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ABSTRACT

**Objectives:** This longitudinal study examined the impact of emerging vocabulary production on the ability to produce the phonetic cues to prosodic prominence in babbled and lexical disyllables of infants with Cochlear Implants (CI) and normally hearing infants (NH). Current research on typical language acquisition emphasizes the importance of vocabulary development for phonological and phonetic acquisition. Children with cochlear implants (CI) experience significant difficulties with the perception and production of prosody, and the role of possible top-down effects is therefore particularly relevant for this population.

**Design:** Isolated disyllabic babble and first words were identified and segmented in longitudinal audio-video recordings and transcriptions for 9 NH infants and 9 infants with CI interacting with their parents. Monthly recordings were included from the onset of babbling until children had reached a cumulative vocabulary of 200 words. Three cues to prosodic prominence, F0, intensity and duration, were measured in the vocalic portions of stand-alone disyllables. In order to represent the degree of prosodic differentiation between two syllables in an utterance, the raw values for intensity and duration were transformed to ratios, and for f0 a measure of the perceptual distance in semitones was derived. The degree of prosodic differentiation for disyllabic babble and words for each cue was compared between groups. In addition, group and individual tendencies on the types of stress patterns for babble and words were also examined.

**Results:** The CI group had overall smaller pitch and intensity distances than the NH group. For the NH group, words had greater pitch and intensity distances than babbled disyllables. Especially for pitch distance, this was accompanied by a shift towards a more clearly expressed stress pattern that reflected the influence of the ambient language. For the CI group, the same expansion in words did not take place for pitch. For intensity, the CI group gave evidence of some increase of prosodic differentiation. The results for the duration measure showed evidence of utterance-final lengthening in both groups. In words, the CI group significantly reduced durational differences between syllables so that a more even-timed, less differentiated pattern emerged.

**Conclusions:** The onset of vocabulary production did not have the same facilitatory effect for the CI infants on the production of phonetic cues for prosody, especially for pitch. It was argued that the results for duration may reflect greater articulatory difficulties in words for the CI group than the NH group. It was suggested that the lack of clear top-down effects of the vocabulary in the CI group may be due to a lag in development caused by an initial lack of auditory stimulation, possibly compounded by the absence of auditory feedback during the babble phase.

## INTRODUCTION

The role of the lexicon in phonological and phonetic acquisition has increasingly been emphasised over the last decade or so (Pierrehumbert, 2003; Stoel-Gammon, 2011). Whereas previous research tended to take a bottom-up approach which concentrated on distributional properties of the acoustic input (Maye, Werker, & Gerken, 2002) or structural-linguistic influences on development (Dinnsen, Green, Morrisette, & Gierut, 2011), there has been a resurgence of interest in the highlighting and constraining effect of vocabulary development on speech perception and production. The present study considers the effect of the emergent vocabulary production on the acoustic phonetics of prosody in early disyllabic utterances of normally hearing (henceforth NH) and severely to profoundly hearing impaired children with cochlear implants (henceforth CI). Prosody was deemed a particular area of interest because it is highly important in typical language acquisition (Morgan & Demuth, 1996), but the implant only provides a significantly degraded input for two of the acoustic cues to prosody (Moore, 2003). For children with CI, an exploration of top-down processes on language acquisition is particularly relevant, as these could in principle be used to counter the inherent limitations in signal processing of the implant. Indeed, recent theories of language development have emphasised bi-directional relations between earlier more basic processes and the acquisition of later, higher-order abilities, where the first not only constrains the second but is in turn shaped

1 by it (Werker & Tees, 2005). Exploring the effect of vocabulary acquisition on phonetic  
2 development in children with CI is therefore timely, as we do not know whether children  
3 with CI are able to draw the same benefit from vocabulary learning as NH children.

## 4

### 5 **The Role Of The Lexicon In Phonological and Phonetic Acquisition**

6 In the earliest stages of language acquisition, the lexicon may already guide  
7 infants' phonetic perception. Computational simulations showed that a small proto-  
8 lexicon can make boundaries between phonetic categories clearer (Feldman, Griffiths,  
9 and Morgan, 2009). Indeed, having a speech sound presented in a word can make it easier  
10 for infants to learn to distinguish it (Yeung & Werker, 2009). For speech production,  
11 children's phonological and phonetic abilities have been linked to the size of their  
12 vocabularies (Beckman & Edwards, 2000; Nicholson, Munson, Reidy, & Edwards,  
13 2015), and even the stability of articulatory speech movements is greater when nonsense  
14 words designate a referent, rather than being repeated as a mere string of syllables  
15 (Heisler, Goffman, & Younger, 2010). Vocabulary effects have not only been described  
16 for segmental acquisition, but also for prosody. Work by DePaolis, Vihman and Kunnari  
17 (2008) suggests reliable word stress may not emerge until first words begin to be  
18 produced. 'Word stress' refers to differences in audible syllable prominence in a word. In  
19 acoustic terms, stressed syllables, e.g. the syllable 'ni' in 'vanilla', typically have higher f0,  
20 intensity and longer duration (Lieberman, 1960; Kochanski, Grabe, Coleman, & Rosner,  
21 2005).

22 Recently, we have argued for an enhancing role of vocabulary in the acquisition  
23 of word stress for typically developing children (De Clerck, Pettinato, Verhoeven &  
24 Gillis, in press). We showed a dramatic expansion of prosodic differentiation in first

1 words. Monthly recordings from nine typically developing Belgian-Dutch speaking  
2 infants were analysed from the onset of babbling until a cumulative vocabulary of 200  
3 words was reached. The majority of disyllabic lexical forms in Dutch start with a stressed  
4 syllable, giving rise to a trochaic (strong-weak) pattern (Cutler, 2005; Daelemans, Gillis,  
5 & Durieux, 1994). This pattern was already visible in the babbled utterances of infants  
6 but became much clearer in first words: words showed significantly more prosodic  
7 differentiation in terms of f0 and intensity. This effect was robust to individual variation.  
8 The increase took place abruptly as soon as first words appeared and did not seem to  
9 relate to the gradual increase in vocabulary size. It was argued that this was because the  
10 advent of words brought about increased attention and allocation of resources to phonetic  
11 detail.

