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Title

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Running title

WI fricative production in NH children and children with CI

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Abstract

Introduction: Fricative production is reported to lag behind in children with cochlear implants (CI) as compared to normally hearing (NH) children in other languages (e.g. English), but not yet for Dutch. In the literature, comparisons are made between children with CI and age-matched NH children. However, phonological development is more closely related to lexicon size than to chronological age. Therefore, we also compare children with equal lexicon sizes.

Method: Word initial fricative development of 10 children with CI and 30 NH children was compared up to 30 months of age, both on chronological and lexicon size (i.e. lexicon size).

Results: Fricative production in children with CI is delayed as compared to that of age-matched NH peers. However, the differences between both groups disappear when they were matched on lexicon size. Thus, the phonological development in children with CI is similar to that of their NH peers with equal lexicon sizes.

Introduction

In the present paper, we aim to compare the early development of word initial fricatives in Dutch-speaking congenitally deaf children with cochlear implants (CI) with that of normally hearing (NH) children. Children with CI have a history of auditory deprivation. After cochlear implantation their speech perception improves (Tyler, Fryauf-Bertschy, Kelsay, Gantz, Woodworth & Parkinson, 1997; Calmels, Saliba, Wanna, Cochard, Fillauw, Deguine & Fraysse, 2004; Leigh, Detmman, Dowell & Briggs, 2013; Liu, Liu, Kirk, Zhang, Ge, Zheng, Liu & Ni, 2015), which has shown to be beneficial for their speech production as well (Blamey, Barry, Bow, Sarant, Paatsch & Wales, 2001; Bouchard, Le Normand & Cohen, 2007; Eriks-Brophy, Gibson & Tucker, 2013; Spencer & Guo, 2013; Faes, Gillis & Gillis, 2016). Despite the positive outcomes of cochlear implantation, the auditory information provided by the cochlear implant is still degraded as compared to the auditory information available in normal hearing, especially in the higher frequency regions (Drennan & Rubinstein, 2008). As high frequency noises, fricatives appear to be particularly vulnerable: 'fricatives are difficult to perceive for people with high-frequency hearing loss due to difficulty extracting high-frequency acoustic cues' (Van Lierde, Vinck, Baudonck, De Vel & Dhooge, 2005, p. 460). Consequently the acquisition of fricatives may be especially challenging for children with CI and therefore may be a more protracted process in comparison with children with normal hearing.

Measures of comparison

In the literature, the language development of children with CI is compared to that of NH children in various ways: chronological age (Nicholas & Geers, 2007; Schramm, Bohnert & Keilmann, 2010; Caselli, Rinaldi, Varuzza, Giuliani & Burdo, 2012; Ertmer, Kloiber, Jung, Kirleis & Bradford, 2012; Eriks-Brophy et al., 2013; Guo, Spencer & Tomblin, 2013; Salas-Provance, Spencer, Nicholas & Tobey, 2013; Von Mentzer, Lyxell, Sahlén, Dahlström, Lindgren, Ors, Kallioinen, Engström & Uhlén, 2015), hearing age (Schramm et al., 2010; Ertmer & Goffman, 2011; Caselli et al., 2012), and language internal measures (MLU: Szagun, 2001; Szagun, 2002, 2004; Expressive vocabulary: Warner-Czyz, 2005) have been used as a basis for comparison. Even though there is a growing tendency to match children with CI and NH children on more than one variable (e.g. chronological age and hearing age: Fagan & Pisoni, 2010; Walker & McGregor, 2013; chronological age and vocabulary size: Lund & Schuele, 2014), NH children and children with CI are often matched on chronological age in order to assess whether children with CI's linguistic functioning is age appropriate (Nicholas & Geers, 2007; Schramm et al., 2010; Caselli et al., 2012; Ertmer et al., 2012; Eriks-Brophy et al., 2013; Guo et al., 2013; Salas-Provance et al., 2013; Von Mentzer et al., 2015). Chronological age is indeed an intuitively appealing measure: a critical question is whether children with CI eventually attain speech and language skills comparable to their normally hearing age mates.

There are numerous factors that affect language development of children with CI (Boons, Brokx, Dhooge, Frijns, Peeraer, Vermeulen, Wouters & Van Wieringen, 2012; Szagun & Schramm, 2016). CI-specific factors include the age at implantation (Connor, Hieber, Arts & Zwolan, 2000; Colletti, Carner, Miorelli, Guida, Colletti & Fiorino, 2005; Schorr, Fox, van Wassenhove & Knudsen, 2005; Connor, Craig, Raudenbush, Heavner & Zwolan, 2006; Levine, Stother-Garcia, Golinkhoff & Hirsh-Pasek, 2016), the residual hearing thresholds before implantation (Niparko, Tobey, Thal, Eisenberg, Wang, Quittner & Fink, 2010; Houston, Stewart, Moberly, Hollich & Miyamoto, 2012; Szagun & Stumper, 2012), the time of implant use (Blamey et al., 2001; Schauwers, 2006; Eriks-Brophy et al., 2013), etc. In general, it can safely be assumed that earlier implantation, better hearing thresholds before implantation and a longer duration of CI use are beneficial for language development in children with CI. The participants in the present study were all young implanted children, i.e. before two years of age. But given children with CI's initial auditory deprivation and later (better) access to speech sounds, it is still to be expected that their onset of spoken language development is delayed as compared to NH children (Svirsky, Robbins, Kirk, Pisoni & Miyamoto, 2000). Therefore, one could question if chronological age is a good basis for comparison. Moreover, age-matched children show a large amount of inter-subject variability (Leonard, Newhoff & Mesalam, 1980; Vihman, Ferguson & Elbert, 1986). Variability

is even more pronounced in children with CI (Svirsky et al., 2000; Duchesne, Sutton & Bergeron, 2009). Thus, it seems that children of the same chronological age have highly variable language levels. As will be shown later, variability is lower when children are matched on lexicon size. Therefore, chronological age may not be the most optimal standard of comparison.

In order to avoid the methodological concern of different onsets of hearing, hearing age is another time-based measure of comparison. In this respect children with the same amount of speech and language experience are compared. In NH children, hearing age corresponds to their chronological age, but in children with CI, hearing age means the time since implant activation, or, in other words, the length of device use. Length of device use appears to be important for the language development of children with CI. For instance Szagun & Stumper (2012) showed that hearing age is a significant predictor of early implanted children's vocabulary growth and mean length of utterance (MLU). However, using hearing age as a measure of comparison is also problematic. Consider a child whose device is activated at 19 months of age. At 24 months of age, this child has a hearing age of 5 months. If, then, this child is compared to NH children matched on hearing age, she is matched with five-month-old NH peers. But, the cognitive, physical and motor development, the articulatory control, etc. - that partly constrain speech production – differ tremendously in a five-month-old and a twenty-four-month-old infant (MacNeilage, Davis, Kinney & Matyear, 2000; Ertmer, Young & Nathani, 2007; Snow & Ertmer, 2009). In other words, comparing children with CI matched for hearing age may be legitimate for some purposes, but comparing children with CI and NH children on their hearing age skews the comparisons and is therefore not optimal.

Language intrinsic measures are sometimes used as an alternative for time-based measures. The idea is to match children on "language age" and to compare particular speech and language abilities relative to that yardstick. Mean length of utterance (MLU) is sometimes used as a proxy for "language age". Another candidate is lexicon size (operationalized as a cumulative vocabulary count). In the literature, lexical and phonological development are shown to be commensurate (Smith, McGregor & Demille, 2006; Stoel-Gammon, 2011; Sosa & Stoel-Gammon, 2012; Van den Berg, 2012; Santos & Sosa, 2015). For instance, Sosa & Stoel-Gammon (2006) pointed out that the development of intraword variability is similar in NH children with the same lexicon size, but not in children with the same chronological age. In a similar vein, the frequency of syllable types in the productions of Dutch-speaking NH children is correlated more readily with lexicon size than with chronological age (Van den Berg, 2012).

