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Children's development of intonation during the first year of cochlear implant experience

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Abstract

This article describes the longitudinal development of intonation in 18 deaf children who received cochlear implants (CIs) before the age of three years and 12 infants with typical development (TD) who served as controls. At the time their implants were activated, the children with CIs ranged in age from 9 to 36 months. Cross-group comparisons were made when the children had equivalent amounts of robust hearing experience but different chronological ages. This paper reports the results for the 6-month period ending 9 months after activation of the child's device for children with CIs, and the 6-month period ending at 12 months of age for TD infants. The findings were compared to a model of early intonation development in children with normal hearing. The results indicated that all groups progressed through 1 or more of the stages predicted by the normative model. At the end of the study period, however, children who had received a cochlear implant later than 24 months reached a more mature stage of intonation development than younger CI-recipients. Moreover, the older CI group reached the same stage of development as the TD infants who had 3 additional months of language listening experience. The findings suggest that the developmental advantage which older children had previously demonstrated shortly after activation of their CIs is maintained throughout most or all of the first year of cochlear implant use.

Intonation refers to distinctive patterns of vocal melody (Crystal, 1991). The melodies of speech are related to all levels of verbal communication ranging from emotional expression to grammar. On the acoustic level, melody patterns result from linguistically significant changes in the fundamental frequency (f_0) of the voice. The physiological correlate of f_0 is the base rate of vibration of the vocal folds. Finally, on the most abstract level, "tone" generally refers to the functional organization of pitch patterns in the phonological system of speakers and listeners (Bolinger, 1986; Cruttenden, 1997).

Clearly, children require robust auditory access to ambient language f_0 patterns in order to acquire adult-like intonation. However, children with cochlear implants have little or no exposure to speech before receiving their implant device, apart from the limited auditory experience that pre-implantation hearing aid trials may provide. Even after implantation, their exposure to intonation patterns may continue to be compromised because the acoustic signal in most or all devices is degraded relative to normal audition (e.g., Kuo, Rosen, & Faulkner, 2008). To date, little is known about intonation development in young deaf children who receive CIs. This investigation comparatively analyzed the changing intonation patterns of deaf children during the first year of CI use and younger, typically developing infants during the first year of life, so that the pattern and timing of post-implantation developments in young CI-users could be better understood.

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Declaration of Interest
The authors report no conflicts of interest

To measure emerging intonation in early childhood, the present study and its background investigation analyzed children's "accent range," the amount of pitch change used in falling or rising contours. Figure 1 illustrates accent range in the speech of Clara, a 4-year-old girl with typical language development). The figure displays the acoustic analysis of a short phrasal statement (*A horse*) spoken by Clara in the interactive context of naming and playing with animal puppets. The upper panel depicts the time waveform, that is, the plot of acoustic energy by time. The lower panel represents the contour of the fundamental frequency (f_0) over time – the acoustic basis of intonation. The accent range is the logarithmic equivalent of the width of f_0 change in the contour beginning at the onset of the last stressed syllable and ending at the right edge of utterance. It is calculated in this example by measuring the maximum and minimum f_0 values in the stressed phrase-final word *horse* and expressed in the frequency difference in the octave scale (100 cents = 1 semitone = $1/12^{th}$ of an octave). This example represents a contour with an accent range of 966 cents, a width of pitch change in falling contours that is within the typical range of preschoolers and adults (Snow, 1998).

Snow (2006) proposed a theoretical model of early intonation development in which advances in accent range production co-occur with milestones of prelinguistic and early meaningful speech. The model was derived from a cross-sectional acoustic investigation of accent range in groups of infants and toddlers between the ages of 6 and 23 months. All 60 children in this study were learning English and had normal hearing. The current version of the model, which incorporates extensions proposed by Snow and Ertmer (2009), is schematically illustrated in Figure 2.

Figure 2 depicts theoretical changes in accent range production from birth to 2 years. The vertical axis represents accent range in a schematic way that reflects statistical findings. For example, all data points plotted at the same level (e.g., values from *c* to *d*) are not theoretically distinct from one another. In contrast, data points at different levels are significantly different from one another (e.g., *d* versus *e*). The "high" level (e.g., 8 to 12 semitones) corresponds to an adult-like accent range, while the "low" level (e.g., 3 to 5 semitones) is not characteristic of moderately emphatic adult speech in utterance-final contexts. A significant change in accent range production is characterized by a discontinuous shift from one level to the other.

On the horizontal axis, the hypothesized intonation changes are plotted relative to normal stages of vocal development from birth to 24 months (adapted from Oller, 1980). The Precanonical, Canonical Babbling, Variegated babbling, Single Word, and Two Word stages are marked respectively by the emergence of vowel-like sounds and cooing vocalizations, followed by true consonants, varied CV syllables, first words, and sentences.

Points *a* and *b* in Figure 2 represent the initial narrow pitch range that infants in the first few weeks of life are hypothesized to produce in comfort state vocalizations. The first change in accent range is the increase between the points marked *b* and *c*. This coincides with the onset of cooing vocalizations, early in the precanonical period, at the age of about 1½ months (Capute, Palmer, Shapiro *et al.*, 1986). During the subsequent "plateau" from *c* to *d*, children typically produce a relatively wide accent range that is comparable in magnitude to adult speech. The second change is a sharp decrease in accent range between *d* and *e*. This change occurs early in the variegated babbling stage and coincides with the onset of intentional communication at about 10 months of age (Bates, Camaioni, & Volterra, 1975). From points *e* to *f* (roughly corresponding to Vihman's (1996) "transition period), there is a period of apparent regression. The narrow accent range that predominates at this time is not typical of utterance-final intonation in English speech. Finally, an increase in accent range occurs between points *f* and *g* in conjunction with the onset of expressive syntax at the age

of 18 months. At this linguistically important juncture, children's accent range recovers from the preceding regression and stabilizes at values that are statistically indistinguishable from those of older children and adults. Thus, the accent range level at point *h* (24 months) is equivalent to the hypothesized level at age 4 years (Snow, 2006), which in turn is comparable to adults' production of falling contours in an experimental setting (Snow, 1998).

Figure 3 illustrates the hypothesized stages of intonation development with examples from individual children. The figure displays the time waveform and fundamental frequency contour of utterances produced by 3 children with normal hearing (Snow, 2006). Each child represents one of the 3 stages of development discussed above. In the top panel, Dory's non-meaningful utterance (a stressed mid central vowel produced in isolation) has a wide accent range (1004 cents) which is typical of the first plateau in Figure 2 (points *c* to *d*). This is the expected stage of intonation development for a 7-month-old infant. Her vocalizations at this time indicate that she had begun to produce canonical babbling (canonical syllable ratio = .22) but not single words (one 1 meaningful word by parent report), so that her intonation production is commensurate with her stage of vocal development. In the middle panel, Abby produces a relatively narrow contour (only 439 cents) in the babbled CV syllable [ta]. At 12 months, the model predicts that her stage of intonation development would correspond to the "regression period," and indeed the relatively flat contour shown here is a typical pattern during this stage. With 4 words in her expressive lexicon, her vocal development corresponds to the single-word stage, which overlaps with the major part of the intonation regression period. Finally, in the bottom panel, Mabel's use of a relatively wide accent range (812 cents) in the final stressed word *horse* is characteristic of children in the final plateau from point *g* to *h*. At 20 months, she had 313 words in her expressive vocabulary and had begun to use word combinations. Her advance to the period of two-word combinations and syntax matches nicely with her age and expressive intonation.

