ABSTRACT

Title of Document: SPEECH RECOGNITION IN NOISE AND INTONATION RECOGNITION IN PRIMARY-SCHOOL-AGED CHILDREN, AND PRELIMINARY RESULTS IN CHILDREN WITH COCHLEAR IMPLANTS

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Fundamental frequency (F0), or voice pitch, is an important acoustic cue for speech intonation and is perceived most accurately through the fine spectral resolution of the normal human auditory system. However, relatively little is known about how young children process F0-based speech intonation cues. The fine spectral resolution required for F0 information has also been shown to be beneficial for listening in noise, a skill that normally-hearing children are required to use on a daily basis. While it is known that hearing-impaired adults with cochlear implants are at a disadvantage for intonation recognition and listening in noise following loss of fine spectral structure cues, relatively little is known about how young children with unilateral cochlear implants perform in these situations.

The goal of the current study was to quantify how a group of twenty normally-hearing children (6-8 years of age) perform in a listening-in-noise task

and in a speech intonation recognition task. These skills were also measured in a small group of 5 children of similar age with unilateral cochlear implants (all implanted prior to the age of five). The cochlear implant participants in this study presumably had reduced spectral information, and it was hypothesized that this would be manifested as performance differences between groups. In the listening-in-noise task, sentence recognition was measured in the presence of a single-talker masker at different signal-to-noise ratios. Results indicated that the participants with cochlear implants achieved significantly lower scores than the normally-hearing participants. In the intonation recognition task, listeners heard re-synthesized versions of a single bisyllabic word ("popcorn") with systematically varying F0 contours, and indicated whether the speaker was "asking" or "telling" (i.e., question-like or statement-like). Both groups of children were able to use the F0 cue to perform the task, and no significant differences between the groups were observed. Although limited in scope, the results suggest that children who receive their cochlear implant before the age of five have significantly more difficulty understanding speech in noise than their normally-hearing peers. However, the two populations appear to be equally able to use F0 cues to determine speech intonation patterns.

SPEECH RECOGNITION IN NOISE AND INTONATION RECOGNITION IN PRIMARY-SCHOOL-AGED CHILDREN, AND PRELIMINARY RESULTS IN CHILDREN WITH COCHLEAR IMPLANTS

By

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Dedication

This dissertation is for those that have loved and encouraged me during this process:

For Kevin, who bore the brunt of my frustrations and foul moods without a sharp word in retort, who had faith in my abilities even when I did not and who has shown me the meaning of unconditional love without asking for anything in return.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Persons with normal hearing (NH) and those with hearing loss, including cochlear-implant users, need access to fundamental frequency (F0) information in order to perform many listening tasks in everyday life. Fundamental frequency is the lowest frequency component of a harmonic series. In human speech, F0 is produced by the periodic vibrations of human vocal folds, and serves as an aid for listening in noise and as a cue to voice pitch (Culling & Darwin, 1993; Rossi-Katz & Arehart, 2005).

Fundamental frequency is perceived in the normal auditory system by means of frequency-place coding in the inner ear, or cochlea. (Frequency-place coding is the response of the human auditory system to an input of a certain frequency at a certain physical point on the basilar membrane and along the auditory nerve.) Accurate perception of F0 requires the spectral resolution capabilities of the normal human auditory system. Additional F0 cues may be derived from the periodicity of the speech waveform (i.e., temporal envelope cues), but frequency-place coding is the dominant cue for transmitting F0 information.

Fundamental frequency is one of the acoustical cues that provides information about speech intonation (along with intensity and duration). Intonation contours contribute to information about the prosodic structure of an utterance. In tonal languages, linguistic information is also carried in the intonation contours of speech. Thus, sensitivity to speech intonation is an important aspect of speech perception.

Because normally-hearing children are generally presumed to have normal spectral and temporal-resolution capabilities, the notion of studying F0 perception in relation to listening-in-noise and as an intonation cue is relatively new. Instead, studies of intonation recognition by children have focused on the developmental time course of intonation use (e.g., Martel, 2002) and the function that intonation serves in early language learning (e.g., Gerken, 1996). There have been several studies of normally-hearing children and their ability to listen in noise, particularly in the context of noisy classrooms. None of these studies have directly examined the role that F0 plays in listening-in-noise, although it is known that children, in general, require more favorable listening conditions than adults in order to accurately perceive speech in noise (Fallon, Trehub & Schneider, 2000; Papso & Blood, 1989; Stuart, Givens, Walker & Elangoven, 2006).

There is a critical difference in the way F0 is perceived in those with cochlear implants and those with normal hearing. In severe sensorineural hearing losses such as those found in cochlear-implant users, the ability of the auditory system to use frequency-place coding cues for the perception of F0 is limited (Faulkner, Rosen & Moore, 1990). The listener must instead rely on temporal cues for F0 perception. Temporal cues (i.e. information derived from the speech envelope as it changes over time) are not as precise in providing F0 information as spectral cues. With reduced access to F0 information, persons with cochlear implants are at a disadvantage for using this cue as an aid in noisy environments and for recognizing changes in voice pitch.

Existing literature on F0 in relation to cochlear implants focuses on improvements in F0 coding for adult cochlear-implant users (Geurts & Wouters, 2001; Geurts & Wouters, 2004; Vandali et al., 2005) and the effect of different talker maskers on speech perception by adult cochlear-implant users (Nelson, Jin, Carney & Nelson, 2003; Stickney, Zeng, Litovsky & Assman, 2004). While there have been some studies on intonation recognition by cochlear-implant users (e.g. Chatterjee & Peng, 2008; Green, Faulkner, Rosen & Macherey, 2005), they have varied in their control of intonation cues, with some directly examining F0 as the only contributor to intonation information and others using all intonation cues in their stimuli (intensity, duration and F0). Peng, Tomblin and Turner (in press) directly investigated intonation recognition by pediatric cochlear-implant recipients. While they observed significant differences in performance on an intonation recognition task between cochlear-implant recipients and normally-hearing controls, their findings cannot be attributed directly to differences in F0 perception only. The stimuli used in that investigation included co-varying duration and intensity cues which are other significant markers of intonation. Thus, relatively little is known about how young children with CIs process F0 information in speech perception tasks. Although listening-in-noise in pediatric cochlear-implant recipients has previously been examined by many researchers, many of the studies regarding listening-in-noise in children with cochlear implants has focused on bilateral implant users, not unilateral implant users.

The goal of this study is to investigate the performance of normally-hearing children in speech perception tasks and make a preliminary comparison to the performance of a small sample of pediatric cochlear-implant recipients. In the present study, two tasks were selected: i) the Pediatric Speech Intelligibility (PSI) test (a measure of speech perception in competing maskers) and ii) an intonation recognition task. The intonation recognition task was designed to yield a measure of sensitivity to changes in F0. The current study seeks to determine if there is a significant difference in performance between the two groups given different means of access to the F0 cue. The PSI test provides a measure of speech perception in the presence of a competing speaker. Performing well on this task would presumably require the ability to separate one speaker from another (i.e., F0 separation). Comparisons on these tasks between the two participant groups may help to highlight some of the functional differences in speech perception by these two populations.

Given the limited scope of this dissertation, we have focused on measuring the performance of a group of twenty NH children (6-8 years old) on these tasks. In addition, we have obtained identical measures with a small group of five 6-to-8-year-old children with unilateral cochlear implants (all implanted before the age of 5 years). The work described here represents a first step toward quantifying the ability of 6-to-8-year-old children to effectively utilize acoustic cues for intonation recognition and for speech perception in noise.

Chapter 2: Review of Relevant Literature

Fundamental frequency is not only a major contributing cue to speech intonation, but also plays an important role for listening-in-noise. Fundamental frequency is the acoustical feature that contributes to the perception of voice pitch. Voice pitch, in turn, is one of the three cues that makes up intonation. Intonation is one of the suprasegmental cues of speech, an implicit message giving the listener additional information about the communicative intent of an utterance.

Children use F0 on a daily basis, though not in an explicit manner. They use F0 changes as a marker for speech intonation and to listen in noise. Since literature has shown that children already require better conditions for listening-in-noise than normally-hearing adults, the noisy environments that they are subjected to (i.e. classrooms) on a daily basis may be problematic. Taking this scenario one step further, children with cochlear implants, who have limited fine spectral structure for intonation and speech in noise perception, and are mainstreamed in classrooms, may experience even further deficits than their normally hearing peers.

Existing literature has shown that adult cochlear-implant users, with their loss of fine spectral structure, have difficulty when listening in background noise and with intonation recognition, as compared to normally-hearing adults. However, very little research has been done to look at how children with cochlear implants specifically use F0 in these tasks. From the existing literature based on adult cochlear-implant users, it is reasonable to infer that pediatric cochlear-implant recipients may have, at the very least, the same, if not greater, difficulties than adults do with auditory tasks that require the use of fine spectral structure. If these children are in the same challenging auditory environments as their normally-hearing peers on a daily basis but are at a further disadvantage for using fine spectral structure, quantitative comparisons between these two populations are warranted in order to highlight the resultant differences in perception and functioning.

Listening in Noise by Children: Signal-to-Noise Ratio and Spectro-temporal Resolution

Evidence has shown that children are not born with fully-mature auditory-processing capabilities and instead demonstrate a developmental time course in processing complex auditory situations, such as listening in background noise or listening to spectrally-degraded speech (Blandy & Lutman, 2005; Eisenberg et al., 2000; Stuart, 2005). Certainly, children need more favorable conditions than do adults in order to achieve comparable listening-in-noise scores (Fallon, Trehub & Schneider, 2000; Papso & Blood, 1989; Stuart, Givens, Walker & Elangoven, 2006).

Blandy and Lutman (2005) studied 189 normally-hearing seven-year-olds and determined the signal-to-noise ratio required by their participants to score 71% correct on a listening-in-noise task to that required by young, normally-hearing adults. They reported that the seven-year-olds in their study, while having overall better thresholds for listening to pure tones, required greater signal-to-noise ratios than those found by the adult NH users in Cattermole (2003) (as cited in Blandy & Lutman, 2005) in order to achieve comparable performance, suggesting that while hearing sensitivity may be better in young children, the ability of young children to listen in noise is not yet comparable to adults. However, interpretation of this comparison should be made with caution, as the referent adult data was collected in another study over which the authors of this study did not exert experimental control. Stuart (2005) suggested a similar disadvantage for young children listening-in-noise when directly comparing 6-to-15-year-old children and normally-hearing young adults. The children in this study were divided into several smaller age groups (i.e., 6 years through 7 years, 11 months; 8 years through 9 years, 11 months, etc.). When compared on their performance on the NU-CHIPS (the Northwestern University Children's Perception of Speech test) in quiet, steady-state and interrupted background noise, the younger children in this study exhibited greater difficulty for listening in both kinds of background noise than the older children and adults, with performance improvements noted with increasing age. Adult-like performance for listening-in-noise was exhibited in the child participants 11 years of age and older. The interpretation of these findings may be somewhat limited by the fact that the NU-CHIPS, word-length stimuli marketed as appropriate for children as young as three years of age, was used for both the adult and child participants. This type of stimuli would have been significantly easier for the adult participants, making it somewhat questionable to compare their performance with that of the children...

Other studies comparing speech perception for children and adults listening-in-noise have not directly suggested immature temporal-resolution capabilities as the source of the difference between the two groups, but have certainly made the case for different requirements for children and adults for successful speech perception in noise. Papso and Blood (1989) compared 4-to-6-year-old children and adults on the Word Intelligibility by Picture Identification task in quiet and in two kinds of background noise (multi-talker babble and pink noise). The adults in that study demonstrated excellent speech perception skills (>90%) in all experimental conditions, whereas the child participants demonstrated significant decrements in speech perception scores for the conditions with background noise. As with in Stuart (2005), the adult and child participants were compared on a task (in this set, a closed set task) that may have been significantly easier for the adult participants. Thus, these results must be interpreted with caution. Fallon, Trehub and Schneider (2000) studied speech perception by children (aged 5, 7 and 11 years of age) and adults on a closed-set task at varying SNRs. They reported that the child participants required better SNRs than the adult participants did in order to achieve comparable levels of speech perception.

