Research Article

The Production of Question Intonation by Young Adult Cochlear Implant Users: Does Age at Implantation Matter?

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Purpose: The purpose of this observational study was to investigate the properties of sentence-final prosody in yes/no questions produced by cochlear implant (CI) users in order to determine whether and how the age at CI implantation impacts CI users' production of question intonation later in life.

Method: We acoustically analyzed recordings from 46 young adult CI users and 10 young adults with normal hearing who read yes/no questions. Of the 46 CI users, 20 had received their CI before the age of 4.0 years (early implantation group), 15 between ages 4.0 and 8.11 years (midimplantation group), and 11 at the age of 9.0 years or later (late implantation group). We assessed the prosodic properties of the produced questions for each implantation group and the normal hearing comparison group (a) by measuring the sentence-final rise in fundamental frequency, (b) by labeling the question-final intonation contour using the Tones and Breaks Index (Beckman & Ayers, 1994; Silverman, Beckman, et al., 1992; Veilleux, Shattuck-Hufnagel, & Brugos, 2006), and (c) by assessing phrase-final lengthening.

Results: The fundamental frequency rises produced by all CI users exhibited a smaller magnitude than those produced by the normal hearing comparison group, although the difference between early implanted CI users and the normal hearing group did not reach statistical significance. Early implanted CI users were more comparable in their use of question-final intonation contours to the individuals with typical hearing than to those users with CI implanted later in life. All CI users exhibited significantly less phrase-final lengthening than the normal hearing comparison group, regardless of age at CI implantation.

Conclusion: The results of this investigation of question intonation produced by CI users suggest that those CI users who were implanted with CI earlier in life produce yes/no question intonation in a manner that is more similar to, albeit not the same as, individuals with normal hearing when compared to the productions of those users with CI implanted after 4.0 years of age.

One of the goals of cochlear implantation is to provide prelingually deaf children with access to spoken language, and it is hoped that better reception of spoken language early on in life will improve the speech production skills—and thereby the intelligibility—of cochlear implant (CI) users. It has been well established that cochlear implantation provides access to the segmental features of spoken language, resulting in improved consonant

and vowel perception and production for CI users (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Firszt et al., 2004; Ganek, McConkey Robbins, & Niparko, 2012; Miyamoto, Kirk, Svirsky, & Sehgal, 1999; Tomblin, Peng, Spencer, & Lu, 2008, *inter alia*). For example, Connor et al. (2006) completed a growth curve analysis on consonant production accuracy by age of implantation and found that children who were implanted before the age of 7 years demonstrated a growth curve advantage with regard to consonant production accuracy and speech intelligibility compared to children who were implanted after the age of 7 years. Furthermore, Tomblin et al. (2008) found that speech sound development stabilizes after 6–8 years of device usage. These results suggest that implantation before the age of 7 years allows for the most development to take place in the speech production system as far as segmental features are concerned.

On the other hand, studies investigating the suprasegmental features, such as pitch and duration, suggest that CI users are less successful in both the perception and

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production of these suprasegmental characteristics of speech (Green, Faulkner, Rosen, & Macherey, 2005; Kalathottukaren, Purdy, & Ballard, 2017; Kuo, Rosen, & Faulkner, 2008; Peng, Chatterjee, & Lu, 2012; Peng, Lu, & Chatterjee, 2009; Peng, Tomblin, Spencer, & Hurtig, 2007; Peng, Tomblin, & Turner, 2008, *inter alia*).

The focus of the current article is the production, rather than the perception, of the suprasegmental features associated with question intonation. In particular, we investigate whether CI users who were implanted with CI earlier in life and who, as a result, had both earlier access to spoken language and longer experience using a CI device fare better when producing suprasegmental features once they reach adulthood.

Intonation

Intonation, following the autosegmental–metrical approach to the analysis of intonation (Beckman & Pierrehumbert, 1986; Ladd, 1992, 1996), refers to the use of suprasegmental features, such as fundamental frequency (F0), duration, and intensity, to express sentence-level pragmatic meaning and to organize spoken language into linguistically relevant structures, such as phrases, sentences, or utterances, beyond the sentence level. One of the main innovations of the autosegmental–metrical approach to the study of intonation was the postulation that intonation is organized in terms of categorically distinct entities, that is, tones and tonal combinations that mark prosodic prominence within and at the boundaries of intonation phrases (Ladd, 1992, 1996). The process of the acquisition of intonation, hence, entails acquiring these categorical entities (tones) in such a way that they can be used to understand and express the syntactic and pragmatic information that is conveyed in spoken language.

Similar to the International Phonetic Alphabet, which is a tool to transcribe the categories of sounds (phonemes) present in a language, transcription systems of intonation allow us to transcribe the categories of tones that can be used to describe the variation in intonation in a given language. For the purpose of investigating the question intonation in the current study, we used the Tones and Breaks Index (ToBI; Beckman & Ayers, 1994; Silverman, Beckman, et al., 1992; Veilleux, Shattuck-Hufnagel, & Brugos, 2006). According to ToBI labeling conventions, prominence within an intonation phrase is marked by a nuclear pitch accent, whereas prominence marking the end of an intonation phrase is labeled by a combination of one phrase tone (L- or H-) and one final boundary tone (H% or L%). The combination of phrase tone and final boundary tone is called the *edge tone*. A falling F0, as often found in declarative sentences in English, is typically annotated with the edge tone combination L-L%, whereas a high-rising F0, such as the one typically found in yes/no questions in English (Cruttenden, 1997; Ladd, 1996; Pierrehumbert & Hirschberg, 1990, *inter alia*), is typically annotated as the edge tone H-H%. The difference in edge tones between declarative and question intonation is illustrated in Figures 1 and 2 below. The blue line

seen in both figures is the depiction of the F0 as calculated by the pitch-tracking algorithm in Praat (Boersma & Weenink, 2016).