A similar lexical-phonological relation is found in children with CI. Vocabulary size, and not chronological age, predicts fricative acquisition in children with CI (Reidy, Beckman, Litovsky & Edwards, 2015). In addition, larger vocabulary sizes are related to a more accurate sibilant fricative production in English-speaking NH children (Nicholson, Munson, Reidy & Edwards, 2015) and children with CI (Reidy et al., 2015). Thus, lexicon size rather than chronological age predicts phonological development in NH children and children with CI. Consequently, when NH children and children with CI matched on lexicon size, are compared, we expect them to have reached a similar point in their phonological development as well. In the present paper, the longitudinal development of word initial (WI) fricatives will be analysed. We expect the accuracy and the error patterns in children's usage of WI fricatives to be similar in children with normal hearing and children with CI matched on lexicon size.

In the literature, the phonological skills of children with CI are mostly compared to those of age-matched NH peers, and not to those of NH peers matched on lexicon size. In other words, even though there seems to be a clear link between lexicon size and phonological development, most literature on phonological development has ignored this relationship. Moreover, in the few studies that matched NH children and children with CI on lexicon size, contrasting results were found. For Dutch, Van den Berg (2012) found that the accuracy of word, syllable, segment productions were similar in children with CI and NH peers matched on lexicon size rather than chronological age. But for English, Warner-Czyz (2005) found that segmental accuracy was higher in NH children than in children with CI, even when matched on lexicon size. Warner-Czyz & Davis (2008) corroborated this finding: NH children outperformed children with CI – matched on lexicon size – at word onset in overall consonant accuracy. These results should be interpreted with some caution due to the small sample size (4 children in each group) and the relatively brief period studied (6 months) (Warner-Czyz, 2005; Warner-Czyz & Davis, 2008). The present paper matches both groups of children on lexicon size and studies them over a period of on average 12 months.

Fricative production of children with CI: comparisons with NH age-mates

As opposed to stops, nasals and glides, fricatives are mostly lacking from NH children's first words (English: Leonard et al., 1980; Stoel-Gammon, 1985; Dutch: Beers, 1995; Van Severen, 2012; Fikkert & Altvater-Mackensen, 2013). Similarly to NH children, fricatives are acquired after stops, nasals and glides in children with CI (English: Serry & Blamey, 1999; Dutch: Schauwers, 2006; Spencer & Guo, 2013; Wiggin, Sedey, Awad, Bogle & Yoshinaga-Itano, 2013). Comparisons between the frequency of fricatives of NH children and

children with CI are lacking for Dutch, but not for children acquiring other languages (Salas-Provance et al., 2013). Age-matched comparisons show that all fricatives have appeared in English-speaking NH children's segment inventories at 42 months of age, while in English-speaking children with CI only /f/, /s/, /z/ and /ʃ/ have been attested by that same age (Salas-Provance et al., 2013). Even though precise frequency differences were not reported, it seems that there occur less different fricatives in children with CI.

With respect to fricative accuracy, Salas-Provance et al. (2013) reported that only /s/ had an accuracy rate of 50% in English-speaking children with CI and the other fricatives were produced less accurately. In contrast, in NH children, not only /s/ but also /f/ had an accuracy rate of 50% by three and a half years of age. Thus, fricative accuracy seems significantly lower in children with CI as compared to age-matched NH children. It should, however, be noted that the sample size was small (5 NH children and 5 children with CI) and that there was a considerable amount of individual variation between the children with CI in Salas-Provance et al. (2013).

Inaccurate production of fricatives results either in a deletion of the fricative or its substitution. Overall, substitutions are more common in Spanish-speaking children with CI as compared to NH peers, but those children were matched at 24 months of hearing age (Moreno-Torres & Moruno-Lopez, 2014). For English, Spencer & Guo (2013) showed that in WI position, substitutions are more likely than deletions in children with CI between 12 and 48 months after implantation. The incidence of fricative deletions and substitutions is not quantified and no comparison of both groups of children on chronological age is provided.

Fricatives are often substituted by stops, a phenomenon called fricative stopping. Stopping is frequently reported in both NH children (Spanish: Macken, 1978; English: Dodd, Holm, Hua & Crosbie, 2003; Dutch: Altvater-Mackensen & Fikkert, 2010) and children with CI (English: Chin, 2003; French: Bouchard et al., 2007; Flipsen & Parker, 2008; Dutch: Baudonck, Dhooge, D'haeseleer & Van Lierde, 2010). Next to fricative stopping, fricative-fricative substitutions are shown to be as common as stopping substitutions in English (Li, Edwards & Beckman, 2009; Holliday, Reidy, Beckman & Edwards, 2015). Neither the likelihood of fricative stopping nor that of fricative-fricative substitution has been compared between both groups of children in the literature on Dutch-speaking children thus far. That is, hence, one of the main aims of the present paper.

To conclude, while in the literature fricative development of children with CI is mostly compared to that of NH age-mates, the present paper considers the matching of both groups of children relative to their chronological age as well as relative to their lexicon size. Moreover, most studies on overall phonological development in children with CI compare those children to age-matched NH children, even though the

literature suggests a strong link between phonological abilities and lexicon size. In the present paper, we aim to compare the WI fricative development of children with CI and NH children on two measures: chronological age and lexicon size. The outcomes of these comparisons are expected to differ. When children with CI are matched with NH children on chronological age, children with CI are expected to lag behind their NH age-mates. In contrast, when both groups of children are matched on lexicon size, we expect different results. In NH children, it is shown that phonological development and lexical development are commensurate. With respect to children with CI, this relationship has only been studied sporadically and the results were contradicting. Thus, it remains to be seen whether there is also a comparably strong relationship between lexicon size and phonological development in children with CI. If so, similar levels of WI fricative development are expected in children with CI and NH children when matched on lexicon size. WI fricative development is studied longitudinally, whereas in the literature, mostly one point in development is considered. Four different aspects are quantified: (1) the frequency of use, (2) the accuracy of WI fricatives, (3) the error patterns (deletion or substitution), and (4) the type of substitutions (stopping).

Method

Participants

A longitudinal approach was taken in order to compare two groups of Dutch-speaking children: children with CI and a control group of NH children. All children were from mid-to-high socioeconomic background living in Flanders, i.e. the northern part of Belgium. The parents were normally hearing monolingual speakers of Dutch.

The corpus of children with CI included ten children with a congenital severe-to-profound hearing loss. In table 1, the demographics of the children with CI are displayed. Before implantation, the mean PTA was 113 dBHL (SD = 8.72) in the better ear. No other patent health, cognitive or developmental problems were reported during data collection. The causes of deafness were genetic (mainly a mutation in the connexion-26 gene, S1, S2, S4 – S7 and S9), a cytomegalovirus infection (S3), and unknown (S8 and S10). Hearing impairment was established following a neonatal hearing screening program (Philips, Corthals, De Raeve, D'haenens, Maes, Bockstael, Keppler, Swinnen, De Vel, Vinck & Dhooge, 2009). As part of the follow-up of the initial diagnosis, all children were fitted with bilateral hearing aids within 1 to 5 months after the detection of the hearing loss and wore those devices for several months. The mean age at fitting of the hearing aids was 4.28 months (SD = 3.12 months) (table 1). In none of the children, however, the hearing thresholds with

hearing aids were sufficient for functional speech sound discrimination. Subsequently, all children received a multichannel Nucleus-24 cochlear implant. The mean age at implantation was 12.05 months (SD = 4.69) and the mean age of implant activation was 13.11 months (SD = 5.39). At 24 months of age, the mean PTA had improved to 40.10 dBHL (SD = 8.24). All children were raised with oral communication and used only a limited amount of lexical signs. Speech samples were collected monthly from one month after implant activation up to 30 months of age. One CI child (S10) dropped out of the study at 25 months of age (13 months of device use). Two children (S7 and S9) received a second CI (Nucleus-24) during data collection, namely at 15 months and 23 months of age.

