Is the spontaneous speech of 7-year-old cochlear implanted children as intelligible as that of their normally hearing peers?

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Abstract

Objectives: Studies on speech intelligibility usually focus on either individual words, sentences or longer sequences of speech. Since these different kinds of speech samples can be judged using different methodologies, a difference in the reported intelligibility scores can either be due to the difference in the type of sample or methodology. The present study compares the speech intelligibility of seven-year-old children with a cochlear implant (CI) with that of their normally hearing (NH) peers. The first aim is to compare the intelligibility of short sentences and longer sequences of speech using the same methodology. Secondly, it has been suggested that i.a. advances in CI technology and changes in candidacy criteria may have had a positive influence on the intelligibility of children with CI. In order to assess this issue, the intelligibility of seven-year-olds implanted ten years apart will be compared.

Method: The speech of two cohorts of early implanted children with CI (n = 16) and NH peers (n = 16), matched on several criteria but implanted in different years, was collected. More specifically, short and longer samples were selected from recordings of a wordless picture book retelling. Both types of samples were judged on a visual analogue scale by 105 inexperienced listeners.

Results: The results showed that the intelligibility of children with CI was lower than that of their NH peers. Moreover, longer samples were significantly more intelligible than short samples for both groups. No significant effect was found between the two cohorts of children with CI. However, the intelligibility of three out of four children with CI was found to be on a par with that of their NH peers, indicating a large amount of variability between subjects.

Conclusion: Listeners ascribed higher intelligibility to longer samples than to short samples, despite the fact that both types were extracted from the same recordings and listeners followed the same judgement procedure. The amount of context thus facilitated speech decoding. No effect of the calendar year of implantation was found, suggesting that e.g., the evolution in CI technology did not have a significant impact on CI users' intelligibility after six years of device use.

Keywords: Spontaneous speech; Speech intelligibility; Primary school aged children; Cochlear implants

1. Introduction

1.1. Intelligibility of HI children: effect of the length of the utterance

Speech intelligibility is often measured to assess the progress in children's speech development. Especially in children with a (congenitally) hearing impairment, monitoring their speech development is of crucial importance. These children receive a hearing device such as a cochlear implant (CI) at a young age, yet their speech and language development is affected by the period of auditory deprivation, the (remaining) hearing loss and the degraded incoming speech signal [1-3]. Measuring speech intelligibility has been "considered the most practical single index to apply in assessing competence in oral communication" [4].

Despite its indisputable importance, the interpretation of the term intelligibility is often problematic. More specifically, intelligibility and comprehensibility are often not distinguished. However, both terms refer to different processes in the speech chain, the communication process between a speaker and a listener. The speech chain is commonly analysed as consisting of various subprocesses [5]. After detecting the speech stream that is sent by the speaker, the listener segments the speech stream. In other words, the listener recognises speech units in the utterance of the speaker, such as (prosodic) words or phrases [6, 7]. It is only after this initial step that the listener starts to attribute meaning to the utterance. Intelligibility refers to the first step: detecting and identifying units in the speech stream. The second step refers to the mental process in which the listener uses verbal as well as non-verbal cues to fully comprehend the message of the speaker. Therefore, this step is also referred to as comprehensibility [8-11]. We consider speech samples to be intelligible when they are recognised and identified by the listeners. However, we are aware that intelligibility and comprehensibility are intertwined, and that both concepts are often used as equivalents.

Speech intelligibility assessments investigate one or more types of samples, such as isolated words, sentences or longer sequences of sentences in the form of an extended discourse [12]. In most studies, one single type of sample is used to assess intelligibility [amongst others: 6, 13-22]. Only very few studies combine and compare two types of samples [23-25]. For example, Khwaileh and Flipsen [24] showed that the intelligibility scores resulting from a closed-set word identification task were higher than those of an imitated sentence transcription task. However, it also became apparent that transcribing single words was more difficult than transcribing sentences. Thus, minimally two factors contribute to the intelligibility measurements: the task performed by the listeners (e.g., a closed-set identification task, a transcription task or a rating scale task) as well as the difference in the assessed type of sample (e.g., words vs. sentences). In order to ensure that the outcome in intelligibility can only be ascribed to the difference in the type of sample, it was therefore suggested that tasks should only differ on one dimension. For example, in an investigation of sentences as well as longer stretches of discourse, both types of samples should be extracted from the same recordings and should be judged in the same way [24].

To the best of our knowledge, Baudonck, Dhooge and Van Lierde [25] is the only study on the speech intelligibility of primary school aged Dutch speaking children combining sentences and longer stretches of discourse. The stimuli in that study originated from the *Percentage Spraakverstaan* (*Percentage Speech Intelligibility*) test, i.e. the only standardized test to measure the intelligibility of Dutch speaking children [26, 27]. The study showed that 8-to-9-year-old hearing-impaired (HI) as well as NH children reach ceiling levels on both types of speech. This result is in line with other studies suggesting that HI children are catching up with their NH peers [16, 28]. However, the *Percentage Spraakverstaan* test is fairly simple because it was developed for children between 2;6 (years;months) and 4;6. More specifically, the sentence test consists of syntactically simple sentences (e.g., *"de schoenen zitten in de tas"* – English: *"the shoes are in the bag"*) that the participants have to imitate. The test with longer stretches of speech consists of four pictures in which low lexical and syntactic complexity is possible. Considering that 8-to-9-year-old HI children reach ceiling scores on the tasks used by Baudonck, Dhooge and Van Lierde [25], the present study wants to assess NH and CI children's intelligibility using a more complex task. More specifically, the speech material stems from spontaneous speech from which short sentences and uninterrupted sequences of sentences are selected. Thus, the research question is whether short and long samples extracted from the same recordings and judged by the same methodology are equally intelligible.

With respect to the methodology, studies on intelligibility mostly use transcriptions or rating scales. Although both types of tasks measure intelligibility, their approaches are quite different. In a transcription task, the listener is asked to orthographically or phonetically transcribe the child's utterance. This transcription is then compared to the model and analysed in terms of the percentage correct. However, transcriptions do not reflect on other aspects that could potentially influence intelligibility, such as resonance, voice quality and prosody [19, 29]. For example, the listeners cannot indicate that deviant prosody affected the intelligibility negatively or that they had to listen several times before transcribing the utterance. Rating scales, on the other hand, encourage the listener to reflect on the overall intelligibility. This type of task enables the listener to take into account aspects such as resonance, voice quality and prosody, leading to a more subjective yet also more holistic view on intelligibility. Moreover, rating scales are especially suited for measuring the intelligibility of longer samples of speech, since this type of task is far less time consuming than transcriptions. Because of these reasons, the short as well as the long samples in the current study are judged by means of rating scales.

1.2. Intelligibility of HI children: effect of the year of implantation

The population of children with CI is called a “moving target” [30]. Since the beginning of pediatric cochlear implantation, many aspects have changed: the criteria for candidacy as well as technological advances have led to changes in the population of CI children. For instance, in 1994 the youngest Belgian implantees were hardly below 6 years of age, but the age at implantation was lowered to below 6 months of age from 2001 onwards. This means that the length of device use of a seven-year-old CI user, has also potentially shifted from around one year to six years and a half. This shift has led to the idea that “participants no longer represent current clinical practice in pediatric implantation as they were fitted with implants over 10 years ago” [31]. Thus, CI children who are implanted in different calendar years may show different speech outcomes (1) because they vary on aspects such as the length of device use, or (2) because of changes in e.g., the implant technology, medical procedures or rehabilitation practices [15, 32].