12         These results may be important because prosody, and in particular word stress,  
13 has been assigned a critical role in language acquisition over the past three decades  
14 (Morgan & Demuth, 1996). Word stress is perceived early in development (Friederici,  
15 Friedrich & Christophe, 2007), and children can use this information to detect words in  
16 the continuous speech stream and as an entry point to the syntax of their language  
17 (Jusczyk, Houston, & Newsome, 1999; Curtin, Campbell, & Hufnagle, 2012). Moreover,  
18 children's early word forms and syllable omissions show a strong influence of the most  
19 frequent stress patterns in the ambient language (Demuth, 1996), and prosodic constraints  
20 on the development of morpho-syntactic production abilities have also been described  
21 (Gerken, 1994).

22

## 23 **Difficulties With The Perception And Production Of Prosody In Children With CI**

24         Given the suggested importance of word stress, a pertinent question is what  
25 happens in language acquisition when infants do not have easy access to the phonetic

1 cues of word stress. This is the case for children with cochlear implants. The spectral and  
2 temporal resolution of the implant does not afford enough detail for adequate f0  
3 perception (Moore, 2003; Green, Faulkner, & Rosen, 2004; O’Halpin, 2010) or changes  
4 in intensity (Drennan & Rubinstein, 2008; Moore, 2003; Meister, Landwehr, Pyschny,  
5 Wagner, and Walger, 2011), but durational properties of syllables seem to be available to  
6 listeners with a CI (O’Halpin, 2010; Meister et al., 2011). Whilst f0 is not available as a  
7 cue for prosody, temporal aspects of the amplitude envelope may still provide cues to  
8 pitch (Green et al., 2004; O’Halpin, 2010).

9         In children and adults with CI, impaired perception has indeed been reported for  
10 word and sentence stress (Most & Peled, 2007; O’Halpin, 2010; Titterton, Henry,  
11 Krämer, Toner, & Stevenson, 2006). Adult and child listeners with CI experience  
12 significant difficulties when asked to determine the emotion behind an utterance or  
13 whether it is a question or a statement (Hopyan-Misakyan, Gordon, Dennis, & Papsin,  
14 2009; Nakata, Trehub, & Kanda, 2012; Peng, Tomblin, & Turner, 2008). Indeed, if  
15 listeners with CI succeed in f0 shape and alignment perception, they do so on far less  
16 fine-grained distinctions (Holt & McDermott, 2013; Holt & Fletcher 2015). However,  
17 some of the negative findings for prosody perception may have been influenced by the  
18 relatively late age of implantation of the participants in most of the studies reviewed. This  
19 is suggested by Torppa et al. (2014), who report equivalent perception of prosody (word  
20 and sentence stress) to NH age-matched peers in early-implanted (before three years),  
21 musically trained school-aged children with CI. Furthermore, recent evidence of Hebrew-  
22 acquiring infants with CI (chronological ages 13-33 months) suggests that early  
23 implanted infants may develop a similar, although less pronounced, sensitivity to the  
24 predominant stress pattern of their native language as NH infants (Segal, Houston, &  
25 Kishon-Rabin, 2015).



1           For production, Lenden and Flipsen (2007) noted abnormalities in word and  
2 sentence stress in a study of conversational speech samples of six children with CI  
3 (chronological ages 3-6 years). Stress production sounded 'excessive, equal or misplaced'  
4 (Lenden & Flipsen, 2007, p.75), whilst measures of phrasing, voice quality and pitch  
5 were relatively unaffected. On nonsense word repetition tasks, 8-9 year old children with  
6 CI only reached 61% accuracy for stress placement (Carter, Dillon & Pisoni, 2002). In  
7 contrast, a study with 6-9 year old Belgian Dutch-speaking children with CI, most of  
8 whom had been implanted before the age of 2 years, found that children's nonsense word  
9 repetitions were mostly rated correctly stressed by adult listeners (Hide, 2013).  
10 Nevertheless, acoustic measurements revealed that the children with CI made less distinct  
11 acoustic differences than a NH control group of the same age. To summarise, the  
12 acquisition of word stress is likely to be more effortful, though not impossible, for  
13 children with CI as it relies on acoustic distinctions which are harder to perceive and  
14 more fragile to noise perturbation (Peters, Moore, & Baer, 1998). The acoustic cues are  
15 unlikely to be accessible to all CI listeners, though the ability to learn to use the reduced  
16 information transmitted by the implant may be partly dependent on early implantation.

17

## 18   **An Exploration Of The Role Of Vocabulary Development on the production of** 19   **phonetic cues to prosody in children with CI**

20           The main aim of the present study was therefore to find out if the same increase  
21 in the ability to produce the phonetic cues to prosody occurs on the first words of children  
22 with CI as in NH children. In order to investigate this question, prosodic modulation in  
23 disyllabic babble and first words of 9 children with CI was compared to that of the 9 NH  
24 children described in De Clerck et al. (in press). Fundamental frequency (f0), intensity  
25 and duration were measured in the vocalic portions of disyllabic utterances of infants

1 acquiring Belgian Dutch. A secondary aim was to compare developmental trajectories of  
2 the acoustic cues in the two groups.

3 Hide's (2013) results with early-implanted children with CI led us to hypothesise  
4 that the CI group should be able to converge towards the same prosodic pattern as the NH  
5 group, but it was not clear how early this would emerge, nor how robust this would be.  
6 Because of the insufficient signal processing of the implant, it was also expected that the  
7 CI group should show reduced use of  $f_0$  and potentially intensity, but should not differ  
8 from the NH group in the use of duration. The prediction regarding the impact of first  
9 words was less clear: on the one hand, top-down effects from the vocabulary had served  
10 to enhance prosodic-phonetic development in NH children (de Clerck et al., in press), and  
11 should therefore also be expected to strengthen development in the CI group. On the  
12 other hand, the initial absence of stimulation raises the possibility of sensitive periods  
13 being disrupted (Knudsen, 2004; Sharma, Dorman & Kral, 2005) and the CI group has  
14 overall had less exposure to speech, meaning that the arrival of first words may not be  
15 enough to trigger greater prosodic differentiation of phonetic cues in this group. To  
16 summarise, the following research questions were investigated in this study:

- 17 1. Is the onset of vocabulary development accompanied by the same  
18 expansion of prosodic modulation in infants with CI as in NH  
19 infants?
- 20 2. Do the two groups follow comparable developmental trajectories?  
21 I.e. does the development of cue use reflect the limitations of the  
22 implant, and do the groups converge on similar prosodic patterns?