The ability to perceive pitch—the perceptual correlate of F0—is important for accurate comprehension of intonational meaning, as illustrated in Figures 1 and 2 above. Hence, difficulties in pitch perception may interfere with the comprehension of intonational meaning.

Question Intonation

Although important for the ability to correctly perceive and produce intonation, the production of a rising F0 in itself is not sufficient to produce a typical yes/no question intonation contour in English. Intonation is described in terms of the categorical entities called *intonational tunes*. Successful rendition of question intonation therefore requires the correct choice of intonation tune and the production of a rising F0. Listeners are sensitive not only to changes in pitch height but also to the shape of these F0 rises, which are captured in terms of accents and boundary tones in the ToBI annotation system. The typical tonal realization expected for English yes/no questions is the H-H% edge tone, illustrated in Figure 2 above and in Figure 3 below. However, there are other edge tone combinations, which, as a result, carry other meanings, which are also realized with a rising F0. Figures 3 and 4 each shows the phrase “a banana.” The depictions are derived from sound files contained in the ToBI training materials (Veilleux et al., 2006). Both figures show a final rising F0. However, whereas Figure 3 shows the H-H% edge tone typical for yes/no questions, Figure 4 shows a rising F0 consistent with an H-L% edge tone.

In a recent corpus study on the distribution of different intonation contours in yes/no questions in American English, Hedberg, Sosa, and Görgülü (2014) found that the H-H% edge tone constituted the most frequently occurring intonation contour in a corpus study using the CallHome Corpus of American English (Canavan et al., 1997). Hedberg et al.’s data revealed that 92% (367 of 410) of analyzed yes/no questions were produced with an H-H% edge tone.

Cochlear Implantation and Pitch Perception

The ability to perceive spoken language successfully after the implantation of a CI has been found to depend on a variety of factors related to the design of the CI device, auditory neuron survival, insertion depth of the electrode array, age at implantation, and other factors related to the individual CI user (see Peterson, Pisoni, & Miyamoto, 2010). However, difficulties with successful perception of pitch have been reported in the literature (Chatterjee & Peng, 2008; Green et al., 2005; Kuo et al., 2008; Peng et al., 2012, 2017, 2007). These difficulties in pitch perception stem from technical limitations inherent in CI devices. For a person with normal hearing, the basilar membrane of the inner ear is responsible for the encoding of the temporal fine structure,

Figure 1. The declarative sentence “You did it.” produced with a falling F0 as an example of the L-L% edge tone intonation contour.

which is used to perceive pitch (Moore, 2003). Current CIs are unable to encode this frequency information, which is encoded in individuals with normal hearing via the repetition rate at which the innervated auditory neurons along the basilar membrane fire, and thus, CI users do not have access to an important cue to prosody.

Hence, studies investigating the ability to perceive pitch in questions, which typically are characterized by F0 rise, reveal that participants with normal hearing are better at distinguishing questions from statements based on F0 cues than CI users. Whereas participants with normal hearing

have no difficulties identifying a question based on rising F0 alone, CI users identified questions versus statements accurately only 67% of the time in a study by Straatman, Rietveld, Beijen, Mylanus, and Mens (2010) and with 70% accuracy in a study by Peng et al. (2008).

CI Users’ Production of F0 in Yes/No Questions

Studies investigating the production of a rising F0 by CI users (Peng et al., 2007, 2008; Snow & Ertmer, 2009) mirror the findings of perception studies. It is not surprising

Figure 2. The question “Is that the tall one?” produced with a high-rising F0 as an example of the H-H% edge tone intonation contour.

Figure 3. The phrase “a banana” produced with a rising F0 as a question with an H-H% edge tone, as may be produced when offering someone a banana and expecting the answer yes or no.

that CI users exhibit problems producing intonation to mark questions via F0, given their difficulty with pitch perception. Peng et al.'s (2007) study illustrates this challenge, documenting that 45% of CI users' productions of a rising F0 contour in yes/no questions were not perceived as rising and 28% of the utterances were judged to have a partial rise, whereas only 27% of the F0 rises produced were judged to contain a full rise.

It is well documented that CI users as a group lack the robust ability to produce a rising F0 when asked to do so or when licensed by linguistic structure. However, the fact that more than half of the utterances produced by the CI users in Peng et al.'s (2007) study were produced with

some discernible degree of rising F0 invites the question of whether some CI users are better able to produce a rising F0 than others. If that is the case, it would be important to know what the defining characteristics of those CI users are. Age at CI implantation and length of experience with the device have both been studied as predictor variables for better expressive prosody in CI users before.

Peng et al. (2007) found that CI users seemed to improve in their ability to produce a rising F0 with increasing length of device use, up to 7 years postimplantation. However, beyond that point, a decline in the ability to produce rising F0 was observed. One of the limitations of that study, however, was that the majority, 14 of the

Figure 4. The phrase “a banana” produced with a rising F0 to express uncertainty with an H-L% edge tone, as may be produced when expressing doubt or uncertainty.

24 participants, had been implanted between 4 and 8 years of age, and only two participants had been implanted after the age of 9 years. Therefore, the information that can be gained about age at implantation is limited, especially for those implanted later in life. Furthermore, the participants varied significantly in age at the time of testing; hence, they were tested at presumably different stages of prosodic development.