Insert table 1 over here.

The corpus of the control group included 30 NH children (16 boys and 14 girls), followed longitudinally and monthly from the age of 6 months until 24 months of age. All children had normal hearing, as checked by *Kind&Gezin*, i.e. the Flemish welfare centre, using an otoacoustic emissions test. No patent cognitive, health and developmental problems were reported during data collection. All children scored well above the bottom percentile 1 on the Dutch version of the MacArthur Communicative Development Inventories, N-CDI (Zink & Lejaegere, 2002).

Children with CI are matched with NH peers in two different ways. First, they are compared on chronological age. In other words, the monthly longitudinal data of both groups of children are matched throughout the entire sample: the speech of children with the same chronological ages is analysed. In these analyses chronological age is a predicting variable. Secondly, children with CI and NH children are matched on lexicon size. Thus, children with CI are compared to NH children with equal lexicon sizes. Lexicon size is operationalized as the child's cumulative vocabulary at each consecutive data point. Cumulative vocabulary is computed automatically as follows (Huttenlocher, Haight, Bryk, Seltzer & Lyons, 1991): in the first transcription, a list is composed of all word types (i.e. distinct word forms) that are produced by the child. The cumulative vocabulary at this point is the number of word types in this list. In the second transcription, each word type is compared to the first list and each new word type is added to this list. The cumulative vocabulary of the second transcription than equals the number of word types in this updated list. This is an iterative procedure. We limited the cumulative vocabulary size to 300 word types.

Data collection and transcription

The corpus used in this paper is part of the CLiPS Child Language Corpus (CCLC), which consists of monthly 60- to 90-minute video recordings of spontaneous, unstructured interactions between the child and the (primary) caregiver at the child's home. These video recordings were collected and transcribed as part of earlier studies on child language acquisition in both groups of children (Schauwers, 2006; Molemans, 2011; Van den Berg, 2012; Van Severen, 2012). After the recording, a 20-minute selection was made in order to keep transcription time within reasonable limits. On average, the transcription process lasted 14 hours, from the video recording at the child's home up to the entire transcription and annotation of a 20-minute selection. In the 20-mintute selections, long pauses, noisy passages, etc. were excluded and only completed, finished interactions were selected (Schauwers, 2006; Molemans, 2011; Molemans, Van den Berg, Van Severen & Gillis, 2012; Van den Berg, 2012; Van Severen, 2012).

Each 20-minute selection was transcribed and annotated in CLAN according to the CHAT conventions (MacWhinney, 2000). Only speech samples in which lexical items appeared were analysed. For NH children, this resulted in a corpus from word onset (mean = 13.67 months, SD = 2.01) up to 24 months of age and for children with CI in a corpus from word onset (mean = 18.60 months, SD = 3.06) up to 30 months of age. Each child's word production was transcribed orthographically and phonemically. Phonemic transcriptions were made in DISC-symbols. The target words, i.e. the adult equivalents of children's renditions, were added to the child's productions and were taken from the Fonilex database (Mertens, 2001). After the target words were added, the phonemic transcriptions of both the children's productions and the target words were syllabified. Next, each child utterance was aligned at the segmental level with the target using a script that was based on the ADAPT algorithm (Elffers, Van Bael & Strik, 2005). The alignments were verified manually and corrected if necessary.

After the transcription process, a list of all WI singleton consonants in children's productions with their corresponding adult target was retrieved from the transcriptions. A total of 37,368 word productions, i.e. word tokens, with initial singleton onsets were available (CI: 10,698 word tokens, NH: 26,670 word tokens), of which 5,045 word tokens with target fricatives (CI: 1,620 target fricatives, NH: 3,425 target fricatives). The children themselves produced 2,094 word tokens with WI fricatives (CI: 642 fricatives, NH: 1,452 fricatives), pointing out that other target fricatives were deleted in the children's productions.

Each 20-minute selection was transcribed by one of the people who collected the CCLC (a total of 4 people). Agreement on phonemic transcriptions of fricatives was computed on approximately 10% of the

corpus (Cucchiarini, 1996). Two reliability procedures were followed: (1) intrarater reliability, i.e. retranscription by the same person after at least 3 months, and (2) interrater reliability, i.e. retranscription by one of the other people who collected the CCLC. Kappa scores were 0.75 for interrater reliability and 0.90 for intrarater reliability. These scores can be interpreted as a *substantial* agreement and an *almost perfect* agreement respectively (Landis & Koch, 1977). More detailed information on participants, data collection and data transcription can be found in Schauwers (2006), Molemans (2011), Van den Berg (2012) and Van Severen (2012).

Dutch consonant inventory

The phonemic inventory of Dutch comprises 20 consonants of which there are nine WI fricatives, /f, v, s, z, x, ɣ, h, ʃ and ʒ/ (Booij, 1995). Table 2 gives an overview of the Dutch phonemic consonant inventory.

Insert table 2 over here.

Phonemes in parenthesis only occur as a result of assimilation (e.g., /ʃ/ as an assimilation of /s/ and /j/ in diminutives such as *musje* (mus-DIM, /məʃə/, "sparrow") and/or in loanwords such as the /ʒ/ in *garage* (/ɣɑraʒə/).

Data analysis

WI fricative development is analysed at four different levels. (1) At the first level the incidence WI fricatives is considered. For this purpose, all WI singleton consonants in children's actual word productions were analysed, leaving out empty onsets. The likelihood of fricatives as WI consonants was compared to all other WI consonants. Thus, consider a sample of five WI singleton child consonant productions /b/, /p/, /f/, /b/ and /z/ (for instance for the Dutch target word productions /buk/ (*boek*, "book"), /pus/ (*poes*, "cat"), /fits/ (*fiets*, "bike"), /bal/ (*bal*, "ball") and /ze/ (*zee*, "sea")). The likelihood of WI fricatives in this sample is 2/5. (2) At a second level, the accuracy of WI fricatives is examined. For this analysis, the adult target words with a WI fricative are selected. Each target word is compared to the child's actual production, and this comparison of the adult target and the child's rendition yields a score "accurate" (e.g. /f/ produced as /f/) or "inaccurate" (e.g. /f/ produced as /p/ or deleted). Thus, the likelihood of correctly produced target fricatives is examined and compared to inaccurate productions. (3) At a third level, the child's inaccurate productions are further analysed. If the child does not render the WI fricative in the target word accurately, the likelihood of WI

fricative deletions (e.g. /f/ is not produced, resulting in an empty onset) is compared to that of WI fricative substitutions (/f/ produced as another phoneme, e.g. /p/ or /s/). (4) Finally, at a fourth level, the likelihood of the different substitutions processes is analysed. As our results point out that only fricative-stop substitution (e.g. /f/ produced as /p/) and fricative-fricative substitution (e.g. /f/ produced as /s/) are common in both groups of children (see further), only those two aspects of fricative substitution are discussed. Both fricative stopping and fricative-fricative substitution are evaluated as compared to all other substitution patterns. In other words, when the child substitutes a WI fricative in an adult target, the likelihood of fricative stopping and that of fricative-fricative substitution is computed.

Statistical analysis

Our dataset exhibits a hierarchical structure: at the lowest level we have individual child productions, which are nested within particular ages (observation sessions), which are in turn nested in individual children. Given the hierarchical structure of the data, multilevel models were selected for the statistical analyses. Statistical analyses were performed in R (R Core Team, 2013) by means of logistic regressions in a multilevel model. Multilevel models consist of two parts: a random part and a fixed part. The random part of the multilevel model considers the nesting of variables in the data (Baayen, 2008; Woltman, Feldstain, MacKay & Rocchi, 2012). We allowed random intercepts and slopes to model variation between children and ages. The fixed part represents the predicting variables.

