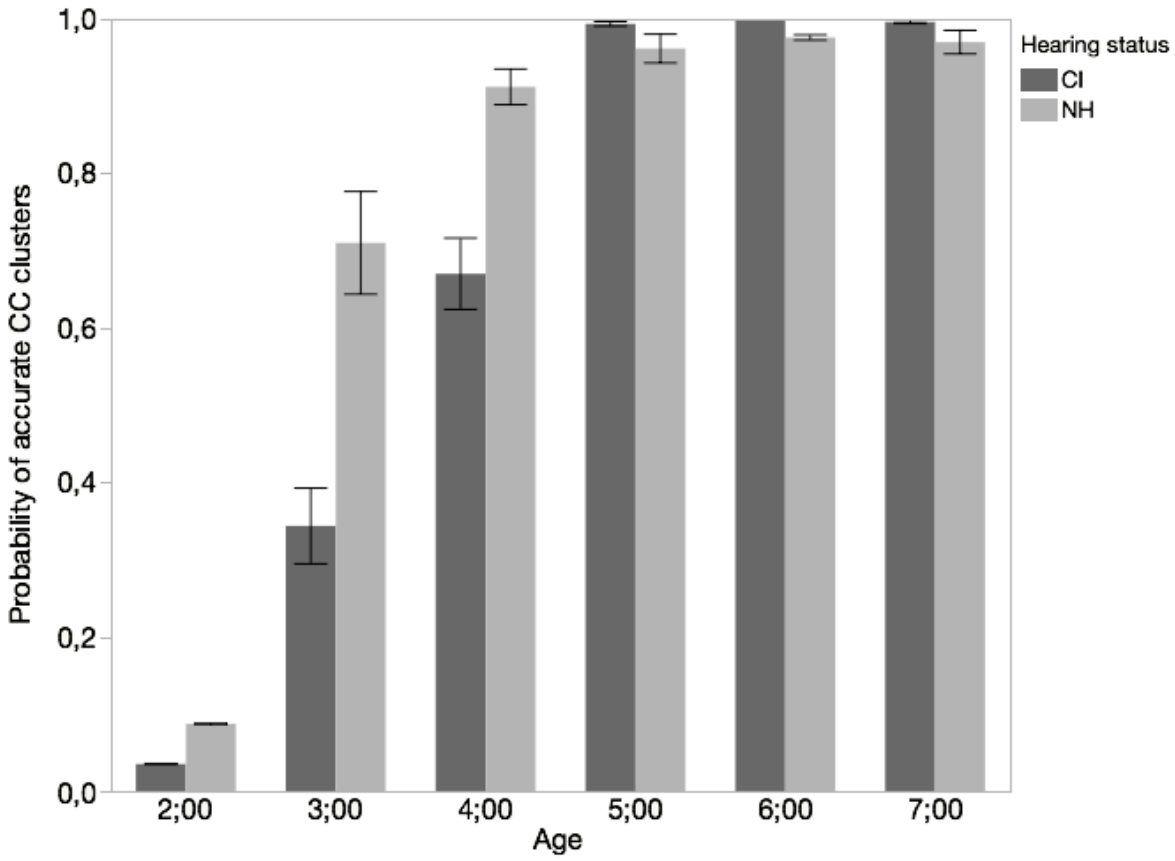

Figure 10. Probability of accurate CC clusters in NH children and children with CI (predicted values)

Types of errors: the likelihood of complete deletion, reduction and simplification

From this section onwards, the cross-sectional comparisons are restricted to ages 2;0, 3;0 and 4;0, as accuracy reaches ceiling percentages from age 5;0. In Table 7, the fixed effect results of the cross-sectional comparisons between NH children and children with CI are presented for the different types of errors). As Table 7 and Figure 11 show, the likelihood of complete cluster deletion is similar in both groups of children at age 2;0 ($p > 0.05$) and could not be estimated after that age, as there were no more deletions from age 3;0 onwards. For cluster reduction, Table 7 and Figure 12 show a significant effect of HearingStatus at age 2;0 ($p < 0.001$): the likelihood of cluster reduction is significantly lower in NH children as compared to children with CI. Hence, cluster simplification is more likely in NH children than in children with CI. From age 3;0 onwards, no significant effects of HearingStatus are found ($p > 0.05$): the difference found at 2;0 has rapidly faded out.