One of the very few intelligibility studies that has taken this factor into account is the study of Montag, AuBuchon, Pisoni and Kronenberger [15]. The study aimed at comparing three cohorts of CI users implanted in different calendar years. The cohorts differed in several respects, e.g., chronological age, unaided PTA and the age at implantation. The study showed that the cohort that was implanted in the earliest calendar year – exact calendar years were not provided – had the lowest speech intelligibility. However, this cohort was implanted at an older age than the children in the other cohorts and once age of implantation was entered into the statistical model, no further effect of cohort was found.

In contrast to Montag, AuBuchon, Pisoni and Kronenberger [15], the present study compares the intelligibility of two cohorts of CI users who differed in the (calendar) year of implantation and recording, but whose chronological age, age at implantation and the length of device use at the time of testing are comparable. Differences in intelligibility can thus only be attributed to the difference in the calendar year of implantation. To date, no other study has investigated the relationship between speech intelligibility and the calendar year of implantation while keeping these variables (chronological age, age at implantation and the length of device use) constant. This study wants to fill this void.

1.3. Aims and hypotheses of this study

The first main aim of this study is to compare the intelligibility of short and longer speech samples in children with NH and CI. Previous studies were either limited to one type of sample, used different methodologies or the complexity of the speech task was not age-appropriate for the participating children. Therefore, the present study uses speech recordings from which short sentences (henceforth: short samples) as well as longer sequences of discourse (henceforth: long samples) were extracted. In the recordings, the children tell the story of the wordless picture book "Frog, where are you" [33], also known as the *frog story*. This book has been used in numerous acquisition studies "since it depicts a fairly long and elaborate series of events, and allows narrators to relate to a variety of topics" [34]. Also, "it allows for different levels of cognitive inferencing between events" [34], hence it is appropriate for children of different ages and different levels of narrative and linguistic development. In line with suggestions of previous studies, we expect to find a difference in intelligibility between the short and long samples. More specifically, we hypothesize that the intelligibility of short samples is lower than that of the long samples because the latter provide the listener with more context [15, 35-37].

The second main goal is to investigate whether the calendar year of implantation has an effect on the speech intelligibility of children with CI. Advances in candidacy criteria, changes in CI technology, and the like obviate the need to consider this possibly influencing factor. For this purpose, this study compares two cohorts of CI children that are matched on chronological age, age at implantation and length of device use. More specifically, the speech intelligibility of children who were implanted in the year 2000 is compared with the intelligibility of children who were implanted approximately ten years later. We expect that, amongst other factors, technological innovations in the implant and the speech processing techniques will affect children's speech. Therefore, we hypothesize that the intelligibility of the children implanted more recently will be higher than that of peers implanted ten years earlier [15, 32].

For both aims, children with CI will be compared as a group to children with NH. With respect to the group results, an increasing amount of studies indicates that early implanted children with

CI reach age-appropriate intelligibility scores at primary school age [15, 16, 25]. However, these studies mostly investigated imitated speech, which is known to be more intelligible than spontaneous speech [36, 38]. In the present study, the speech samples originate from spontaneous speech, which possibly leads to lower intelligibility scores for children with CI as well as children with NH.

Within the group of children with CI, the literature suggests that there is a large amount of individual variability [20, 28, 39-41]. For example, in the study of Peng, Spencer and Tomblin [42], half of the participants with CI achieved high intelligibility scores, whereas others remained fairly unintelligible. Therefore, besides the group results, this study will consider the individual variability as a possibly influencing variable within the cohorts (see §3.2. *Intelligibility: individual variability analysis*).

2. Method

In this study, the intelligibility of two cohorts of children with a cochlear implant (CI) is assessed with short as well as long samples. Moreover, the speech of the children with CI is compared to age-matched normally hearing (NH) peers. This study was approved by the Ethics Committee for the Social Sciences and Humanities (SHW_15_37) of the University of Antwerp. The parents or caregivers of the participating children were informed about the goal of the study and gave their written informed consent.

2.1. Stimuli

Speech samples of sixteen congenitally hearing-impaired children (ten boys, six girls) with CI were used in the present study. All children met the following criteria: (1) they were approximately 6-8 years old at the time of the recordings, (2) were implanted before the age of 24 months, (3) had been using their device for at least 5 years, (4) were raised mostly orally and were native speakers of Dutch, living in Flanders, the northern, Dutch speaking part of Belgium and (5) had no other patent health related problems besides their hearing loss and attended a mainstream primary school.

The study group consisted of two cohorts of children who matched these criteria, yet differed in the calendar year of their implantation. The seven participants in the first cohort received their implant in the year 2000 (designated as CI1-CI7 in Table 1, henceforth: cohort-2000). These children were selected from the patient population of the ENT unit of the Sint Augustinus

Hospital of Antwerp. At the time of the recordings, they were on average 7;1 (years;months) (SD = 0;1). They were implanted at a mean age of 1;01 years (SD = 0;5). Four children underwent sequential bilateral implantation, on average 4;0 years (SD = 2;1) after the first implant, at a chronological age of 4;11 (SD = 2;5). On average, the children had been using their first implant for 6;0 years (SD = 0;6) at the time of the recording and had on average 2;2 years (SD = 2;5) of bilateral experience. Prior to implantation, their average hearing loss was 113 dB HL (SD = 9 dB HL (decibel hearing level)). Their average aided hearing thresholds was 33 dB HL (SD = 9 dB HL). All children received the Nucleus 24 implant with the Nucleus Freedom speech processor of Cochlear®. The bilaterally implanted children (except for CI6) received the Nucleus Freedom implant as their second device, combined with the Nucleus Freedom speech processor. Child CI6 was implanted bilaterally with the Nucleus 24, also combined with the Nucleus Freedom speech processor.

The second cohort consisted of nine children (CI8-16 in Table 1, henceforth: cohort-2010), implanted around one decennium later. These children were recruited with the help of the Institute for the Deaf (KIDS), Hasselt (Belgium), where they attended kindergarten before going to a mainstream primary school. Some children were recruited via an association for parents of children with CI. At the time of the recording, they were on average 7;3 years (SD = 1;0). They were implanted at a mean age of 0;11 years (SD = 0;5). All children were implanted bilaterally: seven children underwent sequential bilateral implantation; two children were simultaneously implanted bilaterally. On average, the children had been using their first (or simultaneously bilateral) implant for 6;4 years (SD = 1;0). For the sequentially implanted children, the bilateral implantation took place 2;0 years (SD = 1;8) after the first implant, at a chronological age of 2;11 (SD = 2;0). At the time of recording, they had been using their bilateral implant for 4;8 years (SD = 2;2). Prior to implantation, the children's average hearing loss was 114 dB HL (SD = 9 dB HL). Their average hearing thresholds wearing the CI was 26 dB HL (SD = 7 dB HL). All children except CI11 and CI13 received the Nucleus Freedom implant bilaterally. These children all used the Nucleus 5 or 6 speech processor. CI11 received an Advanced Bionics® implant and CI13's sequential bilateral implant was the Nucleus Profile. Detailed information on cohort-2000 and cohort-2010 is provided in Table 1. Wilcoxon rank sum tests showed that several factors did not differ significantly for cohort-2000 and cohort-2010, viz. chronological age at the time of recording ($z = 0.000$, $p = 1.000$), age at implantation ($z = 0.428$, $p = 0.668$), length of device use ($z = –0.477$, $p = 0.634$) and aided hearing thresholds ($z = 1.489$, $p = 0.137$).