The models were constructed in a stepwise procedure. First, two predicting variables were added as fixed effects (Model 1). The first predicting variable was Hearing status (NH vs. CI). The second one depended of the matching of groups: when matching NH and CI children on chronological age, the second predicting variable was age in months (Age), centred at 24 months of age. When matching on lexicon size, the second predicting variable was cumulative vocabulary (CumulativeVoc), centred at a cumulative vocabulary of 150 word types. Secondly, a quadratic effect of Age/CumulativeVoc was included (Model 2). By means of an ANOVA, the model fit of Model 1 and the fit of Model 2 were tested. If the fit of Model 2 was significantly better, the quadratic effect of Age/CumulativeVoc as a predicting variable was maintained. As will be shown in the Result section, there were no quadratic Age/CumulativeVoc effects in none of the analyses. Thirdly, an interaction between Hearing status and Age/CumulativeVoc was included in the model (Model 3). Again, the model fits were compared by means of an ANOVA. If the model fit of Model 3 was significantly better, the interaction was maintained in the model. Similarly to the quadratic Age/CumulativeVoc effects, the interaction

effects between Hearing status and Age/CumulativeVoc did not improve the model fits in none of the analyses. The best fitting models (Model1) are thus reported in the results section.

In R, the estimates and standard errors (SE) of logistic regressions are computed in logits. Logits can 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). For instance, logit $= 0$ refers to a likelihood of 50%.

(A) Step 1: $\text{odds} = e^{\text{logit}}$

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

Results

Descriptive statistics on the substitution processes

In figure 1, the likelihood of each substitution process is presented in logits for NH children and children with CI, relative to the children's chronological age (age in months) and relative to their "lexical age" (cumulative vocabulary). This graph shows that two substitution processes are well above a likelihood of 10%, namely fricative-stop substitution (i.e. fricative stopping) and fricative-fricative substitution. Therefore, only those two substitution processes are further analysed in the next two paragraphs.

Insert figure 1 over here.

Comparisons on chronological age

In table 3, the fixed effect results of all the analyses of WI fricative frequency are shown in logits. In the left panes of figures 1 – 4, the results are plotted. The grey shaded areas on the figures indicate the confidence interval. The figures are expressed in logits, but the results will be discussed in terms of likelihoods. We present the four levels of analyses consecutively: (1) incidence of WI fricatives, (2) accuracy of WI fricatives, (3) WI fricative deletion versus substitution, and (4) WI fricative substitution, namely fricative stopping and fricative-fricative substitution.

First, with respect to the frequency of fricatives, table 3 and figure 2 display the likelihood of WI fricatives as compared to other WI singleton consonants in children's actual productions. As figure 2 shows, the

incidence of fricatives is low, but increases with age. In addition, figure 1 suggests that the incidence of WI fricatives is lower in children with CI than in NH children, but the development with age seems similar. Inferential statistical analyses (table 3) reveals that the likelihood of WI fricatives is significantly lower as compared to all other consonant manners at intercept ($p < 0.001$). There is a significant increase with Age ($p < 0.001$), showing that the incidence of WI fricatives increases, as children grow older (figure 2). In addition, the effect of Hearing status is significant ($p < 0.05$), indicating that the likelihood of WI fricatives differs significantly in NH children and children with CI. At intercept, 5.42% of the WI consonants are fricatives in NH children, whereas this is only 1.42% in children with CI. No interaction between Age and Hearing status is found, and therefore not included in the best fitting model reported in table 3. Nevertheless, the lack of an interaction effect shows (a) that the development with age is similar in both groups of children, and consequently (b) that children with CI are not catching up in the period studied: their use of WI fricatives remains lower in comparison with NH children.

Secondly, table 3 and figure 3 present the fixed effect results for WI fricative accuracy as compared to inaccurate WI fricatives. As can be inferred from figure 3, the incidence of an accurate WI fricative is relatively low, but seems to increase with age. In addition, children with CI seem to produce their WI fricatives less accurately and their development with age is similar to that of NH children. Inferential statistics (table 3) indicate that the likelihood of accurate WI fricatives is significantly lower than that of inaccurate WI fricatives ($p < 0.001$), as can be derived from the negative logit value of the intercept. No significant increase with Age is found ($p > 0.05$). However, there is a significant effect of Hearing status ($p < 0.05$): the likelihood of an accurate WI fricative is higher in NH children as compared to children with CI (figure 3). More precisely, the likelihood of an accurate WI fricative is 5.73% in children with CI and 18.09% in NH children at intercept.

Thirdly, inaccurate fricatives are either deletions or substitutions. The likelihood of WI fricative deletion as compared to that of WI fricative substitution is shown in table 3 as well as in figure 4. Figure 4 points out that the incidence of WI fricative deletion is not highly different from logit 0, i.e. a likelihood of 50%. Nevertheless, there seems to be a decrease with age. Figure 4 also suggests that children with CI more often delete a WI fricative than their NH peers, but the decrease with age is similar as compared to NH peers. Inferential statistics (table 3) show that the likelihood of fricative deletion is not significantly higher than the likelihood of fricative substitution in children with CI ($p > 0.05$): 59.51% of the inaccurate fricatives are deleted in children with CI at intercept. Even though the likelihood of deletions is lower in NH children (47.38%), the effect of Hearing status is not statistically significant ($p > 0.05$), meaning that there are no

statistically significant differences between both groups of children. Furthermore, there is a decrease of fricative deletion with Age, but this effect is not statistically significant ($p > 0.05$).

Finally, in table 3 and figure 1, the likelihood of fricative stopping and that of fricative-fricative substitution is displayed as compared to all other possible substitution patterns. Figure 1 suggests that the WI fricatives are more often substituted by a stop in children with CI as compared to NH children and that there is a decrease with age. Indeed, inferential statistics (table 3) show that there is a significant difference between both groups of children (Hearing status, $p < 0.05$): the likelihood of fricative stopping is 62.25% in children with CI, but only 34.89% in NH children at intercept. Even though there seems to be a decreasing effect of Age, this effect is only marginally significant ($p = 0.055$). With respect to fricative-fricative substitution, table 3 shows that the likelihood of fricative-fricative substitutions is 15.23% at the intercept. . In addition, the effect of Hearing status is not significant ($p > 0.05$), indicating that the likelihood of fricative-fricative substitution is similar in children with CI and age-matched NH children. There seems to be no significant effect of Age ($p > 0.05$), suggesting that the likelihood of fricative-fricative substitution remains stable with age.

As can be inferred from table 3, the quadratic Age effects and the interactions between Age and Hearing status did not improve the models and are therefore left out and not reported. The lack of significant interaction effects between Age and Hearing status point out that the age effects for each predicting variable are not significantly different for both groups of children. In other words, children with CI do not seem to catch up with their age-matched NH peers by 30 months of age. This can also be clearly derived from the figures: the lines of both groups of children are approximately parallel. Nevertheless, this also shows that the development over time is similar in both groups of children, but later in children with CI.

Insert table 3 over here.

Insert figures 2 – 4 over here.

Comparisons on lexicon size

This paragraph presents the same analyses, but in these analyses, children with CI and NH children are compared relative to their lexicon size. The fixed effect results are presented in table 4. In the right panes of figures 1 - 4, the results are plotted as a function of lexicon size. The grey shaded areas on the figures indicate the confidence interval. The figures are expressed in logits, but the results will be discussed in terms of likelihood.