Another study by Peng et al. (2008) investigated the production of rising F0 in 26 prelingually deaf CI users, ranging in age at implantation from 1.48 to 6.34 years. The participants in that study were asked to produce syntactically identical sentences once as a question and once as a statement, hence having to use intonation as the sole means to express the difference between questions and statements. The CI users' productions were judged accurately as a question or a statement 73% of the time compared to 97% of the time for the sentences produced by individuals with normal hearing. Peng et al. (p. 343) state that "[...] neither the utterance type accuracy nor the contour appropriateness score was found to be significantly correlated with the variables of age at implantation and length of device experience."

Although both of the above studies by Peng et al. seem to suggest that age at CI implantation and device experience have limited impact on expressive prosody, some evidence exists that age at implantation may predict the development of expressive prosody in CI users. Snow and Ertmer (2009), investigating the pitch range development in children implanted with a CI between 10 and 36 months of age, found that, although neither device experience nor age at implantation alone predicted expressive prosody development, once implanted with a device, the children developed very similar to children with normal hearing at comparable stages of development in their expressive prosody.

In summary, the evidence that early CI implantation or longer device use will lead to better expressive prosody, especially the ability to produce a rising F0, is mixed. Peng and Snow's findings are at odds with one another, and more work is needed to understand what the relation, if any, is between CI age of implementation and acquisition and use of prosody.

CI Users' Perception and Production of Temporal Cues in Yes/No Questions

Although F0 is certainly the most salient cue used to express intonation, durational cues are also well known to be tightly linked to intonation. For example, the fact that syllables preceding prosodic boundaries are longer than those that are not in phrase-final position has been well established in the literature (Cooper & Danly, 1981; Edwards, Beckman, & Fletcher, 1991; Klatt, 1975; Turk & Shattuck-Hufnagel, 2007; Wightman, Shattuck-Hufnagel, Ostendorf, & Price, 1992, *inter alia*) and is often referred to as phrase-final lengthening. Phrase-final lengthening occurs in declarative and interrogative utterances. However, differences in the degree to which phrase-final lengthening occurs have

been found to differ between questions and statements (Patel & Grigos, 2006; Peng et al. 2012).

Peng et al. (2012) measured questions and statements produced by hearing speakers of American English, observing that the ratio of mean syllable duration to the duration of the final syllable was significantly greater in questions compared to statements. Furthermore, they report that listeners with normal hearing were sensitive to this difference when performing a perception task. Specifically in a question/statement identification task using synthesized speech, hearing listeners identified the sentences more often as questions when the duration of the final syllable was longer. In fact, developmental studies of the acquisition of question intonation suggest that the question/statement contrast is primarily expressed as a durational difference in very young children before the rising F0 gains cue dominance in middle childhood (Patel & Grigos, 2006).

Several studies have shown that CI users tend to employ temporal cues to compensate for the difficulties in perceiving pitch. For example, Kuo et al. (2008) report that CI users show use of temporal patterns for the purpose of lexical tone identification, and Chatterjee and Peng (2008) suggest that CI users rely on temporal cues in the perception of intonation. However, in Peng et al.'s (2012) study, the results from the participants who used CIs were mixed. Although 10 of their 13 participants with CIs seemed sensitive to the durational cue, only six showed sensitivity in the same direction as the hearing study participants. Four of the 13 CI users exhibited a reversed pattern and judged stimuli with longer final syllables as statements.

Current Study

F0 and durational cues are important acoustic correlates of intonation, and the ability to perceive and express these cues is important for accurate perception and production of intonation. The results of previous studies, as discussed above, provide mixed results as to whether earlier CI implantation leads to better expressive prosody, in particular with respect to the ability of CI users to produce a rising F0. However, previous studies were limited in terms of the age ranges of the investigated CI users and in the sample size. The current study, with a sample size of 46 CI users and with large enough subgroups in terms of age at implantation, will provide important information on whether the age at CI implantation is a predictor in the ability to produce rising F0. The current study, however, will not be able to shed light on the role of the length of device experience as a predictor variable because age at implantation and device experience are confounded. Those CI users in our study who were implanted with CI earlier in life are also the ones who have had the longest experience with the device.

Furthermore, the tasks that CI users had to perform vary widely in previous studies. Whereas the CI users in Peng et al.'s (2007) study were asked to imitate the rising intonation of yes/no questions, Peng et al.'s (2008) study

required CI users to produce sentences based on a scripted conversation. Although an imitation task and a scripted conversation task tap the ability to produce a rise, they do not necessarily provide information about the use of a rising F0 in questions by CI users, when not explicitly prompted to produce a rise by the experimental task. Although the task participants performed in our study, reading of sentences, did provide information about the questions via syntax and punctuation, participants were not explicitly prompted to produce question intonation, hence leaving some choice as to whether or not to produce an F0 rise to the participants. At the time of data collection, the questions were elicited interspersed and randomly ordered with declarative and imperative sentences. Therefore, participants had no reason to assume that question intonation was something that was the focus of the experimental task.

In summary, the overall objective of the current study was to investigate the role of age at implantation of the first CI as a factor in the successful production of yes/no question intonation. By analyzing the question-final intonation as produced by 46 young adults with differing ages of CI implantation and 10 young adults with normal hearing, we seek to determine whether CI users implanted with CI at an earlier age exhibit differences from those implanted with CI later in life in (a) the production of the question-final rising F0, (b) the question-final intonation contour, and (c) the amount of phrase-final lengthening. All the investigated characteristics have been shown to be associated with question intonation in English. Thus, any similarities in the productions of CI users to those of the normal hearing comparison group can be taken as indicative of more successful production of question intonation.