## MATERIALS AND METHODS

### Participants

The data for this study were taken from the CLiPS Child Language Corpus (CCLC), a collection of longitudinal audio-video data and transcriptions of 10 children with a cochlear implant (CI) and 40 normally hearing children (NH). All parents of the children in the CCLC had signed an informed consent form.

For the purposes of the present study 9 children with a cochlear implant were included: one participant had to be excluded because there were not enough recordings to yield a sufficient number of data points. The children with CI were recruited from an Academic ENT Unit in Antwerp/Belgium in 2000-2001. These participants had all been diagnosed with a profound congenital hearing loss on the basis of a neonatal hearing screening during the first weeks of life. No other patent health or developmental problems were reported. All these children had been implanted with a multichannel Nucleus-24 CI (Cochlear Corp., Sydney, Australia). The Nucleus-24 device consists of 22 intra-cochlear electrodes, like more recent CIs. Since the technology of the implant has not changed in such a way that the perception of fundamental frequency has significantly improved, the data in the present study are still representative.

The infants were implanted before the age of two, ranging from 6 to 19 months ( $M = 12$  months;  $SD = 5$  months). The average unaided hearing loss was more than 90 dBHL in the better ear. Before implantation the range of the Pure Tone Averages (PTA) was 93-120 dBHL ( $M = 113$  dBHL;  $SD = 9$  dB). After implantation, as measured around one year after fitting of the implant, the PTA decreased to 30-52 dBHL ( $M = 40$  dBHL;  $SD = 7$  dB). All recordings used in this study were made while the children were unilaterally implanted. Only CI-7 received her second CI in the same month as the last

1 recording used. The auditory characteristics of the children with CI are summarized in  
2 Table 1. For more information on the participants and the aetiology of their hearing  
3 losses, see Schauwers, Gillis and Govaerts (2008).

4 **INSERT TABLE 1 ABOUT HERE**

5 The mean age of the children with CI at the start of the recordings was 17  
6 months ( $SD = 4$  months). The mean age at the cut-off point was 24 months ( $SD = 4$   
7 months). The ages of the individual children at the time of recording are summarized in  
8 Table 2.

9 **INSERT TABLE 2 ABOUT HERE**

10

11 As a control group for this study, 9 normally-hearing children were selected from the  
12 CCLC corpus. All families from both the CI and NH groups are considered to be from  
13 mid to high socio-economic class, based on the parents' education, wage and occupation.  
14 At least one parent had a bachelor or master degree (80% of all parents had a bachelor or  
15 masters degree), the income level was above the minimum wage and all parents worked  
16 full time. The infants were recruited from day-care centres, families known by the  
17 researchers and by announcements. Just like the children with CI, the normally-hearing  
18 children had been raised in monolingual homes acquiring the standard variety of Belgian  
19 Dutch (Verhoeven, 2005). The typical development of these children had been  
20 established on the basis of parent report and a checklist of the attainment of  
21 communicative and motor milestones, largely based on the checklist developed by 'Kind  
22 en Gezin', the Belgian infant welfare centre (Molemans, van den Berg, van Severen, &  
23 Gillis, 2012). Normal language development had been verified by means of the Dutch

version of the CDI ("N-CDI") administered at ages (years; months) 1;0, 1;6 and 2;0 (Zink & Lejaegere, 2001). The N-CDI was filled out by the parents of the NH children to test productive and receptive vocabulary development. The mean percentile for the infants included in this study was 37,9 (SD = 28,4; range = 5.5 - 94.5) at 1;0, 46.9 (SD = 23; range = 20-90) at 1;6 and 51.7 (SD = 29.5; range = 10-90) at 2;0. The mean age of the NH children at the time of the recordings was 6 months (SD = 0,72 months). The mean age at the cut-off point was 22 months (SD = 3 months). The ages of the individual children at the time of recording are specified in Table 2.

## **Corpus**

The corpus consisted of monthly recordings of spontaneous interactions between the children and their caretakers in their home environment (for more details on the corpus and transcription, see: Molemans et al., 2012). A JVC digital video was used to record the NH participants while children with a CI were filmed with a Panasonic NV-GS3 digital video camera with zoom microphone function. Recordings lasted 60-90 minutes and the fragments during which the child was most vocally active and in uninterrupted interaction with a caretaker were selected. The final selection was 20 minutes long.

These interactions were transcribed following CHILDES CHAT conventions (MacWhinney, 2000). The criteria for distinguishing words from babble were based on Vihman and McCune (1994). In order to qualify as a lexical item, utterances had to meet at least two out of three criteria: a determining context or the mother's identification clarified the meaning (e.g. the child utterance *baba* was interpreted as *bal* 'ball' by the mother), an exact or prosodic match to the target word (i.e. *pal* for *bal* 'ball'), or the

1 relation to other vocalisations such as imitation or an invariant production (i.e. consistent  
2 use of *popo* for *opa* ‘grandpa’).

3 CHAT transcriptions were converted to a Praat (Boersma & Weenink, 2014)  
4 texgrid using the CHAT2PRAAT function in the CLAN program (MacWhinney, 2013).  
5 The video files were converted to audio files by means of Free-Video-Converter ("Free-  
6 Video-Converter," 2012). The resulting textgrids were time-aligned at the utterance level  
7 to the audio files as illustrated in Figure 1.