Hartley, Wright, Hogan and Moore (2000) suggested not only a developmental time course for temporal-resolution capabilities in children, but a developmental time course for spectral resolution capabilities, as well. Similar to the findings of Stuart (2005), Hartley et al. indicated that adult-like temporal-resolution capabilities were not reached until approximately 11 years of age.

Hartley and colleagues compared tone detection capabilities in children aged 6-11 years of age to that of adults on a backward masking task, a task commonly used as a measure of temporal resolution. However, in a further comparison of the adult and child participants in this study on a tone detection task in varying background noises (bandpass-filtered background noise or spectrally notched background noise), they demonstrated that spectral resolution capabilities in children reach adult-like performance by 6 years of age, much younger than when temporal-resolution capabilities are thought to have fully developed. Both Stuart (2005) and Hartley and colleagues (2000) provide evidence of the development of temporal-resolution abilities in children, as measured by two different tasks and both reported that temporal resolution is not fully mature until approximately 11-years-of-age in children. However, in an interesting contrast, Hartley and colleagues provided evidence that spectral resolution, a separate yet crucial auditory skill, matures much earlier than temporal resolution does in children, suggesting that young children who do not have fine spectral resolution (i.e. in hearing loss) are a disadvantage until later in their auditory maturation than those who are able to use earlier emerging auditory skills (i.e. spectral resolution vs. temporal resolution).

While Hartley and colleagues indicated that spectral resolution capabilities were mature in children as young as 6 years of age, Eisenberg et al. (2000) proposed somewhat different developmental timelines for spectral resolution capabilities in children, based on the comparative performance of two different age groups of children (5-7 years of age and 10-12 years of age) and adults on a speech perception task. By systematically controlling the amount of spectral information available through noise-band vocoders (simulators that use band-pass filters applied to channels of noise to approximate cochlear-implant-processed speech), they reported that while the older children and adults demonstrated similar performance with the same amount of spectral resolution available, the younger children needed more spectral information in order to achieve comparable speech-perception scores. These results are in disagreement with Hartley et al. (2000) and indicate that children do not have fully mature spectral resolution skills until the age of 10-12 years, around the same time as their temporal resolution skills are reaching full maturity. However, the apparent discrepancy may be at least in part due to the differing demands of the tasks used in the two studies. It is possible that the spectral resolution observed in young children in the psychophysical experiments does not translate to the perception of degraded speech, which would presumably require more top-down processing, until further development has occurred. From these findings, it is reasonable to infer that very young normally-hearing children who do not have mature spectro-temporal skills are at a disadvantage in many of their listening environments and may not be able to use one auditory skill (such as spectral resolution) to aid in complex listening situations in the absence of other mature auditory skills.

Given that children's auditory systems are not as proficient at processing sounds in complex listening situations when compared to adults, it comes as no surprise that they also required better signal-to-noise ratios than adults do for listening in noisy environments (Stuart, Givens, Walker & Elangoven, 2006).

Stuart, Givens, Walker and Elangoven (2006) compared preschool children with adults on their ability to listen in noise at various SNRs and in steady-state or interrupted background noise. While both groups demonstrated greater overall difficulty in the steady-state background noise, the preschool-aged participants needed better SNRs in order to achieve comparable speech perception scores with the adult participants for all types of background noise. However, because both participant groups in this study demonstrated similar decreases in performance for the steady-state background noise, Stuart and colleagues argued that this was evidence for poorer overall processing capabilities in children and not a result of less mature temporal-resolution capabilities in children.

Several studies have investigated the effects of poor acoustical environments found in classrooms on childrens' speech perception. Children spend large amounts of time in classrooms, which are not quiet environments. The acoustical challenges presented by a classroom listening environment are two-fold: poor signal-to-noise ratios and increased reverberation. As the signal-to-noise ratio decreases and the reverberation increases, children's speech perception deteriorates (Jamieson, Kranjc, Yu & Hodges, 2004; Johnson, 2000).

Jamieson, Kranjc, Yu and Hodgetts (2004) demonstrated that school-aged children have difficulties with speech recognition in signal-to-noise ratios that are often found in modern classrooms. Jamieson et al. selected a variety of speech stimuli and studied average classroom noise levels in order to present the most realistic classroom conditions in their study. By comparing different age groups on the same listening tasks, they found that younger school-aged children (5-6 years of age) had even more speech perception difficulties than did older school-aged children (age 7-8 years of age) in the same conditions. These results are significant in that they help to illustrate the fact that younger children (who may not have fully mature spectral or temporal resolution abilities) are at disadvantage in real-life classroom situations as compared to older students.

Johnson (2000) examined consonant and vowel identification in children and adults at varying presentation levels, in four different listening conditions: in quiet, in noise only, with reverberation only and in noise and reverberation. Vowels were easier to identify for all participants and comparable scores on vowel identification were achieved by all age groups across all listening conditions. However, consonant identification demonstrated age effects for all of the listening conditions presented. Consonant identification, unlike vowel identification, did not reach adult-like levels until the late teenage years in the listening condition that combined noise and reverberation. Yacullo and Hawkins (1987) reported similar effects of noise and reverberation on school-aged children (8-10 years of age) on speech perception. Simulating "typical classroom conditions" in terms of noise level and reverberation, Yacullo and Hawkins tested speech perception at two different SNRs (+2 dB and +6 dB) with and without reverberation effects. They observed that reverberation had a particularly deleterious effect on speech perception, independent of the level of background noise.

Listening-in-noise, particularly modulated noise (noise that does not have a flat envelope and instead is manipulated in time or amplitude) or interrupted background noise, presents a problem for many listeners, although it seems to pose a greater challenge for children, when compared to adults. There is debate as to whether this is a result of differences in temporal and spectral resolution capabilities or merely a result of better processing capabilities in adults. Whatever the case, the acoustic environment found in most classrooms present difficulties for children, particularly as poor signal-to-noise ratios and reverberation are present in combination.

Normally Hearing Children and the Emergence of The Processing of Prosodic Cues

Relatively little is known about how normally-hearing children learn to use intonation, both perceptually and productively. Gerken (1996) suggested that prosodic contours serve two important functions in early language learning: 1) to mark natural boundaries in sentence segments and 2) as a cue to sentence syntactic structure. While the work of Gerken (1996) may seem irrelevant to school-aged children, prelingually deafened children who are not able to access these cues until significant interventions are made may follow similar timelines of prosodic development.

Prosody serves as an indicator to sentence segmentation and syntactic structure and aids in language learning in this way, and this is the focus of existing literature. Previous studies have supported the notion of infants using prosodic contours as a cue to sentence segmenting (Hirsh-Pasek, Kemler-Nelson, Jusczyk, Cassidy, Druss & Kennedy, 1987; Kemler-Nelson, Hirsh-Pasek, Jusczyk

& Cassidy, 1989) by demonstrating that infants listen longer to speech that has pauses inserted at natural segment boundaries instead of speech that has pauses within sentence segments. Hirsh-Pasek et al. (1987) studied 7-to-10-month old infants on a head-turning task. The stimulus was infant-directed speech with speech pauses inserted at natural clausal boundaries and at other non-clausal boundary points in the sentence. Results indicated that the infants oriented longer to the speech stimuli that included the pauses at natural clausal boundaries, suggesting that infants are oriented to pauses inserted in speech (pauses being a part of the perceptual feature of prosody) as a meaningful grammatical marker at a very young age.

Investigators have constructed a developmental timeline for early intonation perception and use (Doherty, Fitzsimons, Asenbauer & Staunton, 1999; Martel, 2002). Doherty and colleagues (1999) tested 40 normally-hearing children between the ages of 5 and 9 years on a number of intonation recognition tasks and measured their recognition of prosodic markers in music and in speech, including a prosodic recognition task requiring the participants to differentiate between sentence and question prosodic contours. Results indicated that recognition of prosodic cues that express emotion in music were in place early in development, but demonstrated a significant effect of age on the recognition of prosodic cues in speech tasks, indicating that recognition of prosodic cues continues to improve and develop with age. Martel (2002) described a developmental timeline for use of prosody in a much younger group of children (between the ages of 25 and 41 months). Three distinctive stages of prosodic development were described after studying the tape-recorded dialogues of participants with an examiner. The first stage, between the ages of 25 and 28 months, is marked by use of prosody for communicating the intent of the utterance only, usually as a rising contour only. As children develop more complex syntactical systems, they move into the second stage (between the ages of 28 and 35 months of age) where prosody not only indicates the communicative intent of the utterance but is also used to highlight certain words or phrases within the utterance. It is at this second stage where Martel first recognized the used of a lengthened final syllable as part of the prosodic contour of a sentence. The third stage (between the ages of 35 months and 41 months) features the introduction of falling intonation contours to indicate a statement and overall intonation contours take on more adult-like forms. Taken together, the above studies suggest that while children may be able to use prosodic markers in speech at an early age as a segment marker in longer utterances, their overall recognition of prosodic contours for other purposes continues to develop and improve well into the school-aged years.

Speech Cues Transmitted by Cochlear Implants

Cochlear implants transmit speech cues through a number of parameters. An understanding of how speech cues are encoded in cochlear implant speech processors helps to illustrate the limits of the system. Cochlear implants approximate the human speech stream using temporal, spectral and amplitude cues, although for the purposes of this dissertation, the focus will remain on temporal and spectral cues. For the recognition of F0, temporal cues are the most important feature of the processing strategy.

Temporal. Temporal cues (along with spectral cues) in the human speech stream convey information about the F0 of the speaker's voice. In modern cochlear implants, temporal information is the primary conveyor of voice pitch and F0 information (Geurts & Wouters, 2004; Shannon, 2007). Temporal information is perceived via the changing heights (i.e., amplitudes) of biphasic electrical impulses that are presented in rapid succession to adjacent channels in the cochlea. The rate at which these pulses are presented to each channel is known as the pulse rate. Pulse rates dictate the maximum envelope frequency that speech processors can transmit when coding sound. This, in turn, determines the range of voice pitch cues that the implant user can access.

Chatterjee and Peng (2008) examined nine cochlear-implant users' performance on a modulation frequency discrimination task and observed that adult cochlear-implant listeners (both pre- and post-lingually deafened) had more difficulty detecting changes in modulation frequency as modulation rates increased. This suggests that adult cochlear-implant listeners are better able to perceive temporal information from envelope waveforms at lower envelope frequencies as opposed to higher envelope frequencies, which helps to highlight some of the limitations of temporal resolution through cochlear implant coding systems.

Geurts and Wouters (2001) studied the effects of F0 information on vowel perception by four adult cochlear-implant users. They observed that vowel perception was significantly worse in coding strategies where all F0 information was provided only through temporal envelope information as compared to vowel perception in coding strategies where F0 information was enhanced by other cues in channel outputs (such as increasing channel modulation depths). From this, we can reasonably infer that F0 information can be enhanced in cochlear implant coding strategies by making the temporal cues that provide F0 information more salient for the listener and that these temporal enhancements have implications for improvements in speech perception as well.

Spectral. In cochlear implants, spectral information is provided via “channels” of information. The incoming signal is processed through a series of filter banks and the frequency components of the signal are directed toward a specified channel that codes only frequency information in a given range. These channels, in turn, stimulate their designated intra-cochlear electrode. Stimulation of these electrodes is designed to take advantage of the tonotopic organization of the auditory nerve. Different places (i.e., “frequencies”) along the auditory nerve are stimulated depending on the frequency information in the incoming signal. Cochlear implants have significantly less fine spectral resolution than that of the normal human auditory system, yet even with fewer channels of spectral information, cochlear-implant listeners are able to accurately perceive speech in most situations (Dorman & Loizou, 1998). Spectral information provided by cochlear implants is reduced because of limitations of the channels (or electrodes) within the system. Providing enough “channels” of spectral information to approximate the spectral resolution capabilities of a normal auditory system is not feasible because of physical limitations (electrode size and number required to fit within the confines of the cochlea) and device limitations (i.e., channel interaction, where the spread of electrical current from one electrode would interfere with another closely placed electrode and thus cause stimulation in a spectral channel that was not represented in the original stimulus). Large amounts of channel interaction have been have been observed for stimuli presented on adjacent electrodes, although the overall effect is individually variable and dependent on the stimulus parameters (Chatterjee & Shannon, 1998).