Child	**Age at implantation (years;months)**	**Calendar year of implantation**	**Age at recording (years; months)**	**Calendar year of recording**	**Length of device use (years; months)**	**PTA unaided (dB HL)**	**PTA aided (dB HL)**	**Implant type**	**Speech processor**
CI1	1;2 (6;3)	2000	7;1	2006	5;11	120	35	Nucleus 24 & Freedom	Nucleus Freedom
CI2	0;10 (5;10)	2000	7;1	2007	6;3	115	25	Nucleus 24 & Freedom	Nucleus Freedom
CI3	1;6	2000	7;1	2006	5;7	113	42	Nucleus 24	Nucleus Freedom
CI4	1;5 (6;4)	2000	7;1	2006	5;8	93	32	Nucleus 24 & Freedom	Nucleus Freedom
CI5	0;9	2000	7;2	2006	6;5	120	37	Nucleus 24	Nucleus Freedom
CI6	0;5 (1;3)	2000	7;1	2007	6;8	117	17	Nucleus 24	Nucleus Freedom
CI7	1;7	2000	7;0	2006	5;5	112	42	Nucleus 24	Nucleus Freedom
CI8	0;7 (0;7)	2013	5;8	2018	5;0	120	19	Nucleus Freedom	Nucleus 6
CI9	0;10 (1;8)	2010	8;8	2018	7;10	120	33	Nucleus Freedom	Nucleus 5
CI10	0;10 (1;11)	2012	6;11	2018	6;1	120	20	Nucleus Freedom	Nucleus 6
CI11	1;7 (1:7)	2012	7;1	2018	5;6	120	15	AB HiRes 90K	Naída CI Q70
CI12	0;7 (2;2)	2012	6;4	2018	5;9	106	23	Nucleus Freedom	Nucleus 6
CI13	1;7 (7;3)	2011	7;9	2018	6;2	120	35	Nucleus Freedom & Profile	Nucleus 5&6
CI14	0;10 (1;9)	2011	7;9	2018	6;11	114	27	Nucleus Freedom	Nucleus 6
CI15	0;9 (2;10)	2012	6;8	2018	5;11	114	35	Nucleus Freedom	Nucleus 6
CI16	0;11 (2;8)	2010	8;8	2018	7;9	95	27	Nucleus Freedom	Nucleus 6

Table 1: Characteristics of the CI children (between brackets in the second column: age at second implant; dB HL: decibels hearing level)

Sixteen NH children (ten girls, six boys) participated as a control group. These children were also native speakers of Dutch and attended a mainstream primary school. The children were recorded at an average age of 7;2 years (SD = 0;7), which is comparable to the chronological age of the children with CI (Wilcoxon rank sum test: z = –0.11382, p = 0.9094). In order to obtain a balanced sample, the same number of CI and NH children were included in this study. Moreover, for both hearing statuses, two age cohorts were collected. Similar to the group of children with CI, the recordings of the NH children were performed one decennium apart: seven NH children were recorded in 2006 or 2007, which is the same time frame as the CI children from cohort-2000. The other nine children were recorded around ten years later, i.e. in the year 2018, which is the same year of recording as the CI children of cohort-2010. Therefore, the NH cohorts will also be referred to as cohort-2000 and cohort-2010. The hearing of both NH cohorts was tested in the first weeks of their life as part of the Universal Neonatal Hearing Screening (UNHS) and showed no impairment.

2.2. Selection of the stimuli

The picture book "Frog, where are you" [33] was used in the audio recordings. Prior to the recordings, the children were allowed to look at all the pictures to grasp the idea of the story. Next, the children were instructed to tell the story to the researcher and/or a present caregiver as if they had never heard the story. The recordings were made in a quiet setting in the comfort of the children's home or school. The researcher (or caregiver) was allowed to guide the children through the story, but the children were encouraged to tell the story independently.

For the purpose of this study, short and longer samples were extracted. For the short samples, in order to be eligible for study, the utterances had to be syntactically complete and contain roughly seven words. Utterances were not eligible if they contained long pauses, nonsense words (e.g., *bomboe* [bɔmbu:]) or revisions (e.g., *"en dan gaan die, dan vallen die in het water"* – English: *"and then they go, they fall into the water"*). Of the eligible utterances, a random selection of ten short samples per child was made. In total, there were 320 short samples with a mean length of 6.96 words (SD = 0.97). The length of the short samples was comparable for cohort-2000 and cohort-2010 (Wilcoxon Rank Sum Test: z = –0.71018; p = 0.4776).

Three long samples of each child were selected, resulting in 96 long samples. The long samples were around 30 seconds long and were comparable in length for both cohorts (Wilcoxon Rank Sum Test: z = 1.86499; p = 0.0622). The number of words uttered by the children in both cohorts was also comparable (Wilcoxon Rank Sum Test: z = –1.51453; p = 0.1299). For some children, it was impossible to select long samples without interference of the researcher or the caregiver. If this was the case, samples containing the least contextual information of the researcher or caregiver were selected, yet their utterances were not excluded in order to preserve the coherence of the sample. On average, the long samples consisted of 49 words of the child and 12 words of the researcher or caregiver. Examples of the short and long samples are provided in Table 2.

Short samples
▪ de hond kijkt ook naar de kikker *(the dog also looks at the frog)* ▪ de schoenen staan op de grond *(the shoes are on the floor)* ▪ de hond rent weg van de bijtjes *(the dog runs away from the bees)*
Long sample
*CHI: en dan komen de bijen op de hond af *(and then the bees are coming towards the dog)* *CHI: en de jongen kruipt ondertussen bij de boom *(and the boy crawls in the meantime near the tree)* *CHI: en kijkt eens in het gat *(and looks in the hole)* *CHI: wat er zou kunnen zitten in de boom *(what there could be in the tree)* *RES: mhm *(uh-huh)* *CHI: en dan komt vliegt daar een uil uit *(and then there comes flies an owl)* *CHI: en dan valt het jongetje uit de boom *(and then the boy falls out of the tree)* *CHI: en dan opeens vliegen al de bijen achter de hond aan *(and then suddenly all the bees are chasing the dog)* *CHI: omdat die daar aan is gekomen aan de korf *(because he touched it the hive)* *CHI: en dan dan dan wacht die tot de uil weg gaat *(and then then then he waits until the owl goes away)* *CHI: en dan gaat die proberen op de steen te staan *(and then he tries to stand on the stone)*

Table 2: Examples of three short samples and one long sample including a literal English translation (*CHI = child utterance; *RES = researcher utterance)

2.3. Procedure

A total of 320 short samples and 96 long samples were selected from the recordings. This selection was divided into five series and entered in the online tool Qualtrics®, Version 2018 (Qualtrics, Provo, UT). For the short samples, this resulted in 64 utterances per series, i.e., two utterances of each child per series. For the long samples, four series contained 19 samples and the last series contained 20 samples. The same number of samples of NH and CI children was included in each series. In addition, it was ensured that the three long samples of each child were distributed among three different series. Within the series, the stimuli were presented in the same order to all listeners.

One hundred and five listeners participated in this study. Each series was judged by at least 20 listeners. Each listener completed one series. They were all native speakers of Dutch and language students at the University of Antwerp. They were, on average, 23 years old (SD = 5 years), had no experience with the speech of HI individuals and self-reported to have no hearing problems. The students performed the experiment on campus, in a computer lab wearing headphones. For the purpose of this study, they were instructed to judge the short as well as the long samples on a visual analogue scale (VAS). Figure 1 is a screenshot of the rating scale. The design was rather straightforward: the scale did not contain any numbers but only two extremes that were labelled “fully unintelligible” and “fully intelligible”. The middle of the scale was marked with dashes. The slider’s default starting position was on the extreme left, from which the participants could move the slider to a point on the scale which they judged appropriate. The listeners could listen three times to the short samples before judging. The long samples could only be heard once.