Method

Participants

The CI user data analyzed for the current study were drawn from a larger data set (see Marschark et al., 2015, for a more detailed description). A total of 46 young adult CI users who were prelingually deafened and used at least one CI were included in the current study. All CI user participants were students at the Rochester Institute of Technology at the time of the study. The participants were grouped according to age at implantation into three groups: 20 participants had received their CI before the age of 4 years (early implantation group), 15 between ages 4.0 and 8.11 years (midimplantation group), and 11 at the age of 9.0 years or later (late implantation group).

For the purpose of comparison, we recruited 10 undergraduate students at New Mexico State University with normal hearing. All participants with normal hearing were native speakers of American English, reported no history of hearing impairment, and passed a bilateral pure-tone hearing screening for octave frequencies of 500, 1000, 2000, and 4000 Hz at 20 dB HL. Informed consent was obtained from all participants at New Mexico State University, who received course credit in exchange for study participation. The

demographic characteristics of the study participants are summarized in Table 1.

Stimuli

All participants were asked to read a set of 36 phonetically balanced sentences (McGarr, 1983). The sentences were presented to the participants in randomized order on a computer screen, and participants viewed and read the McGarr sentences aloud while positioned approximately 12 in. from a highly directional condenser microphone (Audio-Technica AT897 for CI participants, Shure SM48-LC for participants with normal hearing). The input was recorded via a PC in waveform audio file format for subsequent acoustic analysis. From the set of the 36 sentences, four yes/no questions were isolated and analyzed for the current study. The questions were as follows: “Did you brush your teeth?” “Is there no more milk?” “Is that the tall one?” and “May I have a piece of cake?” The question-final word in each of these questions was set to be one syllable long to eliminate word length as a confounding factor.

Analysis

In order to investigate the question-final intonation in the four yes/no questions in our study, we analyzed the F0, the intonation contour, and phrase-final lengthening.

F0. In order to determine whether differences in rising F0 exist depending on age at implantation of the first CI, the maximum and minimum F0s over the phrase-final syllable/word were measured for each of the four yes/no questions as produced by all 56 study participants using Praat (Boersma & Weenink, 2016). In order to determine the amount of F0 rise in hertz for any given utterance, the F0 range was determined by subtracting the F0 minimum from the F0 maximum. For a rising contour, the F0 minimum precedes the F0 maximum in the phrase-final syllable, and the F0 range, as a result, yields a positive Hz value. For a falling contour, the maximum F0 precedes the minimum F0 in the final syllable, and hence, the F0 range value yields a negative value.

Intonation contour. As discussed earlier, the edge tone for each question was labeled using the ToBI annotation guidelines (Beckman & Ayers, 1994; Silverman, Beckman, et al., 1992; Veilleux et al., 2006). The first author was trained in ToBI annotation during a Prosodic Transcription workshop at Ohio State University and served as the primary labeler. The first author trained the two additional labelers using the online course materials available through MIT Open Course Ware (Veilleux et al., 2006). All questions were annotated by the first author (Labeler 1), and the two additional labelers annotated 20 different questions (approximately 10%) each. Agreement on edge tone combinations between Labelers 1 and 2 was 90%, and agreement on edge tone combinations between Labelers 1 and 3 was 93%. Questions that lacked in agreement were discussed by all three labelers and were labeled according to majority judgment. Figure 5 below shows examples of each of the

Table 1. Participants in each of the four participant groups.

Participant information	Early implantation group <i>n</i> = 20	Mid-implantation group <i>n</i> = 15	Late implantation group <i>n</i> = 11	Normal hearing group <i>n</i> = 10
Age range at test (years)	17.6–20.7 (<i>M</i> = 18.9, <i>SD</i> = 0.83)	18.4–25.2 (<i>M</i> = 19.6, <i>SD</i> = 1.62)	18.2–25.2 (<i>M</i> = 19.8, <i>SD</i> = 1.44)	19.0–27.0 (<i>M</i> = 21.0, <i>SD</i> = 2.44)
Age range at implant (years)	1.4–3.6	4.0–8.11	9.0–20.0	N/A
Gender	Female = 8 Male = 12	Female = 7 Male = 8	Female = 2 Male = 9	Female = 6 Male = 4

Note. N/A = not applicable.

four different edge tone combinations as produced by the participants in all four of our investigated groups (for a complete list of all edge tone combinations produced by each participant, please refer to the Appendix). Although we attempted to provide examples from the same sentence (“Is there no more milk?”), not all of the groups produced examples of all edge tones on this particular sentence. If only one example of an edge tone was produced per group, we used this example, even if the contour was not of very good quality, such as for the H-H% contour, which was produced by only one participant in the late implanted group. If no example of a given edge tone was produced by the participants in a given group on this question, we provide an example of this edge tone on a different question, such as the L-H% edge tone in the normal hearing group.

We only included the edge tone, consisting of the phrase and boundary tone, in the statistical analysis. The reason for this decision was the observation that the questions produced by speakers in the late implantation group exhibited significantly more intrasentential pauses compared

to those found in the productions of speakers in the early and midimplantation group. As a result of these intrasentential pauses, some of the questions produced contained discontinuities in the contour such that the nuclear pitch accent was separated from the edge tone by an intrasentential pause. In order to avoid discarding those data, we focus on the edge tone alone because all participants produced a question-final edge tone in all analyzed questions. An example of an utterance produced with two intrasentential pauses is provided in Figure 6 below.