The amount of spectral information required for adequate speech perception is relatively small when amplitude and temporal information are preserved. Shannon, Zeng, Kamath, Wygonski and Ekelid (1995) have shown that good speech perception is possible in normally-hearing listeners with only three spectral bands of information. There were no further improvements noted with the addition of a fourth spectral band, suggesting that when adequate amplitude and temporal information are present, greater spectral resolution is not necessary for good speech perception.

The minimal number of channels required for asymptotic speech perception may also demonstrate a developmental effect. Thus, in their study cited previously, Eisenberg and colleagues (Eisenberg, Shannon, Martinez, Wygonski & Boothroyd, 2000) found that younger child participant group (5-7 years of age) needed more channels of spectral information than did the older children (10-12 years of age) and the adults, in order to obtain comparable levels of speech perception. From this, Eisenberg et al. (2000) suggested a "long learning period for robust acoustic pattern recognition" is needed by younger implant users.

Spectral information not only has implications for speech recognition, but also for voice pitch perception. By manipulating both temporal and spectral information in normally-hearing and cochlear-implant listeners, Fu, Chinchilla and Galvin (2004) demonstrated that when relatively little spectral information was available (4 channels), speaker-gender identification improved with increased temporal information. However, this dependence on temporal information declined when more spectral channels were added. These findings indicate that even when spectral information is reduced, some clues to voice pitch (such as those required to differentiate between male and female speakers) can be extracted from temporal information with less fine spectral structure present.

The above studies provide a foundation for understanding how speech cues are transmitted and perceived in cochlear-implant users. Certainly, there are limitations inherent to cochlear implant systems and their ability to code sounds. However, human listeners have demonstrated their ability to perceive speech with accuracy even with degraded spectro-temporal information.

Listening in Noise in Adults with Hearing Loss and Cochlear Implants

Listening in background noise poses great difficulty to both persons with hearing impairment and persons with cochlear implants. Cochlear-implant users are not able to use the same cues that normally-hearing listeners do in noise, in part because of reduced spectral resolution (Friesen, Shannon, Baskent & Wang, 2001). In normally-hearing children, the differences between their speech perception abilities in noise and those of adults have often been compared. However, the literature regarding pediatric cochlear-implant recipients and listening-in-noise primarily focuses on the benefits of bilateral cochlear implantation and not on how children with CIs are at a disadvantage from their loss of fine spectral structure. In this case, we must examine the literature on adult cochlear-implant users and their disadvantage for listening-in-noise to see how these disadvantages might also apply to pediatric cochlear-implant recipients.

Normally-hearing listeners often find it easier to listen in modulated background noise vs. steady-state noise because they are able to use “release from masking” to take advantage of the “gaps” in modulated background noise to listen to and perceive a target stimulus. Cochlear-implant users display no such advantage, putting them at an even greater disadvantage for listening-in-noise. Qin and Oxenham (2003) simulated implant conditions in normally-hearing participants. They reported significant differences between the perception of unprocessed speech in background noise and speech perception through simulated implant conditions in the presence of background noise, even when large amounts of spectral information were present in the latter case. Modulated background noise caused more interference than steady-state background noise in the processed speech conditions, which is the inverse of what would be expected for normally-hearing listeners listening to unprocessed speech, suggesting that the loss of spectral structure in synthesized speech is a detractor to listening-in-noise abilities. The authors make a strong case for their suggestion that steady-state background noise used in speech tests may not accurately recreate the most difficult listening situation for cochlear-implant users.

Fu and Nogaki (2004) compared normally-hearing listeners' and cochlear-implant listeners' performance on sentence recognition in the presence of steady-state or modulated noise. The NH listeners attended to acoustic simulation of CI-processed speech. Consistent with the findings of Qin and Oxenham (2003), Fu and Nogaki observed that as the number of spectral channels was reduced, modulated background noise made speech perception in noise more difficult for both normally-hearing listeners and cochlear-implant users. As the spectral resolution of simulations decreased, so did the ability of the normally-hearing participants to utilize release from masking. When the implanted participants listened in modulated noise, speech perception was similar to that of the normally-hearing participants listening to simulated speech with 4 channels of spectral information. However, the best CI listeners' performance was similar to that of NH listeners' performance with 8-16 channels of spectral information.

Other studies have also focused on the disadvantages cochlear-implant users face in the presence of modulated background noise (Nelson et al., 2003; Stickney et al., 2004). Stickney and colleagues investigated different types of speech maskers in normally-hearing and implanted listeners (Stickney et al., 2004). They used speech-shaped noise, single male talkers and single female talkers over IEEE sentences (sentences developed for the use of testing electronic devices, from the Institute of Electrics and Electronical Engineers recommendations for speech quality measurements). They reported that the normally-hearing participants were not able to use release from masking with simulated implant conditions and that implant users in their study also were not able to use release from masking, similar to the findings of Qin and Oxenham (2003). The normally-hearing participants were able to obtain release from masking when listening to unprocessed speech conditions, suggesting that the greater interference experienced by CI listeners with modulated noise was related to reduced spectral information. This study also noted no difference between CI listeners' performance with maskers that were the same or a different talker (i.e., the same or difference F0) from those delivering the target sentences. Nelson and colleagues also adapted IEEE sentences to evaluate normally-hearing and implanted participants' speech recognition in steady-state and fluctuating noise (Nelson et al., 2003). They examined speech perception at varying modulation rates, in steady-state noise and in quiet. Their results were in agreement with other studies – normally-hearing listeners were able to achieve release from masking in the dips of the modulated masker, whereas cochlear-implant users were not able to use modulated noise to their advantage. For the implanted listeners in their study, modulated noise at a rate of 2-4 Hz produced the most interference. The implanted group needed a greater SNR to perform similarly to the normally-hearing group. IEEE sentences provide very few contextual cues and the choice of these stimuli provide few limitations on the above studies, making them a strong choice for stimuli in speech in noise studies.

While none of the above studies focused directly on the parameter of F0 for listening-in-noise, they highlight the difficulty that cochlear-implant users and even normally-hearing participants experience when listening-in-noise with reduced spectral resolution and thus, reduced access to F0 information. While not directly stated in any of the above investigations, it is reasonable to speculate that F0 (or lack thereof) was an influencing factor in all of these studies as spectral fine structure, which is missing/limited in cochlear implants and synthesized speech was a condition in all of these studies. Qin and Oxenham (2003) explicitly noted that one of their female maskers had an usually low F0, possibly making it a more effective masker for the male talker target than originally intended.

Fundamental frequency is more effective as a grouping cue with larger differences in F0 between two simultaneous incoming stimuli (Culling and Darwin, 1993; Rossi-Katz & Arehart, 2005). Rossi-Katz and Arehart (2005) compared vowel identification in normally-hearing participants and participants with cochlear hearing loss based on varying ΔF0 between simultaneous incoming stimuli. They reported that while those with hearing loss were still able to use F0 as a grouping cue, this ability was limited to differences in F0 perceived in lower frequency regions. Culling and Darwin (1993) reported that normally-hearing listeners were able to use even small ΔF0 to separate simultaneous incoming stimuli. However, there were widely varying degrees and configurations of hearing loss in the Rossi-Katz and Arehart study and no defined audiological screening in the Culling and Darwin study, making it difficult to draw strong conclusions regarding the effects of extreme hearing loss from these findings. Stickney, Assmann, Chang and Zeng (2007) investigated the specific implications of increasing F0 separation as an aid to listening-in-noise by adult cochlear-implant recipients. Stickney and colleagues administered a listening-in-noise task where the target and competing stimulus were separated by varying degrees of ΔF0. The listening-in-noise task was administered to the normally-hearing group through two implant-processing simulation algorithms, one which aimed to enhance the temporal fine structure of the stimulus. While Stickney and colleagues observed no further improvements in performance with increased F0 separation for the cochlear implant group or the normally-hearing group with the unenhanced algorithm, they did note improved speech perception in the normally-hearing group with the enhanced processing algorithm. These improvements progressed in a manner similar to those observed with increasing ΔF0 in unprocessed speech, suggesting that the addition of temporal fine structure information to implant processing algorithms may be beneficial to current cochlear-implant users.

Fundamental Frequency Processing by Listeners with Normal Hearing and with Cochlear Implants

In normally-hearing listeners, F0 is encoded via frequency-place coding and temporal envelope changes in the speech stream. Fundamental frequency is critical for speech understanding in noise. Fundamental frequency also serves as a grouping cue and helps to separate simultaneous incoming speech streams into discrete streams of information and also provides information about voice pitch. Voice pitch is one of the cues (along with duration and intensity) that provides prosodic information in the speech stream (Pickett, 1999).   Cochlear (sensorineural) hearing loss degrades the spectral resolution of the ear and makes it more difficult for hearing impaired listeners to use F0 information (Bernstein & Oxenham, 2006). The resulting loss of spectral resolution in cochlear hearing loss compels those with this type of hearing loss to be more dependent on temporal envelope cues in order to make use of F0 information. Similarly, cochlear implant coding strategies do not convey F0 information through spectral cues. Instead, they convey this information primarily through temporal envelope cues.

While listeners may be able to extract F0 information when only temporal information is available, the addition of other cues, such as co-varying intensity or duration changes, help to make F0 information more salient in the speech stream and aid in speech perception. Rogers, Healy and Montgomery (2006) demonstrated that both normally-hearing listeners and cochlear-implant users showed greater sensitivity to changes in F0 or intensity of a middle-stressed syllable in synthesized words. Rogers et al. (2006) presented synthesized word stimuli in the soundfield to normally-hearing participants and cochlear implantees. The synthesized stimuli had increases in intensity, F0 or a combination of these two cues on the stressed syllable of the word. The cochlear implant participants needed greater difference limens in F0 than their normally-hearing counterparts for comparable discrimination performance. However, when presented with stimuli that included both intensity and F0 cues in the same token, these difference limens dropped significantly for the cochlear implant group, suggesting that cochlear-implant users are able to successfully integrate two different cues that help make F0 information more salient.

In tonal languages (e.g. Mandarin Chinese), F0 information provides contrasting lexical meanings depending on the F0 contour of the syllable or word, making access to F0 critical for communicative success in users of tonal languages. Luo and Fu (2006) demonstrated that when low-frequency residual acoustic information is preserved in cochlear implant simulations, speech perception of Mandarin Chinese individual phonemes and sentences in noise improves. Normally-hearing participants were asked to identify Chinese tones, vowels, phonemes and sentences in simulated implant conditions. Performance improved significantly when acoustical low-frequency information was added to noise-band vocoder-processed stimuli.

Pediatric cochlear-implant recipients who speak Mandarin Chinese have been shown to be at a disadvantage for not only perception of tonal semantic contours (Luo & Fuo, 2006), but also in the production of these contours as well (Han et al., 2007; Peng, Tomblin, Cheung, Lin & Wang, 2004). Han and colleagues examined Mandarin Chinese tone production in 14 pediatric cochlear-implant recipients and compared them to age-matched normally-hearing children. They observed that while overall performance was highly individually variable, the cochlear-implant recipients were significantly worse at accurate tone production than their normally-hearing peers. However, overall better outcomes were noted in children who were implanted at an earlier age. Peng and colleagues also noted significant deficits in tone production in pre-lingually deafened pediatric cochlear-implant recipients. Tone perception tasks yielded slightly improved results and the cochlear implant participants in that study demonstrated tone identification abilities at better than chance levels (72.88% correct). Peng and colleagues note that their participant population included only children who were pre-lingually deafened and thus, with the amount of variability noted in their results, it is necessary to consider other influencing variables (other than age at implantation) that may affecting these tone production and perception outcomes.