The preceding sketch of early intonation production shows that the earliest unmistakable beginnings of intonation or "f_0 patterning" (MacNeilage & Davis, 1990) emerge in infant vocalizations as early as 5 or 6 weeks of age. Studies of perception provide even more compelling evidence that intonation is an early-developing system. For example, babies as young as 1 month can discriminate rising and falling contours (Morse, 1972) and disyllabic stress patterns cued primarily by pitch (Spring & Dale, 1977). In first weeks and months of life, infants are able to recognize familiar intonation patterns based on exposure to the input. For example, 4-month-olds recognize and prefer the intonation of motherese versus adult-directed speech (Fernald & Kuhl, 1987). Newborns even prefer the intonation patterns of their native language over the patterns of a non-native language. Because newborns have virtually no post-natal experience with the ambient language, their preference is presumably based on listening experience and learning before birth (Mehler, Jusczyk, Lambertz *et al.*, 1988). Perception studies have also documented a regression pattern of development. At 10 to 11 months, for example, infants are no longer able to discriminate intonation patterns (Best, Levitt, & McRoberts, 1991), even native patterns that they had easily discriminated at an earlier stage of development (see Morse, 1972).

Similarly, children with CIs often have difficulty perceiving and producing f_0 patterns. The perceptual deficits stem partly from inherent limitations of implant devices. Whereas f_0 is richly represented in both the timing and frequency domains of normal auditory processing, fundamental frequency cues are rather weakly signaled in most implant devices (Kuo *et al.*, 2008). Indeed, an implant's pitch processing effectiveness is directly related to the number of channels (Lin, Lee, Huang, & Peng, 2007), which is very limited compared to the fine tuning of normal auditory pr. As a result, children with CIs may have difficulty using f_0 cues to comprehend words with lexical tones (Ciocca, Francis, Aisha, & Wong, 2002) or to

appropriately produce intonation contrasts using rising vs. falling f_0 patterns (Peng, Tomblin, Spencer, & Hurtig, 2007). In spite of the pessimistic note of these studies of CI experience, some investigations have documented positive post-implantation gains in pitch production and/or perception, two examples of which are Lenden & Flipsen (2007) and the investigation discussed next which provided the background and impetus for the present study.

Snow and Ertmer (2009) compared the accent range produced by six children with CIs to the normative model depicted in Figure 2. The results showed that all of the children proceeded through one or more stages of development that were similar to those of children with normal hearing However, the pace of development varied according to the children's age at the time of implantation: Children who had received a cochlear implant after the age of 24 months reached a more advanced stage of intonation development than children with the same amount of CI-assisted hearing experience who had been implanted at or before the age of 24 months.

Snow and Ertmer (2009) speculated that the advantage of the older CI recipients is owing to their greater maturation of social-affective, pragmatic, motoric, and cognitive skills. Indeed, such skills arguably constitute the nonlinguistic underpinnings of intonation (Snow, 2006). Unlike segmentally-based spoken language skills, however, children's development in such areas as emotional expression and gestural communication may proceed normally in spite of severe or profound hearing loss. For example, deaf children typically use gestures for pragmatic communication in the same way and at the same stage of development as children with normal hearing (Petitto, 1987). Similarly, deaf infants produce precanonical vocalizations such as emotionally expressive cooing sounds at the same age as typically developing infants (Oller, 1980). Prelinguistic skills, then, might continue to foster intonation development in the absence of robust hearing, an effect that was found to be especially striking in children who were implanted after the age of 2 years.

The findings summarized in the preceding paragraphs were described as preliminary because the study involved a small group of six children and a short time frame extending to 2 months after implant activation. Thus, in time, the advantage of the older CI-recipients could weaken and the gap between age-at-implant groups might narrow or disappear. To investigate the possibility of a diminishing effect of chronological age, the present study followed a larger group of children over a longer period of time than was previously investigated. As an additional extension of the present study's design, a control group of TD infants participated in data-collections sessions at the age of 6, 9, and 12 months. The principal aims were 1) to determine whether the children with CIs and TD infants progress through one or more of the nonlinear stages of intonation development that are theoretically predicted by a normative model, and 2) to determine whether the time-course of intonation development differs among older CI-recipients, younger CI-recipients and TD infants.

Methods

Participants

Two groups of children participated in the current study. The CI group consisted of 18 children (seven boys and eleven girls) who were enrolled in a longitudinal investigation of prelinguistic vocal development following cochlear implantation. The CI group was not controlled for gender because research with TD children has not indicated consistent gender effects on expressive intonation in the first two years of life (Snow, 2006). Background audiometric information can be found in Table 1. Each of the children in the CI group had a bilateral hearing loss in the severe to profound range and received a CI between 8 and 35 months of age (M = 21.6 months). Device activation occurred within 1 month of surgery.

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Thirteen of the children had a single CI throughout data collection. Five children received a second implant during the investigation. All of the children were fitted with hearing aids (HAs) before implantation. The length of the HA trials ranged from 3 to 18 months ($M = 8.3$ months). All of the children in the CI group were enrolled in family-centered programs at an oral language center or preschool in the Midwestern United States. English was the only language spoken in their homes. None of the children was identified as having auditory neuropathy. Three of the implanted children were believed to be at risk for disabilities in addition to hearing loss. These included concerns about attention, behavior, and motor development (CONO), behaviors associated with Autism Spectrum Disorders (IAGE), and hypotonia and cognitive, communicative, and socio-emotional delays (LILA).

Seven boys and five girls who were typically developing (TD group) entered the study at 6 months of age. The ages of the TD children permitted comparison with the CI group after 6, 9, and 12 months of robust hearing experience. By parent report, all of the children in the TD group had passed hearing screenings soon after birth and did not have developmental delays at the start of the study. One child (ELCA) was eventually diagnosed as having a speech delay and a low vocabulary at 24 months of age. The remainder of the children exhibited no developmental delays during the course of the study.

Research Design and Data Collection

A longitudinal research design was used to examine the time-course of intonation development in the CI and TD groups. Twenty-minute video- and audio-recordings of adult-child play interactions were collected at six different intervals before and after cochlear implantation. Because not every child was available before or shortly after implantation, the number of participants at the early intervals is relatively small: four children provided samples prior to implantation, and eight gave samples within 2 months after device activation. All children with CIs provided samples after 3, 6, 9 and 12 months of CI use. All children in the TD group were recorded when they were 6, 9, and 12 months old.

Using a sampling rate of 44.1 kHz, video- and audio-recordings were made with Sony mini-DVD camcorders (model DCR-DVD405) coupled with Bluetooth wireless microphones (frequency response 300–9,000 Hz). The microphones were worn in fitted, front vest pockets to ensure a consistent microphone-mouth distance of less than 4 inches. Recordings were made by each child's early interventionist (EI) so that all adults in the recording sessions were familiar to the child. Mothers interacted with their children in most sessions, but children interacted with their EI or a daycare provider if a parent was unable to participate (approximately 15% of sessions). Recordings for 17 of the CI children were made at the child's intervention center; recordings for the remaining child (CAST) were made in her home due to state early education requirements. Mothers were involved in all of the recording sessions for the TD children. These sessions were conducted in a playroom setting in the second author's laboratory. The mothers and children in both groups chose items from standard set of toys (e.g., books, puzzles, dolls, toy cars) to play with during each session.