Table 4 and figure 2 display the likelihood of WI fricatives as compared to all other word initial consonants. As figure 2 shows, the incidence of WI fricatives is low in both groups of children and there seems to be no significant increase with increasing lexicon size. In addition, children with CI do not seem to differ from NH children. Inferential statistical analyses showed a significant negative effect of the intercept (table 4). This indicates that the likelihood of a WI fricative is significantly lower than other WI manners of articulation ($p < 0.001$). There is no significant increase with increasing lexicon size, as the effect of CumulativeVoc is not significant ($p > 0.05$), meaning that the incidence of WI fricatives does not change significantly over the period studied. In addition, there is no significant effect of Hearing status ($p > 0.05$). In other words, the likelihood of WI fricatives is similar in both groups of children.

In table 4 and figure 3, the likelihood of accurate WI fricatives as compared to that of inaccurate WI fricatives is presented. Figure 3 suggests that accurate WI fricatives are infrequent in both groups of children and there seems to be only a slight increase with increasing lexicon size. Moreover, both groups of children seem to attain a similar level of accuracy. Inferential statistical analyses (table 4) point out that the likelihood of accurate WI fricatives is significantly lower than that of inaccurate WI fricatives at intercept ($p < 0.001$). No significant effect of CumulativeVoc is found ($p > 0.05$), showing that the likelihood of accurately produced WI fricatives does not increase significantly with increasing lexicon size. No significant effect of Hearing status is found ($p > 0.05$), indicating that the accuracy of WI fricatives is similar in both groups of children when matched on lexicon size (see also figure 3).

With respect to WI fricative deletion, table 4 and figure 4 display the fixed effect results of the likelihood of WI fricative deletion as compared to WI fricative substitution. Figure 4 shows that the likelihood of WI fricative deletion is around logit 0, i.e. a probability of 50%. There seems to be no important change of the incidence with increasing lexicon size, and no difference between both groups of children. Inferential statistical analyses (table 4) show that inaccurate WI fricatives are equally likely to be deleted than to be substituted ($p > 0.05$) at intercept. No significant effect of Hearing status ($p > 0.05$) is found, indicating that the likelihood of deletions and substitutions is similar in both groups of children. No significant effect of CumulativeVoc is found neither ($p > 0.05$), meaning that there is no significant change of WI fricative deletion with increasing lexicon size.

Finally, table 4 and figure 1 display the fixed effect results concerning fricative substitutions, more precisely fricative stopping and fricative-fricative substitution. The likelihood of fricative stopping is compared to all other substitution patterns. Figure 1 shows that fricative stopping is relatively infrequent in both groups

of children's speech and that there is a decrease with increasing lexicon size. In addition, figure 8 suggests that children with CI less often use fricative stopping. Inferential statistics (table 4) show a significant negative effect of the intercept, which indicates that fricative stopping is significantly less likely than all other substitution processes ($p < 0.05$). The possible substitution patterns (e.g. a fricative substituted by a stop, or by a nasal, etc.) are thus divided more equally when children are matched on lexical age. Even though there seems to be a decrease with increasing lexicon size, this effect is not statistically significant ($p > 0.05$). In addition, all effects are similar in both groups of children, as no significant effect of Hearing status is found ($p > 0.05$) (see also figure 8).

With respect to fricative-fricative substitution, figure 1 suggests that the likelihood of fricative-fricative substitution differs in both groups of children. Inferential statistics (table 4) indeed showed a significant effect of Hearing status ($p < 0.001$). The likelihood of fricative-fricative substitution is 46.03% in children with CI, but only 20.39% in NH children at the intercept. In addition, there is an increase of fricative-fricative substitutions with increasing lexicon size ($p < 0.05$). Thus, fricative-fricative substitutions become more frequent with increasing vocabulary size. This developmental trend is similar in both groups of children, as no interaction between lexicon size and Hearing status is found (and therefore not included in the best fitting model reported in table 4).

Insert table 4 over here.

Discussion

The present study assessed WI fricative development in Dutch-speaking NH children and young implanted children with CI. Spontaneous speech samples of both groups of children were compared from word onset up to 24 months of age for NH children and up to 30 months of age for children with CI. Four aspects of WI fricative development were studied: frequency, accuracy, the incidence of deletions vs. substitutions and that of fricative stopping. Furthermore, children with CI were compared to both age-matched NH peers and to NH peers matched on lexicon size.

Comparisons on chronological age

Overall, the incidence of WI fricatives is low in both groups of children, but there is an increase with age. This finding is in line with the literature suggesting that fricatives are lacking from children's earliest word

productions irrespective of their hearing status (Serry & Blamey, 1999; Chin & Pisoni, 2000; Warner-Czyz, 2005; Warner-Czyz, Davis & Morrison, 2005; Schauwers, 2006; Ertmer & Goffman, 2011; Salas-Provance et al., 2013; Spencer & Guo, 2013). Moreover, the incidence of WI fricatives is lower in children with CI as compared to NH children: 1.64% vs. 5.42% at the intercept. Thus, the incidence of WI fricatives in Dutch-speaking children with CI differs significantly from that of NH age-mates. Similar results are found for English-speaking children with CI (Salas-Provance et al., 2013). In addition, the development of fricative use runs parallel in both groups: WI fricatives remain less frequent in children with CI throughout the period studied, suggesting that children with CI do not seem to catch up with their hearing age mates, but at the same time the developmental path appears to be similar in both groups: the incidence of WI fricatives increases steadily.

The accuracy of WI fricatives is relatively low in both groups of children and remains low in the period studied. However, there is a significant difference between both groups of children: the likelihood of accurate fricative production is 18.09% in NH children, and only 5.73% in children with CI. Furthermore, there is no significant age effect in children with CI. This indicates that children with CI are not catching up on their NH age-mates in the period studied. However, the lack of an interaction between the variables age and hearing status shows that the development of accuracy with age is similar in both groups of children. Thus, children with CI lag behind their NH age-mates not only on the incidence of WI fricatives, but also on the phonemic accuracy of WI fricatives. Salas-Provance et al. (2013) found similar results for English-speaking children.

An explanation for the relative sparseness of fricatives and the inaccuracies in the production of fricatives can partly be found in the degraded perception of these segments, which may be consequential for their production. When perception is degraded at frequencies relevant for fricatives, this may result in greater production difficulties. For instance in older NH adults, Gluth & Hoole (2015) showed that even mild hearing loss affected the distinctness of sibilant fricative production: less accurate perception of /s/ and /ʃ/ led to lower distinctiveness in production. Similarly, the perception in children with CI is affected due to the degraded signal provided by the cochlear implant (Drennan & Rubinstein, 2008). In other words, children with CI perceive the acoustic cues in the higher frequencies relevant for fricatives less well, and this may well be responsible for their less accurate production of these segments. Similarly to Gluth & Hoole (2015)'s outcomes concerning older NH adults, an effect of degraded speech perception on the acoustics of speech production is found in children with CI as well. They produce less contrast between spectral peaks of sibilant fricatives as compared to NH peers so that the distinction between these segments is rendered less clearly (Todd, Edwards

& Litovsky, 2011). In a similar vein, Neumeyer, Schile & Hoole (2015) concluded that children with CI shift the frequency of the first spectral moment of /s/ downwards. As a result, /s/ and /ʃ/ productions are less distinct in children with CI. Thus, there is an overlap of the typical noise frequencies of sibilant fricative productions of children with CI, which is not apparent in NH peers (Liker, Mildner & Sindija, 2007). Neumeyer et al. (2015) hypothesised that the reduced auditory input and feedback in children with CI affects their production of sibilant fricatives. Thus, at an acoustic level, sibilant fricative production of children with CI differs from that of NH children as a result of degraded perception at the higher frequencies. The present study shows, similarly to Salas-Provance et al. (2013), that the production of fricatives is not only less accurate from an acoustic point of view, but also at the phoneme level.

An inaccurate production of a WI fricative is represented by a deletion or a substitution of the target segment. Our results suggest that both error types (deletion and substitution) are equally likely in both groups of children and that there is no effect of age. In other words, there is no significant difference in the likelihood of both error patterns in the period studied between the two groups of children nor does the likelihood of both types of inaccuracy (deletion and substitution) develop with age. These results differ from those reported in the literature to some degree.