Phrase-final lengthening. To assess phrase-final lengthening, a final lengthening ratio was calculated for each question. In order to do so, the mean syllable duration for each question was computed by dividing the utterance duration by the number of syllables. Next, the ratio of final syllable duration and mean syllable duration was computed, yielding the final lengthening ratio. If the final syllable is longer than the mean syllable duration, the lengthening ratio will yield a number greater than 1. A ratio of 1 or smaller, on the other hand, suggests that no phrase-final lengthening is present.

Figure 5. Examples of different edge tone configurations as produced by a speaker from each of the participant groups. All contours are taken from the final word *milk* in the question “Is there no more milk?,” with the exception of the normal hearing L-H% edge tone shown, which was only produced on “Is there no more cake?” in this data set.

Figure 6. The question “Did you brush your teeth?” as produced by a late implanted cochlear implant user. Two intrasentential pauses, expressed as silence in the spoken signal and marked as <SIL>, are visible; the first was after “you,” and the second was after “brush.”

Because there were more intrasentential pauses present in the questions produced by the late implanted group compared to the early implanted group, the utterance length of all questions containing intrasentential pauses—regardless of whether they were produced by participants in the early implanted, midimplanted, late implanted, or normal hearing group—was adjusted such that the amount of intrasentential pause duration present in the utterance was subtracted from the overall utterance duration. This was done to avoid bias against the late implanted group for the assessment of phrase-final lengthening.

Statistical analysis. The statistical analysis of the data was based on linear mixed-effects modeling using the lme4 (Bates, Mächler, Bolker, & Walker, 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2016) libraries for R (R Core Team, 2016). For each dependent variable (F0 rise, edge tone, and final syllable lengthening ratio), a saturated model with interaction terms for all fixed effects (age at implantation of first CI, implantation group, number of CIs, and gender) with random intercepts and slopes was constructed (Barr, Levy, Scheepers, & Tily, 2013). We included number of CIs as a fixed effect in our model as a precaution, because 14 of our 46 CI participants were fitted with a second CI after the reception of the first CI. We felt it was better to take this precaution despite a lack of reports in the literature that bilateral CI uses improve prosody perception or production in CI users.

The models were simplified due to nonconvergence; the resulting converging models included age at implantation of first CI, gender (female, male), implantation group (early, mid, late, normal hearing), and number of CIs (one or two) as fixed effects, and subject and question were random effects with random intercepts but no random slopes. Implantation group was treatment coded according to group characteristics as laid out in Table 1.

Likelihood ratio tests between models with and without the predictor of interest were conducted to obtain chi-square

and p values. Where necessary, post hoc testing was used by performing t tests with Satterwaite approximations to degrees of freedom using the lmerTest library (Kuznetsova et al., 2016).

Results

F0

The first model assessed the F0 change over the question-final syllable in order to determine whether CI users implanted at an earlier age would produce yes/no questions with a rising F0 more so than those users with CI implanted later in life. Seeing that we used a linear mixed-effects model in part to be able to analyze the data without having to eliminate data due to the unequal size of participants in each group, we did not transform the raw F0 data to obtain z scores for each of the questions relative to the sample standard deviation for each participant. We did not do so because transforming the raw data into z scores essentially sets the intercept for each participant to zero, which defeats the purpose of including “subject” as random effect in the model. However, in order to assess if speakers in any of the groups showed an inherently greater pitch range, we calculated z scores of the absolute F0 range and subjected the results to an analysis of variance with the z -scored F0 range as the dependent variable once we randomly eliminated subjects from each group to obtain an equal sample size of 10 subjects per group to satisfy the analysis of variance assumption of an equal sample size per group. The difference between the four groups was not significant, $F(3, 220) = 0.0026$, $p = .99$. Figure 7 below shows the z -scored F0 range by participant group.

The model for F0 rise using the raw data included fixed effects for implantation group, gender, and number of CIs, as well as the Gender $\times$ Implantation Group interaction. Subject and question were modeled as random effects.

Figure 7. The F0 range transformed into z scores for each of the four groups with group means indicated by the solid line within each boxplot. NH = normal hearing.

The results provided in Table 2, which shows chi-square *df*, and *p* values between the saturated model and the predictor under investigation, suggest that the F0 range over the final syllable differed marginally between groups.

Post hoc testing using *t* tests with Satterwaite approximations revealed that the normal hearing comparison group performed significantly differently from the mid-implanted group ($b = -43.3$, $SE = 18.43$, $t = -2.35$, $p = .04$) and from the late implanted group ($b = -47.8$, $SE = 19.23$, $t = -2.49$, $p = .03$). However, the difference between the early implanted group and the normal hearing group was not found to be statistically significant ($b = -30.7$, $SE = 18.42$, $t = -1.67$, $p = .12$). Figure 8 shows the F0 rise by group using Hz values.

In summary, the CI users who were implanted with CI later in life performed significantly different from those with normal hearing, whereas those implanted with CI earlier are neither statistically different from the normal hearing control group nor did they differ significantly from the other CI users. Looking at Figure 8, we can see that the early implanted group performed in between the normal

hearing group and the later implanted group in terms of the mean F0 rise. Keeping in mind that the mean F0 values average across all F0 changes that were produced per group over the final syllable in the questions, it should be noted that outliers as depicted by the circles outside the boxplots were produced with more of a rising F0 than the mean in the normal hearing and early implanted groups. Outliers in these groups occur predominantly above 150 Hz in the normal hearing group and between 50 and 150 Hz for the early implanted group. For the late implanted participants, outliers occurred above or below the mean, meaning that some participants produced more F0 rise than the mean whereas others produced less F0 rise than the mean. For the midimplanted group, outliers occur predominantly below the mean F0 rise, suggesting more falling F0s.