Table 7. Fixed effect results of the cross-sectional comparisons between NH and CI: the likelihood of complete deletion, reduction and simplification

		2;0	3;0	4;0
		Estimate (SE	*Estimate (SE)*	*Estimate (SE)*
Likelihood of complete cluster deletion	*Intercept*	-3.51 (0.57)***	No more deletions occurring in the dataset	
	HearingStatus [NH]	1.04 (0.68)		
Likelihood of cluster reduction (vs. cluster simplification)	*Intercept*	3.13 (< 0.01)***	0.92 (0.56)	-1.85 (0.43)*
	HearingStatus [NH]	-0.62 (< 0.01)***	-0.61 (0.92)	0.20 (0.66)

p ≤ 0.05*, p ≤ 0.01**, p ≤ 0.001***

CI is the reference category

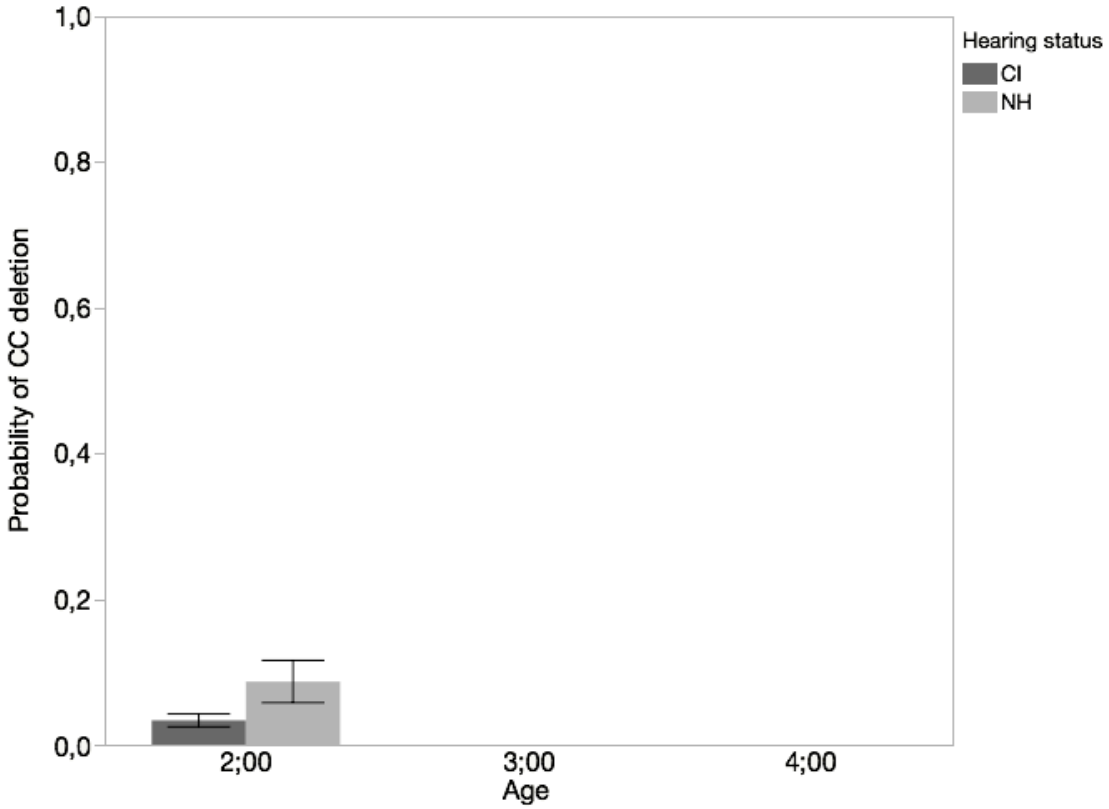

Figure 11. Probability of complete cluster deletion in NH children and children with CI (predicted values)