Substitution errors were found to be more frequent in Spanish speaking children with CI as compared to NH children (Moreno-Torres & Moruno-Lopez, 2014). However these findings pertain to the substitution of all types of consonants in all word positions and are thus not restricted to WI fricatives, as is the case here. Moreover, these children were not matched on chronological age, but on hearing age. More specifically, the NH children in Moreno-Torres et al.'s study were 24 months of age, while the children with CI were observed at a hearing age of 24 months, which corresponded to a chronological age of 41 months. This discrepancy between the children's chronological ages may impact the results, since developmental constraints on speech production, such as articulatory control, evolve considerably in the period studied (MacNeilage et al., 2000; Ertmer et al., 2007; Snow & Ertmer, 2009). In this respect, substituting a segment, instead of deleting it, requires finer motor control, which is obviously better developed at an older chronological age. This may explain the differences between our results and those of Moreno-Torres & Moruno-Lopez (2014): the chronological ages at which our subjects' speech was analysed, were well below the ones studied by Moreno-Torres et al. (2014) .

Our results also differ from those of Spencer & Guo (2013). They found that in WI position, substitutions – regardless of consonant manner – are more common than deletions in English-speaking children with CI

between 12 and 48 months of hearing age. The mean corresponding chronological ages were between 35 and 67 months of age. In contrast, our results show that both error patterns are equally likely between word onset and 30 months of (chronological) age. The children with CI in the present study have a mean hearing age 12 months, i.e. 12 months of CI use (SD = 5 months) at chronological age 24 months, i.e. the intercept of our inferential statistical analyses. Thus, the age at which our data collection ceased corresponds to the age at which Spencer and Guo (2013) started their data collection. This may suggest that the current study and the study of Spencer and Guo (2013) track two consecutive developmental stages. Initially, deletions and substitutions are equally likely – up to 30 months of age, as indicated by our results -, but gradually, substitutions become more likely than deletions – from 35 months of age onwards, according to Spencer and Guo (2013)'s results.

In addition to the deletion of WI fricatives, these segments are often substituted, mostly by a stop (fricative stopping) or a fricative. The literature shows that fricative stopping is common in NH children as well as children with CI (Macken, 1978; Chin, 2003; Dodd et al., 2003; Bouchard et al., 2007; Flipsen & Parker, 2008; Baudonck et al., 2010; Altvater-Mackensen & Fikkert, 2015). The present study adds to the body of knowledge by indicating that fricative stopping is significantly more likely in children with CI as compared to NH age-mates: the likelihood of fricative stopping is 62.25% in children with CI and only 34.89% in NH age-mates. Furthermore, the likelihood of fricative stopping seems to decrease with age and this decrease is similar in both groups of children. In other words, even though fricative stopping is more frequent in children with CI as compared to their NH peers, the development with age (i.e. a decreasing effect) is similar in both groups of children. Next to fricative stopping, the present study showed that fricative-fricative substitutions are common in Dutch-speaking NH children and children with CI, similarly to English-speaking children (Li et al., 2009; Holliday et al., 2015). In contrast to fricative stopping, our results point out that the likelihood of fricative-fricative substitutions is similar in both groups of children at the intercept.

Compared to NH age-mates, the course of development of WI fricative production in children with CI is similar: the incidence of WI fricatives and their accuracy increase with age. But, children with CI lag behind their NH age-mates: they produce fewer WI fricatives and do so less accurately. As the development with age is similar in both groups of children, this suggests that children with CI are not readily catching up with their NH peers in the period studied. However, Dutch-speaking children with CI have been shown to catch up with their NH age-mates on overall phonemic accuracy (not restricted to WI fricatives) by age five (Faes et al., 2016).

Comparisons on lexicon size

To recapitulate, our results suggest that children with CI lag behind age-matched NH children with respect to WI fricative production, and more specifically for frequency of use, accuracy and incidence of fricative stopping). However, when matching children with CI with NH peers on lexicon size rather than on chronological age, the significant differences between both groups of children disappear. Thus, WI fricatives are equally frequent in NH children and children with CI with equal lexicon sizes. In addition, children with CI produce them as accurately as NH children matched on lexicon size. Furthermore, the likelihood of fricative stopping is similar in both groups of children when matched on lexicon size. In contrast, the likelihood of fricative-fricative substitutions is higher in children with CI as compared to NH children matched on lexicon size.

Thus, the WI fricative development of children with CI is not statistically different from that of their NH peers matched on lexicon size. This outcome corroborates the findings of Van den Berg (2012) who pointed out that (1) the correlation between syllable type frequency and lexicon size is higher than that of syllable type frequency and chronological age, and (2) the overall production accuracy of words, syllables, and segments of children with CI is similar when compared to NH children matched on lexicon size, but not when compared to NH children matched on chronological age. In the present study, fricative accuracy is found to be similar in both groups of children when they are matched on lexicon size. In contrast, Warner-Czyz (2005) and Warner-Czyz & Davis (2008) showed that overall segmental accuracy remains lower in children with CI than in NH children when compared on lexicon size. This discrepancy between the latter studies and the present one may possibly be attributed to differences in the ranges of lexicon size studied. But information about the exact ranges of the lexicon size in Warner-Czyz's studies were not reported, so that further comparisons cannot be made.

Comparison of comparisons

Our results suggest that phonological ability and lexicon size are more closely related to one another than phonological ability and chronological age. NH children and children with CI with equal lexicon sizes show comparable levels of phonological ability and speech accuracy. This is in line with the claim that phonological development is more closely related to lexicon size than to chronological age (Smith et al., 2006; Sosa & Stoel-Gammon, 2006; Stoel-Gammon, 2011; Sosa & Stoel-Gammon, 2012; Santos & Sosa, 2015). In the

present paper, the fricative production of children with CI lags behind that of NH children matched on chronological age, but not that of NH children matched on lexicon size. Thus, children with CI are similar in their fricative productions when they are compared to NH peers with comparable cumulative vocabulary sizes. In addition, acoustic studies on sibilant fricative production showed that sibilant fricative production is best predicted by vocabulary size (Nicholson et al., 2015; Reidy et al., 2015). Thus, fricative production is more related to lexicon size than to chronological age in both groups of children. This observation is explained by the development of phonological representations. Accuracy of phonological representations increases with increasing vocabulary size (Ainsworth, Welbourne & Hesketh, 2015). In other words, the development of phonological representations is related to lexicon size. Accurate phonological representations are indispensible in production. If the phonological representations, i.c. of WI fricatives, become more accurate with increasing lexicon size, this affects also phonological ability, i.c. WI fricative production.

Our findings show a different developmental picture of NH and CI children's production of WI fricatives, depending on the basis of the comparison: are the two groups compared relative to their chronological age or relative to their lexicon size? We showed that children with CI lag behind their NH peers when they are matched on chronological age. However, when both groups of children are matched on lexicon size, children with CI do not lag behind their NH peers. In other words, when matched on chronological age, children with CI differ significantly from their NH peers. However, when matched on lexicon size, there are no statistical significant differences between NH children and children with CI. In the literature, phonological ability and lexicon size have already been shown to be commensurate in NH children. The present paper shows that this is also the case in children with CI. In the early phonological development, children with CI typically lag behind their age-matched NH peers, but are on a par with their NH peers matched on lexicon size. Children with CI should be able to reach similar levels of phonological development as compared to NH peers matched on lexicon size. In other words, when considering the phonological development of children with CI, they are expected to lag behind their age-matched NH children, at least in the age bracket studied here. However, their production of WI fricatives shows the same (or, at least, highly similar characteristics) as the WI fricatives of NH children with a similar lexicon size. Hence, also from a clinical perspective it appears to be of utmost importance to evaluate children with CI's performance not only relative to their chronological age, but also relative to their lexicon size. Children with CI are expected not to be at an age appropriate level straight after CI activation, due to i.a. their early auditory deprivation. But their performance is expected to be comparable to that of NH children matched on lexicon size. Consequently, while an age related delay may be expected,

especially early on in development, a delay relative to lexicon size seems more troublesome, given the outcome of the present study. Several as yet unanswered questions turn up in this respect. First of all, if a child with CI's production is deviant as compared to NH children with the same lexicon size, what does the phonological profile of that child look like? How does it deviate from the profile of NH children? Secondly, how should such differences be interpreted? Should this be considered as a deviant phonological profile or a delayed phonological profile? When should clinicians intervene? These points are open for discussion and further research.