## 8 **Data selection**

9 For the present study, speech data were included from the onset of babbling until  
10 children had reached a cumulative vocabulary of 200 words. This cut-off point was  
11 randomly chosen but motivated by other studies using vocabulary level as developmental  
12 point (Vihman, DePaolis & Davis, 1998). Onset of babbling was determined by a True  
13 Canonical Babbling Ratio (tCBR) of 0.15 or higher (Chapman, Hardin-Jones, Schulte, &  
14 Halter, 2001; Molemans et al., 2012). The tCBR is the proportion of the syllables with  
15 true consonants (i.e. all consonants except glottals (/h/, glotal stop) and glides (/w/, /j/))  
16 over all syllables produced. Cumulative vocabulary was used as a measurement of lexical  
17 development and was obtained by counting the different word types produced per  
18 transcribed recording. The newly produced word types in the following recording were  
19 added to the amount of different word types of previous recordings and so forth. The cut-  
20 off point of a cumulative vocabulary of 200 words was motivated by the amount of data  
21 that was provided in the recordings. The aim was to incorporate enough data to sketch a  
22 substantial profile of the longitudinal development of prominence production. Since a  
23 longitudinal approach is taken in the current study, no artificial boundaries are placed  
24 between a babbling phase and a lexical phase as there is a transitional period where

1 babble and words co-occur. Disyllables tagged as babble are likely to contain a number  
2 of words, and words are likely to contain some babble, especially during the transition  
3 phase when these co-occur. To illustrate: the status of a particular utterance may be  
4 unclear as it may start out as babble, but be interpreted as a word by the parents.  
5 Conversely, attempts at words may not be recognized as such. Both scenarios are equally  
6 likely, thus this noise should be evened out statistically. The fact that this is a longitudinal  
7 study, which goes beyond this transitional phase also serves to counteract this temporary  
8 noise.

#### 9 Inclusion Criteria For Disyllables.

10         The waveforms and spectrograms associated with the speech files were examined  
11 in order to identify the words and babble so that they could be tagged in the PRAAT  
12 textgrids (see Figure 1). Sound sequences were considered to be disyllables when they  
13 consisted of two vocalic phases minimally separated by a clear consonantal phase (see  
14 *Segmentation criteria for consonants and vowels* for specification). Additional  
15 consonants flanking the vocalic sections were allowed. The inclusion criteria for the  
16 disyllables were based on DePaolis et al. (2008). In order to be included, disyllables had  
17 to be clearly perceived as single utterance. This meant that the two syllables of the  
18 utterance had to occur within the same intonation contour or adjacent to a prosodic break  
19 such as a pause or an inbreath at the beginning of a new breath group (Lieberman, 1984).  
20 Furthermore, disyllables had to be separated from surrounding speech by a silence of at  
21 least 400 ms with an intersyllabic pause of less than 400 ms. For a small number of items  
22 produced at a low speech rate, the pause criterion was relaxed up to 500ms as long as the  
23 two syllables were part of a single intonation contour, indicating cohesion. Disyllables  
24 were excluded if there was concurrent speech or noise or if they were produced with a

1 creaky, breathy, excessively loud or whispery voice. An example of a selected utterance  
2 is provided in Figure 1.

### 3 **Segmentation Criteria For Consonants And Vowels.**

4         The disyllables identified by the procedure described above were further  
5 segmented into consonants and vowels, since the acoustic measurements in this study  
6 were conducted in the vocalic portion of each syllable. Figure 1 illustrates the annotation  
7 of an utterance. The waveform, spectrogram, f0 and intensity curve were used (a) to  
8 determine the word boundaries and (b) to segment the disyllables into consonants and  
9 vowels. The segment boundaries were identified on the basis of the consistent application  
10 of the segmentation criteria which are described in detail in DePaolis et al. (2008) and to  
11 which the interested reader is referred to for more information. Since the authors did not  
12 specify any criteria for the segmentation of /l/, the onset and offset of the lateral  
13 approximant were determined on the basis of the discontinuity on the spectrogram in the  
14 intensity and/or frequency of the formants of /l/ and those associated with the preceding  
15 or following vowel.

### 16 **Reliability Of Segmentation**

17         The words and segments were annotated by the author IDC. Approximately 12%  
18 of the data ( $n = 250$ ) was re-segmented by the author MP. The reliability of the placement  
19 of the segment boundaries was analysed by means of the Pearson's product-moment  
20 correlation between the segment durations of both annotators. The correlation between  
21 both sets of annotations was 0.99 ( $p < .0001$ ). As annotators located the boundaries of  
22 segments at virtually the same time points, it was not deemed necessary to carry out  
23 separate reliability checks for duration, intensity and f0 of the vowels (see section below)  
24 as the Praat script would have returned extremely similar values.



## 1    **Acoustic Analysis**

2            The disyllables that were identified by the procedure described above were  
3 analysed acoustically for the prosodic cues which are relevant to the perception of  
4 syllable prominence, i.e. duration, intensity and f0. The acoustic analyses were carried  
5 out by means of a PRAAT script (Boersma & Weenink, 2014). Each of the three acoustic  
6 parameters was measured for the vowels of the disyllables only, not for the entire  
7 syllable. This was done to reduce potential effects of syllable composition on the  
8 measurements. Duration (in ms) was measured from the start to the end of each vowel.  
9 Intensity was measured in dB as the mean energy averaged over the total number of  
10 analysis frames in the vowel. F0 was determined by means of the PRAAT autocorrelation  
11 method and expressed in Hz as the mean f0 averaged over the total number of analysis  
12 frames in the vowel. Intensity and f0 were analysed by the PRAAT analysis settings  
13 adjusted to child speech, i.e. f0 range was set at 150-800 Hz and intensity range was set at  
14 0-100 dB. It should be mentioned that intensity measurements in general need to be  
15 treated with caution. Intensity is very sensitive to background noise and recording  
16 quality. Since participants in this study were highly mobile and clip-on microphones were  
17 not used, we controlled for possible problematic intensity values by applying rigid  
18 selection criteria, cleaning the collected dataset for outliers and most importantly: by  
19 computing the ratio between the intensity measurements of the two syllables. The  
20 purpose of this study was to investigate the acoustic differentiation between syllables of  
21 utterances. Therefore, a ratio between the measurements in each syllable was computed  
22 to quantify this differentiation (i.e.  $\text{durationV1}/\text{durationV2}$  and  $\text{intensityV1}/\text{intensityV2}$ ).  
23 This also had the effect of normalising the intensity in louder utterances. The perceptual  
24 f0 distance between the first and the second vowel in each disyllable was calculated by  
25 means of the formula  $/39,86 \log_{10}(f0V2/f0V1)/$ . This specifies the perceptual distance in

semitones between the first and the second vowel in each disyllable.