Data Analysis

Mini-DVD recordings of parent-child interaction sessions were reviewed by research assistants so that child utterances could be parsed from DVDs and saved as separate digital soundfiles. An utterance was defined as a vocalization or group of vocalizations separated from all others by either audible ingressive breaths or by judges' intuitions about utterance boundaries which are often indicated by a silence of one second or longer (Lynch, Oller, and Steffens, 1989). Only protophone vocalizations (i.e., precursors of speech, Oller, 2000) were examined. Fixed signal vocalizations such as crying and laughter, and vegetative sounds

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such as sneezing, burping, and hiccups were not saved or analyzed because they do not become more speech-like with age. The first 50 utterances meeting the selection criteria were parsed and saved from each recording session. However, fewer than 50 utterances were produced in 9% of the sessions for the CI group and in 21% of the sessions for the TD group.

Intonation Analysis

Of the total number of utterances available for each post implant session, only monosyllabic (i.e., V, CV, CVC or VC) voiced productions that were of acceptable intensity and free from background noise were chosen for intonation (f_0) analysis. Monosyllabic utterances without acoustic interference (e.g., overlapping speech or background noise) were analyzed to mirror the unit of analysis in a previous investigation of intonation development in TD children (Snow, 2006). Because the pre-implant and early post-activation sessions were sparsely represented and contained very few applicable data points, the data from these two sessions were not analyzed further. The remaining database for acoustic analysis included 287 utterances for TD infants and 474 utterances for children with CIs. Tables 2 and 3 list the number of monosyllabic utterances that were analyzed for each child and session. The children with CIs (Table 3) are organized in two age groups. Each child in the “Younger Group” was 2 years old or younger at the time of implantation and each member of the “Older Group” was more than 2 years old. The tables show that there were no missing data for the TD infants (Table 2) and for children with CIs at the 3-month post-activation session (Table 3). There were no data meeting the selection criteria for 2 to 4 children with CIs at each of the other sessions.

Instrumental Analysis

The duration and f_0 contour of each utterance selected for analysis was measured using the Computerized Speech Laboratory (CSL) signal analysis system from Pentax-Kay Elemetrics. In accordance with procedures described by Allen and Hawkins (1980), the analyzed portion of each syllable was the vocalic nucleus. The beginning and ending boundaries of each vocalic nucleus were set by inspection of wide-band spectrograms. Each boundary began or ended a portion of clear periodicity (i.e., f_0 and 2 or more harmonics were represented).

The pitch extraction algorithms of CSL generated the fundamental frequency (f_0) contour between the syllable boundaries. Portions of the signal that the automatic routines failed to analyze correctly were edited. That is, the analyst deleted f_0 data points that reflected large and abrupt departures from adjacent data points. The analysis program computed the minimum, maximum, and mean f_0 values for each utterance. “Accent range" was defined as the logarithmic difference between the maximum and minimum f_0, expressed in cents (1 octave = 1200 cents) and calculated by the formula $(1200/\log2)*(\log(\max f_0/\min f_0))$. This logarithmic measure permitted the frequency data to be expressed in terms of perceptually equivalent units (Burns & Ward, 1982). Using the data from Clara as an example (see Figure 1), the accent range of the stressed utterance-final word *horse* is computed by evaluating the expression $(1200/\log2)*\log(298/170) = 966$ cents.

Intra- and inter-judge reliabilities were based on a 10% random sampling of the monosyllabic utterances produced by each of the children with CIs whose data were analyzed. A second person carried out reliability judgments on the same 10%e sample. The mean differences between the intra-judge reliability analyses were 3.4 ms (duration), 0.7 Hz (f_0 range), and 8.8 cents (accent range). The corresponding results of the inter-judge analyses were as follows: 11 ms (duration), 21 Hz (f_0 range), and 123 cents (accent range). The reliabilities are representative of those obtained in previous studies of intonation

development in infants and toddlers (Snow, 2002, 2006; Snow & Ertmer, 2009). The intra-judge reliabilities are especially strong. The inter-judge reliability for accent range is within the frequently reported range from 100 to 130 cents. This range is equal to or slightly greater than 1 semitone – the just noticeable difference in pitch change (Allen, 1983).

The statistical analysis of the accent range data followed the procedures that Snow and Ertmer implemented in their 2009 background study. Tests of groups of children by session (e.g., CI versus TD) were initially evaluated by analysis of variance using a mixed design. Due to missing data in the CI groups and extensive variability in all groups, the ANOVAs were followed up by nonparametric tests which entailed fewer assumptions about the distribution of the data. The goal of both statistical tests was to evaluate the association between groups of children and a categorical decrease or increase in accent range over all or part of the period of study.

Interpreting the Data

To study the development of children with CIs and TD infants in relation to the normative model sketched in Figure 1, the statistical tests described in the preceding paragraph identified significant increases or decreases in accent range across sessions. The observed direction of pitch change across sessions was matched to a corresponding discontinuity in the model. If a group of children consistently demonstrated an increasing or decreasing pattern, we made the simplifying assumption that they had completed the full extent of that increase or decrease. Thus, the children’s ending point of intonation development was hypothesized to lie somewhere along the level “plateau” that immediately followed the change from low to high or high to low. For example, if the children’s accent range over a 6-month period consistently reflected decreasing values, this profile would match with the theoretical decrease that occurs between points *d* and *e* in Figure 1. The children’s development, then, would correspond to some point on the following plateau, namely the steady state portion beginning at point *e* and ending at *f* (see the example utterance by Abby in the middle panel of Figure 2). An increasing pattern, on the other hand, matches with either the early discontinuity between the points labeled *b* and *c* or the more advanced one between *f* and *g*. Developmental criteria could then be used to choose between these 2 extremes. For example, if younger children with CIs demonstrated an increasing pattern of pitch change over time, and the other groups demonstrated the opposite pattern, the development of the younger children with CIs would be theoretically situated in the earlier plateau of the model, that is, the steady-state interval from *c* to *d* (see the example utterance from Dory in the top panel of Figure 2).

Results

The instrumental data are listed for the TD infants in Table 4 and for children with CIs in Table 5. A preliminary omnibus test used a mixed 2X3 ANOVA to evaluate the data for 1) TD infants at 6, 9, and 12 months of age and 2) children with CIs for the sessions at 6, 9, and 12 months post-activation. The dependent variable was accent range (mean values by child within session). The between-subjects variable was participant group (2 levels) and the within subjects variable was session (3 levels). The analysis did not reveal any main effects or interactions. Thus, there was no evidence that either of the participant groups demonstrated changes in accent range over the period of study or that children with CIs developed intonation differently than TD infants. In spite of the null findings, inspection of the data suggested some provocative trends which are explored next for each group separately.