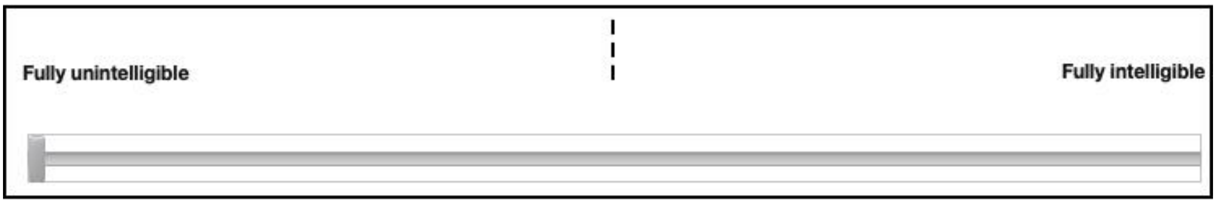

Figure 1: Screenshot of the VAS rating scale (translated labels)

2.4. Data analysis

The position on the VAS scale was first transformed into a numerical value between 0 (for the position “fully unintelligible”) and 100 (for the position “fully intelligible”). For the first part of the results section, these scores were the dependent variable in the statistical analyses, which were performed in JMP Pro®, Version 14.0 (SAS Institute Inc., Cary, NC). Statistical analyses were done by means of mixed models. This type of analysis is especially suited for hierarchical structured data. The hierarchy in this study is present in the children as well as the listeners. On the one hand, there are random effects. In the present study, these are the individual listeners, the individual children and the utterances that are nested within the individual children. These effects are random since a random selection from the population of children and listeners who meet specific selection criteria was made. Concerning the utterances, a random selection out of all possible (eligible) utterances was made. On the other hand, there are fixed effects, i.e. predicting variables. In this study, these effects are Hearing status (with values NH and CI), Cohort (with values cohort-2000 and cohort-2010), Type of sample (with values short and long) and Chronological age. The latter factor is included in the study since this factor has been shown to contribute to the children's speech and language outcomes [39]. For the analyses, a significance threshold of $p < 0.05$ was set. Prior to the analyses, the number of caregiver utterances was entered as a fixed effect in the subset of long samples. However, this factor did not affect the rating scale scores significantly ($p = 0.69$). Hence, this factor was not further considered in the analyses.

The second part of the results section discusses the individual variability between the children with CI. For this purpose, an individual estimated rating scale score of each child is calculated using the function *ranef* from the R package *lme4* [43]. This function calculates the estimated deviance from the intercept for each child, based on the null model containing only the individual children as a random effect.

3. Results

3.1. Intelligibility: main effects analysis

The aim of this study is to measure the intelligibility of short and long samples in normally hearing (NH) children and children with a cochlear implant (CI). Moreover, this study investigates whether the intelligibility of two cohorts of CI users differs. The intelligibility of the children was measured by means of a rating scale, leading to a numerical dependent variable. The statistical model is reported in Table 3 and contains the fixed effects that are of interest to this study (Hearing status, Type of sample, Cohort and Chronological age) and their interactions. The parameter estimates of this model are reported in Table 4.

The tables show two significant effects, i.e. Hearing status and Type of sample. In brief, these results indicate that the intelligibility of NH and CI children differs significantly and that the intelligibility of short and long samples differs significantly. It is however striking that one of the main variables, i.e. Cohort, does not have a significant effect on the intelligibility scores. In what follows, the results will be discussed in more detail.

	DFDen	F Ratio	Prob > F
Hearing status	26.9	8.386	0.007
Type of sample	367.9	7.673	0.006
Cohort	26.0	3.126	0.089
Chronological age	25.1	0.017	0.898
Hearing status * Type of sample	367.8	0.557	0.456
Hearing status * Cohort	25.0	1.886	0.182
Hearing status * Chronological age	25.0	0.001	0.975
Type of sample * Cohort	370.0	0.015	0.903
Type of sample * Chronological age	369.3	0.653	0.420
Cohort * Chronological age	25.0	0.479	0.495

Table 3: Results mixed model containing the fixed effects Hearing status, Type of sample, Cohort and Chronological age and their interactions

	Estimate	Std. Error	DFDen	t Ratio	Prob>|t|	95% Lower	95% Upper
Intercept	75.220	90.454	25.1	0.83	0.414	–111.020	261.461
Hearing status [CI]	–6.299	2.175	26.9	–2.90	0.007	–10.764	–1.835
Type of sample [short]	–2.119	0.765	367.9	–2.77	0.006	–3.623	–0.615
Cohort [cohort-2010]	5.444	3.079	26.0	1.77	0.089	–0.885	11.773
Chronological age	–0.139	1.075	25.1	–0.13	0.898	–2.353	2.074
Hearing status [CI] * Type of sample [short]	0.566	0.759	367.8	0.75	0.456	–0.926	2.058
Hearing status [CI] * Cohort [cohort-2010]	–3.006	2.189	25.0	–1.37	0.182	–7.514	1.502
Hearing status [CI] * Chronological age	–0.009	0.277	25.0	–0.03	0.975	–0.579	0.561
Type of sample [short] * Cohort [cohort-2010]	0.096	0.794	370.0	0.12	0.903	–1.464	1.657
Type of sample [short] * Chronological age	0.083	0.102	369.3	0.81	0.420	–0.118	0.283
Cohort [cohort-2010] * Chronological age	0.751	1.085	25.0	0.69	0.495	–1.484	2.986

Table 4: Parameter estimates of the fixed effects and their interactions

The first significant factor of the model in Table 3 and 4 is Hearing status. The results show that the intelligibility of children with CI is significantly lower than that of NH children ($p = 0.007$). Thus, around the age of seven, children with CI are less intelligible than their NH peers. For this study, NH and CI children were matched on their chronological age at the moment of testing and hence, there is only little variability in the chronological ages of the children. Nonetheless, because the factor is often suggested to be significant in previous studies, it was entered into the model. However, chronological age did not improve the model significantly, and hence it cannot be considered as a significant predictor or fixed effect.

The second significant factor in the model in Table 3 and 4 is Type of sample ($p = 0.006$). More specifically, the intelligibility of the long samples is rated to be significantly higher than that of the short samples. Interestingly, the interaction between the factor Hearing status and Type of sample is not significant, suggesting that the increase in intelligibility that occurs for long samples is comparable for children with NH and CI, as is visualised in Figure 2.

A post hoc analysis in which the hearing statuses are paired with the types of samples is presented in Table 5. This analysis shows that the intelligibility of children with CI differs significantly from that of NH children in three respects. First of all, the intelligibility of the CI children's short samples is significantly lower than that of the short samples of NH children ($p = 0.042$) as well as NH children's long samples ($p = 0.002$). Also, both groups' long samples differ significantly ($p = 0.026$). In terms of VAS scores, the children with CI reach an estimated VAS score of 57, resp. 60, whereas the NH children reach estimated scores of 70, resp. 75. The only non-significant pair is the comparison between the long samples of the CI group and the short samples of the NH group ($p = 0.269$). Considering that, in both groups, intelligibility increases for the longer samples, this result indicates that the intelligibility of CI children's long samples has increased enough to be on a par with the intelligibility of the short samples of NH children.