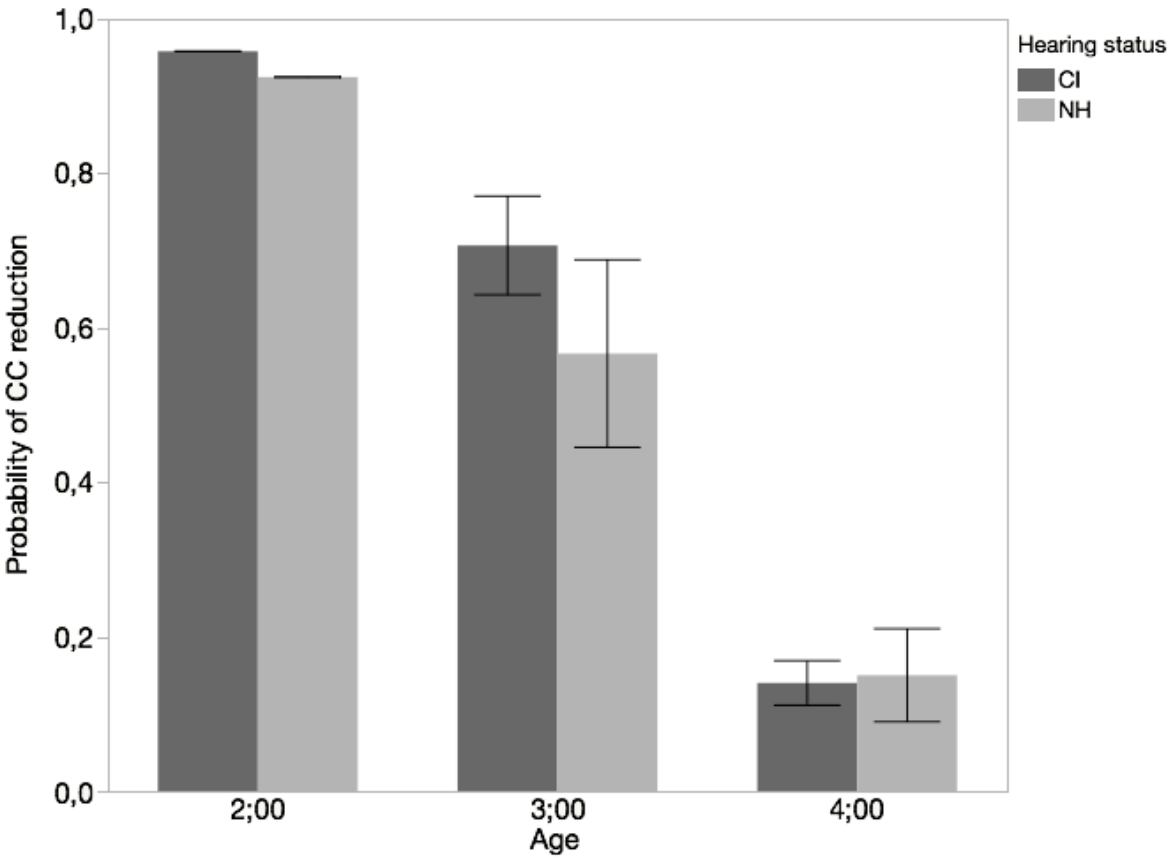

Figure 12. Probability of cluster reduction (vs. cluster simplification) in NH children and children with CI (predicted values)

Reduction processes

The last part of the results presents the cross-sectional comparisons between NH children and children with CI regarding the reduction processes. The statistical models are displayed in Table 8.

The likelihood of reduction to one of the target consonants as opposed to reduction to another consonant is similar at age 2;0 (intercept $p > 0.05$). In addition, there is no difference between both groups of children at this age, as the effect of HearingStatus was not significant ($p > 0.05$). By age 3;0, however, a different picture appears. In children with CI, the likelihood of reduction to one of the target consonants is still not statistically significantly different from that of reduction to another consonant (intercept $p > 0.05$). The NH children, however, differ significantly from children with CI ($p < 0.05$). At age 3;0, the likelihood of reduction to a target consonant is 71.10% in NH children, whereas this is only 47.25% in children with CI. At age 4;0, the effect of HearingStatus was no

longer statistically significant ($p > 0.05$). Moreover, at this age, all children are more likely to reduce to one of the target consonants than to another consonant, as shown by the significant effect at the intercept ($p < 0.001$). The development of both patterns is shown in Figure 13.