Ideally, perception of F0 would include both temporal envelope and frequency-place cues available to the cochlear-implant listener. Research is investigating the use of combining temporal envelope cues from the implanted ear along with residual spectral information from the contralateral hearing impaired ear for maximal access to F0 information, particularly to strengthen speech perception in noise. Turner, Gantz, Vidal, Behrens and Henry (2004) compared 3 users of short electrode cochlear implants (designed to preserve low-frequency acoustic hearing) with 20 users of long-electrode cochlear implants and demonstrated a 9 dB "better" SRT in a background of multi-talker noise for the short electrode-participants over the traditional implant users in the study. While the "short-electrode" implant group in this study was very small, these findings still demonstrate the benefits of residual low-frequency hearing for listening-in-noise. This suggests that cochlear-implant users are able to successfully combine acoustical and electrical F0 information and use it as a benefit for listening-in-noise. Kong, Stickney and Zeng (2005) reported similar success with traditional (long electrode) cochlear-implant users. They utilized residual low-frequency information from the non-implanted ear (through the use of a hearing aid) to supplement information delivered by the implanted ear to provide acoustic cues for listening-in-noise. Results showed that the addition of low-frequency acoustic information can be beneficial for melody recognition and improve speech recognition in noise. However, this study included only participants with significant benefit from the hearing aid in the non-implanted ear and thus, maximal access to low-frequency information. The results, therefore, may not apply to cochlear-implant users who may not have as much residual low-frequency hearing in the non-implanted ear. Qin and Oxenham (2006) exposed normally-hearing listeners to the same type of listening conditions (simulated electrical hearing with spectrally limited noise bands and the addition of low-frequency acoustic information), and also demonstrated increases in speech perception with the combined F0 cues. These increases in perception did not, however, reach the levels of perception that were achieved when listening to the unprocessed, original stimulus, indicating that additional low-frequency acoustical information is helpful, but not able to fully restore speech perception (Qin & Oxenham, 2006).

The benefits of added spectral resolution through the use of a hearing aid in the non-implanted ear has also been demonstrated in children (Holt, Kirk, Eisenberg, Martinez & Campbell, 2005). Children in this study who wore a hearing aid in the non-implanted ear demonstrated improved speech perception in noise over the use of a cochlear implant alone. The participants in this study were tested on the word recognition task at 6-month intervals and the authors noted that the capability to use both combined spectral and temporal envelope information increased with experience (Holt et al., 2005).

Low frequency residual hearing may be an untapped resource in cochlear-implant users as an additional source of F0 encoding. If access to low frequency information can be improved in cochlear-implant users through the use of any remaining spectral resolution and added low frequency information, their speech perception in noise and access to prosodic cues may be improved.

In summary, in normally-hearing adults, F0 is coded by temporal envelope cues and through spectral resolution of the harmonics of speech. When spectral resolution is damaged and place-coding of F0 is impaired or not available, such as in those with certain types of hearing loss, the listener is forced to rely on temporal envelope cues for F0 information. Cochlear implants primarily code F0 through temporal envelope cues. However, research devoted to improving F0 information in cochlear implants is focusing on the use of residual spectral resolution (in the non-implanted ear) for improving F0 recognition as well making the F0 cue more salient in the speech stream for hearing-impaired listeners. The majority of studies on the benefits of added F0 information include adult participants only. To date, the study by Holt and colleagues (2005) was the only one to examine this issue in a pediatric population.

Limitations of Pitch Coding in Cochlear Implants

Current literature demonstrates that listeners are at a disadvantage for pitch perception (both musically and in the speech stream) when accessing pitch information through temporal envelope cues only (as is coded through cochlear implants) (Deeks & Carlyon, 2004; Landsberger & McKay, 2005; McKay &

Carlyon, 1999). Others have focused on making F0 information more salient in the coding strategy of cochlear implants (Geurts & Wouters, 2001; Geurts & Wouters, 2004; Vandali et al., 2005).

When pitch information is delivered via temporal cues only (in this case, rate of pulse trains), listeners, both normally-hearing and cochlear-implanted, are able to perceive only pitch changes through increases in rate. McKay and Carlyon (1999) provided pitch information to 4 normally-hearing adult listeners and 4 cochlear-implant listeners through differing pulse rates. They found that given differing rates or different modulation depths of a pulsatile stimulus both resulted in the perception of differing pitch, but stimuli with both modulation and differing rates provided no greater benefit in pitch perception. These findings were similar to those reported by McDermott and McKay (1997) in an earlier study with a cochlear-implant user and detection of pitch. That study varied three parameters – stimulus rate, modulation rate and place of stimulation within the cochlea and found that while rate and modulation could effectively convey pitch information, this was limited to a certain frequency range. Place coding of frequency was also found to be useful for detecting the pitch and served as the dominant cue for pitch when both place and rate information were used to code pitch.

Deeks and Carylon (2004) reported on the benefits of differing pulse rate as a means to code differing fundamental frequencies for a speech target stimulus and a masker. With normally-hearing participants listening to stimuli through a six-channel noise-band vocoder, they found that processing a masker at a different pulse rate than the target sentence provided only limited benefit. Performance improved only when the target sentence was processed at 140 pulses-per-second (as opposed to 80 pulses-per-second), suggesting limited benefit for using pulse rate as a temporal separator for incoming speech and noise. Both of these studies are alike in that they have small overall participation. However, both studies serve to highlight the limitations of coding F0 using pulse rate (i.e., periodicity of the signal) as a means to providing F0 and voice pitch information.

While timing (temporal) and place (spectral) cues together contribute to the perception of F0, the human auditory system is able to extract F0 information from temporal envelope cues alone (McDermott & McKay, 1997) in either acoustic or electrical stimulation (McKay & Carlyon, 1999). McDermott and McKay (1997) manipulated pitch information in a musically-experienced cochlear-implant user by changing pulse rate and stimulated electrodes (thus effectively manipulating temporal and place-coded information for the perception of pitch). The participant in that study was able to make pitch discriminations using only temporal information for a limited range (approximately two octaves). McKay and Carlyon (1999) demonstrated this same phenomenon in both normally-hearing participants and cochlear implantees when they found that both groups were able to use changing pulse rates to perceive changes in pitch information when listening to modulated pulse trains through their implant on a single electrode or through a noise-band vocoder.

Vandali et al. (2005) made similar discoveries using different F0 values of sung vowels to help cochlear-implant users in a pitch-ranking task. While cochlear-implant users did not do as well in the task as compared to their normally-hearing peers, current coding strategies (such as ACE) were worse at aiding the listener in pitch perception as compared to experimental coding strategies (the Peak Derived Timing strategy, Modulation Depth Enhancement strategy, the F0 Synchronized ACE strategy and the Multi-channel Envelope Modulation strategy) that make F0 information more salient. With a relatively large overall n (eleven cochlear-implant users) this study made a strong case for further investigation of different coding strategies that highlight F0 information. Few deficits in speech perception were found when the experimental strategies were compared to the ACE coding strategy in a speech perception task.

Vandali et al. (2005) were not alone in their efforts to find and compare coding strategies that emphasize F0 and aid in pitch discrimination. In previous work, investigators were already attempting to make temporal envelope cues more salient in the speech processing of cochlear implants, thus improving F0 recognition. Geurts and Wouters (2001) reported that greater modulation depths presented to single channels of cochlear implants make detection of changes in pitch recognition easier. However, when these differing modulation depths were added to a continuous-interleaved sampling (CIS) speech processing strategy, they reported that greater modulation depths reflecting changes in F0 made no difference in F0 recognition when compared to the standard processing strategy (where no extra cues were given to indicate changes in F0). However, Geurts and Wouters (2004) later demonstrated that place coding of the first harmonic of complex sounds decreased F0 difference limens, improving sensitivity when participating in a pitch discrimination task. These authors argued for the use of place coding as well as temporal information for coding F0 information in cochlear implant uses. While these findings have not yet been applied to current speech processing strategies (i.e., ACE or SPEAK), they are an important first step towards understanding how to improve F0 perception through the use of cochlear implants alone.

Specific Studies Investigating Intonation Recognition by Cochlear-Implant Users

One early study that examined the perception of intonation by cochlear-implant users focused on the MPEAK processing strategy and variations of this strategy (Richardson, Busby, Blamey & Clark, 1997). The MPEAK strategy, an early speech processing strategy that is no longer in use, used pulse rate to code the F0 of the speech stimulus. Richardson et al. (1997) reported that the best performance on the intonation tasks was with the MPEAK processing strategy as compared to the MPEAK variants used in their experimental conditions. Current speech processing strategies do not specifically encode F0 information, but the findings of this study may warrant future investigations that compare intonation recognition in the MPEAK processing strategy and other commercially used processing strategies (such as ACE and SPEAK).

Green and colleagues (2005) were one of the first groups to directly examine intonation recognition in cochlear-implant users and in normally-hearing users attending to acoustic simulations of cochlear implant processed speech. Using two processing strategies (the standard CIS strategy and one experimental strategy that enhanced envelope modulation information and increased pulse rate information for voiced syllables), they tested intonation recognition on sentence length materials and vowel identification. They reported that both the cochlear implant participants and the normally-hearing participants listening to simulated implant conditions performed better on the intonation recognition task when using the modified processing strategy. However, the cochlear implant participants experienced a significant decrease in their ability to correctly identify isolated vowels when using the modified processing strategy as opposed to the CIS strategy, suggesting that added pitch information may improve intonation recognition, but at the cost of the perception of other parts of the speech signal.

The stimuli for the intonation recognition task in the Green et al. (2005) study were sentence length and included all of the relevant cues that contribute to intonation information (pitch, duration and intensity). Chatterjee and Peng (2008) conducted a similar investigation in cochlear-implant users and normally-hearing adults, but instead, directly studied F0 information and how it contributes to intonation recognition. Using bi-syllabic word stimuli controlled for intensity and duration cues, ten adult cochlear-implant users and four adult normally-hearing listeners were asked to identify the word stimuli as either a question-like or a statement-like utterance. The authors reported that the normally-hearing participants demonstrated a significant decrease in their ability to identify the intonation contour once the stimulus was spectrally-degraded (through the use of a noise-band vocoder). The cochlear implant participants' performance was comparable to that of the normally-hearing listeners attending to spectrally-degraded speech. These findings suggest that with the loss of spectral resolution, both normally-hearing and cochlear-implant users lose critical information that aids in intonation recognition. Because other cues to intonation were controlled in the stimuli, these decrements in performance with the loss of spectral resolution may reasonably be attributed to reduced access to F0 information.

One of the only studies to look at intonation recognition in children compared 26 pediatric cochlear-implant users with 17 normally-hearing users on their identification of intonation contours on syntactically neutral sentence-length stimuli (Peng, Tomblin & Turner, in press). The cochlear-implant participants demonstrated significantly less accurate intonation identification than their normally-hearing peers (70.13% accuracy for the CI group and 97.11% accuracy for the normally-hearing group). Additionally, the authors reported a significant effect of length of device use on intonation identification accuracy. While the stimuli in this study were not specifically controlled for F0 and included all cues to prosodic information, the syntactically neutral sentence-length stimuli provide a good basis for the examination of the real-world function of pediatric cochlear-implant recipients and how their perception may differ from their normally-hearing peers.

Other Factors Affecting Speech Perception in Children with Cochlear Implants

There are a myriad of factors that can affect speech perception abilities in cochlear-implant users. Some of the most salient factors in speech perception outcome studies include age at implantation and age of onset of deafness. Other studies have focused on device type, insertion depth of the electrode array, communication mode of educational setting and therapy type.

Age at onset of deafness has an impact on speech perception outcomes, however, this depends on whether the child was pre- or post-lingually deafened. Osberger, Todd, Berry, Robbins and Miyamoto (1991) found no significant difference in speech perception outcomes between children who were born deaf and those who lost their hearing sometime in the first three years of life. However, participants who experienced onset of deafness after age five (i.e., after they had acquired language) performed significantly better overall in terms of speech perception than those who had lost their hearing earlier in life. Furthermore, pediatric cochlear-implant recipients demonstrated significant improvements in open set speech recognition after implantation compared to their speech scores with hearing aids prior to implantation (Osberger et al., 1991). They also reported that there were few significant differences in speech perception scores between children who were using oral or total communication skills. This difference in communication mode would be debated in later studies (Kirk, Miyamoto,Ying, Perdew & Zuganelis, 2002; Robbins, Bollard & Green, 1999).