The dataset was split into four subsets, i.e. words-CI, words-NH, babble-CI and babble-NH. The data in each subset were cleaned by means of the interquartile rule (IQR). Any measurement above or below the IQR threshold was identified as an outlier. The final dataset consisted of 2076 disyllables of which 925 were CI utterances and 1151 were NH utterances (for numbers per utterance type and participant, see Table 3). For the pitch distance 105 disyllables were considered outliers, for intensity ratios there were 49 outliers and for duration ratios 111 outliers.

**INSERT TABLE 3 ABOUT HERE**

### Statistical approach

Linear mixed models (LMM) were used for the data analysis (Baayen, 2008). LMM are particularly suited to analyse longitudinal corpus data because of their hierarchical structure: the observations ( $n = 2076$ ) are measured at different time points embedded in different participants ( $n = 18$ ) and different groups (i.e. CI or NH). Moreover, linear mixed models are robust to missing and unequal numbers of observations for participants and time points. Importantly, when examining the effects of independent variables LMM take into account variation at the participant level as well as variation over time.

The analyses were carried out in R (R Core Team, 2013) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) to generate models for each prosodic cue. Every model consisted of random and fixed effects. In all analyses the random part provided random intercepts and slopes per individual. The fixed effects of interest were 'age' to investigate whether a cue showed development over time, 'group' (i.e. NH or CI) and 'utterance type' (i.e. babble, or words). The analyses described in the results section

detail which fixed effects and interactions between fixed effects yielded the best fitting model. The statistical procedure consisted of two phases. A hierarchical approach was taken to build the models as random and fixed effects were added in stepwise fashion from a simpler to a more complex model. At each step, a likelihood ratio test was carried out to arrive at the best-fitting model for the data, i.e. the model explaining the largest amount of variance with the fewest predictors. In the second phase we took the best-fitting model and checked which effects were significant predictors. The estimates (henceforth E), standard errors (S.E.), t- and p-values of the fixed effects of the best-fitting models are reported in the results section.

Research question one was addressed by comparing the effect of words on the acoustic cues in the groups and considering their combined effect. For research question two, developmental slopes of cues were compared between groups. In addition, group and individual means or medians for each cue were considered in order to examine whether groups were approximating similar stress patterns.

## RESULTS

Table 4 displays the means and standard deviations of the acoustic cues in babble and words in each group and at individual level.

**INSERT TABLE 4 ABOUT HERE**

### **Pitch Distance**

**INSERT FIGURE 2 ABOUT HERE**

**INSERT FIGURE 3 ABOUT HERE**

For the pitch distance, the best fitting model consisted of the fixed effects of age,

participant group (CI or NH), utterance type (babble or word) and the interaction between the latter two. The results are illustrated in Figures 2 and 3 and Table 1 in the supplementary material gives the output of the statistical model.

The estimate for this statistical model was 1.958 ( $S.E. = 0.186$ ,  $t = 10.550$ ,  $p < 0.001$ ). The fixed effect of age evidenced development over time ( $E = 0.045$ ,  $S.E. = 0.016$ ,  $t = 2.734$ ,  $p = 0.011$ ), as pitch distances increased when the infants got older. The fixed effect of participant group was significant ( $E = 1.300$ ,  $S.E. = 0.241$ ,  $t = 5.400$ ,  $p < 0.001$ ), as the NH disyllables had bigger pitch distances compared to those from the CI group. (For descriptive statistics at the group and individual level, see table 4). Although the fixed effect of utterance type significantly improved the model, it did not reach significance ( $E = -0.123$ ,  $S.E. = 0.173$ ,  $t = -0.709$ ,  $p = 0.478$ ).

Additionally there was a significant interaction between participant group and utterance type ( $E = -0.592$ ,  $S.E. = 0.221$ ,  $t = -2.679$ ,  $p = 0.008$ ), indicating a difference in how the two groups instantiated pitch distances in words and babble, as NH children had larger pitch distance increases than children with CI. At an individual level, eight out of the nine NH children increased their mean pitch distances in words (Table 4), although note that the child who did not show evidence of an increase also had the fewest data points in words (Table 3). Much smaller increases from babble to words were also seen in seven out of the nine children with CI (Table 4).

The significant interaction between participant group and utterance type was further examined through post-tests. NH infants had significantly smaller pitch distances in babble than in words ( $E = -0.715$ ,  $S.E. = 0.165$ ,  $z = -4.346$ ,  $p < 0.001$ ). Although the same tendency was present in the CI group, it was much reduced and was not statistically significant ( $E = -0.123$ ,  $S.E. = 0.173$ ,  $z = -0.709$ ,  $p = 0.887$ ). Possibly, the small

1 difference between babble and words in the CI group may have counteracted the larger  
2 difference in the NH group and prevented the fixed effect of utterance type from reaching  
3 significance. Furthermore, comparisons of the babble of both groups showed that the NH  
4 group already had larger pitch distances at the babbling stage ( $E = 0.707$ ,  $S.E. = 0.222$ ,  $z$   
5  $= 3.190$   $p = 0.007$ ). When comparing the words of both groups, the difference was even  
6 larger ( $E = 1.300$ ,  $S.E. = 0.241$ ,  $z = 5.400$ ,  $p < 0.001$ ).