When children reduce the CC cluster to one of the target consonants, the sonority hypothesis (SH) predicts that the least sonorous consonant is preserved word initially. Table 8 shows no significant effects of HearingStatus regarding the likelihood of adherence to the SH. This means that children with CI are equally likely to adhere to the SH as NH children at all ages (2;0, 3;0 and 4;0). The development of adherence to the SH is shown in Figure 14.

When children do not reduce a CC cluster to one of the target consonants, the new consonant often comprises features of the target consonants, i.e. coalescence. No significant effects of HearingStatus regarding the likelihood of coalescence are found in Table 8, indicating that coalescence is equally likely in both groups of children at all ages (2;0, 3;0 and 4;0). The development of coalescence is shown in Figure 15.

Table 8. Fixed effect results of the cross-sectional comparisons between NH and CI: likelihood of the different reduction processes

		2;0	3;0	4;0
		Estimate (SE)	*Estimate (SE)*	*Estimate (SE)*
Likelihood of reduction to one of the target consonants	*Intercept*	-0.07 (0.36)	-0.11 (0.16)	1.10 (0.23)***
	HearingStatus [NH]	0.25 (0.46)	1.01 (0.42)*	0.15 (0.61)
Likelihood of adherence to the sonority hypothesis	*Intercept*	4.99 (1.40)***	1.45 (0.32)***	0.49 (0.62)
	HearingStatus [NH]	-2.28 (1.42)	1.92 (1.15)	-0.65 (1.08)
Likelihood of coalescence	*Intercept*	0.61 (0.45)	-0.07 (0.43)	0.39 (0.70)
	HearingStatus [NH]	-0.56 (0.58)	2.04 (1.12)	-0.39 (1.47)

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***
CI is the reference category