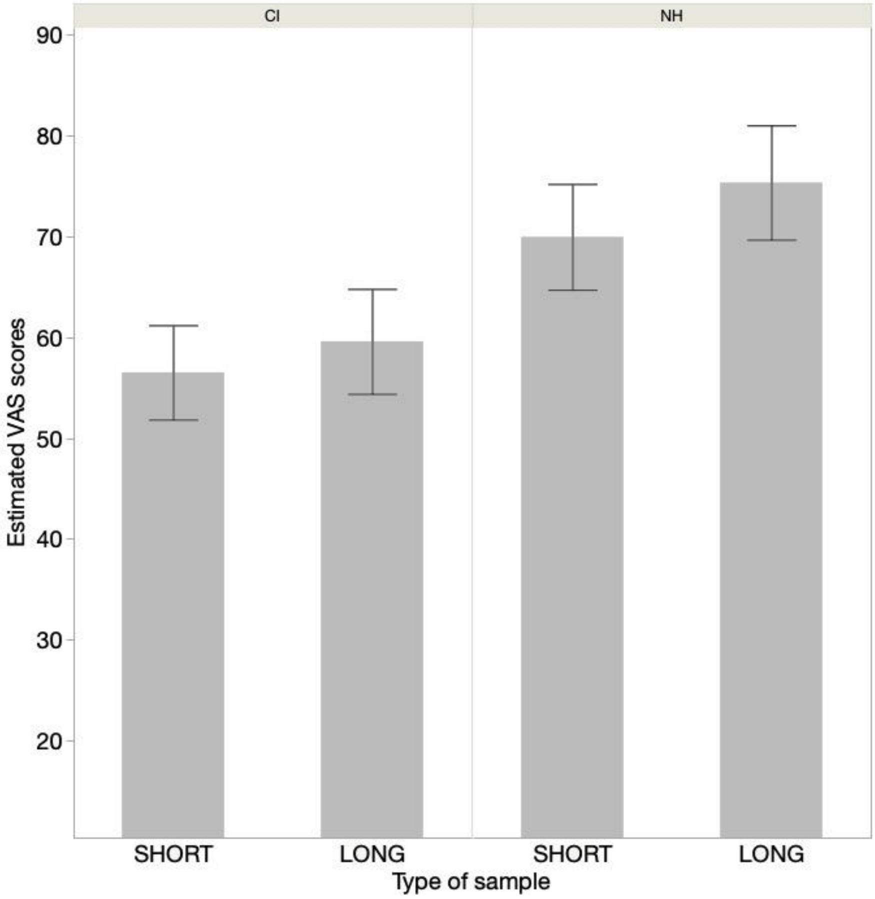

Figure 2: Estimated scores on the visual analogue scale for children with CI and NH, taking into account the type of sample (error bars indicate standard errors of the mean)

	Difference	**Std. Error**	**t Ratio**	**p**	**lower 95%**	**upper 95%**
CI_Short - NH_Short	–11.467	4.330	–2.65	0.042	–22.642	–0.291
CI_Short - NH_Long	–16.836	4.612	–3.65	0.002	–28.738	–4.934
CI_Long - NH_Long	–13.730	4.869	–2.82	0.026	–26.297	–1.164

Table 5: Post hoc pairwise comparisons using Tukey HSD for the factors Hearing status and Type of sample, only significant results

Furthermore, the mixed model contains the factor Cohort (with values cohort-2000 and cohort-2010). However, neither the main factor nor any of the interactions including this factor, has a significant effect on the results ($p > 0.05$). This means that the judgements of listeners of the intelligibility of children's speech does not reflect a difference between the two NH cohorts nor between the two CI cohorts. This result is confirmed by the post hoc pairwise comparisons. In the group of children with CI, as well as in the group of NH children, there is no significant difference between cohort-2000 and cohort-2010 ($p > 0.05$). However, both CI cohorts differ significantly from NH children, as is reported in Table 6. Thus, we can conclude that the intelligibility of children with CI, whether they are implanted around the millennial change or ten years later, reach comparable scores which are lower than those of NH children.

	Difference	**Std. Error**	**t Ratio**	**p**	**lower 95%**	**upper 95%**
CI_cohort-2010 - NH_cohort-2010	–18.610	5.204	–3.58	0.008	–32.925	–4.296
CI_cohort-2000 - NH_cohort-2010	–23.487	6.183	–3.80	0.004	–40.495	–6.478

Table 6: Post hoc pairwise comparisons using Tukey HSD for the factors Hearing status and Cohort, only significant results

3.2. Intelligibility: individual variability analysis

The results showed a main effect of hearing status in that the estimated intelligibility of children with CI was lower than that of NH peers. However, in line with other studies on the speech of children with CI, the results show a large amount of intersubject variability, as is displayed in Figure 3. Therefore, the aim of this section is to investigate whether particular children with CI reach age-appropriate intelligibility scores.

The individual scores of the children with CI and NH were plotted in Figure 3, which already indicates a large amount of overlap between the children with NH and the children with CI. This preliminary observation is confirmed by the estimated individual scores. For the children with NH, the mean score is 71.12 (SD = 10.92). The results show that seven children with CI score within 1 SD of the mean score of the NH children. Of these children, two children (CI13 and CI16) even score above the average score of 71.12. Another five children with CI score within 2 SDs of the mean score of the NH children. Thus, in total, twelve children are within 2 SDs. Considering that the sample consisted of sixteen children, this means that three out of four children with CI score within the normative ranges of NH children. Only one out of four scores below these ranges. These children have lower intelligibility scores than the least intelligible NH child. No effect of cohort is found in these results.

Taken together, this study provides evidence that most children with CI reach age-appropriate intelligibility scores. The CI group is characterised by a large amount of intersubject variability, but this variability can mostly be ascribed to the children with the lowest scores. Thus, there seems to be a discrepancy within the CI group: on the one hand, there are children that are on a par with their NH peers, but other children do not (yet) reach those levels of speech intelligibility.