7 **INSERT FIGURE 4 ABOUT HERE**

8 **INSERT FIGURE 5 ABOUT HERE**

9  
10 If we are also interested in the direction of the stress pattern, the absolute  
11 numbers given by the semitone conversion formula are not informative. Instead, the  
12 signed numbers should be considered, as negative numbers indicate higher  $f_0$  on the first  
13 syllable and positive numbers are obtained with the opposite pattern. These numbers are  
14 represented by the boxplots in Figures 4 and 5, with the negative polarity plotted in the  
15 upper half of the x-axis for ease of reading. For the NH participants, Figure 5 shows a  
16 tendency towards the trochaic pattern at the babbling stage, where 5 children have  
17 medians in the trochaic range. This pattern becomes more pronounced in words, where 8  
18 children have medians in the trochaic range, along with increased distances. (Participant  
19 NH6, who does not show a trochaic tendency also has few data points for words, see  
20 table 3). For children with CI, a trochaic tendency does not seem apparent at the babble  
21 stage, as only two children have medians in the trochaic range. In this group, in addition  
22 to less clear increases of pitch distances in words, there is also less of a trend towards a  
23 trochaic pattern, as only 4 children have medians in the trochaic range for words.

2 **INSERT FIGURE 6 ABOUT HERE**

3 **INSERT FIGURE 7 ABOUT HERE**

The best-fitting model for the intensity ratio consisted of the fixed effects of age, group and utterance type (see Table 2 in the supplementary material). The intercept of this model was estimated at 1.009 ( $S.E. = 0.007$ ,  $t = 140.136$ ,  $p < 0.001$ ). The effect of age significantly improved the model and approached significance ( $E = 0.001$ ,  $S.E. = 0.001$ ,  $t = 1.925$ ,  $p = 0.060$ ). The groups also differed in their use of this cue, with the NH group making overall slightly larger intensity differences between syllables ( $E = 0.023$ ,  $S.E. = 0.009$ ,  $t = 2.510$ ,  $p = 0.019$ ). The main effect of utterance type ( $E = -0.015$ ,  $S.E. = 0.005$ ,  $t = -2.811$ ,  $p = 0.005$ ) suggests that intensity was not used in the same manner for babble and words, with Figures 6 and 7 confirming that the intensity ratio was smaller for babble in both groups. No post-hoc tests were carried out since the interaction between group and utterance status did not significantly improve the fit of the model. The mean ratios indicate that in words, both groups place greater intensity on the first syllable (Table 4), in accordance with a trochaic pattern. For babble, the mean ratio at group level may lead to the assumption that the CI group is qualitatively deviating from the NH pattern, as the mean ratio just below 1 suggests more intensity on the second syllable, unlike the pattern seen in the NH group. However, this conclusion is difficult to support, since individual mean ratios (Table 3) show four out of the nine children with CI have the unexpected pattern, but three of the NH children also show evidence of higher intensities on the second syllable in disyllabic babble.

## 20

1 **INSERT FIGURE 8 ABOUT HERE**

2 **INSERT FIGURE 9 ABOUT HERE**

3 The best fitting model for the duration ratio included age, utterance type,  
4 participant group and the interaction between utterance type and participant group (see  
5 Table 3 in the supplementary material) in the fixed effects. Figures 8 and 9 illustrate the  
6 findings. The intercept was estimated at 0.908 ( $S.E. = 0.047$   $t = 19.254$ ,  $p < 0.001$ ). There  
7 was a significant effect of age on the duration ratio ( $E = 0.013$   $S.E. = 0.004$ ,  $t = 3.326$ ,  $p$   
8  $= 0.002$ ), as duration ratios increased over time. The fixed effect of participant group  
9 significantly improved the fit of the model, but did not reach significance ( $E = -0.072$ ,  
10  $S.E. = 0.063$ ,  $t = -1.131$ ,  $p = 0.269$ ). Utterance type was a significant main effect, as  
11 lexical disyllables had larger duration ratios in both groups ( $E = -0.165$ ,  $S.E. = 0.037$ ,  $t = -$   
12  $4.363$ ,  $p < 0.001$ ). Post-tests on the significant interaction effect between groups and  
13 utterance type ( $E = 0.155$ ,  $S.E. = 0.050$ ,  $t = 3.118$ ,  $p = 0.002$ ) showed that only the CI  
14 group made a significantly smaller duration ratio in babble compared to words ( $E = -$   
15  $0.165$ ,  $S.E. = 0.038$ ,  $z = -4.363$ ,  $p < 0.001$ ). No other comparisons reached statistical  
16 significance. The ratios below 1 indicate that the second syllable was longer for both  
17 groups and in both types of disyllables (see Table 4). In words, ratios increase closer to 1.  
18 This increase is evident in all children with CI and in seven out of the nine NH children  
19 (Table 4).

## 21 **DISCUSSION**

22 The present study examined the impact of the emerging vocabulary on the ability  
23 to produce the phonetics of prosody in children with CIs and with NH. A second aim was  
24 to examine the developmental trajectories of the acoustic cues in both groups and to find

out how early children with CI start to approximate the patterns seen in NH children. To this end, the pitch distance, intensity and duration ratios of babbled disyllables and first words in children with CI and NH children were compared. It was hypothesized that the CI group would be able to converge towards the same pattern as the NH group, although it was unclear how early this ability would emerge, nor how robust it would be. Because of the restrictions in signal processing, reduced use of  $f_0$  and possibly intensity by the CI group in comparison to the NH group was predicted, whereas no differences in duration use were predicted between the groups. We first discuss the results for each cue and then draw evidence from all three cues to bear on the research questions.

In both groups, mean pitch distances increased over time, but this happened to a far lesser degree in the utterances of the CI groups: the main effect of group indicated that pitch distances in NH disyllables were higher than in CI disyllables. This is likely due to processing limitations of the implant. This effect was exacerbated in words, as only the NH group significantly increased their pitch distances from babble to words. Although a similar tendency was present in the CI group, it did not reach statistical significance. Development over time was evident in both groups, however, when comparing the regression lines in figures 2 and 3, the most dramatic increase seems to be occurring in the words of the NH group. Figure 5 suggests that this increase in pitch differentiation was accompanied by a shift towards a more clearly trochaic pattern in disyllabic words. In essence, a trochaic tendency at the babble stage appears to become crystallised at the word level for the NH group. Figure 4 does not appear to give evidence of a trochaic pattern for the CI group at babble stage; at word level, there is some evidence of a shift of pitch distances into more trochaic values in four participants, nevertheless the move towards trochaic values is far less evident in this group. Therefore, in answer to research question one, no enhancement for  $f_0$  use was seen for the words of the CI group. For



1 research question two, the effect of the implant's processing limitations were visible, in  
2 that overall development was slower and smaller in the CI group and there was no  
3 evident convergence towards the ambient trochaic pattern.