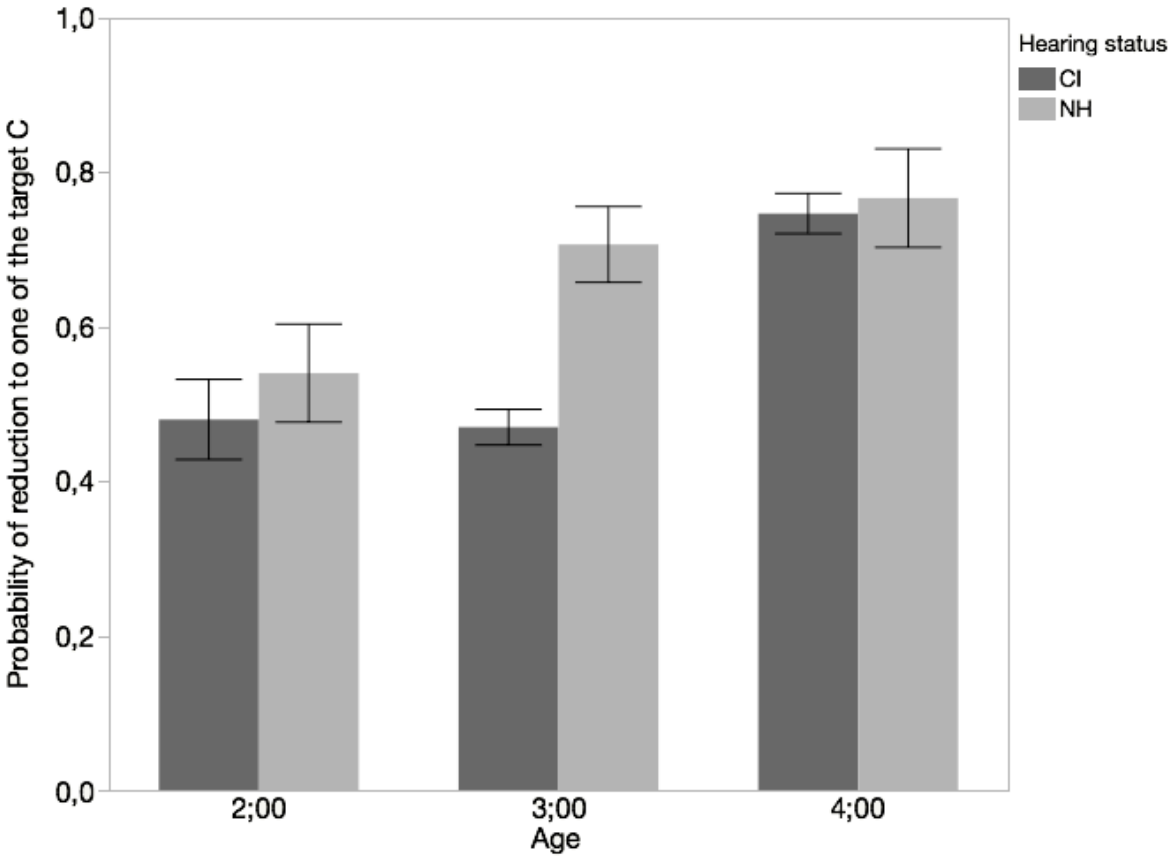

Figure 13. Probability of reduction to one of the target consonants in NH children and children with CI (predicted values)

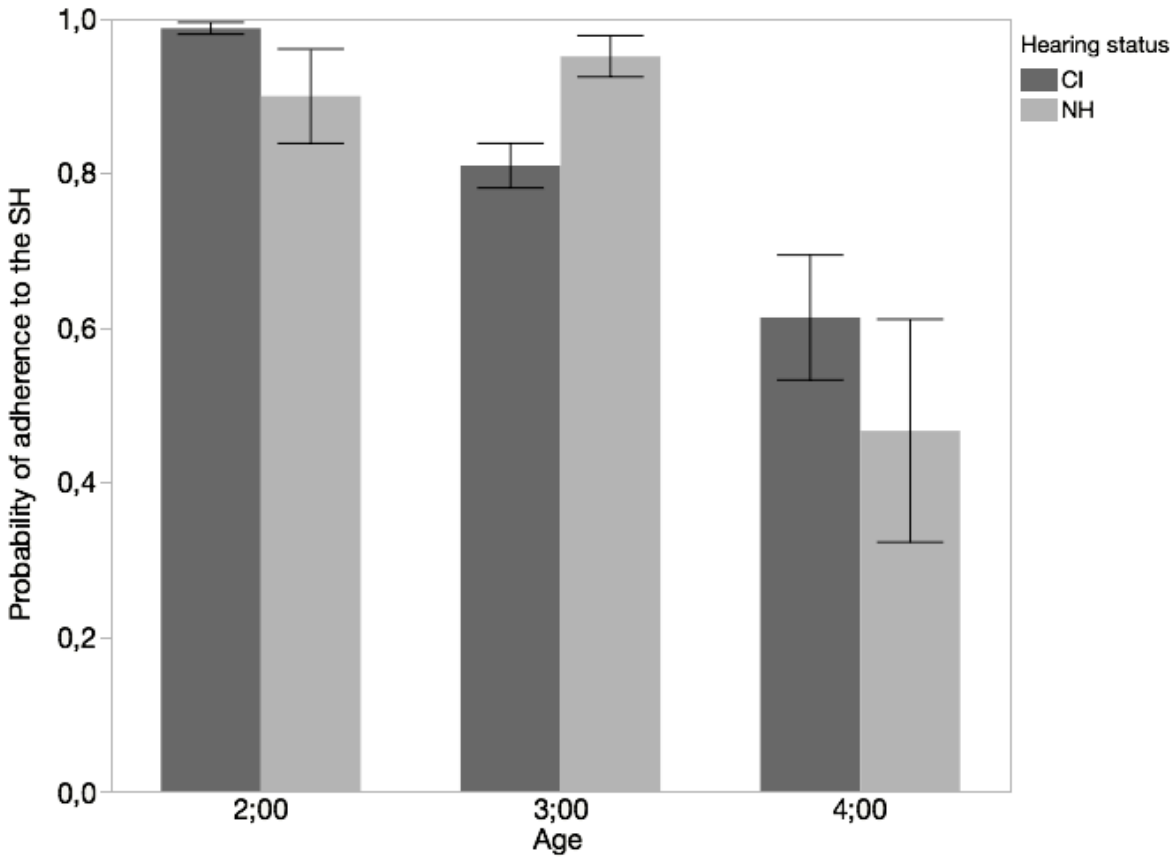

Figure 14. Probability of adherence to the SH in NH children and children with CI (predicted values)