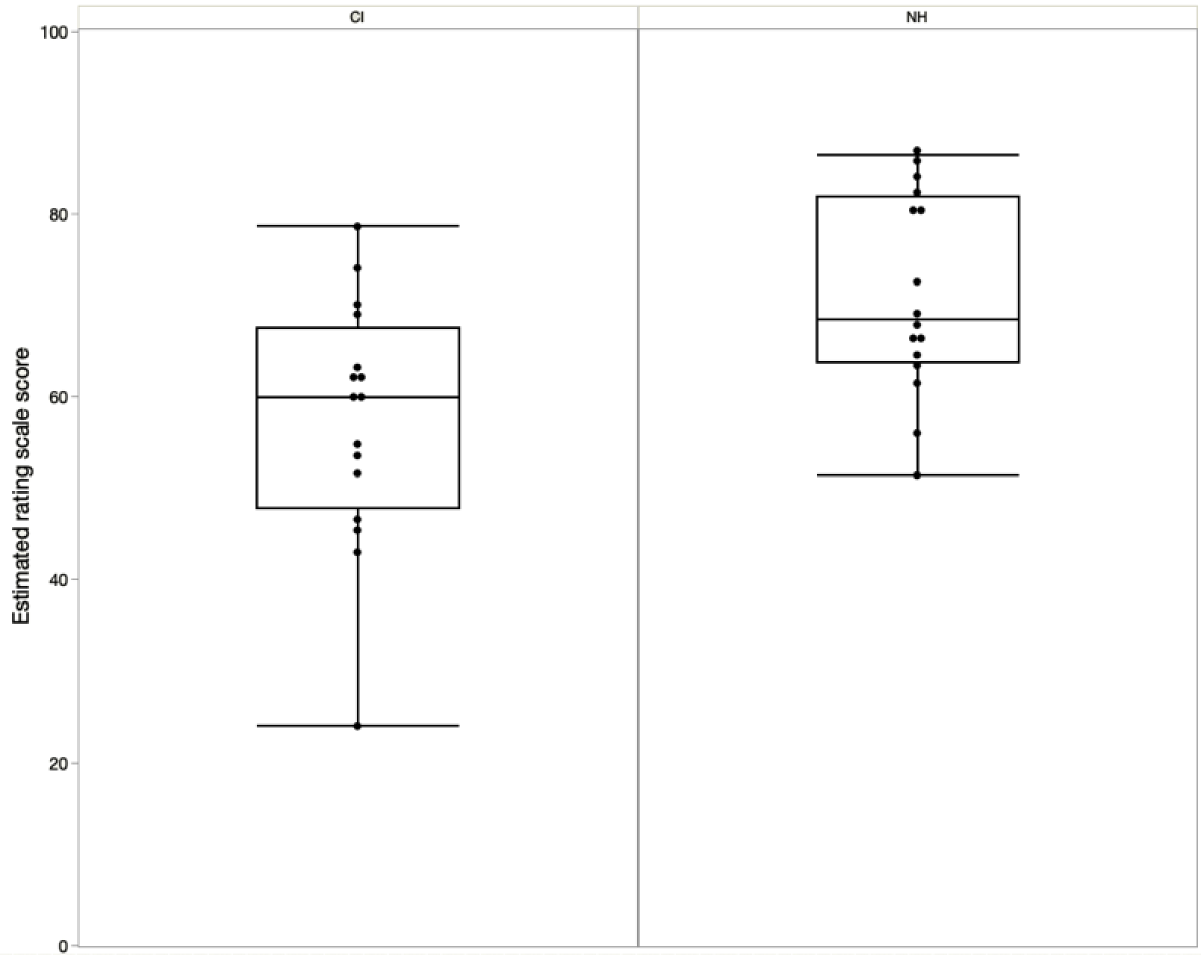

Figure 3: Estimated rating scale scores for CI and NH children (based on individual estimated scores (each dot represents the estimated intelligibility score of an individual child))

4. Discussion

In this study, the intelligibility of seven-year-old normally hearing (NH) and cochlear implanted (CI) children was investigated. The first main aim was to compare the intelligibility of short and long speech samples. The second aim of this study was to investigate the effect of the calendar year of implantation, by comparing two age-matched cohorts of children with CI who were implanted in different years, i.e. cohort-2000 vs. cohort-2010.

Deviances in intelligibility between children with NH and CI

The focus of the current study was to compare the intelligibility of children with NH and CI with respect to different factors. One of the main factors affecting speech intelligibility was hearing status. The results showed that the intelligibility of both groups of children differed significantly. Even though the children with CI were implanted at a very young age and already had about six years of device experience, their overall estimated intelligibility was lower than that of NH peers. At first sight, this result seems to suggest that the children with CI in our sample did not reach age-appropriate scores, which would contradict other studies [16, 25, 28].

However, it should be noted that children with CI showed a larger degree of intersubject variability. This should be taken into account when interpreting the results of this study. More precisely, the results showed that three out of four children with CI reached intelligibility scores within 2 SDs of the mean intelligibility score of the NH children. Thus, these children reached age-appropriate scores. The fact that the CI group showed high intersubject variability and that some children reached age-appropriate scores, whereas others did not, is in line with other studies [12, 44-46].

Speech intelligibility of short and long samples

One of the main research questions was whether the intelligibility of short and long samples differed and whether the effect of the length of the sample differed for children with NH and CI. The results showed that long samples were rated as more intelligible than short samples. Because both types were extracted from the same recordings and judged on the same rating scale by the same listeners, this result strongly indicates that the mere presence of more context led to this result. The fact that a higher degree of context probably leads to a higher intelligibility was already suggested in previous research [15, 35-37]. Interestingly, the effect was found to a similar extent in both hearing statuses. In other words, there is an improvement in intelligibility between short and long samples and this improvement is similar for children with NH and CI.

Effect of the year of implantation

The second aim of this study was to investigate the effect of the calendar year of implantation. Now that pediatric cochlear implantation has become a standard procedure in particular HI individuals, the question arises whether changes in e.g., the implant technology and the candidacy criteria have affected the children’s speech. In other words: are children with CI whose implantation took place in different decades still comparable with respect to their speech and language outcome or did a shift take place? Thus, there is a need for comparisons between cohorts that are implanted in different calendar years.

If these comparisons show differences between the cohorts, this result would strongly suggest that technological advances or changing candidacy criteria have an influence on speech outcome measures. For example, the study of Montag, AuBuchon, Pisoni and Kronenberger [15] consisted of three cohorts implanted in different calendar years and showed that the cohort of CI users that were implanted first had the lowest speech intelligibility. However, this cohort also had the oldest age at implantation and this factor was shown to be highly predictive of the intelligibility score. Besides the age at implantation, the cohorts also differed in, for example, their length of device use at the moment of testing and their chronological ages. In the present study, two cohorts of children that only differed in the calendar year of implantation and recording were included. At the time of the recording, the two cohorts had the same chronological age, the same length of device use, etc. By matching the cohorts on these parameters, the only difference was the calendar year of implantation and its possible consequences with respect to e.g., the changes in the implant technology, the medical procedures and rehabilitation practices. For the NH children as well, two cohorts were recorded around the same time as the children with CI.

The results did not show a significant effect of cohort. In other words: the intelligibility of the two cohorts was comparable. For NH children, this result was to be expected. For children with CI, this result suggests that the change of devices did not influence their intelligibility scores. The fact that the speech intelligibility outcomes in seven-year-old children have not changed significantly for children implanted in the early 2000’s and ten years later is in contrast to Montag, AuBuchon, Pisoni and Kronenberger [15] where the cohorts did perform differently. However, in the study of Montag, the CI users were implanted up to 21 years prior to the assessment and the cohorts were not matched on parameters such as age at implantation, length of device use and chronological age. Exact calendar years are not provided, yet it is very likely that the implantations took place in the early stages of pediatric cochlear implantation in the 1990s, whereas the present study contained children implanted in 2000 and 2010. Future studies should consider including a greater time span between the years of implantation of different groups of CI children while controlling for chronological age at testing.

Clinical implications and limitations

The results of this study suggest that the intelligibility of children with CI is lower than that of their NH peers. This is the case for short as well as long samples. Thus, after six years of device use, the speech of early implanted children with CI still shows deviances compared to NH peers. Therefore, this study emphasizes the need to continue providing speech and language therapy to children with CI on a long-term basis with the target of reaching the child's full potential in terms of intelligibility. Considering that most children scored within NH children's range, the therapy should not be limited to learning to adapt to a hearing life, but should contain all the elements and goals of traditional speech therapy for normally hearing children. The study also shows that long speech samples were rated as more intelligible than short speech samples, suggesting that an increase in context affects intelligibility positively. In clinical practice, children with CI thus have to be taught how to express themselves elaborately considering that this increases intelligibility.

Moreover, the intelligibility of the short and long samples increased to a similar extent for NH and CI children. Hence, future studies could be narrowed down to one type of sample, i.e. either short or long speech samples. Because of several reasons, short samples would be preferred over long samples. First of all, judging short samples is less time-consuming than judging long samples. Secondly, short speech samples can easily be investigated by means of transcription tasks. This type of task could offer a reliable and feasible alternative measurement for children's intelligibility [47, 48]. For long (spontaneous) speech samples, transcriptions would be extremely time consuming and complex [24, 48, 49]. Thus, when comparing the different types of samples, spontaneous short samples have the advantage of realistically representing everyday speech without the disadvantages of long samples.

Finally, a number of important limitations of the present study need to be considered. First of all, the number of participating children was rather small. The cohorts included seven, respectively nine children. Despite creating homogeneous groups of CI children by matching on aspects such as chronological age, hearing thresholds, implantation age and length of device use, there was a high degree of intersubject variability. The results should thus be interpreted with some caution and, ideally, the study should be replicated with a larger sample in order to confirm the results. Preferably, such a study should also contain a larger group of NH children. In the present study, the intelligibility of the NH children did not reach ceiling scores, which is in contrast with other studies in which children with NH already reach ceiling scores around the age of four [50, 51]. There are two possible explanations for these conflicting results. First of all, the stimuli of this study originated from spontaneous speech, which is known to have lower intelligibility than imitated or read speech [52]. Thus, it is possible that the same children would reach higher (ceiling) intelligibility scores in an imitation task or in a reading aloud task. Secondly, the present study used rating scales to measure the children's intelligibility. Especially for long stretches of speech, this type of measurement has been the standard procedure in intelligibility studies. However, this type of task can be perceived as difficult, especially for inexperienced listeners who are not familiar with this type of task [16, 38, 47]. Thus, there is a need for studies that approach the intelligibility of spontaneous speech differently. For example, transcription tasks could confirm whether seven-year-old children's intelligibility is indeed still not at ceiling level. A follow-up study in which the spontaneous speech intelligibility of the children is measured by means of transcription wants to fill this void.