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TD Infants

As shown in Table 4, the accent range data for the TD control group steadily declined over the period of study. For example, at 6, 9, and 12 months of age, the infants' mean accent range was 475, 443, and 399 cents, respectively. To evaluate this trend non-parametrically as a simple categorical increase or decrease, we first simplified the data set by condensing the original sessions (6, 9 and 12 months) from 3 to 2. The most consistent pattern of longitudinal pitch change was obtained by collapsing the data across the 6- and 9-months sessions. The resulting composite (6–9-months) session was then compared to the single session at 12 months. These data are shown in columns 4 and 5, respectively, of Table 4 (the corresponding legends are in bold type). For each child in the table, a plus sign (+) in the column labeled "Pitch Change" (column 6) indicates that the child demonstrated an increasing pattern from the 6–9-months session to the 12-month session. A minus sign (−) indicates a decreasing pattern. The overwhelming majority of the TD infants (10 out of 12) demonstrated a decreasing pattern, a result which was significant by a sign test ($z = 2.02$, df $= 1$, $p < .05$)

Children with CIs

As in our background study (Snow & Ertmer, 2009), inspection of the data for the CI groups suggested a partial interaction between hearing experience and age. To explore this trend, the data were simplified and the variability reduced by condensing the original sessions (3, 6, 9, and 12 months post-activation) from 4 to 2. The most consistent pattern of longitudinal pitch change among and between groups was obtained by pooling the data for the 6- and 9-month sessions. The reader may recall that the same rationale was used to analyze the data for the TD group in the preceding paragraph. For the CI group, however, the comparison with the composite session that was the most consistent with the predicted interaction involved the single session at 3 months post-activation. The relevant data are shown in columns 3 and 6 of Table 5 (the corresponding legends are in bold type). In sum, the TD infants were evaluated over a 6-month period ending at 12 months and the children with CIs were evaluated over an equal time period ending at 9 months post-activation.

The accent range data for the children with CIs (columns 3 and 6 of Table 5) were submitted to an ANOVA with a mixed 2X2 factorial design. The dependent variable was accent range, the between-subjects variable was age group (2 levels), and the within-subjects variable was session (2 levels). The ANOVA did not reveal any main effects, but there was a significant interaction between age group (based on age at implantation) and amount of CI-assisted hearing ($F = 6.141$, df = 1,16, $p = .025$). Thus the initial effect of post-implant hearing experience on intonation development was different for children who received CIs at older versus younger ages. For the younger children, accent range increased from the session at 3 months post-activation to the composite session (6 to 9 months post-activation). Older children demonstrated the opposite pattern.

Nonparametric statistics corroborated the significant interaction. In the last column of Table 5 labeled "Pitch Change" (column 8), a plus sign (+) indicates that the child's accent range increased over time, that is, it was wider in the 6–9-months composite session than in the 3-months session. A minus sign (−) indicates that the child's accent range decreased; that is, it was wider in the 3-months session than in the 6–9-months session. The table shows that 8 out of the 10 children in the younger group demonstrated an increasing pattern of pitch change, but the majority of the older children (6 out of 8) demonstrated a decreasing pattern. The results (chi square = 5.45, df = 1, $p = .025$) confirm the hypothesis that the pitch range development of children with 9 months of CI-hearing experience is different for younger versus older children. The table also shows that 14 out of the 18 children with CIs demonstrated the longitudinal pattern of pitch change (increasing or decreasing according to

age group) that the interaction hypothesis predicted. Based on a sign test of correlated samples, this result was significant ($z = 2.12$, $p < 0.05$).

Four of the children in the group of 18 CI recipients had either a secondary impairment (IAGE, LILA, and CONO) or a progressive hearing loss (JORO). It is not known whether these participants are representative of children with normal development in all areas except hearing. To rule out the possibility that children with secondary impairments may have influenced the results, the statistical tests were repeated with data only for the14 children who did not have any secondary impairments. The parametric and non-parametric tests did not reveal any main effects or interactions. The absence of a group effect was probably due to the fact that all four of the exceptional children were members of the older group. The unevenly represented groups apparently weakened the power of the statistical tests to detect any consistent effects.

However, inspection of the individual results showed that all but one of the exceptional children demonstrated the same cross-session pattern of pitch change that the older CI-recipients demonstrated as a group. The single exception was JORO, the child who had a progressive hearing loss. Thus, insofar as intonation is concerned, the children with both hearing and secondary impairments appear to be representative of children who have impairments in hearing only.

Interpreting the Results

In Figure 4, the results for all 3 participant groups are compared to the theoretical model that was described in the introduction. Dotted vertical lines represent the model's predictions for infants with normal hearing at the ages of 9 and 12 months (or children with CIs with 9 and 12 months of robust hearing experience). The TD infants in this study demonstrated a decreasing accent range. In accordance with the approach described in the concluding paragraphs of the Methods section, this suggests that these infants were developmentally situated at a point following the decrease from *d* to *e*, that is, somewhere on the plateau from *e* to *f* (bold horizontal line in the middle of Figure 4), which corresponds to the regression phase as exemplified by Abby in the middle panel of Figure 2 (narrow and restricted accent range). The older children with CIs demonstrated the same developmental pattern as the TD controls.

In contrast to the TD infants and older children with CIs, the younger group of children with CIs demonstrated an increasing pitch range over the 6-month period of study (3 to 9 months of CI-assisted hearing experience). This increase seems to fit the discontinuity in the model from *b* to *c*. Accordingly, the children's development is theoretically situated after the rise, that is, at some point on the subsequent plateau from *c* to *d* (bold horizontal line on the left-hand side of the figure), which corresponds to the phase of the model exemplified by Dory in the top panel of Figure 2 (a wide and expressive accent range). As expected, none of the groups attained the final stage of development (the plateau between points *g* and *h*) which is exemplified by the relatively wide contour produced by Mabel in the bottom panel of Figure 2.

Comparing these findings (bold horizontal lines) with the theoretical predictions (dotted vertical lines), the TD infants, at 12 months of age (hence, 12 months of robust hearing experience), reached the same level of development as the model predicted for that age range. The younger children with CIs reached a point that was equal to or slightly less advanced than what the model predicted. In contrast, the older children with CIs reached a point that was more advanced than the model predicted for 9 months of hearing experience.

Discussion

This study investigated the development of intonation in younger CI recipients, older CI-recipients, and TD infants. Consistent developmental changes in accent range were observed in all three participant groups over a 6-month period of study ending at 9 months post-activation for children with CIs and 12 months of age for TD infants.

The results showed that each group progressed through 1 or more of the early stages of intonation development that were predicted by a normative model based on amount of hearing experience. That is, each participant group demonstrated a statistically significant increase or decrease in accent range that could be unambiguously assigned to a corresponding point of discontinuity in the model.

By the end of the study, all of the groups demonstrated a stage of development that equaled or exceeded the model's predictions. By 12 months of age, for example, the TD infants had advanced to the stage of development that the model predicted for 12 month-olds with normal hearing. This anticipated finding served to confirm and validate the theory-based predictions of the model. At 9 months post-activation, the younger children with CIs reached a point in development that was equal to or slightly less than what the model predicted for 9 months of CI-assisted hearing experience. Relative to infants with normal hearing, then, the younger CI-recipients did not have a material advantage or disadvantage with respect to the pacing of intonation development.

The older children with CIs differed from the other groups. By the end of the study, they had reached a stage that was beyond the one predicted by the model for children with the same amount of hearing experience. In fact, after only 9 months of CI use, the older group advanced to a point in the steady-state portion of the plateau that marks the regression phase of early intonation, whereas the model predicted that that they would progress only to the final edge of the preceding stage.

Because the younger CI-recipients had reached the predicted stage only, but not beyond, the results indicated that the older CI-recipients developed intonation more rapidly than younger CI-recipients who had the same amount of CI use. In fact, the results suggested that the older children with CIs progressed even more rapidly than the control group of TD infants. That is, the children with CIs reached the same point of development after 9 months of hearing experience that the TD infants reached with the benefit of 3 additional months of robust exposure to the auditory input.