4         For intensity, little overall development over time was seen in ratios in both  
5 groups, but an enhancement of intensity differences was present in words in comparison  
6 to babble in both groups. The fact that including an interaction between group and  
7 utterance type did not increase the fit of the model indicates that both groups did this to  
8 the same degree (see also Table 4). Nevertheless it is unclear whether the two groups  
9 truly follow the same developmental trajectories. On group means (Table 4), the CI group  
10 appears to start out from a pattern in babble which deviates from the NH pattern, as the  
11 ratio below 1 suggests that intensity was higher on the second syllable, contra the  
12 predominant trochaic (strong-weak) pattern for Dutch. Recall however that four out of  
13 the nine children with CI displayed the unexpected pattern, but three of the NH children  
14 also showed evidence of higher intensities on the second syllable in babble. Judgement  
15 on whether the developmental trajectory of the CI group represents an atypical pattern of  
16 intensity use should therefore be withheld. In words, all NH children and eight Children  
17 with CI transitioned to ratios above one. It was again the case that the CI group had  
18 smaller ratios than the NH group, i.e. smaller differences between syllables in terms of  
19 intensity. The answer to the first research question is entwined with the answer to the  
20 second one: since neither group made very clear use of intensity both in terms of size of  
21 difference nor in terms of the direction of the stress pattern, it is difficult to tell whether  
22 children with CI truly expand their intensity ratio on words. Nominally, the implant  
23 seems to have little effect on intensity, but note that there is also very little development  
24 over time in both groups, therefore it is not clear how functional the use of intensity is in

1 either group.

2           For duration, the mean group ratios (Table 4) below one in babble and words  
3 indicate that the second syllable was longer for both groups. Since these were disyllables  
4 spoken in isolation, it is very likely that utterance-final lengthening (an increase in  
5 duration of the final syllable) is at work and may potentially obscure durational effects of  
6 prosodic prominence (White, 2014). Interestingly, the duration ratios in words are closer  
7 to 1, which suggests that the difference between syllables lessens, giving a less  
8 modulated pattern. In terms of individual data (Table 4), all the children with CI  
9 increased their mean duration ratios in words, but in the NH group, two slightly  
10 decreased their mean ratios from babble to words. In response to the first research  
11 question, the words of children with CI are in fact less modulated, but it is unclear  
12 whether this is due to a failure to produce word stress, or differences in final lengthening  
13 in the groups. For inferential statistics, age, utterance type and group were needed for the  
14 best fit of the model with the first two reaching significance. When considering the  
15 regression lines in Figures 8 and 9, a developmental trend appears to be present in the  
16 babble and words of the CI group, whereas in the NH group only words show an increase  
17 in duration ratios. Statistically, this was reflected in a significant interaction between  
18 utterance type and group, followed up by post-tests which showed that only the CI group  
19 significantly increased their ratios from babble to words. In terms of research question  
20 two, the difference between groups ran contra to our prediction for duration, since this  
21 cue is available to CI listeners. However, as durational phenomena in this dataset are  
22 unlikely to be a simple result of prosodic prominence at the level of the word, it is  
23 difficult to make strong statements on the use of duration for signalling prosody in  
24 children with CI. It is striking that although both groups had duration ratios in words

1    which indicated that syllables were less modulated, this was only statistically significant  
2    for the CI group.

3           Why would words become less modulated for children with CI? It has been  
4    suggested that children may simplify rhythmic properties to give equal weight to each  
5    syllable in an utterance when acquiring new linguistic structures (Snow, 1994; Redford &  
6    Sirsa, 2011), as a more isochronous rhythm is thought to be easier to acquire (Goffman,  
7    1999; Payne, Post, Astruc, Prieto, & Vanrell, 2011). The children with CI started  
8    producing canonical babble and words later, and therefore had less opportunity to  
9    practice speech planning and articulation than the NH group. It may be that the effort of  
10   integrating a clear adult target and attempting to produce it is more costly to the less  
11   mature speech planning system of the CI group. Indirect evidence for lower articulatory  
12   maturity in this group comes from Vanormelingen, De Maeyer & Gillis (in press), who  
13   found lower articulation rates for the infants with CI included in the present study than  
14   NH age matches. Articulation rate has been used as a proxy for speech maturity as  
15   children's articulation rate slowly increases towards adult values over the first ten years of  
16   life (Lee, Potamianos, & Narayanan, 1999; Redford, 2014). Similarly, the infants with CI  
17   included in this study were also shown to have significantly less complex syllable  
18   structures in words than both age and vocabulary matched NH controls (van den Berg,  
19   2012), and Faes et al. (2015) showed that their word accuracy was significantly more  
20   affected by phonological complexity than NH controls. Therefore, the rhythmic  
21   simplification in words may fit with a general tendency for simplified linguistic structure  
22   in the CI children's speech.

23           Summarising the findings for the three cues, and in response to the main  
24   research question, the advent of recognizable word use did not trigger the same expansion

1 of prosodic differentiation in children with CI as in NH children; this was most clearly  
2 visible on f0. For intensity, although participants with CI had smaller ratios, they did  
3 increase the difference between the first and second syllable in words. However, it was  
4 unclear to what degree this cue was used reliably to signal a trochaic pattern by either  
5 group. Duration ratios indicated that for the children with CI, the transition to words may  
6 have posed an additional articulatory challenge. For individual data, only descriptive  
7 statistics were considered and these indicated larger variation in the CI group for f0 and  
8 intensity in terms of the direction of stress; conversely, duration showed less variation in  
9 the CI group than the NH group.