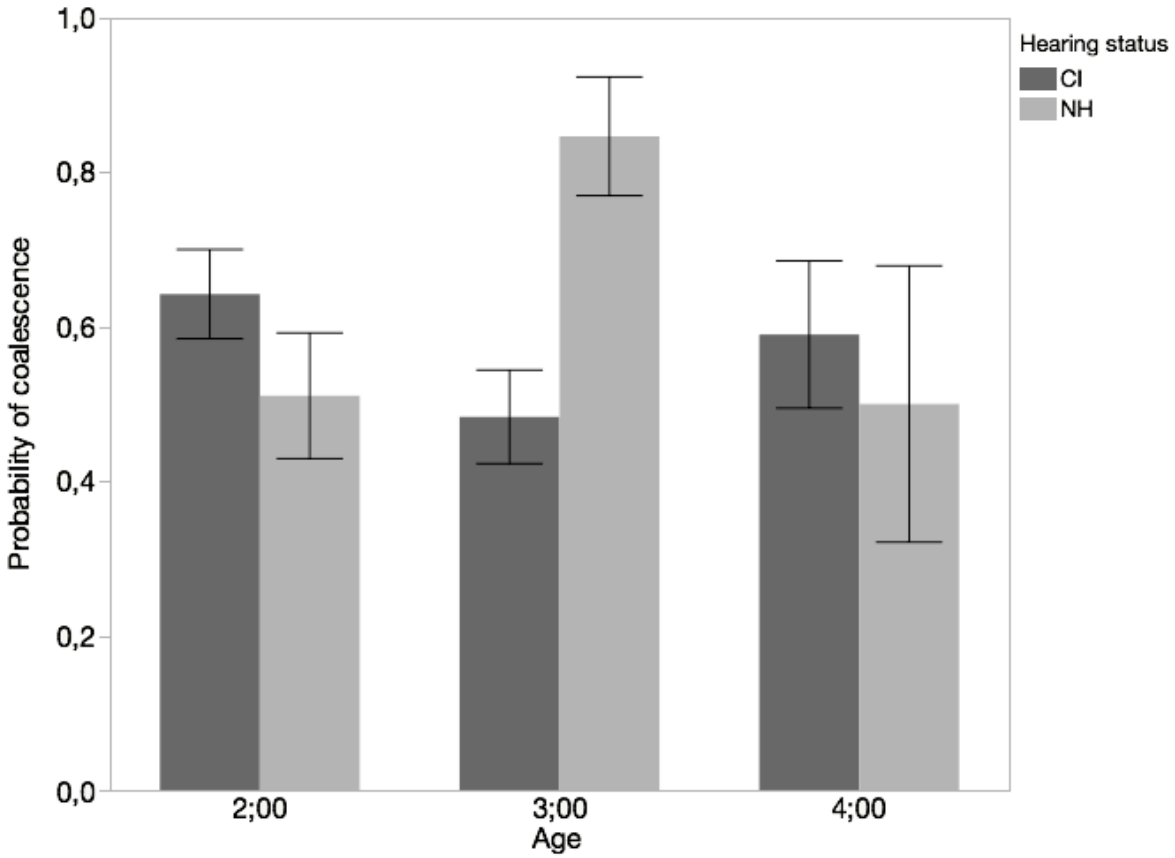

Figure 15. Probability of coalescence in NH children and children with CI (predicted values)

Discussion

The present paper has traced the longitudinal development of word initial CC consonant clusters in the spontaneous speech of Dutch-speaking children with CI. Their use of CC clusters was compared in cross-sectional analyses with a group of age-matched NH children.

Longitudinal analyses of children with CI

The longitudinal analyses of children with CI revealed two main conclusions, the first with respect to development with age and the second with respect to age at implant activation.

Development with age

Our results show that as Dutch-speaking children with CI get older, consonant clusters become more frequent in their spontaneous speech. Their likelihood of producing consonant clusters accurately also increases with age. Thus, with age, they produce more consonant clusters and their consonant

cluster productions become more accurate, which is in line with Chin and Finnegan (2002)'s findings for English-speaking children with CI and those of Phoon et al. (2015) for English-speaking NH children.