These results bolster our conclusion that the more mature nonverbal development of older CI-recipients confers an advantage for late implantation, an advantage which accelerates the pace of intonation development in these children. The data suggest that the amount of advantage is equivalent to about 3 months of exposure to robust auditory cues in the input. That is, older CI-recipients required only 9 months of hearing experience to reach the stage of development that the TD infants attained after 12 months of similar experience. Collectively, the findings suggest that the advantage which older CI-recipients had previously demonstrated only 2 months after CI activation is maintained at least through the first 9 months of CI use.

The apparent group difference among children with CIs could be due to subject characteristics other than age. For example, the older group included 4 children who had a progressive hearing loss or secondary impairments in addition to the primary impairment in hearing. All of these children were in the "older group." When these children were excluded from a follow-up analysis, the findings were not significant, probably because the older group was too small (N = 4) and the statistical power too weak to support the group by

session analyses. Inspection of the individual data, however, showed that the children with secondary impairments all demonstrated a stage of intonation development that was typical for the older group as a whole. Among the children with a complex history, the child with a progressive hearing loss demonstrated a pattern that differed from the older group as a whole. The findings for that child may indicate a more advanced stage of development than the rest of the older group with CIs, perhaps as a result of early hearing experience.

Secondary impairments may have had little or no adverse effect because intonation is a specialized communication system that is mediated by a different cerebral hemisphere than the one that subserves most components of language in adults (e.g., Blumstein & Cooper, 1974; Weintraub, Mesulam, & Kramer, 1981) and children (Bell, Davis, Morgan-Fisher, & Ross, 1990; Cohen, Branch, & Hynd, 1994). As a result of this functional and neuroanatomical independence, intonation may be unaffected by moderate or severe impairments in other cognitive-linguistic domains. For example, intonation is not typically impaired in children with specific language impairment in spite of delays in phonology, lexical development, and grammar that are hallmarks of this developmental language disorder (Snow, 2001; Wright, 2002; Wells & Peppé, 2003).

The most important finding for the CIs- recipients is the apparent advantage of the children who received their implant after the age of 2. We hypothesize that this advantage stems from the greater nonverbal maturity of the older children. However, variables other than chronological age could account for the results. For example, it is possible or even likely that the older group had longer hearing aid trials on average than children who were implanted at an earlier age. The advantage of the older children, then, could be due simply to the benefit they received from additional exposure to the input.via hearing aids (HA). The children's files were reviewed for data bearing on this issue. For 15 of the 18 participants, parent report data indicated the child's age at the time that he or she was first fitted with a hearing aid (see Table 1). Additional observations from 6 of the parents indicated that the children wore their HA regularly during the trial period. Accordingly, the length of the HA trial was defined as the number of months between the HA fitting and the date of implantation (1 month before activation). Although the HA trials of the older children on average were longer than those of the younger group (9 vs. 7.7 months), the difference as evaluated by a t-test was not significant. Thus, there was no evidence that the length of the HA trial differed across groups. To confirm this conclusion, the ANOVA which had indicated a significant interaction between age group and session was re-evaluated using length of the HA trial as a covariate. When the variance associated with the HA trial was removed, the original interaction was still significant (df = 1,12, $F = 5.854$, $p = .032$).

Another potential source of variance associated with the HA trials is the severity of the children's hearing loss in the speech frequencies. If a child's aided thresholds reflected only moderate losses in the speech frequencies, he or she might have at least partial access to f_0 in conversational speech. Moreover, if degree of access to f_0 was unevenly distributed across the age groups in favor of the older children, the type and severity of the aided hearing loss could account for the observed differences between the age groups.

To investigate this issue, the children's audiometric records were reviewed. Aided thresholds, minimal response levels, or real ear measures were available for 13 of the children with CIs. It was determined that 6 of the children were likely to have limited access to f_0 cues at conversational intensities, and 7 did not have access. A chi square test of the relation between access to f_0 and age group did not approach significance. Thus, there was no evidence that the age groups were dependent on a global measure of aided hearing acuity within the speech frequencies. For confirmation, the original ANOVA was re-evaluated with the categorical variable "access to f_0"as a covariate. When the covariate was statistically

controlled for, the session by age group interaction was still significant (df = 1,10, $F = 7.360$, $p = .022$).

The combined results of tests associated with the HA trials suggest that the pre-implant trials did not account for the rapid advances in language development that the older children demonstrated after implantation. This is consistent with judgments from the 6 parents who provided qualitative information about their children's HA trials. All 6 reported that that there was no change in the children's speech or spoken language development during the HA trial period.

The second major finding of the study is that the older children with CIs progressed even more rapidly than the TD controls. This result also points to the key role of nonverbal skills in the development of expressive intonation. However, the advantage of the older children with CIs could be attributed to the intensive speech therapy that the CI-recipients received, arguably a richer and more structured source of input than TD infants are exposed to in the context of daily interactions. If post-implantation experiences explained the older children's advantage over the TD infants, the younger CI-recipients should have had a similar advantage because the oral language therapy for both groups of children with CIs were based on the same intervention model and the same curriculum across the data collection sites; yet the younger group with CIs did not have an advantage or disadvantage with respect to the TD controls.

If the children at different ages received the same kind and intensity of speech therapy, the style of intervention probably developed from an emphasis initially on family-centered therapy, then child-centered interactions, and finally clinician-directed intervention. Compared to the younger group, the older children with CIs might maximally from this progression of clinical experiences because they have better joint attention skills and a greater knowledge of conversational pragmatics and turn-taking. An account of the older group's advantage that is based on an evolution of therapy experiences is attractive from the perspective of intuitive appeal and parsimony, for it is fully in agreement with the social-cognitive hypothesis that this study has highlighted. That is, we can conclude that the same sophisticated cognitive, social-emotional, and pragmatic skills allow the older CI-recipients to benefit optimally from supportive therapy experiences and from robust CI-assisted cues to intonation in daily life.

In summary, this study longitudinally analyzed the intonation production of CI recipients who were implanted at or before 24 months of age (Younger Group), CI recipients who were implanted after 24 months (Older Group), and infants who were typically developing (TD). Two of the three groups reached the stage of development that the normative model anticipated. The exception was the group of older children with CIs who reached a stage of development that was more advanced than the model predicted. In fact, by observation or inference, the older group of CI-recipients progressed more rapidly than the other groups, even the TD controls. Overall the results support the idea that, once robust auditory cues are available, the relatively greater nonverbal maturity of older CI recipients serves to accelerate the development of intonation – a linguistic system that is deeply rooted in nonverbal domains of cognition, emotion, and social interaction.

Our preliminary investigation had suggested that, after only 2 months of CI use, older CI-recipients developed intonation more rapidly than younger CI recipients. The present results extend the previous study by showing that the developmental advantage of the older children is maintained and possibly further consolidated after 9 months of CI-assisted hearing experience. Indeed, as we look ahead to future research, we expect that older children with

CIs will command the intonation skills of TD 2-year-olds quite early in the second year of CI use.