Considering Figures 7 and 8, the fact that the magnitude of F0 range based on z scores did not differ significantly between the groups, while the raw F0 rises, which average over rising and falling F0 values does differ between the groups, suggests that the difference between the normal hearing and the early implanted group on the one hand and the midimplanted and late implanted group on the other hand is driven by the frequency of use of a rising F0 compared to a falling F0 by the different groups.

Table 2. Model comparison statistics of implantation group, number of CIs, and gender as well as the Gender $\times$ Implantation Group interaction on F0 change over the final syllable in yes/no questions.

Variables	F0 range		
	χ^2	<i>df</i>	<i>p</i>
Implantation group	9.24	3	.06
Gender	2.36	1	.68
Number of CIs	0.1357	1	.71
Gender $\times$ Implantation Group	1.42	2	.67

Boundary Tone Contour

In order to assess whether edge tones differed significantly dependent on implantation group, a model was constructed with edge tone (H-H% or other) as the dependent variable and implantation group, gender, and number of CIs as fixed effects. Subject and question were again modeled as random effects.

Figure 8. The amount of rising F0 in hertz by group with group means indicated by the solid line within each boxplot. The mean F0 rise produced by the normal hearing (NH) control was 47.2 Hz, that by the early group was 11.7 Hz, that of the mid group was -1.08 Hz, and the late group was -2.05 Hz. The three cochlear implant user groups (early, mid, and late) did not differ significantly from each other, but the NH group differs significantly from the midimplanted and late implanted groups, but not from the early implanted group.

As shown in Table 3, there was a significant main effect of group on the distribution of edge tones. Post hoc testing using *t* tests with Satterwaite approximations between the groups yielded the following results: The early implanted group differed significantly from the late implanted group ($b = -0.2$, $SE = 0.08$, $t = -2.67$, $p = .01$) and the midimplanted group ($b = -0.2$, $SE = 0.07$, $t = -2.21$, $p = .03$). The normal hearing control group also differed significantly from both the late implanted group ($b = -0.18$, $SE = 0.07$, $t = -9.49$, $p > .001$) and the midimplanted group ($b = -0.15$, $SE = 0.16$, $t = -2.46$, $p > .001$). However, no significant difference between early implanted CI users and the normal hearing comparison group was found. Figure 9 below shows the distribution of edge tones produced by the four investigated groups, illustrating the similarities in use of edge tones between early implanted CI users and the normal hearing comparison group.

Figure 9 illustrates that both participants with normal hearing and early implanted CI users produced the H-H% edge tone more frequently compared to late and

midimplanted users. The participants with normal hearing in our study produced the H-H% edge tone 45% (18/40) of the time, early implanted CI users produced it 35% of the time, and midimplanted users produced the H-H% tone in approximately 17% (10/60) of yes/no questions, whereas late implanted users produced this edge tone only in 9% (4/44) of all produced questions (see the Appendix for detailed information of the produced edge tones for all study participants). Whereas the H-L% edge tone was the boundary configuration most frequently produced by participants in the midimplanted and late implanted groups, for both study participants with normal hearing and those implanted with CI before the age of 4 years, the H-H% edge tone was the most frequently produced edge tone in yes/no questions.

Compared to the results from the study of Hedberg et al. (2014), discussed earlier, who report that typically hearing individuals used the H-H% edge tone in 92% of all yes/no question productions, the participants—even the ones with normal hearing—in our study did not use the H-H% contour nearly as frequently. This difference is most likely due to the difference in task. Hedberg et al.'s percentages are based on conversational speech between known conversation partners, whereas the current study investigated read sentences. Prosody, especially intonation, has been reported to differ in read and spontaneously spoken language with respect to the amount of rising intonation contours (Blaauw, 1995; Silverman, Blaauw, Spitz, & Pitrelli, 1992). Silverman, Blaauw, et al. (1992) report that fewer rising intonation contours were observed in read speech compared to spontaneously spoken speech. In fact, they report that, in their study, close to half (47%) of the rises in the spontaneous version were realized as falls in the read version of

Table 3. Model comparison statistics of group, number of CIs, and gender on the edge tone contour of yes/no questions.

Variables	Boundary tone contour		
	χ^2	df	p
Group	9.98	3	.04*
Gender	0.72	1	.39
Number of CIs	0.03	1	.85

*Indicates a statistically significant difference at an alpha level of .05.

Figure 9. The distribution of edge tones in the set of questions produced by each of the four groups, illustrating the relative similarities and differences between the groups. NH = normal hearing.

their data set of 80 spontaneously spoken sentences that later were read by their study participants. Many others, in addition to Silverman, Blaauw, et al., have also observed that a laboratory reading task lacks the conversational context that may motivate a speaker to use prosody for the benefit of the listener (see Breen, 2014; Snedeker & Trueswell, 2003, among others). In summary, the comparison of edge tone productions in yes/no questions produced by CI users and individuals with normal hearing suggests that early implanted CI users produce edge tones that are more similar to individuals with normal hearing, albeit not the same, than the edge tones produced by those CI users implanted with CI later in life.

Final Syllable Lengthening

The final linear mixed-effects model was constructed to assess final syllable lengthening in order to identify whether age at CI implantation impacted the realization of the duration of the final syllable in the investigated yes/no questions. As described earlier, the lengthening ratio was obtained by dividing the duration of the final syllable by the mean syllable duration of the question. Values greater than 1 indicate that the final syllable was lengthened, whereas values of 1 or smaller indicate the absence of final syllable lengthening. The model for lengthening ratio included fixed effects for implantation group, gender, and number of CIs, whereas subject and question were again modeled as random effects.