With respect to errors, our results show that complete deletion, reduction and simplification of the consonant cluster co-occur in the spontaneous speech of Dutch-speaking children with CI. A similar observation has been made for NH children (Chin, 2007; Fikkert, 1994; Jongstra, 2003; McLeod & Hewitt, 2008; McLeod et al., 2001a) and for English- and Hebrew-speaking children with CI (Adi-Bensaid & Ben-David, 2010; Chin & Finnegan, 2002).

Comparisons between those three types of errors revealed that the complete deletion of the consonant cluster is rare as compared to cluster reduction and cluster simplification. Similar results were found for Hebrew-speaking children with CI up to age 4;5 (Adi-Bensaid & Ben-David, 2010). In contrast, Chin and Finnegan (2002) reported that complete deletion of consonant clusters is absent in English-speaking children with CI at age 9;9. This observation is probably due to the age of the children with CI: our results show that complete deletion of the consonant cluster is absent from age 3;0 onwards, while the children in Chin and Finnegan (2002) were older than nine. Comparisons between the other two types of errors further revealed that, initially, Dutch-speaking children with CI produce their inaccurate consonant clusters as a singleton consonant (cluster reduction), but gradually they produce more consonant clusters, albeit with at least one incorrect consonant (cluster simplification).

Cluster reduction to a target consonant is equally likely than reduction to another singleton consonant, and this remains stable over age. In the literature there is no comparable information about this phenomenon. When children with CI reduce a consonant cluster to one of the target consonants, they adhere to the sonority hypothesis (SH) in approximately 95% of the cases. This is in line with the observations of English-speaking children with CI (Chin, 2006). However, our results show that this adherence to the SH decreases with age. In addition, when a consonant cluster is reduced to another singleton consonant, almost 90% of the productions merge features of the target consonants, i.e. coalescence. In contrast, Adi-Bensaid and Ben-David (2010) found only a few instances of coalescence in Hebrew-speaking children with CI. Our results show that coalescence is

frequent in Dutch-speaking children with CI, which indicates that they have at least some knowledge of the two target consonants (Chin & Dinnsen, 1992). The difference between Hebrew and Dutch might be due to the language-specific input (Yavas, 2013).

Age at implant activation

The age at implant activation affects the production of consonant clusters. Even though the range of ages at implant activation was relatively small in the present study (6 – 21 months), earlier implant activation leads to better outcomes. This finding is in agreement with the observation in the literature that children with CI benefit from early implantation as regards speech production (Leigh et al., 2013) and speech production accuracy (Connor et al., 2006; Schauwers et al., 2008; van den Berg, 2012). Children with later implant activation are less accurate than peers with earlier implant activation, but they catch up as shown by a faster increase of their accuracy rates. Our results suggest that later implanted children are less aware of the target consonants and have poorer suprasegmental representations. For instance, they are more likely to completely delete consonant clusters and the decrease of this type of errors is slower in these children. In addition, a consonant cluster is more often reduced than simplified. Thus, only one consonant is more often produced instead of a(n incorrect) cluster. Moreover, children with CI with later implant activation reduce the consonant cluster less frequently to a target consonant. This adds to our hypothesis that they are less aware of the target consonants. A final indication is the likelihood of coalescence, which is lower in children with CI with later implant activation. As this reduction process is less likely in children with CI with later implant activation, it suggests that those children are less aware of the target consonants as compared to children with CI with earlier implant activation.

Cross-sectional comparisons between children with CI and NH children

The cross-sectional comparisons of NH children and children with CI revealed few differences: children with CI differ from their NH peers only with respect to consonant cluster accuracy, the likelihood of cluster reduction as compared to cluster simplification, and the likelihood of reduction

of a consonant cluster to a singleton consonant that is one of the target consonants. The other measures are similar at all ages in both groups of children (i.e. likelihood of occurrence between ages 2;0 and 7;0 and the likelihood of complete deletion, adherence to the SH, and coalescence between ages 2;0 and 4.0).