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TABLES

Table 1. Characteristics of the CI group

ID	Gender	PTA unaided	PTA with CI	Age hearing aid fitting	Age 1st CI	Age 1° CI activation	Age first word
S1	F	120	48	9.10	13.49	14.89	20.00
S2	F	120	30	1.13	6.69	7.66	16.00
S3	F	115	33	1.59	10.00	11.66	20.00
S4	M	113	48	10.00	18.16	19.30	20.00
S5	M	93	38	4.79	16.89	17.89	18.00
S6	M	120	53	1.69	8.76	9.66	16.00
S7	F	117	42	4.00	5.16	6.13	15.00
S8	F	112	38	2.00	19.46	21.13	23.00
S9	F	103	28	5.26	8.69	9.69	15.00
S10	F	91↓117	43	3.20	13.23	14.13	22.00
Mean		*113*	*40.10*	*4.28*	*12.05*	*13.11*	*18.50*
SD		*8.72*	*8.24*	*3.12*	*4.96*	*5.39*	*2.92*

PTA = Pure Tone Average in dBHL (decibel hearing level)

Ages are represented in months

↓ = progressive hearing loss

Table 2. Dutch consonant inventory

	Labial	Coronal	Dorsal	Glottal
Stop	p, b	t, d	k, (g)	
Fricative	f, v	s, z (ʃ, ʒ)	χ, ɣ	h
Nasal	m	n	ŋ	
Liquid		l, r		
Glide	w	j		

Table 3. Fixed effect results of the comparisons on chronological age

	Frequency	Accuracy	Deletion	Stopping	Fricative-fricative substitution
Fixed effects	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*
(Intercept)	-4.241 (0.389)***	-2.801 (0.522)***	0.385 (0.390)	0.500 (0.423)	-1.717 (0.567)**
Age	0.133 (0.028)***	0.031 (0.051)	-0.043 (0.051)	-0.113 (0.059)	0.088 (0.083)
Hearing status NH	1.382 (0.429)**	1.291 (0.543)*	-0.490 (0.20)	-1.124 (0.493)*	0.532 (0.617)

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***

CI is the reference category

Table 4. Fixed effect results of the comparisons on lexicon size

	Frequency	Accuracy	Deletion	Stopping	Fricative-Fricative substitution
Fixed effects	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*	*Estimate (SE)*
(Intercept)	-3.875 (0.358)***	-2.455 (0.415)***	0.276 (0.313)	-0.952 (0.389)*	-0.259 (0.369)
CumulativeVoc	-0.010 (0.003)	0.001 (0.001)	0.002 (0.001)	-0.004 (0.002)	0.005 (0.002)*
Hearing status NH	0.489 (0.399)	0.752 (0.466)	-0.276 (0.354)	0.278 (0.474)	-1.203 (0.446)**

$p \leq 0.05$*, $p \leq 0.01$**, $p \leq 0.001$***

CI is the reference category

FIGURES

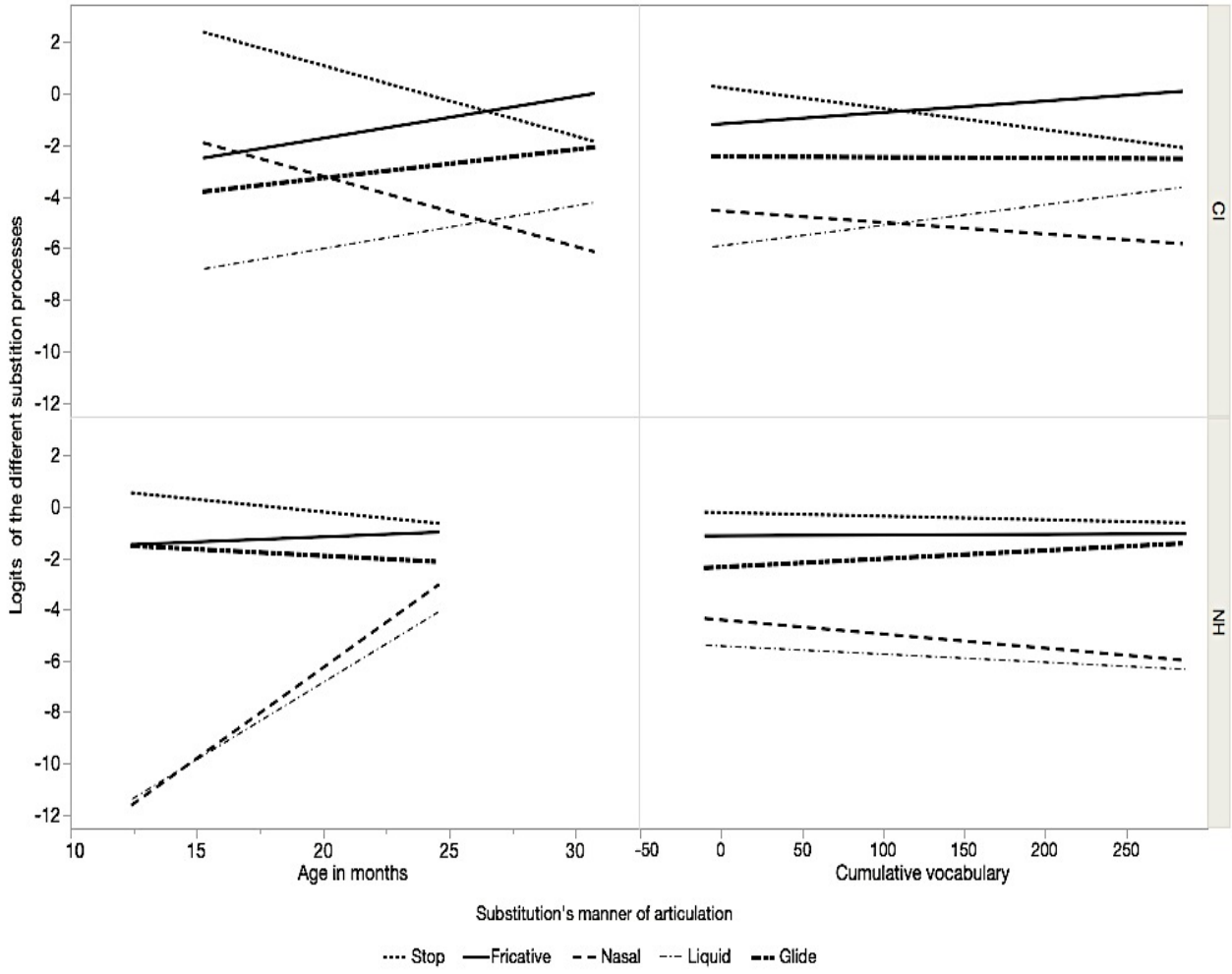

Figure 1. The likelihood of WI fricatives substitution processes (in logits) as a function of chronological age and lexical age in the NH children and in children with CI (predicted values)