The results showed that the degree of phrase-final lengthening differed significantly between implantation groups and between male and female speakers, but no difference between CI users with one versus two CIs was seen (see Table 4 for χ^2 , df , and p values).

Post hoc testing revealed that all CI user groups differed significantly from the normal hearing comparison group. The early implanted group differed significantly from the normal hearing group ($b = 0.5$, $SE = 0.11$, $t = 4.4$, $p < .009$) as did the midimplanted group ($b = -0.5$, $SE = 0.11$, $t = -4.39$, $p < .009$), and the late implanted group ($b = -0.6$, $SE = 0.11$, $t = -5.00$, $p < .004$). However, the CI user groups did not differ from each other. Figure 10 below illustrates the differences in the lengthening of the phrase-final syllable between the CI users and the normal hearing comparison group.

Finally, participants across all groups were found to show a gender difference in phrase-final lengthening. Male participants produced more final lengthening than female participants ($b = -0.1$, $SE = 0.04$, $t = -2.92$, $p < .005$). This held for all four groups, because, as shown in Table 4, no significant Gender $\times$ Implantation Group interaction was found.

Discussion

The current study set out to investigate different aspects of question intonation in yes/no questions as produced

Table 4. Model comparison statistics of implantation group, number of CIs, and gender on the lengthening ratio of the final syllable in yes/no questions.

Variables	Final lengthening		
	χ^2	df	p
Implantation group	13.94	3	< .002**
Gender	8.01	1	.004**
Number of CIs	1.08	1	.2
Gender $\times$ Implantation Group	0.13	3	.9

**Indicates a statistically significant difference at an alpha level of .01.

Figure 10. The amount of utterance-final syllable lengthening by group with group means indicated by the solid line within each boxplot. The mean lengthening ratio for the early implanted group was 1.37, that for the late implanted group was 1.31, that for the midimplanted group was 1.36, and that for the normal hearing (NH) control group was 1.76. The three cochlear implant user groups (early, mid, and late) do not differ significantly from each other, but the NH group exhibits significantly more final lengthening than the three cochlear implant groups.

by CI users to determine whether expressive prosody differs depending on age at CI implantation. The aspects investigated were the amount and frequency of rising F0 over the question-final syllable, the use of edge tones to mark yes/no questions, and the amount of phrase-final lengthening.

The results revealed that, although the amount of F0 range did not differ significantly between the investigated groups, the CI users who were implanted with CI after 4 years of age performed significantly different from those with normal hearing. The CI users implanted with CI before 4 years of age are neither statistically different from the normal hearing control group nor did they differ significantly from the other CI users, suggesting an intermediate performance (see also Figure 8).

Peng et al. (2007) found that the degree to which CI users realized a rising F0 over the final syllable in yes/no questions did not differ significantly with age at implantation. Although our findings are consistent with Peng et al., our study did reveal several differences in the prosody as produced by CI users, depending on age at implantation. The addition of the normal hearing comparison group and the resultant finding that early implanted CI users were not statistically different from the normal hearing comparison group in terms of rising F0 production suggest that, despite the lack of statistical significance, early implanted CI users exhibit F0 rises intermediate between individuals with normal hearing and later implanted CI users. However, to what extent these differences in expressive prosody in CI users implanted earlier in life lead to receptive gains for the listener is a question for future research on the perception of the question intonation in CI users implanted with CI at different ages.

The difference between the individuals with normal hearing and the early implanted CI users on the one hand and the midimplanted and late implanted CI users on the other manifests itself even more pronouncedly in the use of edge tones. The early implanted CI users differed significantly in their use of the H-H% edge tone from both midimplanted and late implanted CI users, whereas no significant

difference between early CI users and the normal hearing comparison group was found. This suggests that early implanted CI users have better acquired the tonal aspects of yes/no question intonation than those implanted with CI after the age of 4 years.

Although the tonal aspect of yes/no questions seems to have been at least partially acquired by early implanted CI users but not by those implanted later, phrase-final lengthening was exhibited by all investigated CI user groups, regardless of age at implantation. One possible explanation as to why all CI users were able to produce some amount of phrase-final lengthening could be related to what we know about prosodic development in typical hearing children. Snow (1994) reports that hearing children acquire the control of phrase-final intonation pattern before they acquire phrase-final timing patterns. This dissociation of intonation and timing pattern during the process of prosody acquisition could account for the fact that CI users—whether or not they have acquired final question intonation—are able to learn that the phrase-final syllable is longer than nonfinal syllables. However, what exactly causes the magnitude difference in the amount of phrase-final lengthening is at this point only a matter of speculation, and further investigation is needed. It is possible that CI users depend on timing cues more heavily than individuals with normal hearing because timing cues are more readily available to them. This may impact the production of timing cues in this population differently from individuals with normal hearing.

The finding that male participants across all investigated groups in the current study exhibited more phrase-final lengthening also warrants further investigation. Although it has been established that gender differences are present in prosodic patterns in American English (Clopper & Smiljanic, 2011), to our knowledge, no study has specifically investigated gender differences in phrase-final lengthening in American English. Studies investigating this question in other languages (Rao, 2010) have found female speakers to exhibit longer final syllables, not male speakers, as our study showed.