10           With respect to the secondary research question, which concerned  
11 developmental trajectories in groups, the results may be indicative of a developmental  
12 lag: possibly children with CI only reach the level of prosodic differentiation in words  
13 NH children already display when they are babbling, as the group results for pitch  
14 distance and intensity approached more trochaic levels in words (although individual  
15 variation should be kept in mind). If the initial auditory deprivation is taken into account,  
16 the idea of a lag is inherently appealing: after all, children with CI have had less aural  
17 exposure to language than the comparison group, and they should therefore still be  
18 catching up when they are in the word stage. The lack of auditory stimulation may  
19 become compounded by atypicalities in babbling: Infants with CI have had less time to  
20 explore their own speech production via auditory feedback, and work by Koopmans-van  
21 Beinum, Clement and Den Dikkenberg-Pot (2001) as well as Schauwers, Gillis and  
22 Govaerts (2008) has reported less variegated babble in infants with CI. For speech  
23 production, it may be that babbling provides an important training ground for the  
24 phonetic features of the ambient language, so that these can quickly become stabilized

1 once vocabulary items appear. Therefore, the initial lag in babbling development may  
2 have contributed to difficulties in starting to approximate the native stress pattern at word  
3 level.

4 In order to strengthen the conclusions of the present study, perceptual ratings of  
5 prosodic prominence in children's utterances will be needed. Considering cues separately  
6 does not give a complete picture of prosodic abilities, since prosody is a multi-  
7 dimensional phenomenon and cues may interact and be in trade-off relations (Lieberman,  
8 1960). This would clarify the somewhat ambiguous findings for intensity. In addition, we  
9 have only presented descriptive statistics for the directions of stress patterns, and future  
10 investigations should contain inferential statistics. Furthermore, since the analyses were  
11 carried out on spontaneous recordings, two of the participants have few data points: one  
12 infant with CI at the babbling stage, and one NH infant at the word stage. When  
13 comparing two groups of 9 infants each, this is likely to affect the robustness of the  
14 findings, although the statistical treatment is designed to take account of differential  
15 datapoints per individuals and mitigate this. Finally, more controlled recordings in sound-  
16 insulated laboratories and the use of clip-on microphones would be particularly beneficial  
17 for investigations of intensity use.

18 Keeping these reservations in mind, it remains interesting to consider the lack of  
19 top-down effects on prosodic modulation in the words of children with CI in terms of the  
20 clinical implications and future research. The fact that phonetic development does not  
21 seem boosted to the same degree in words raises the question of the nature of the  
22 developmental lag: is this merely slow phonetic development, brought about by a lack of  
23 auditory stimulation and verbal practice during the babbling stage, or does this represent  
24 a more deep-seated problem in abstracting phonological patterns from the statistical

1 regularities of the ambient language, as McKean, Letts & Howard (2013) found to be the  
2 case for NH children with language delay? Houston and Bergeson (2014) suggested that  
3 in infants with CI, it is not just the perception of speech which is affected, but attention to  
4 speech may also be atypical. The causal relations between attenuated perception and  
5 attention are still under investigation, but one conclusion from this work and the present  
6 study is that interventions should strive to highlight linguistic structure in words, since  
7 pattern extraction and attentional mechanisms may be sub-optimal in this population.

8         Another area for further investigation concerns the relation between the present  
9 results and later difficulties with speech intelligibility in children with CI (Flipsen, 2008;  
10 Montag, AuBuchon, Pisoni, Kronenberger, 2014). Lenden and Flipsen (2007) reported  
11 problems with stress production in conversational speech samples of children with CI,  
12 and Hide (2013) found weaker phonetic cue use even in correctly stressed nonsense  
13 words. Can this profile in older children with CI be related back to their early speech  
14 development? Is it the case that children who have more clearly trochaic items, either in  
15 babble or at the transition to words, also go on to develop more fluent and intelligible  
16 speech? The literature review of typical language development has shown that the  
17 transition to words may be particularly important, since vocabulary development acts as a  
18 kind of bootstrap for phonetic development. In terms of the present research, we could  
19 ask whether those four children with CI whose use of f0 in words showed evidence of an  
20 emerging trochaic pattern also have more advanced abilities in the kinds of syllable  
21 structures they can produce and in terms of their intelligibility, at that particular time-  
22 point and in further development. In order to tackle these questions, research will need to  
23 determine which level of analysis is the most informative: is it enough to take children's  
24 ability to use individual cues as an indicator of competence? It may be that perceptual

1 ratings of stress have stronger predictive value for intelligibility, as they encompass all  
2 acoustic aspects of prosody (Lieberman, 1960). Such research is likely to need larger  
3 samples and necessitate more complex modelling of developmental trajectories (e.g.  
4 Ullman, 2001) than presently available. However, we hope to have drawn the research  
5 community's attention to the transition from babble to first words as a potentially  
6 promising area of investigation in terms of early intervention and prediction.

7         In conclusion, we carried out a phonetic production study of prosody in  
8 disyllabic babble and first words of CI and NH infants. The results indicated that infants  
9 with CI had weaker acoustic cue use, broadly in line with the signal processing  
10 limitations of the implant. In addition, infants with CI did not benefit to the same degree  
11 from lexical effects, as they did not show the same enhancement of phonetic cues on first  
12 words as NH infants did.

13

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## FIGURE LEGENDS

**Figure 1:** An annotated lexical disyllable (“auto”, /  $\Lambda$ uto/, English: “car”). Legend: a = first lexical syllable; b = second lexical syllable; v = vowel; c = consonant

**Figure 2:** Scatterplots for the absolute values of the pitch distances of the children with CI. Shaded area = confidence interval

**Figure 3:** Scatterplots for the absolute values of the pitch distances of the NH children. Shaded area = confidence intervals

**Figure 4:** Boxplots for the pitch distances of babbled and lexical utterances of children with CI. Negative values indicate higher f0 on the first syllable, positive values higher f0 on the second syllable

**Figure 5:** Boxplots for the pitch distances of babbled and lexical utterances of NH children. Negative values indicate higher f0 on the first syllable, positive values higher f0 on the second syllable

**Figure 6:** Scatterplots of the values of the intensity ratios for the children with CI. Shaded area = confidence intervals

**Figure 7:** Scatterplots of the intensity ratios for the NH children. Shaded area = confidence intervals



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2 **Figure 8:** Scatterplots of the duration ratios for the children with CI. Shaded area =  
3 confidence intervals

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5 **Figure 9:** Scatterplots of the duration ratios for the NH children. Shaded area =  
6 confidence intervals

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