Robbins, Bollard and Green (1999) assessed the expressive and receptive language skills of children before implantation (while using hearing aids) and six months after their implantation. The data was analyzed for communication mode. Their results demonstrated that while pediatric implant recipients learn language at a slightly faster rate than those of normally-hearing children, the difference was not statistically significant. Additionally, there was no difference in language learning rate between children from oral and total communication backgrounds. Conversely, Blamey et al. (2001) found the rate of progress of hearing impaired children (who either wore hearing aids binaurally or had cochlear implants) was slower than that of their normally-hearing peers. Svirsky, Teoh and Neuburger (2004) found that children implanted at an earlier age (before the age of 2) had better speech and language outcomes. The participants in their study who were implanted the earliest performed the best and reached "near normal" (meaning age appropriate) language skills during follow-up testing. This study is strengthened through ensuring that confounding factors, such as developmental age and prior experience with the vocabulary items used as stimuli were considered.

Kirk, Miyamoto, Ying, Perdew and Zuganelis (2002) supported the findings of Robbins et al. (1999) in finding that there were no significant differences in language outcomes among children who used total or oral communication after implantation. One potential limitation of these studies is that they do not consider the fact that children who are better performers may gravitate toward an oral educational environment whereas those who are not doing as well with their cochlear implant may seek out environments where more cues are available, such as total communication.

Other investigators have examined several implant factors and speech perception outcome measures at once in order to determine which factors most impact speech perception outcomes after implantation. Geers and Brenner (2003) studied 181 children with cochlear implants, all between the ages of 8 and 9 years of age that had been implanted by the age of five years. Using multiple regression, the investigators attempted to find relationships between demographic factors and the various speech perception measures used. After balancing for several other factors (such as age and family support) they concluded that communication mode of the educational setting is one of the factors that contributes the most variance to speech perception scores. They additionally reported a positive correlation between non-verbal IQ scores and communication mode after implantation (that is those with higher IQ scores were more likely to use a more verbal communication mode). One limitation to this study is the large number of participants with a variety of devices and other background factors. While this may appear to add to the statistical power of the study, it instead makes it difficult to analyze for all possible confounding factors.

While there are many factors that are reported to affect speech and language outcomes in cochlear implants, there is no one clear predictor of speech and language outcomes in children with cochlear implants. Younger age at implantation has been shown to have better long-term outcomes, while a general consensus regarding communication mode and educational setting has not yet been reached. When considering cochlear implant studies with children, it is important to consider each of these factors as possible variables in outcomes.

The Pediatric Speech Intelligibility Test

The Pediatric Speech Intelligibility (PSI) test (Jerger, 1984) has previously been used with hearing impaired children and pediatric cochlear-implant recipients. The Pediatric Speech Intelligibility test was originally developed to be a speech perception test for children that yielded a performance-intensity function for listening to speech in noise. Much of the literature that exists on the PSI examined the test's applicability to different populations, such as aphasic adults (Jerger, Oliver & Martin, 1990), children with central nervous system lesions (Jerger, 1987) and children with auditory processing disorders (Jerger, Johnson & Loiselle, 1988). Other researchers have used the PSI in modified form, such as the use of the sentence materials in the message-to-competing ratio task (Brown, 1994; Gravel & Wallace, 1992). The PSI has been utilized in examining children with hearing loss (Gravel et al., 2006) as well as children with cochlear implants (Bergeson, Pisoni & Davis, 2003; Eisenberg et al., 2006; Wang et al. 2008). Bergeson, Pisoni and Davis (2003) used the PSI repeatedly in children to assess the development of audiovisual speech in pre-lingually deafened children with cochlear implants. Eisenberg and colleagues (2006) re-recorded the sentence and competing stimuli of the PSI and used it as part of an overall investigation designed to develop a speech battery for testing pediatric cochlear-implant recipients and their normally-hearing peers. Eisenberg and colleagues reported that their normally-hearing participants performed near ceiling in quiet conditions (98%-99% correct). The cochlear implant participants' performance was poorer (63% correct at baseline and 80-86% correct at follow-up) in the quiet condition.

Wang et al. (2008) used the PSI in the same manner in a continuation of the investigation performed by Eisenberg et al. (2006). The speech testing battery was administered to recipients based on their age and language abilities and yielded an overall score called the "speech recognition index" (Wang et al., 2008). They reported specific results for the normally-hearing group only, indicating a near perfect performance of 94% correct sentence identification in quiet on the PSI.

Reliability information available in the PSI test manual indicates a slight improvement upon re-testing of the PSI for both normally-hearing and hearing-impaired children. However, these improvements in test scores were considered minimal for both groups. For the sentence identification tasks in noise, normally-hearing children demonstrated, on average, a 2.5% improvement upon retesting whereas the hearing impaired children demonstrated a 3.3% improvement upon re-testing. Jerger and Jerger (1984) compare their reliability testing to results from reliability testing of other pediatric speech tests (such as the BKB Sentence Test) and note that their reliability findings are similar to other such tests. Additionally, the authors point to the strong positive correlation between scores obtained for test-retest for both groups (0.82 for the normally-hearing group and 0.96 for the hearing impaired group) as further proof of the reliability of the PSI.

Summary and Purpose

A review of existing literature indicates that cochlear-implant users have more difficulty in noisy listening environments than do their normally-hearing peers (e.g. Fu & Nogaki, 2004; Qin & Oxenham, 2003). This may be a result of limited spectral information provided by cochlear implants (e.g. Dorman & Loizou, 1998; Shannon et al., 1995). However, perception of pitch is significantly more difficult for cochlear-implant users, for the same reasons (reduced spectral information). Although fewer studies have been done in children, even normally-hearing children have greater spectral requirements (Hartley et al., 2000) and have more difficulty listening-in-noise than do their adult counterparts (Fallon, Trehub & Schneider, 2000; Stuart et al., 2006). The use of intonation has been examined in normally-hearing children, but these studies have been limited to developmental timelines for the use of prosody (Doherty et al., 1999; Martel, 2002) and how young children use intonation as a language learning tool (Gerken, 1996; Kemler-Nelson et al., 1989).

The long-term goal of the present study is to investigate the use of F0 information in children with cochlear implants as compared to normally-hearing children. While studies have shown that normally-hearing children are in situations where F0 is needed frequently (noisy classrooms, judging the communicative intent of an utterance), F0 information has not been studied as a direct factor in these situations. In fact, relatively little is known about how normally-hearing children use F0 for a variety of auditory tasks. This study takes the first steps in establishing performance of normally-hearing children on tasks that presumably require F0 information. It also attempts to see how a small group of children with cochlear implants may compare with their normally-hearing peers in their use of F0. The present study is somewhat limited in its scope, a result of the small age range (between 6 and 8 years of age) and the small size of the cochlear implant participant group.

Chapter 3: Experimental Questions and Hypotheses

The goals of this dissertation were to determine how normally-hearing children and children with cochlear implants use F0 to perceive intonation contours, how well they can recognize sentences in competing noise, and whether their performance in one task is related to performance in the other. The specific questions that this project aims to answer were:

1. Will there be a significant difference between normally-hearing children and children with cochlear implants in their ability to listen in competing speech?
2. (a) Are normally-hearing children able to determine whether a word is a statement or a question based on F0 changes only?

   (b) Are children with cochlear implants able to determine whether an word is a statement or a question in the same manner?
3. Is there a significant difference between these two groups in identifying an word as a statement or question?
4. What is the nature of the relationship, if any, between determination of intonation contour and speech recognition in competing speech in children with cochlear implants and in normally-hearing children?
5. Are there any intervening factors that may affect these abilities, such as age, gender or non-verbal intelligence?

It was hypothesized that the speech perception scores of children with cochlear implants would be degraded by the addition of competing speech, and that their normally-hearing peers would be significantly better at the listening-in-noise task when compared on a set criterion basis. The normally-hearing participants in this study were expected to exhibit the same degradation of performance for listening-in-noise with poorer signal-to-noise ratios, although their overall accuracy might remain higher than those participants with cochlear implants. For the intonation recognition task, the normally-hearing group was expected to display overall better accuracy at identifying the stimulus as a statement or question than the cochlear implant group. Based on the notion that sensitivity to F0 would play an important role in both tasks, it was anticipated that there would be a significant positive relationship for both groups between speech perception abilities in competing speech and intonation. It was expected that other factors, such as non-verbal intelligence would not be a contributing factor to differences in individual performance.

Chapter 4: Methods

Participants

There were two groups of participants enrolled in this study – children with cochlear implants and normally-hearing children. Participants with cochlear implants and normally-hearing participants were recruited from The River School in Washington, DC and through general word of mouth. Parents of eligible participants (both normally-hearing and with cochlear implants) recruited from The River School were solicited via a letter sent directly to the home. Normally-hearing participants were recruited through general word of mouth, with the aid of recruitment fliers (see Appendix D).

Participants were between the ages of 6 and 8 years of age. The selection of this age range was driven by the greater availability of 6-8 year old children with cochlear implants, and also the need to ensure that all participants were able to understand and perform the experimental tasks as accurately as possible while reducing, to the extent possible, the amount of variability in the data due to maturation differences. The average age of all participants enrolled in this study on the day of testing was 7 years, 4 months and 25 days. Age averages by group were 7 years, 3 months and 24 days (S.D. = 10 months) for the normally-hearing group and 7 years, 9 months (S.D. = 10.6 months) for the cochlear implant group. A total of 20 normally-hearing children and five children with cochlear implants participated in this study. There were a total of 17 females and 8 males enrolled in this study; 4 females and one male in the cochlear implant group and 13 females and 7 males in the normally-hearing group.

The participants in the cochlear implant group all had been deafened by the age of 3, had received their cochlear implant before five years of age, and had been using their cochlear implant for at least one year. Information regarding age at onset of deafness and age at implantation were gathered by means of a questionnaire included with the recruitment letter sent home to parents or via parental interview at the time of participation. Two of the participants with cochlear implants were recruited from The River School in Washington, DC. The other three cochlear-implant participants were from mainstreamed regular education classrooms. While the specifics of each child's aural habilitation were not available, all of the cochlear-implant participants were part of oral communication programs and communicated via spoken language. All cochlear-implant participants were children of normally-hearing parents. See Table 1 for group demographics of the cochlear implant group.

Subject ID	**Age at identification of HL**	**Age at implantation**	**Length of device use**	**Device**
I1	18 months	4 years, 11 months	41 months	Cochlear Freedom
I2	Birth	4 years, 1 month	43 months	Cochlear Freedom
I3	Birth	4 years	45 months	Cochlear Freedom
I4	23 months	2 years, 7 months	44 months	Advanced Bionics Harmony
I5	18 months	2 years	74 months	Cochlear Freedom

Table 1: Cochlear implant group demographics

As an inclusion requirement for this study, participants in the normally-hearing group had to demonstrate hearing sensitivity within normal clinical limits (15 dB HL or better) across the frequencies traditionally used in audiometric testing (250, 500, 1000, 2000, 4000 and 8000 Hz).

Hearing status was determined via means of a brief audiological exam. Otoscopic inspection and tympanograms (utilizing a standard 226-Hz probe tone) were obtained for each participant. Hearing evaluations for participants with cochlear implants were performed in the soundfield and participants with normal hearing were tested under earphones. Hearing screening included speech reception threshold measures and pure-tone audiometric evaluation at 250, 500, 1000, 2000 and 4000 and 8000 Hz. Pure-tone average (PTA) was determined for each participant by averaging the pure-tone audiometric threshold at 500, 1000 and 2000 Hz.