Although the current study did not focus on whether the number of CIs a CI user wears impacts expressive prosody performance, the statistical analysis did control for the number of CIs as 14 of the 46 participants were using bilateral CIs. However, there was no evidence that unilateral versus bilateral CI use predicts differences in performance on any of the prosodic characteristics investigated.

The results reported here only shed light on the role of age at implantation of a CI device on expressive prosody later in life. This study does not contribute information about how the length of device use may impact the development of prosody in CI users because age at implantation and length of device use are confounded. Additional studies are needed in order to investigate whether both of these variables predict prosodic development in the same way or whether they affect different aspects of prosodic development.

Conclusions

The results of the current study, investigating the role of age at CI implantation for the production of successful expressive question prosody, suggest that CI users who received their device before the age of 4 years show intonation patterns that are more similar to the patterns produced by individuals with normal hearing compared to those patterns exhibited by CI users implanted with CI later in life. The early implanted CI users in our study were found to be most similar to speakers with normal hearing in terms of the question-final intonation, somewhat similar to the normal hearing group in the production of a rising F0, and not similar to the normal hearing controls in phrase-final lengthening. Overall, these results provide some evidence that early CI implantation may positively impact the ability to produce prosody expressively later in life. However, more research is needed to see what other variables may lead to improved outcomes in prosody production of CI users, especially to what extent interventions targeted at improving prosody lead to improvements.

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Appendix

Edge Tone Productions for Each Study Participant for Each of the Four Questions Produced

Participant ID	Implantation group	Gender	Q1 Did you brush your teeth?	Q2 Is there no more milk?	Q3 Is that the tall one?	Q4 May I have a piece of cake?
CI01	early	female	H-H%	H-H%	H-H%	L-H%
CI02	early	female	L-L%	L-L%	L-L%	H-L%
CI03	early	female	H-L%	L-H%	H-H%	L-H%
CI04	early	male	H-H%	L-H%	H-H%	H-L%
CI05	early	female	L-H%	L-L%	H-H%	H-L%
CI06	early	male	H-L%	H-H%	H-H%	H-L%
CI07	early	male	H-L%	H-H%	L-H%	H-L%
CI08	early	female	H-H%	H-H%	H-H%	L-H%
CI09	early	male	L-L%	L-L%	L-H%	H-L%
CI10	early	female	H-L%	H-L%	L-L%	H-L%
CI11	early	male	L-L%	H-L%	L-L%	H-H%
CI12	early	female	H-L%	H-L%	H-L%	L-H%
CI13	early	female	H-H%	H-H%	H-H%	L-L%
CI14	early	male	H-L%	H-H%	L-L%	H-H%
CI15	early	male	H-L%	L-H%	H-H%	H-H%
CI16	early	male	H-L%	H-L%	L-H%	H-L%
CI17	early	male	H-H%	H-H%	H-H%	H-L%
CI18	early	male	H-L%	H-L%	H-L%	L-L%
CI19	early	male	H-L%	H-H%	L-H%	H-H%
CI20	early	male	H-L%	H-H%	H-H%	L-H%
CI21	mid	male	L-H%	L-H%	H-L%	H-L%
CI22	mid	male	L-H%	H-H%	L-H%	L-L%
CI23	mid	female	H-H%	L-H%	L-H%	H-H%
CI24	mid	female	H-H%	H-H%	H-H%	L-L%
CI25	mid	female	H-L%	L-L%	H-H%	H-L%
CI26	mid	female	H-H%	H-H%	L-H%	H-L%
CI27	mid	female	H-L%	H-H%	H-L%	H-H%
CI28	mid	male	H-L%	H-L%	L-L%	L-L%
CI29	mid	female	H-L%	L-L%	L-L%	H-L%
CI30	mid	male	H-L%	H-L%	L-H%	H-L%
CI31	mid	male	H-L%	L-L%	L-L%	H-L%
CI32	mid	male	H-L%	L-L%	L-L%	L-L%
CI33	mid	male	H-L%	H-L%	L-L%	H-L%
CI34	mid	male	L-L%	L-L%	L-L%	H-L%
CI35	mid	female	H-L%	H-L%	H-L%	L-L%
CI36	late	male	H-L%	L-L%	L-L%	L-L%
CI37	late	female	H-L%	H-L%	H-L%	H-L%
CI38	late	male	H-L%	L-L%	H-L%	H-H%
CI39	late	male	L-H%	H-H%	H-H%	L-H%
CI40	late	male	L-L%	L-H%	L-H%	H-L%
CI41	late	male	H-L%	H-L%	H-L%	H-L%
CI42	late	male	L-L%	H-L%	L-H%	L-L%
CI43	late	female	H-L%	L-H%	H-H%	H-L%
CI44	late	male	H-L%	L-L%	L-L%	L-L%
CI45	late	male	H-L%	H-L%	H-L%	H-L%
CI46	late	male	H-L%	L-L%	L-L%	L-L%
NH01	N/A	female	L-L%	H-H%	H-H%	L-L%
NH02	N/A	male	H-L%	H-H%	H-H%	L-H%
NH03	N/A	female	L-L%	L-L%	L-L%	L-L%
NH04	N/A	female	H-H%	H-H%	H-H%	L-L%
NH05	N/A	female	H-H%	H-L%	H-L%	L-L%
NH06	N/A	male	H-H%	H-H%	H-H%	H-H%
NH07	N/A	female	H-H%	H-L%	H-H%	H-L%
NH08	N/A	male	H-L%	H-L%	H-H%	H-L%
NH09	N/A	male	H-L%	H-L%	H-H%	H-L%
NH10	N/A	female	H-H%	H-L%	H-L%	H-H%

Note. N/A = not applicable.