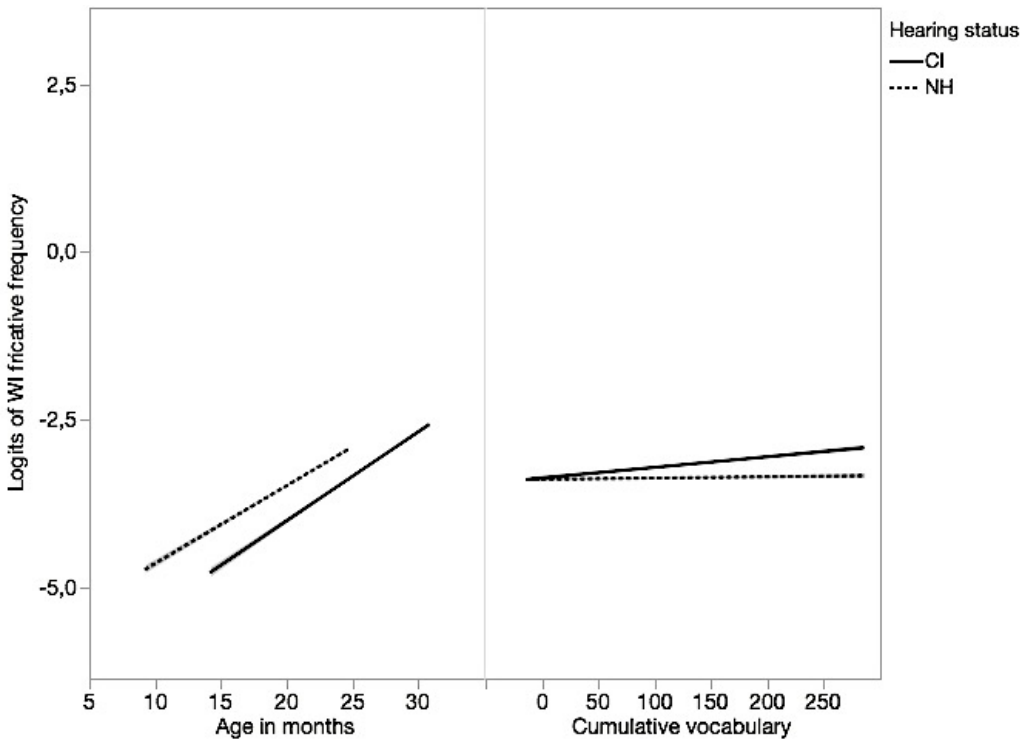

Figure 2. The likelihood of WI fricatives (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)

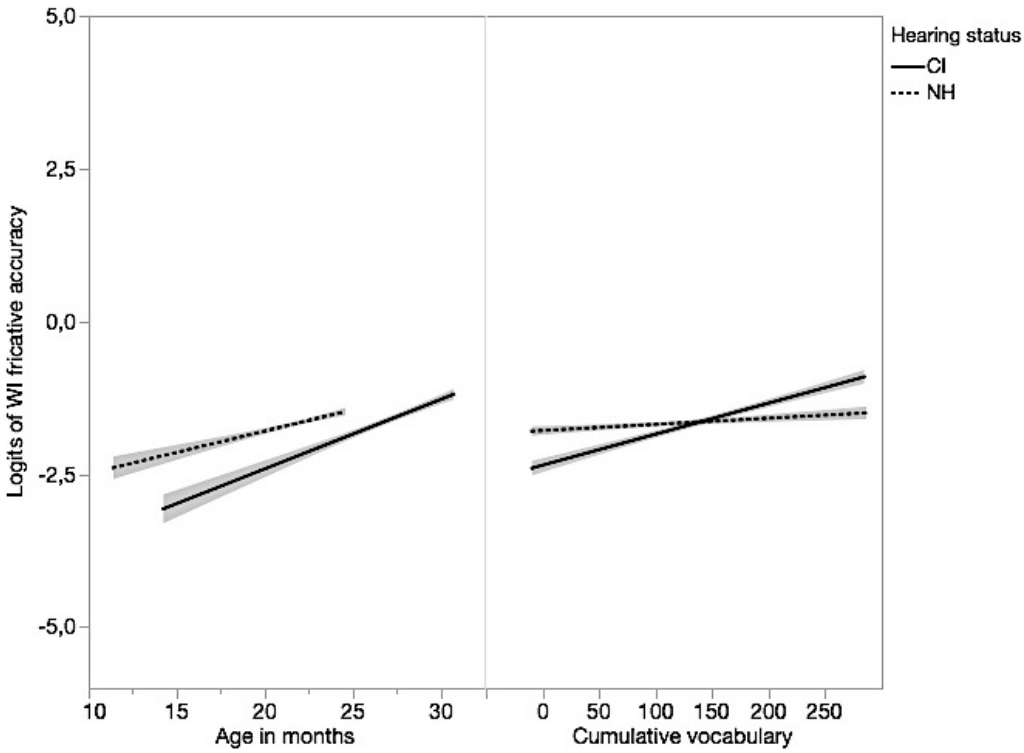

Figure 3. The likelihood of accurate WI fricatives (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)

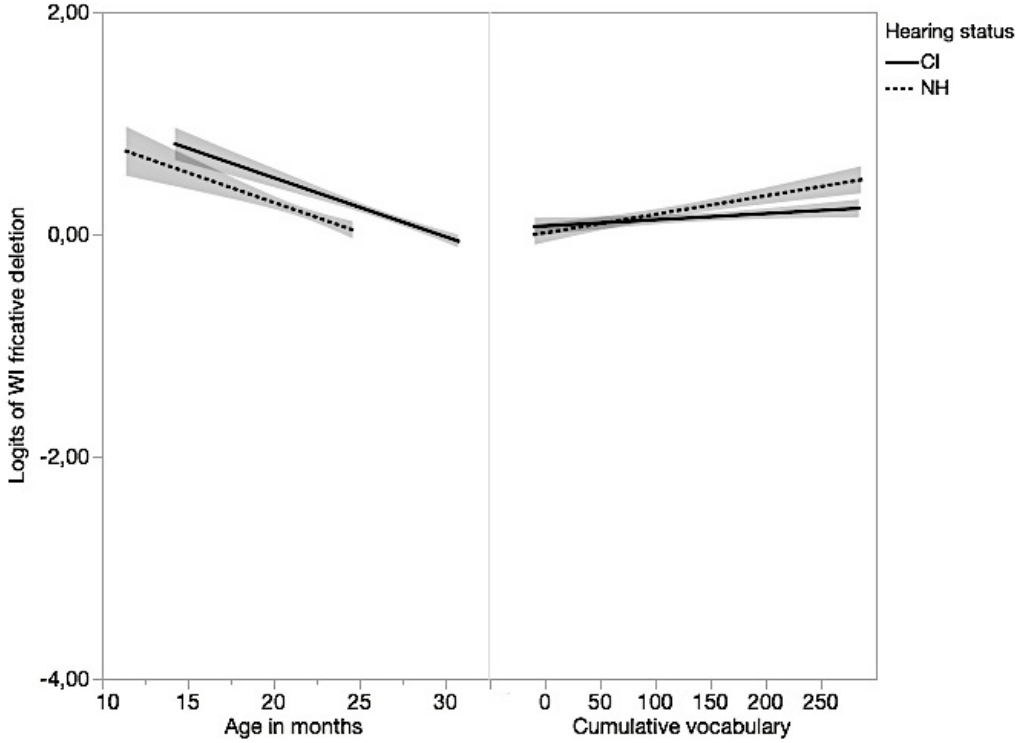

Figure 4. The likelihood of WI fricative deletion (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)

FIGURE CAPTIONS

Figure 1. The likelihood of WI fricatives substitution processes (in logits) as a function of chronological age and lexical age in the NH children and in children with CI (predicted values)

Figure 2. The likelihood of WI fricatives (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)

Figure 3. The likelihood of accurate WI fricatives (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)

Figure 4. The likelihood of WI fricative deletion (in logits) as a function of chronological age and lexical age in the NH children and children with CI (predicted values)