Stimuli

Two sets of stimuli were used in this study. Sentence materials were taken from the Pediatric Speech Intelligibility test (Jerger, 1984) and utilized for the listening-in-noise task. For the intonation recognition task, words with variable F0 contours provided by Dr. Shu-Chen Peng at the University of Maryland, College Park, were utilized. The Pediatric Speech Intelligibility Test (developed by Jerger & Jerger, 1984) is a closed-set speech perception test that includes sentence and single-word materials in the presence of a competing message and in quiet. The Pediatric Speech Intelligibility test (PSI) includes an auditory stimulus

CD and laminated response cards that are placed in front of the child during testing. For the purposes of this study, only the sentence length materials in the presence of a competing message were used. The competing and target messages were recorded on a separate track and can be manipulated independently of each other. The presentation level of the competing message was varied while the presentation level of the target sentences remained fixed. Target sentences were presented at 40 dB SL above the PTA of the participant. The level of the competing messages was adjusted to obtain previously determined experimental signal-to-noise ratios (SNR). The SNRs used in this study were +4 dB, 0 dB, -4 dB, -8 dB and -12 dB. A "training" SNR of +16 dB was utilized for one listening trial at the beginning of the listening-in-noise task for each participant in order to ensure understanding of the task. A latin squares design was used to determine the order of SNR values presented to each participant.

Participants listened to ten sentences at each experimental SNR. After each presentation of the target sentence, participants were instructed to point to the picture that was indicated by the target message. The response cards were five simple color drawings on each of two cards that illustrate an animal performing an action (example: bear eating sandwich) (See Appendix A).

The stimuli for the intonation recognition task comprised 60 re-synthesized tokens of a bi-syllabic word, "popcorn". The F0 of the word "popcorn" was manipulated to give the word an intonation contour that indicates a statement or a question. All other cues to prosody (intensity and duration) were kept constant so that the only prosodic information in the word was coded via F0.

Two different F0 heights, or starting points, 120 Hz and 200 Hz, were generated as the token onset in order to represent both male and female voices. The overall change in F0 across the word varied as a portion of an octave change, in either a positive (rising intonation) or negative (falling intonation) direction. The stimuli selected for this task represent a variety of "octave change ratios" (ΔF0). These octave change ratios are a measure of the ratio of the ending F0 of the token and the starting F0 (either 120 Hz or 200 Hz). The octave change ratios used in this study were +0.58496, -0.41504, +0.32193, -0.19265, + 0.16993, ±1.00000 and no change (flat contour). Intonation task stimuli were presented at 40 dB SL above the PTA of the participant. Recorded stimuli were presented to the participant through the loudspeaker. Chatterjee and Peng (2008) have argued that the "popcorn" stimuli, although re-synthesized, are still appropriate as a representation of real-world stimuli. They observed a strong correlation in performance measures on two intonation recognition tasks, one using the "popcorn" stimuli and the other with more naturally-produced stimuli.

Intonation materials were randomized for each participant to avoid order effects. Prior to starting the testing trials, each participant was given practice with the task, consisting of 4 intonation tokens of the largest degree of ΔF0. A total of 64 words were presented.

The Kaufman Brief Intelligence Test (K-BIT), second edition (Kaufman & Kaufman, 1997) was used as a measure of non-verbal intelligence. The K-BIT is a standardized, objective measure of IQ. The K-BIT includes both verbal intelligence and non-verbal intelligence scales and administration of both scales yields a composite intelligence score. Only the non-verbal intelligence scale was administered for this study. Overall average non-verbal intelligence quotient (NVIQ) for the participants in this study was 107 (S.D. = 16), compared to a normative mean of 100. Non-verbal IQ scores by group were 105 (S.D. = 15) for the normally-hearing group and 116 (S.D. = 18) for the cochlear-implant group.

Procedure

This study included two tasks: the Pediatric Speech Intelligibility task (as a measure of speech perception in noise) and the above-described intonation task. Participants were tested in the Audiology Clinic on the campus of the University of Maryland or at the campus of the River School. A sound level meter was used to calibrate the output sound levels of the loudspeakers prior to testing at each location.

The participant was seated at a table one meter away from a loudspeaker in a double-walled, sound treated booth. Testing order alternated between participants. Half of the participants began testing with the listening-in-noise task and then moved on to the intonation task, while the order was reversed for the other half of the participants. All testing sessions were videotaped. A portion of the videotaped sessions (4 out of the total 25 taped sessions) were reviewed at a later date by an independent observer. Recorded responses between the two investigators were compared in order to ensure initial experimenter objectivity. There was a 99.28% agreement rate between experimenters on the listening-in-noise task and a 98.97% agreement rate for the intonation recognition task, indicating good overall agreement between the two experimenters.

For the listening-in-noise task, the participant was instructed to point to a picture in response to an auditory prompt. For example, the child heard “A bear is combing his hair" and the child was expected to point to one of five small line drawings on one laminated sheet. There were two different cards with five line drawings on each card. The card used alternated between participants, with half of the participants viewing card “A” for testing and the other half viewing card “B” for testing. Before testing began, the child was familiarized with the line drawings on the card by means of review of the pictures with the examiner. The experimenter determined the accuracy of the response and recorded the response on an answer sheet on the investigator’s side of the test booth.

The second task measured intonation recognition. Each trial in this task involved a single presentation of one of the re-synthesized stimuli (the word “popcorn”) described previously. After each word, the child was asked to indicate whether the utterance was “asking” or “telling”. Prior to beginning the intonation recognition task, the task was explained to the participant by the investigator and a few naturally occurring practice “tokens” were reviewed with the participant, as needed. When the participant demonstrated a good subjective (as judged by the examiner) understanding of the task, testing began with the pre-recorded “popcorn” stimuli, with four practice tokens with a one octave positive or negative change ratio administered first. The experimenter recorded the child’s response on an answer sheet on the other side of the booth.

At the end of each testing task, a final compliance measure was administered. On the intonation task, the compliance measure consisted of four "popcorn" tokens, with a negative or positive one octave change ratio. The participant was still expected to respond whether the token was "asking" or "telling". All participants, with the exception of four, scored a 100% correct on the compliance task at the end of the intonation task. Three of the participants (normally-hearing participants H3, H4 and H19) who did not achieve a perfect score on the compliance task (all three had scores of 75% correct) had more trouble with the intonation task in general. The fourth participant (I4) scored a 25% correct on the compliance task and demonstrated overall very poor performance on all experimental tasks. However, the experimenter judged this poor performance to be secondary to actual perception difficulties and not a result of behavioral reasons. The listening-in-noise task compliance measure consisted of one testing trial (ten target sentences) with no competing message. All participants scored a 100% correct on the compliance task for the listening-in-noise task. While these compliance tasks did not count towards the participant's overall performance, they ensured that the participant was not guessing or had any unusual biases at the end of each testing task.

Participants were given a choice of tangible rewards as reinforcers, such as pennies (which could later be exchanged for candy) or stickers. These reinforcers were received at intervals throughout the testing session. This investigation was approved by the Institutional Review Board at the University of Maryland, College Park. Informed consent was obtained from all parents/guardians and informed assent was obtained from all participants before testing began. All participants completed the experimental tasks in one testing session.

Chapter 5: Results

Listening in Noise

Figure 1 shows average percent correct identification for the various signal-to-noise ratios (SNR) used in this study. Performance at each experimental SNR was averaged across participants in each group.

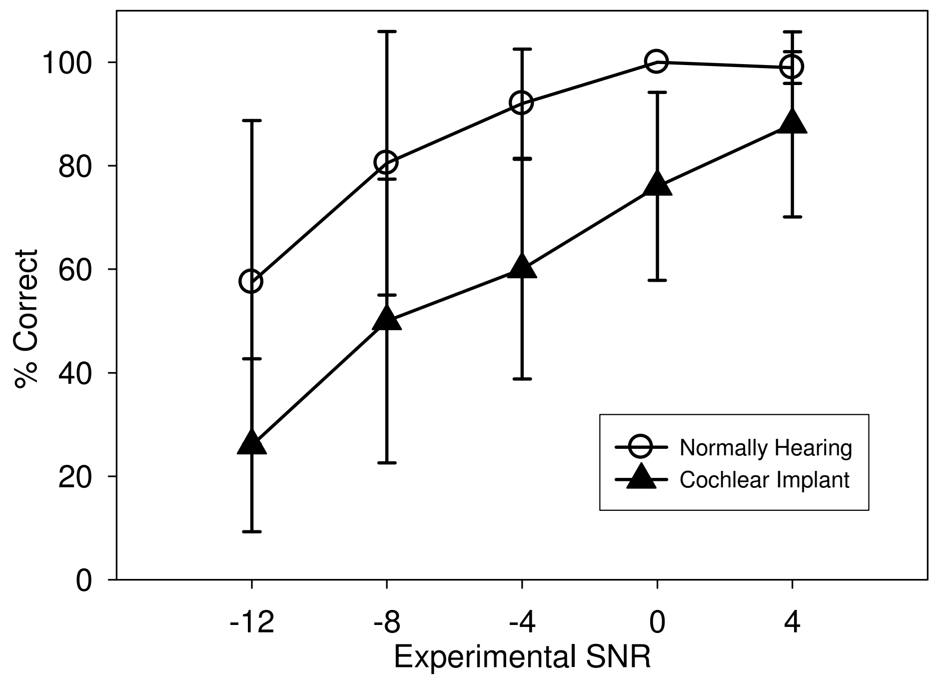


Figure 1: Group performance on the listening in noise task as a function of experimental SNR. Error bars represent ± 1 S.D.

The normally-hearing group performed better than the cochlear implant group for all SNR values. Considerable variability was observed in both groups for all SNR values, particularly for the poorer values of -12 dB and -8 dB. The exception to this observation is seen for the normally-hearing group at the 0 dB

SNR value, where all group members performed the task with 100% correct identification for all test items given. Overall, the variability of the normally-hearing group was considerably smaller than that of the cochlear implant group, which may partially be a result of the difference in group sizes (n=20 vs. n=5). Both participant groups, despite differences in overall performance, demonstrated an improvement in percent correct identification as SNR values increased. Specific group averages are presented in table 2.

Group	SNR Value (dB)				
	-12	*-8*	*-4*	*0*	*4*
Normally-hearing	57.5%	80.5%	92%	100%	99%
NH Standard Deviation	31.3	25.4	10.6	0	3.1
Cochlear Implant	26%	50%	60%	76%	88%
CI Standard Deviation	16.7	27.4	21.2	18.2	17.9

Table 2: Group Average Percent Correct and standard deviations for given SNR condition.

Individual results for the listening-in-noise task were plotted on graphs similar to the graph represented in figure 1. These individual graphs were then fitted with 3-parameter sigmoid function curves (see figure 4) and the resulting equation solved for arbitrarily selected percent correct values (50%, 70% and 90%). In this way, the required SNRs for the individual to achieve 50% correct, 70% correct and 90% correct (i.e., SNR50, SNR70, SNR90) on the listening-in-noise task were estimated.

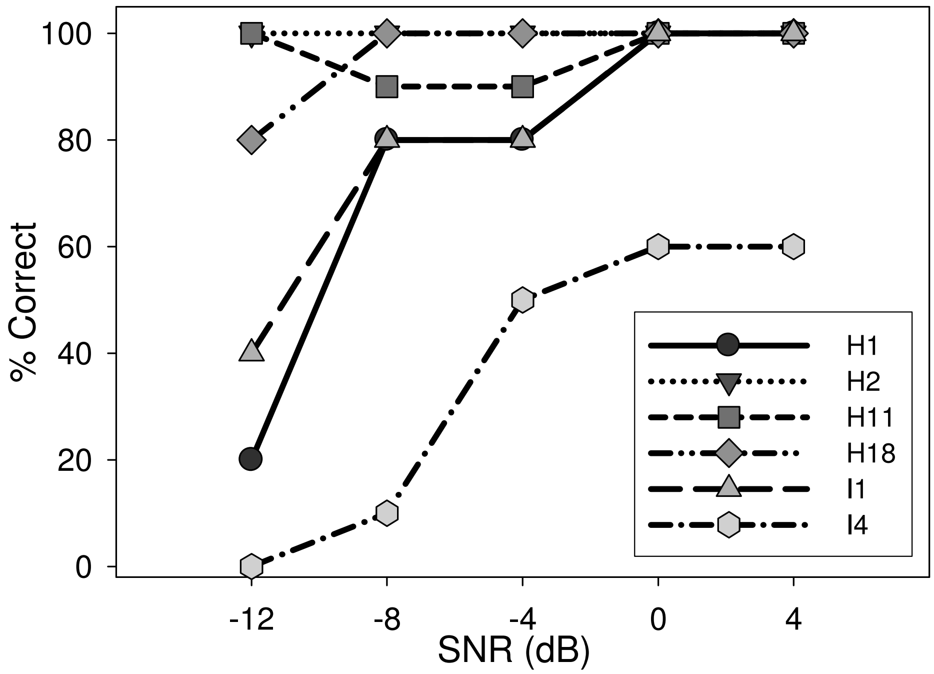


Figure 2: Representative sampling of individual performance graphs for listening in noise task. Percent correct identification as a function of experimental SNR condition.