Also to be considered is that this study focused on speech with a high ecological validity, i.e. representative for everyday speech. For this purpose, children were instructed to spontaneously tell the frog story. However, it is possible that some children were not attracted to the topic of the story or books in general, which could affect their speech production. Therefore, future studies should also include completely unstructured speech, for example recordings of family dinner table conversations. In such a study, the amount of utterances that originate from caregivers should also be considered. In this study, these utterances were kept to a minimum and they did not affect the intelligibility score significantly. Alternatively, future studies could include recordings of spontaneous monologues, but it is questionable whether this is a feasible task for young children.

Finally, this study only investigated the intelligibility of short sentences and longer sequences of extended spontaneous speech. Isolated words were not included in the sample. Ideally, this type of stimuli would have been added to the sample in order to cover the complete scope or range of intelligibility [24]. Again, in order to only investigate the influence of the type of the sample, these isolated words would have to be judged in the same manner as the other samples. Further research including isolated words, short sentences and longer sequences of speech should clarify the variability of intelligibility.

5. Conclusion

In this study, normally hearing (NH) and cochlear implanted (CI) children's intelligibility of short and long spontaneous speech samples was examined by means of a visual analogue scale. The results showed that, at age seven, the intelligibility of early implanted children with CI is still lower than that of their NH peers. However, when considering these children individually, the majority of the children with CI reached scores within NH children's range. The results also showed that, for NH as well as CI children, long stretches of speech were more likely to have a higher intelligibility score than short samples. Moreover, the calendar year of implantation did not affect the results, suggesting that the speech intelligibility of children with CI has remained stable in the last decennium.

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Declaration of interest

The authors declare no conflict of interest.

Bibliography

[1] A.M. Korver, R.J. Smith, G. Van Camp, M.R. Schleiss, M.A. Bitner-Glindzicz, L.R. Lustig, S.I. Usami, A.N. Boudewyns, Congenital hearing loss, Nat. Rev. Dis. Primers. 3 (2017) 16094. https://doi.org/10.1038/nrdp.2016.94

[2] G. O'Donoghue, Cochlear implants — Science, serendipity, and success, N. Engl. J. Med. 369 (2013) 1190-1193. https://doi.org/10.1056/NEJMp1310111

[3] A. Kral, G.M. O'Donoghue, Profound deafness in childhood, N. Engl. J. Med. 363 (2010) 1438-1450. https://doi.org/10.1056/NEJMra0911225

[4] J. Subtelny, Assessment of speech with implications for training, in: F. Bess, Childhood deafness: Causation, assessment, and management, Grune & Stratton, New York, 1977, pp. 183-194.

[5] A.C.M. Rietveld, V.J. van Heuven, Algemene fonetiek, Coutinho, Bussum, 2016.

[6] V. Freeman, D.B. Pisoni, W.G. Kronenberger, I. Castellanos, Speech intelligibility and psychosocial functioning in deaf children and teens with cochlear implants, J. Deaf Stud. Deaf Educ. 22 (2017) 278-289. https://doi.org/10.1093/deafed/enx001

[7] T.L. Whitehill, V. Ciocca, Perceptual-phonetic predictors of single-word intelligibility: A study of Cantonese dysarthria, J. Speech Lang. Hear. Res. 43 (2000) 1451-1465. https://doi.org/10.1044/jslhr.4306.1451
[8] N. Miller, Measuring up to speech intelligibility, Int. J. Lang. Commun. Disord. 48 (2013) 601-612. https://doi.org/10.1111/1460-6984.12061
[9] M. Hodge, T. Whitehill, Intelligibility Impairments, in: J.S. Damico, N. Müller, M.J. Ball, The Handbook of Language and Speech Disorders, Wiley-Blackwell, Chichester, 2010, pp. 99-114.
[10] N. Müller, Intelligibility and negotiated meaning in interaction, Clin. Linguist. Phon. 17 (2003) 317-324. https://doi.org/10.1080/0269920031000080028
[11] L. Fontan, I. Ferrane, J. Farinas, J. Pinquier, J. Tardieu, C. Magnen, P. Gaillard, X. Aumont, C. Fullgrabe, Automatic speech recognition predicts speech intelligibility and comprehension for listeners with simulated age-related hearing loss, J. Speech Lang. Hear. Res. 60 (2017) 2394-2405. https://doi.org/10.1044/2017_JSLHR-S-16-0269
[12] P. Flipsen, L.G. Colvard, Intelligibility of conversational speech produced by children with cochlear implants, J. Commun. Disord. 39 (2006) 93-108. https://doi.org/10.1016/j.jcomdis.2005.11.001
[13] Y.L. Li, Y.H. Lin, H.M. Yang, Y.J. Chen, J.L. Wu, Tone production and perception and intelligibility of produced speech in Mandarin-speaking cochlear implanted children, Int. J. Audiol. 57 (2018) 135-142. https://doi.org/10.1080/14992027.2017.1374566
[14] T.Y.C. Ching, N.X. Rattanasone, G. Macdonald, V.W. Zhang, L. Button, K. Demuth, Intelligibility of speech produced by children with hearing loss: Conventional amplification versus nonlinear frequency compression in hearing aids, J. Commun. Disord. Deaf Stud. Hear. Aids. 3 (2015) 135. https://doi.org/10.4172/2375-4427.1000135
[15] J.L. Montag, A.M. AuBuchon, D.B. Pisoni, W.G. Kronenberger, Speech intelligibility in deaf children after long-term cochlear implant use, J. Speech Lang. Hear. Res. 57 (2014) 2332-2343. https://doi.org/10.1044/2014_JSLHR-H-14-0190
[16] S.B. Chin, M.J. Kuhns, Proximate factors associated with speech intelligibility in children with cochlear implants: A preliminary study, Clin. Linguist. Phon. 28 (2014) 532-542. https://doi.org/10.3109/02699206.2014.926997
[17] I. Castellanos, W.G. Kronenberger, J. Beer, S.C. Henning, B.G. Colson, D.B. Pisoni, Preschool speech intelligibility and vocabulary skills predict long-term speech and language outcomes following cochlear implantation in early childhood, Cochlear Implants Int. 15 (2014) 200-210. https://doi.org/10.1179/1754762813y.0000000043

[18] S.V. Bharadwaj, P.F. Assmann, Vowel production in children with cochlear implants: Implications for evaluating disordered speech, Volta Rev. 113 (2013) 149-169.

[19] S.B. Chin, T.R. Bergeson, J. Phan, Speech intelligibility and prosody production in children with cochlear implants, J. Commun. Disord. 45 (2012) 355-366. https://doi.org/10.1016/j.jcomdis.2012.05.003

[20] M.G. Habib, S.B. Waltzman, B. Tajudeen, M.A. Svirsky, Speech production intelligibility of early implanted pediatric cochlear implant users, Int. J. Pediatr. Otorhinolaryngol. 74 (2010) 855-859. https://doi.org/10.1016/j.ijporl.2010.04.009

[21] D.J. Ertmer, Speech intelligibility in young cochlear implant recipients: Gains during year three, Volta Rev. 107 (2007) 85-99.