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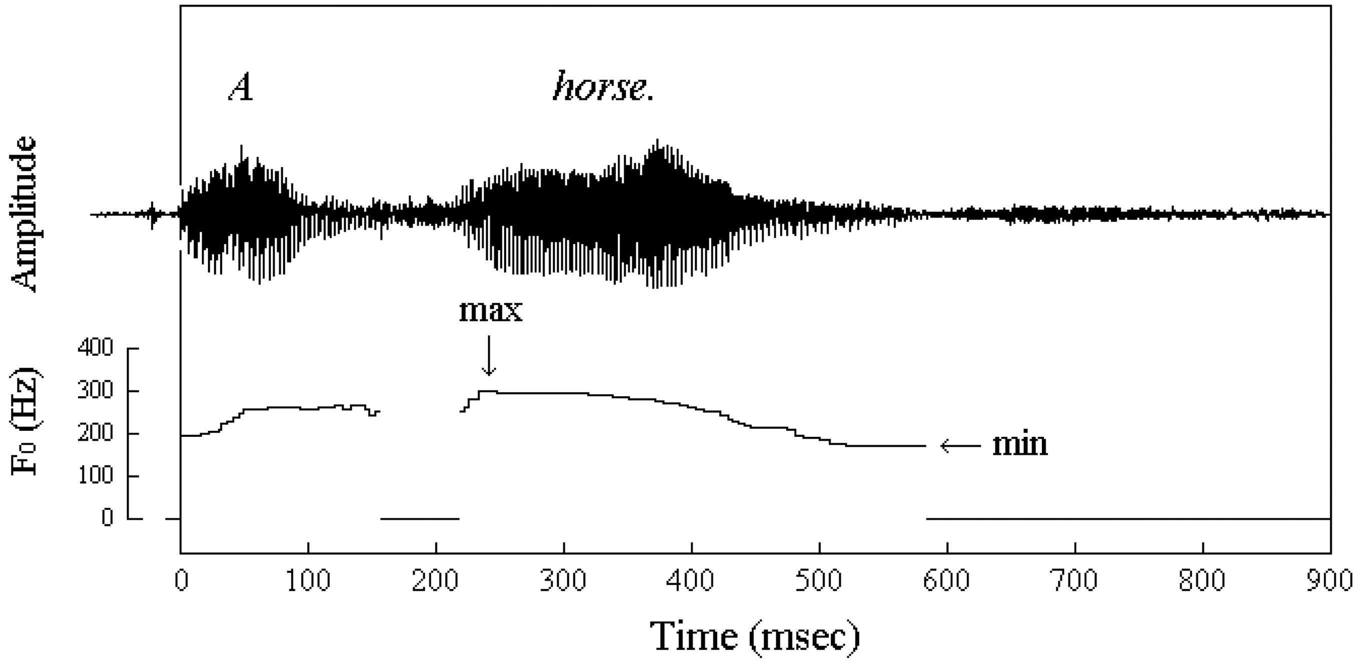

Figure 1.

Time waveform (upper panel) and fundamental frequency contour (lower panel) of the phrase *A horse* in the speech of Clara, a 4-year-old girl (max = maximum f_0, 298.0 Hz; min = minimum f_0, 170.3 Hz; accent range = 966.3 cents).

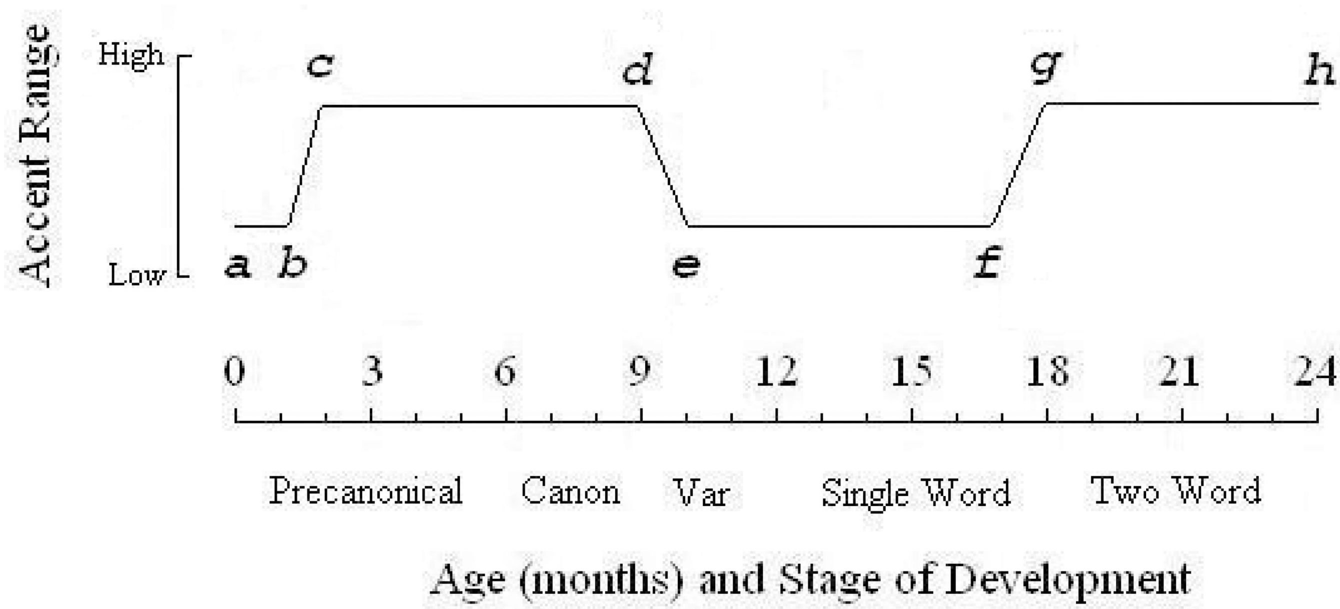

Figure 2.
A theoretical model of accent range development in children with normal hearing from birth to 24 months (Precanonical = Reflexive, Cooing, and Expansion stages; Canon = Canonical Babbling; Var = Variegated Babbling).