The variability demonstrated for each group in figure 1 is further illustrated by examining individual plots. As seen in Figures 2 and 3, individual results varied widely between participants and between groups. Most normally-hearing participants demonstrated a "ceiling effect" by obtaining 100% correct identification during the listening-in-noise task for several of the better SNRs. One individual (H2) demonstrated 100% identification for all SNR conditions. In cases such as these unusual performance patterns, individual results could not be fitted with a 3-parameter sigmoid function and values for X could not be found. These individuals (3 from the NH group and one from the CI group) were excluded from further analysis.

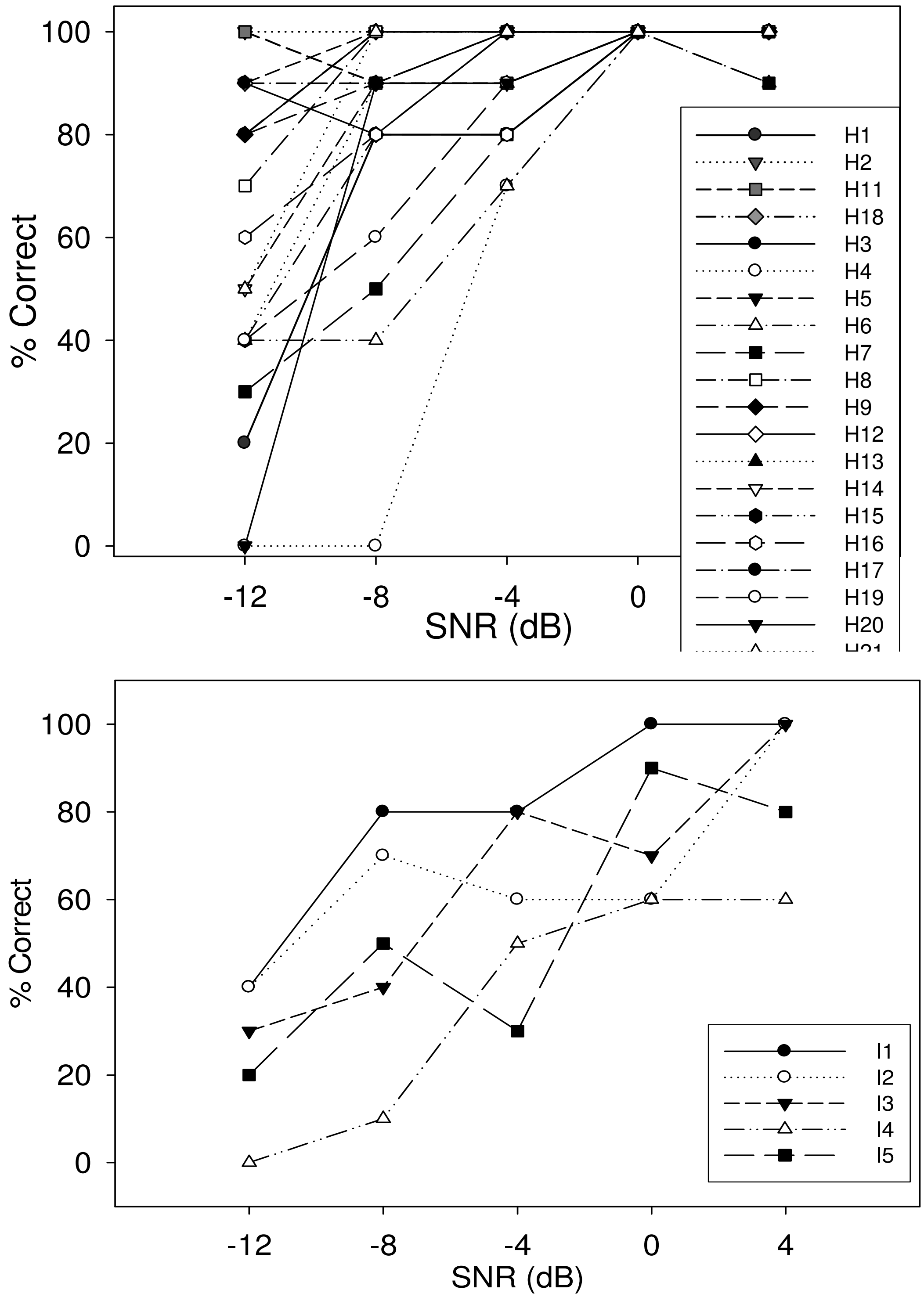


Figure 3: Individual performance graphs of the NH group (top panel) and CI group (bottom panel) for listening in noise task. Percent correct identification as a function of experimental SNR condition.

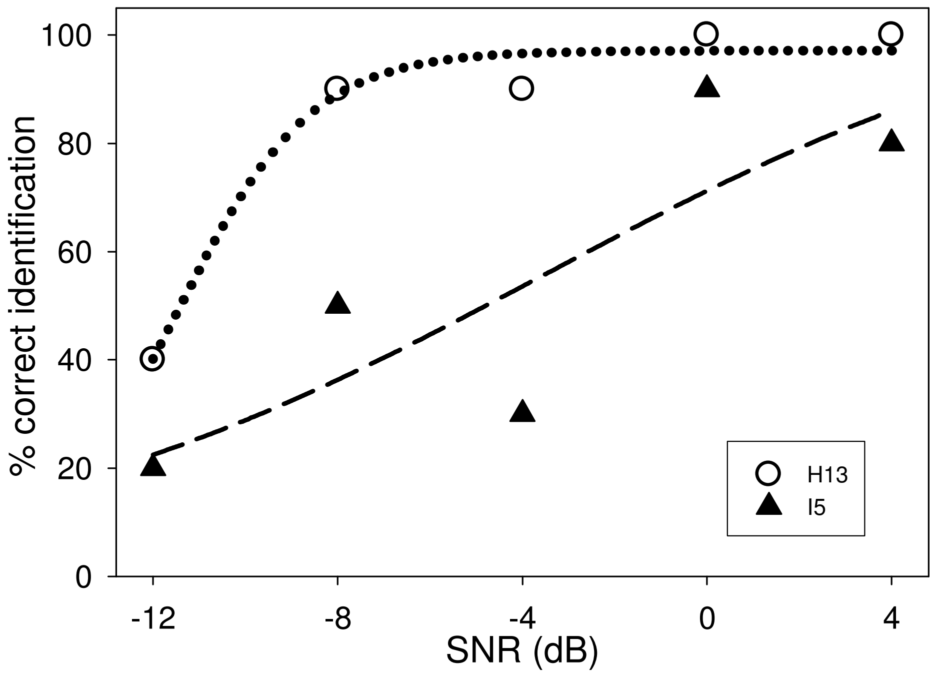


Figure 4: Two selected participant performance graphs fitted with 3-parameter sigmoid functions. Regression lines are 3-parameter sigmoid functions.

Group performance on the listening-in-noise task was averaged across (1) all SNR (SNR_all) values and (2) the three most difficult SNR values (SNR_hard, corresponding to -12 dB, -8 dB and -4 dB SNR) and a single group performance mean was found. The group overall percent correct mean of the cochlear implant group was worse than that of the normally-hearing group for all SNR conditions (60% correct and 85.8% correct, respectively) and for the harder SNR conditions (45.3% correct and 76.6% correct, respectively) (figure 5).

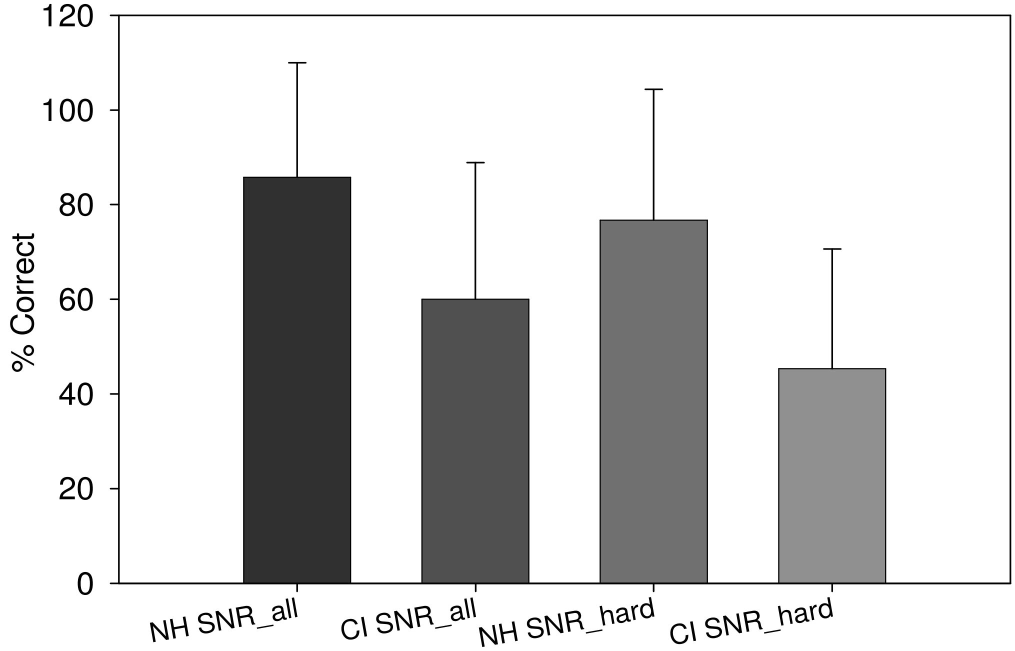


Figure 5: Group means for performance on the listening in noise task for SNR_all and SNR_hard. Error bars represent 1 +S.D.

Independent samples t-tests were used to compare group means across all SNR conditions. Significant differences were found between groups for average percent correct across all SNR conditions (t= 4.581, p= .000) and across harder SNR conditions only (t=3.980, p= .000).

Required SNRs for percentage correct identification were compared between groups using a one-way ANOVA. Values derived from the sigmoid functions on individual performance plots for the listening-in-noise task were compared. Significant differences were found between groups for SNR required in order to get 70% correct and 90% correct ($F(1,19)$ =7.612 and $F(1,19)$ = 16.753 respectively). Required SNR for 50% correct was not significantly different between groups (F(1,20) = 2.715). See table 3 for average SNRs required for the criterion values of percent correct for each group.

	Criterion "Percent Correct" values		
	50%	**70%**	**90%**
Normally-hearing	-14.79 dB	-11.62 dB	-7.59 dB
NH Standard Deviation	9.8	5.5	4.1
Cochlear Implant	-7.35 dB	-3.47 dB	1.75 dB
CI Standard Deviation	3.0	3.5	4.1

Table 3: Average SNR values (in dB) and standard deivations required to obtain specified percent correct for NH and CI groups. Results are shown for SNR50, SNR70 and SNR90.

Intonation Recognition

Figure 6 illustrates overall group performance on the intonation recognition task. Note that both groups have generally the same performance (as measured by % question), but that the normally-hearing group demonstrates a slightly steeper function (i.e., as the intonation contour of the sentence gets larger and more positive, indicating a question, the participant identifies the test item as a question more frequently) for the positive octave change ratios. Also notable is the large individual variability for both groups, particularly at the more positive octave change ratios. However, by looking at this graph, we see evidence that both groups were eventually able to use the F0 to determine the intonation (i.e., question vs. statement), as both functions demonstrate a positive slope.