[22] C.-Y. Huang, H.-M. Yang, Y.-J. Sher, Y.-H. Lin, J.-L. Wu, Speech intelligibility of Mandarin-speaking deaf children with cochlear implants, Int. J. Pediatr. Otorhinolaryngol. 69 (2005) 505-511. https://doi.org/10.1016/j.ijporl.2004.10.017

[23] S.B. Chin, K.R. Finnegan, B.A. Chung, Relationships among types of speech intelligibility in pediatric users of cochlear implants, J. Commun. Disord. 34 (2001) 187-205. https://doi.org/10.1016/S0021-9924(00)00048-4

[24] F.A. Khwaileh, P. Flipsen, Single word and sentence intelligibility in children with cochlear implants, Clin. Linguist. Phon. 24 (2010) 722-733. https://doi.org/10.3109/02699206.2010.490003

[25] N. Baudonck, I. Dhooge, K. Van Lierde, Intelligibility of hearing impaired children as judged by their parents: A comparison between children using cochlear implants and children using hearing aids, Int. J. Pediatr. Otorhinolaryngol. 74 (2010) 1310-1315. https://doi.org/10.1016/j.ijporl.2010.08.011

[26] T. Ramakers, J. Sonnenschein-Bindels, R. Buekers, Percentage Spraak Verstaanbaarheid (PSV-k) bij jonge kinderen — Een normeringsonderzoek bij Nederlandse kinderen van 2;6 t/m 4;6 jaar, Logopedie en Foniatrie. 6 (2009) 184-189.

[27] R. Buekers, PSV - Percentage spraakverstaanbaarheid bij kinderen van 2;6 tot 4;6 jaar, Garant, Antwerpen, 2011.

[28] A.E. Geers, J.G. Nicholas, Enduring advantages of early cochlear implantation for spoken language development, J. Speech Lang. Hear. Res. 56 (2013) 643-655. https://doi.org/10.1044/1092-4388(2012/11-0347)

[29] M. Ozbic, D. Kogovsek, Voice quality, articulation, nasality, prosody and overall intelligibility in the speech of subjects with hearing impairment, Croatian Review of Rehabilitation Research. 46 (2010) 41-56.

[30] A.E. Geers, Spoken language in children with cochlear implants, in: P.E. Spencer, M. Marschark, Perspectives on deafness. Advances in the spoken language development of deaf and hard-of-hearing children, Oxford University Press, New York, NY, 2006, pp. 244-270.

[31] E. Yanbay, L. Hickson, N. Scarinci, G. Constantinescu, S.J. Dettman, Language outcomes for children with cochlear implants enrolled in different communication programs, Cochlear Implants Int. 15 (2014) 121-135. https://doi.org/10.1179/1754762813y.0000000062

[32] C.V. Ruffin, W.G. Kronenberger, B.G. Colson, S.C. Henning, D.B. Pisoni, Long-term speech and language outcomes in prelingually deaf children, adolescents and young adults who received cochlear implants in childhood, Audiol. Neurootol. 18 (2013) 289-296. https://doi.org/10.1159/000353405

[33] M. Mayer, Frog, where are you?, Penguin Putnam Inc, New York, 1969.

[34] R.A. Berman, D.I. Slobin, Relating events in narrative: A crosslinguistic developmental study, Lawrence Erlbaum Associates, Hillsdale, NJ, 1994.

[35] N.S. McGarr, The intelligibility of deaf speech to experienced and inexperienced listeners, J. Speech Hear. Res. 26 (1983) 451-458. https://doi.org/10.1044/jshr.2603.451

[36] M.J. Osberger, Speech intelligibility in the hearing impaired: Research and clinical implications, in: R.D. Kent, Intelligibility in Speech Disorders: Theory, measurement and management, John Benjamins, Amsterdam/Philadelphia, 1992, pp. 233-264.

[37] R. Patel, N. Usher, H. Kember, S. Russell, J. Laures-Gore, The influence of speaker and listener variables on intelligibility of dysarthric speech, J. Commun. Disord. 51 (2014) 13-18. https://doi.org/10.1016/j.jcomdis.2014.06.006

[38] M. Gordon-Brannan, B.W. Hodson, Intelligibility/severity measurements of prekindergarten children's speech, Am. J. Speech Lang. Pathol. 9 (2000) 141-150. https://doi.org/10.1044/1058-0360.0902.141

[39] T. Boons, L. De Raeve, M. Langereis, L. Peeraer, J. Wouters, A. van Wieringen, Expressive vocabulary, morphology, syntax and narrative skills in profoundly deaf children after early cochlear implantation, Res. Dev. Disabil. 34 (2013) 2008-2022. https://doi.org/10.1016/j.ridd.2013.03.003

[40] J.G. Nicholas, A.E. Geers, Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss, J. Speech Lang. Hear. Res. 50 (2007) 1048-1062. https://doi.org/10.1044/1092-4388(2007/073)

[41] O.B. Wie, Language development in children after receiving bilateral cochlear implants between 5 and 18 months, Int. J. Pediatr. Otorhinolaryngol. 74 (2010) 1258-1266. https://doi.org/10.1016/j.ijporl.2010.07.026

[42] S.-C. Peng, L.J. Spencer, J.B. Tomblin, Speech intelligibility of pediatric cochlear implant recipients with 7 years of device experience, J. Speech Lang. Hear. Res. 47 (2004) 1227-1236. https://doi.org/10.1044/1092-4388(2004/092)
[43] D. Bates, M. Mächler, B.M. Bolker, S.C. Walker, Fitting linear mixed-effects models using lme4, J. Stat. Softw. 67 (2015) 1-48. https://doi.org/10.18637/jss.v067.i01
[44] J.M. Lenden, P. Flipsen, Prosody and voice characteristics of children with cochlear implants, J. Commun. Disord. 40 (2007) 66-81. https://doi.org/10.1016/j.jcomdis.2006.04.004
[45] L.W. Kretschmer, R.R. Kretschmer, Intervention for children with auditory or visual sensory impairments, in: J.S. Damico, N. Müller, M.J. Ball, The Handbook of Language and Speech Disorders, Wiley-Blackwell, Oxford, 2010, pp. 57-98.
[46] L. Duchesne, A. Sutton, F. Bergeron, Language achievement in children who received cochlear implants between 1 and 2 years of age: Group trends and individual patterns, J. Deaf Stud. Deaf Educ. 14 (2009) 465-485. https://doi.org/10.1093/deafed/enp010
[47] N. Schiavetti, Scaling procedures for the measurement of speech intelligibility, in: R.D. Kent, Intelligibility in Speech Disorders: Theory, measurement and management, John Benjamins Publishing Company, Amsterdam, 1992, pp. 11-34.
[48] T.B. Lagerberg, J. Asberg, L. Hartelius, C. Persson, Assessment of intelligibility using children's spontaneous speech: Methodological aspects, Int. J. Lang. Commun. Disord. 49 (2014) 228-239. https://doi.org/10.1111/1460-6984.12067
[49] P. Flipsen, Intelligibility of spontaneous conversational speech produced by children with cochlear implants: A review, Int. J. Pediatr. Otorhinolaryngol. 72 (2008) 559-564. https://doi.org/10.1016/j.ijporl.2008.01.026
[50] C.E. Weiss, Weiss intelligibility test, CC Publications, Tigard, 1982.
[51] S.B. Chin, P.L. Tsai, Speech intelligibility of children with cochlear implants and children with normal hearing: A preliminary report, Progress Report, Indiana University, 2001.
[52] M.J. Osberger, M. Maso, L.K. Sam, Speech intelligibility of children with cochlear implants, tactile aids, or hearing aids, J. Speech Hear. Res. 36 (1993) 186-203. https://doi.org/10.1044/jshr.3601.186