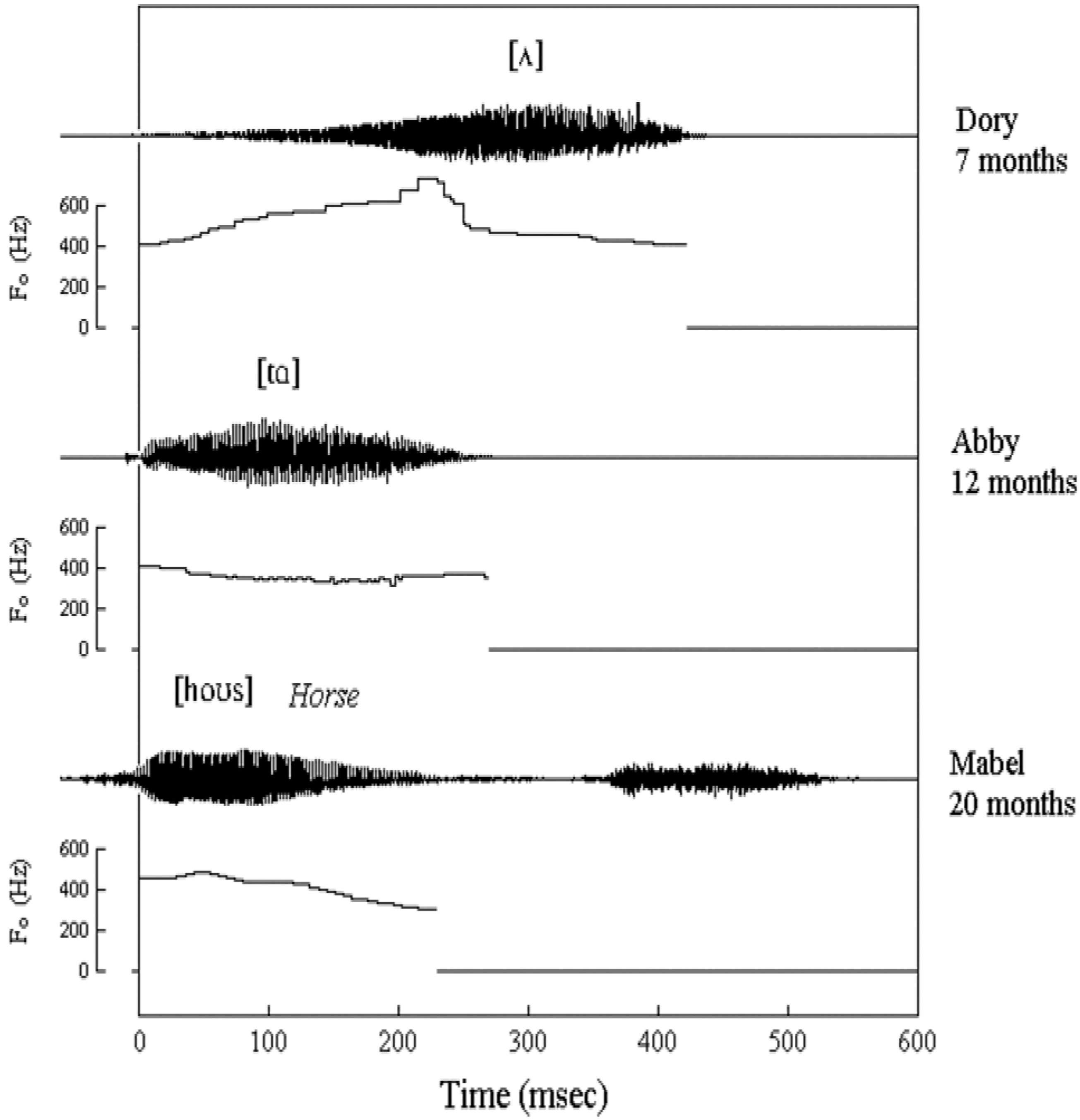

Figure 3.

Accent range in three children with normal hearing at different stages of intonation development [top panel (Dory) maximum f_0 = 727.7 Hz; minimum f_0 = 407.4 Hz; accent range = 1004.2 cents; middle panel (Abby) maximum f_0 = 410.0 Hz; minimum f_0 = 318.9 Hz; accent range = 439.4 cents; bottom panel (Mabel) maximum f_0 = 487.7 Hz; minimum f_0 = 305.1 Hz; accent range = 812.1 cents].

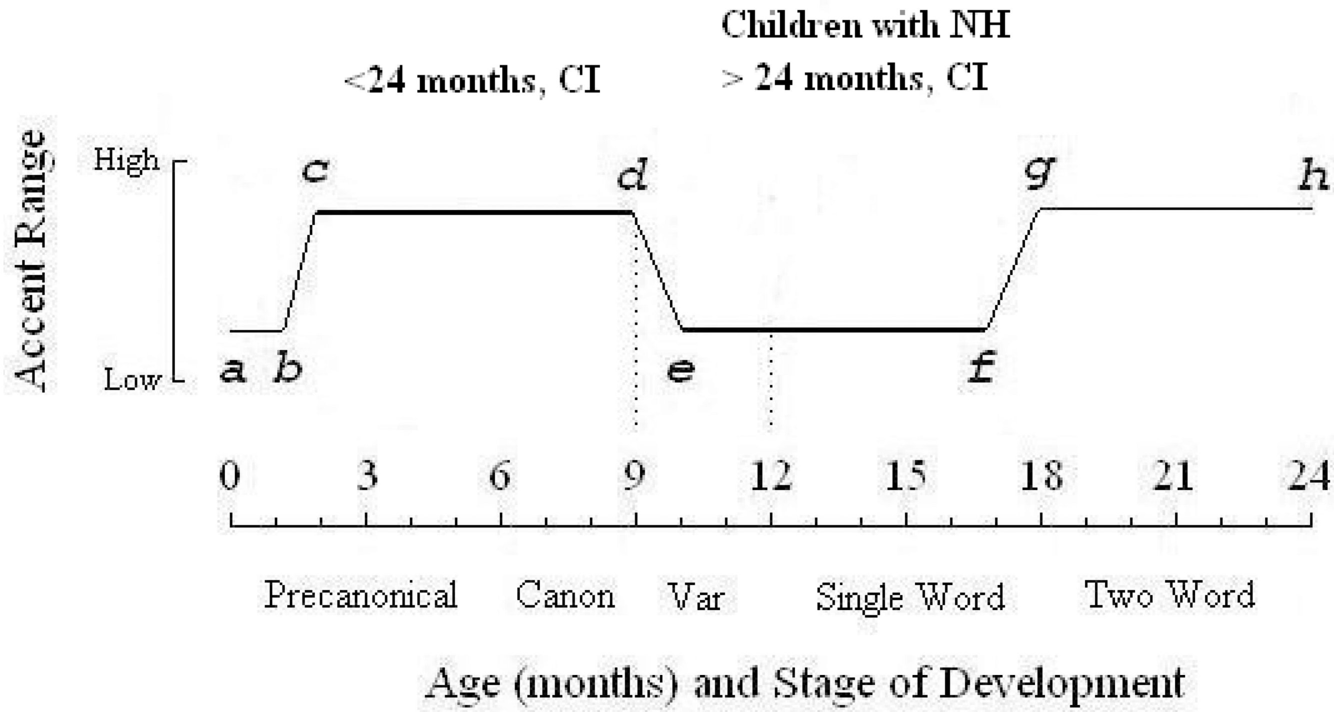

Figure 4.
Summary of inferred intonation development in younger CI-recipients (≤ 24 months, CI), older CI-recipients (> 24 months), and infants with normal hearing (NH) [other legends as in Figure 2].

Table 1

Audiometric and cochlear implant information for the participants with CIs.

Child	Gender	HL identified (NHS[1]/ months)	Age at 1st hearing aid fitting (months)	Age at 1st CI activation (months)	Age at 2nd CI activation (months)	Etiology	Device (processing strategy)	Pre-CI unaided thresholds better ear (dB HL)	Mean CI-aided thresholds SF[2] or better ear 6−12 mos (dB HL)	NISP[3]
AAWI	F	22	22	36		Cytomegal-ovirus	Freedom (ACE[4])	NR[5]	26	40
ABHO	F	NHS	--	27		Unknown	PSP[6] (HiRes[7]-P)	89	18.75	48
ANLO	F	12	21	30		Unknown/ family history	Freedom (ACE)	Aided 78; NR ≥4k	30	18
CONO	M	NHS	22	31		Inner ear malforma-tion	Freedom (ACE)	86	28.75	60
DAST	M	11	12	21		Malformed cochlea	Freedom (ACE)	76; NR ≥4k	18	44
ETKO	M	20	22	26		Prenatal complica-tions & prematurity[8]	Freedom (ACE)	90[9]	23	26
GIAI	F	NHS	6	13		Unknown	Freedom (ACE)	100	23	66
JAES	M	NHS	--	16		Unknown	PSP (HiRes-P)	bilateral profound[10]	13	20
JAWE	F	NHS	6	19		Connexin 26	PSP and Harmony (HiRes-P)	Mod-severe to profound[11]	21	40
JOIR	M	NHS	1 (R)/ 11 (L)	12		Unknown	Freedom (ACE)	106	20	25
JORO[12]	F	NHS	17	36		Unknown	Freedom (ACE)	96; NR ≥2k	26	16
OLHE	F	NHS	--	25		Unknown/ dysplasia[13]	Freedom (ACE)	80	38	66
OWJO	M	NHS	2	9		Unknown	Freedom (ACE)	NR	19	72