The accuracy of the clusters of children with CI lags behind their NH peers up to age 4;0, but by age 5;0, they have caught up and accuracy reaches ceiling percentages in both groups. In contrast to our findings, Fulcher et al. (2014) report no differences between English-speaking CI and NH children at ages 3;0 and 4;0. However, our findings are in line with Von Mentzer et al. (2015), who showed that the accuracy of consonant clusters is lower in Swedish-speaking children with CI as compared to their NH peers. According to Von Mentzer et al. (2015), even at 7;4 years the lower accuracy persisted, while our results show a catch up by age 5;0. A possible explanation for these different findings may be found in the children's task. In the present study consonant clusters were studied in spontaneous speech, whereas Von Mentzer et al. (2015) analysed consonant cluster production in a nonword repetition task that involved the repetition of nonwords after only one auditory presentation, i.e. without any context, referent or lexical representation. Articulatory stability is higher when a nonword is accompanied by a referent, e.g. a picture (Heisler, Goffman, & Younger, 2010), meaning that an out-of-context nonword repetition task is more effortful than a contextualized one. In spontaneous speech, words are produced in a referential context, and those words may be assumed to have lexical representations. Therefore, we assume that the nonword repetition task in Von Mentzer et al. (2015) is more demanding than the spontaneous speech recorded in the present study. This may explain why we have found that both groups of children attain similar accuracy scores at age 5;0, whereas Von Mentzer et al. (2015) still found significantly lower scores for children with CI at approximately age 7;0.

Children with CI are also found to lag behind their age-matched NH peers with respect to the likelihood of cluster reduction (production of a singleton consonant) as compared to that of cluster simplification (production of 2 consonants, at least one of which is incorrect). At age 2;0, children with CI are more likely than their NH peers to produce a reduced cluster, whereas cluster simplification is more likely in NH children at this age. From age 3;0 onwards, differences between

the groups have disappeared. Next, children with CI also lag behind their NH peers concerning the reduction of the consonant cluster to one of the target consonants. At age 2;0, both groups of children reduce a consonant cluster to a singleton that is part of the target cluster in approximately half of their cluster reductions. The switch to more often reducing a consonant cluster to one of the target consonants is already present at age 3;0 in NH children, but is not present until age 4;0 in children with CI.

Children with CI catch up earlier on the number of consonants they produce than on accuracy. The decline of cluster reduction (CV) in favour of the increase of cluster simplification (CCV) concerns a suprasegmental development (i.e. the prosodic structure of consonants clusters), whereas accuracy involves segmental properties (i.e. accurate production of each consonant). Our results show that children with CI catch up earlier on the suprasegmental properties than on the segmental properties. This is in accordance with the literature on overall phoneme production (thus not only consonant clusters). For instance Willstedt-Svensson, Löfqvist, Almqvist, and Sahlén (2004) showed that suprasegmental performance in nonword repetition is better than segmental performance in Swedish-speaking children with CI. Similar outcomes in nonword repetition tasks are found for children with CI acquiring English (Carter, Dillon, & Pisoni, 2002; Dillon, Cleary, Pisoni, & Carter, 2004) and Spanish (Moreno-Torres & Moruno-Lopez, 2014), and in NH Swedish-speaking children (Sundström, Samuelsson, & Lyxell, 2014). Our results apply to spontaneous speech productions of children with CI acquiring Dutch.

Conclusions

The present paper has traced the longitudinal development of consonant cluster production in the spontaneous speech of Dutch-speaking children with CI. Accuracy is shown to increase with age and, hence, the different types of errors decrease with age. In addition, our results suggest that children with CI benefit from earlier implantation and earlier implant activation.

Cross-sectional comparisons between children with CI and age-matched NH peers revealed some group differences. Children with CI lag behind their age-matched NH peers with regard to accuracy

up to age 5;0. In addition, inaccurately produced consonant clusters are more often reduced than simplified in children with CI as compared to NH peers at age 2;0. Furthermore, with respect to cluster reduction, children with CI produce less often a singleton consonant that is one of the target consonants of the cluster as compared to their NH peers up to age 3;0. Nevertheless, children with CI do catch up. They catch up by age 3;0 on the likelihood of cluster reduction and cluster simplification, by 4;0 on cluster reduction to one of the target consonants, and by 5;0, on accuracy. Thus, children with CI seem to catch up earlier on the number of consonants they produce than on accuracy.

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