Child	Gender	HL identified (NHS[1]/ months)	Age at 1st hearing aid fitting (months)	Age at 1st CI activation (months)	Age at 2nd CI activation (months)	Etiology	Device (processing strategy)	Pre-CI unaided thresholds better ear (dB HL)	Mean CI-aided thresholds SF[2] or better ear 6–12 mos (dB HL)	NISP[3]
CAST	F	NHS	2½	13	19	Unknown	Freedom (ACE)	NR ABR[14]	30	30
JOLO	F	13	13	21	21	Unknown	Freedom (ACE)	94	28	48
IAGE	M	NHS	21	27	34	Unknown	Freedom (ACE)	Aided 59; NR ≥ 4k	25	24
LILA	F	17	18	27	27	Unknown (hypotonia)	Freedom (ACE)	102.5[15]	25	60
MAMA	F	13	14	18	20	Unknown	Freedom (ACE)	100	25	12
Mean			13.3	22.6	24.2				24.1	39.7
SD			8.0	8.1	6.30				5.7	19.3

[1] Newborn Hearing Screening,

[2] Sound Field,

[3] Nittrouer Index of Social Position (Nittrouer & Burton, 2005),

[4] Advanced Combinational Encoder,

[5] No response to pure- or warble-tones,

[6] Platinum Series™ Sound Processor,

[7] HiResolution,

[8] Apnea due to prematurity, indirect hyperbilirubinemia, ototoxic medications (Ampicillin and Gentamicin), presumed sepsis, and cerebellar hemorrhage,

[9] based on 0.5k and 2k; better ear responded to 0.5k at 80dB,

[10] No audiogram on file; hearing loss reported as “bilateral profound”,

[11] No audiogram on file; hearing loss reported as “moderately severe to profound”,

[12] JORO was identified with a mild bilateral loss by ABR testing at 1 month; bilateral mild to severe loss at 19 months, and a moderately severe to profound loss (right ear) with a severe to profound hearing loss (left ear) at 20 months of age,

[13] Bulbous deformity on apical turns bilaterally,

[14] Auditory Brainstem Response,

[15] LILA had difficulty conditioning to the VRA task but responded to speech at 80dB HL.

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Table 2

Number of monosyllabic utterances analyzed by child and session: TD infants.

	Chronological Age (months)			
Child	**6**	**9**	**12**	**Total**
WIAB	10	10	8	28
TRTO	11	4	18	33
SYNE	6	5	6	17
PARI	7	4	5	16
LIRO	3	3	7	13
HOWA	10	6	10	26
SASN	1	10	7	18
ELCA	8	12	7	27
FACO	5	9	14	28
COKU	4	5	13	22
ISIL	7	16	15	38
OLHA	10	8	3	21
Group Total	82	92	113	287

Table 3

Number of monosyllabic utterances analyzed by child and session: Children with CIs.

Group/	Months Post-Activation				
Child	3	6	9	12	Total
Younger Group					
OWJO	8	3	14	20	45
GIAI	11	9	11	12	43
JOIR	1	16	4	7	28
CAST	10	6	3	13	32
JAES	2	11	0	3	16
MAMA	8	6	15	10	39
JAWE	4	0	6	6	16
DAST	7	10	9	7	33
JOLO	5	3	11	10	29
OLHE	9	6	6	11	32
Group Total	65	70	79	99	313
Older Group					
ABHO	9	3	5	5	22
ETKO	8	4	14	0	26
IAGE	4	8	2	3	17
LILA	7	0	10	3	20
CONO	9	4	0	0	13
ANLO	1	6	5	0	12
JORO	5	13	11	10	39
AAWI	6	0	6	0	12
Group total	49	38	53	21	161
Both groups	114	108	132	120	474

Table 4

Mean accent range (cents)by child and chronological age: TD infants.

	Age (months)				Pitch Change[b]
Child	**6**	**9**	**6/9**	**12**	**(colum s 4,5)**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
WIAB	431.2	733.7	582.4	433.8	−
TRTO	377.9	270.5	349.3	310.0	−
SYNE	911.1	308.6	637.3	562.9	−
PARI	551.1	551.3	551.2	183.0	−
LIRO	465.2	605.5	535.3	278.5	−
HOWA	321.0	559.0	410.2	398.7	−
SASN	335.0	257.6	264.6	794.4	+
ELCA[a]	520.5	778.2	675.1	465.4	−
FACO	347.6	318.7	329.0	305.9	−
COKU	358.8	245.4	295.8	604.3	+
ISIL	486.2	376.7	410.0	229.6	−
OLHA	590.3	307.3	464.5	221.8	−
Group	474.7	442.7	458.7	399.0	

[a]Speech delayed;

[b]Pitch Change = difference between columns 4 and 5 (age legends are in bold type): plus sign (+) = increase, minus sign (−) = decrease.

Table 5

Mean accent range (cents) by child, age group, and time post-activation: Children with cochlear implants.

Group/ Child	**Age at Activation**	**Time Post-Activation (months)**					**Pitch Change[d] (columns 3,6)**
		3	**6**	**9**	**6/9**	**12**	
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Younger Group							
OWJO	9	227.4	348.7	463.7	443.4	792.4	+
GIAI	13	729.9	475.4	468.7	471.7	255.3	−
JOIR	12	97.8	490.0	335.7	459.1	329.2	+
CAST	13	317.6	258.7	670.7	396.0	503.6	+
JAES	16	379.9	352.1	--	352.1	368.5	−
MAMA	18	654.9	707.0	673.6	683.1	675.1	+
JAWE	19	520.1	--	718.5	718.5	394.3	+
DAST	21	480.9	508.4	451.5	481.5	358.7	+
JOLO	21	331.8	391.6	695.7	630.5	309.7	+
OLHE	25	276.5	368.6	391.2	379.9	312.1	+
Group Mean	17	401.7	433.4	541.0	501.6	429.9	
Older Group							−
ABHO	27	601.6	631.5	355.5	459.0	608.7	−
ETKO	26	553.7	756.1	486.7	546.6	--	−
IAGE[a,b]	27	845.9	491.3	653.7	523.8	598.9	−
LILA[a]	27	628.4	--	321.2	321.2	371.6	−
CONO[a]	31	389.6	269.1	--	269.1	--	−
ANLO	30	267.5	293.3	531.0	401.4	--	+
JORO[c]	36	430.7	444.5	546.4	491.2	497.7	+
AAWI	36	472.7	--	357.1	357.1	--	−
Group meam	30	523.8	481.0	464.5	421.2	519.2	

[a]Secondary disorder,

[b]Possible Autism spectrum disorder,

[c]Progressive hearing loss,

[d]Pitch Change = difference between columns 3 and 6 (time post-activation legends are in bold type):plus sign (+) = increase, minus sign (−) = decrease, -- = data not available.