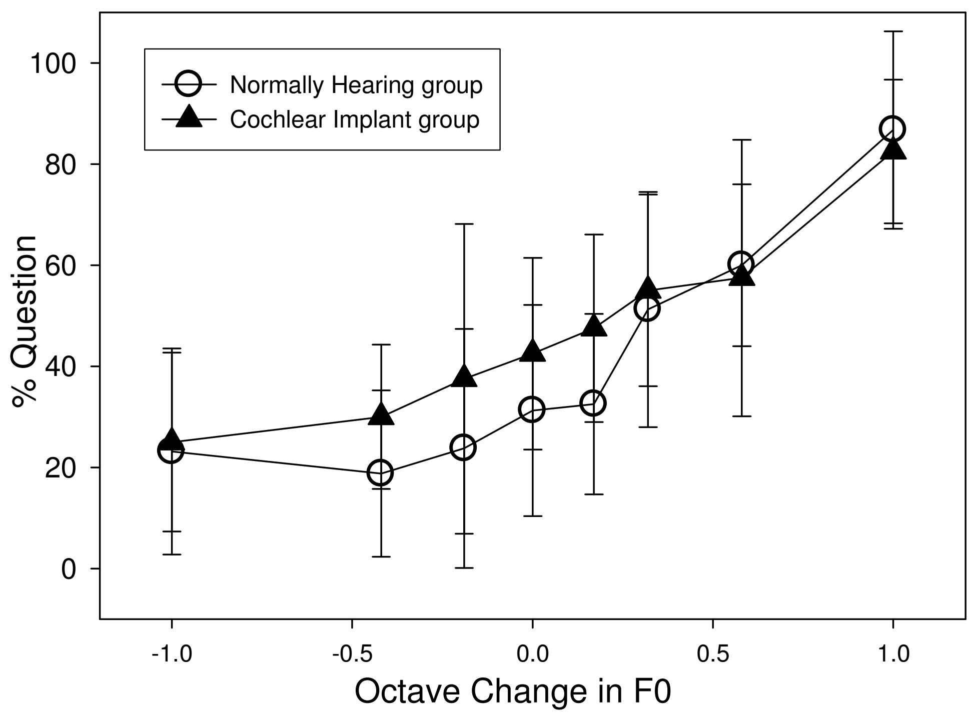


Figure 6: Performance on the intonation recognition task plotted as a function of the octave change in F0. Open circles represent the mean results of the NH group; filled triangles represent the mean results of the CI group. Error bars represent ± 1 SD from the mean.

Individual performance on the intonation recognition task was quantified by calculating the cumulative d' scores for each participant. The calculation of d' scores is standard practice in signal detection theory (MacMillan & Creelman, 2005). Question scores (i.e., percentage of time a stimulus token was identified as a question) were converted to Z-scores in order to normalize the results to the standard normal distribution. The d' (the difference in Z-scores between consecutive points along the abscissa) was calculated at each input F0 ratio. Note that the Z-score obtained at $\Delta F0=-1$ served as the reference point. The cumulative d' is the sum of all d' values calculated across the range of input $\Delta F0$. A higher cumulative d' indicates greater sensitivity to the F0 cue. An independent samples t-test indicated no significant differences between groups on the cumulative d' scores (t=1.165, p=0.256) for the intonation recognition task.

Individual Z-scores were graphed as a function of ΔF0 and these individual functions were then fit with a linear regression line. The regression line demonstrated significance for 14 of the 20 participants in the normally-hearing group and 2 of the 5 participants in the cochlear implant group. Group analyses performed in the same manner demonstrated significant results (i.e., regression lines had significant values) for both groups, suggesting that both groups, on the whole, are able to use F0 information to determine whether an word is a statement or a question. Figure 7 illustrates the individual performance plots of all members in the CI group as Z-score as a function of octave change in F0. Figure 8 illustrates average group performance on the intonation recognition task as Z-score as a function of octave change in F0.

The NH group's performance on the intonation recognition task was analyzed for effects of the listener's gender (figure 9). An independent samples t-test performed on the participants in the normally-hearing group did not indicate significant differences in cumulative d' scores on the basis of gender (t=0.238, p= 0.814).

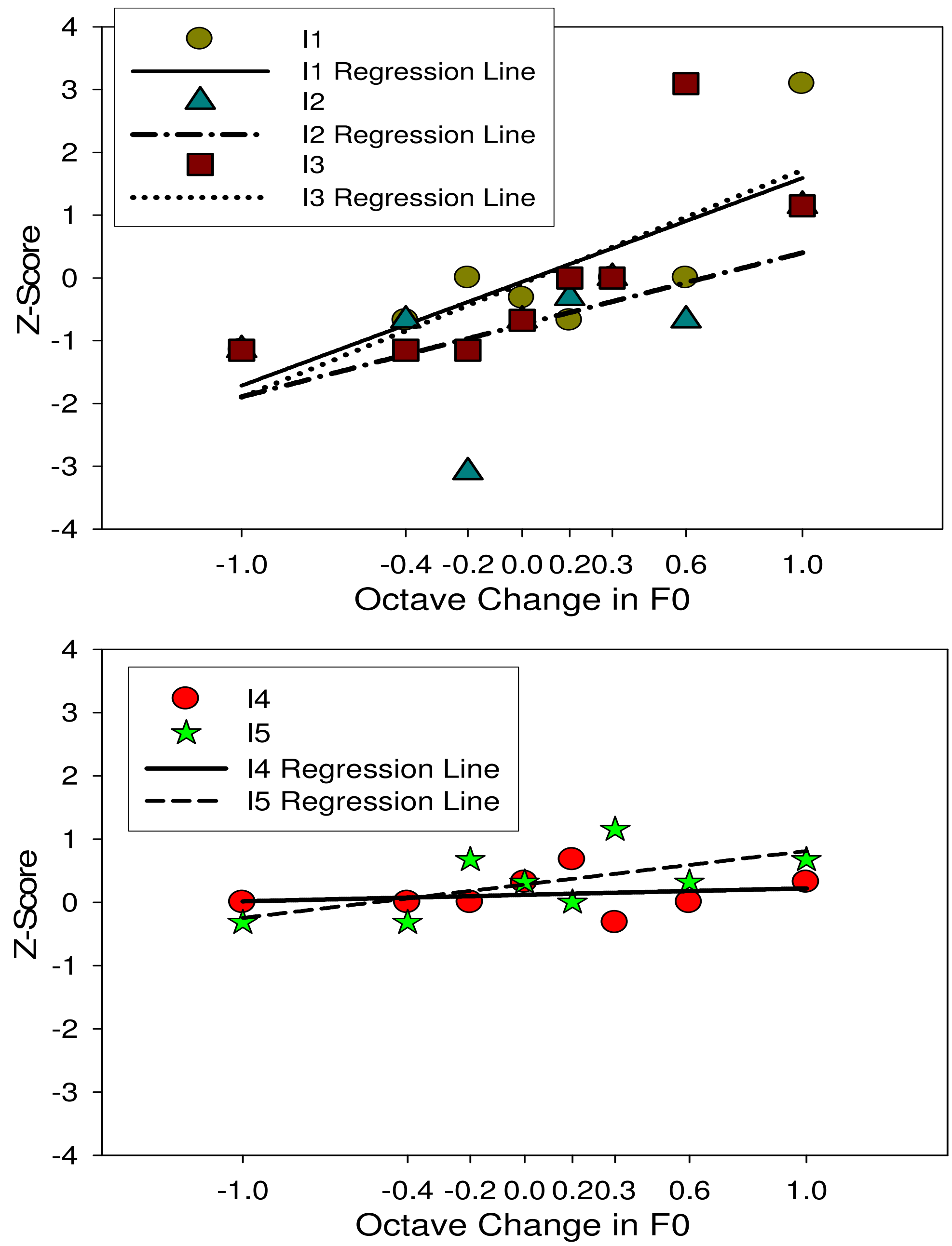


Figure 7: Individual performance plots of participants in the CI group. Z-Score on the intonation identification task as a function of direction and amount of octave change. CI group participants I1, I2 and I3 (top panel) and I4 and I5 (bottom panel) are shown.

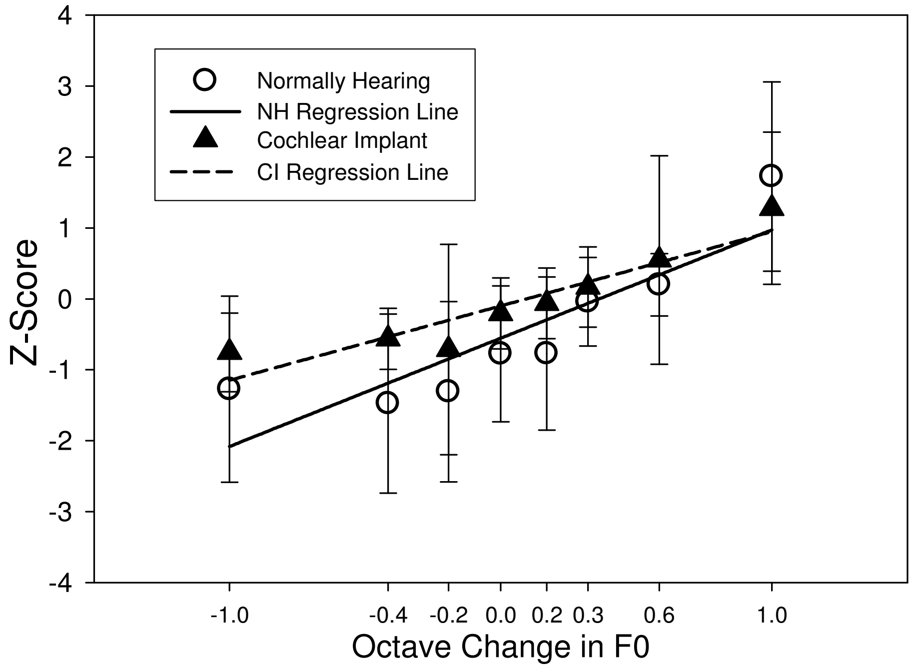


Figure 8: Group performances (averaged across group) on the intonation identification task, plotted as Z-score as a function of octave change in F0. Error bars represent ± 1 S.D.

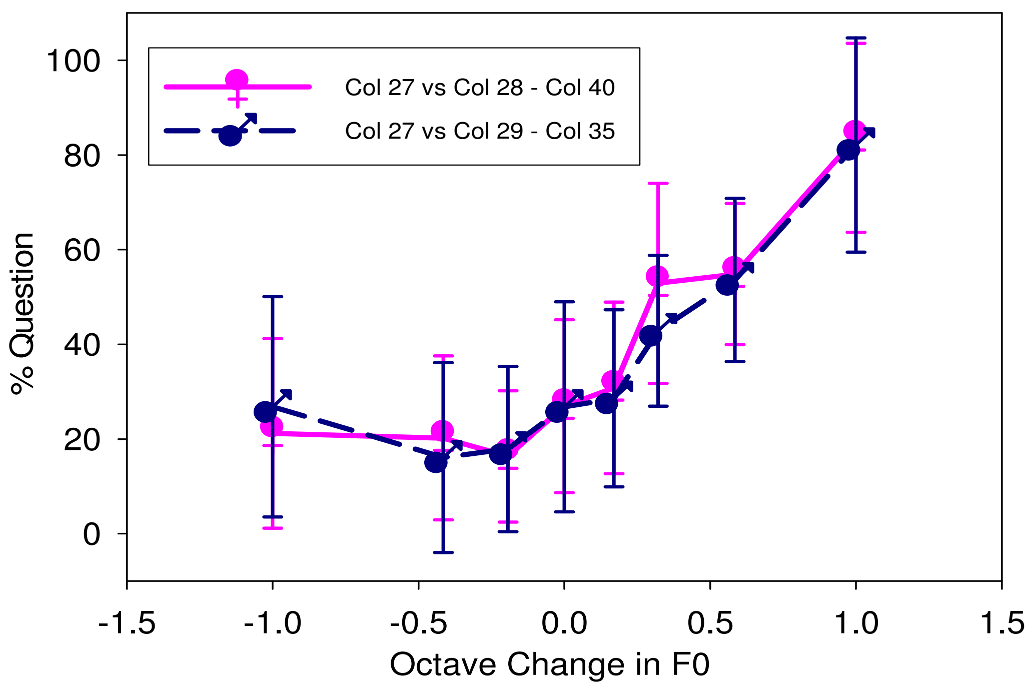
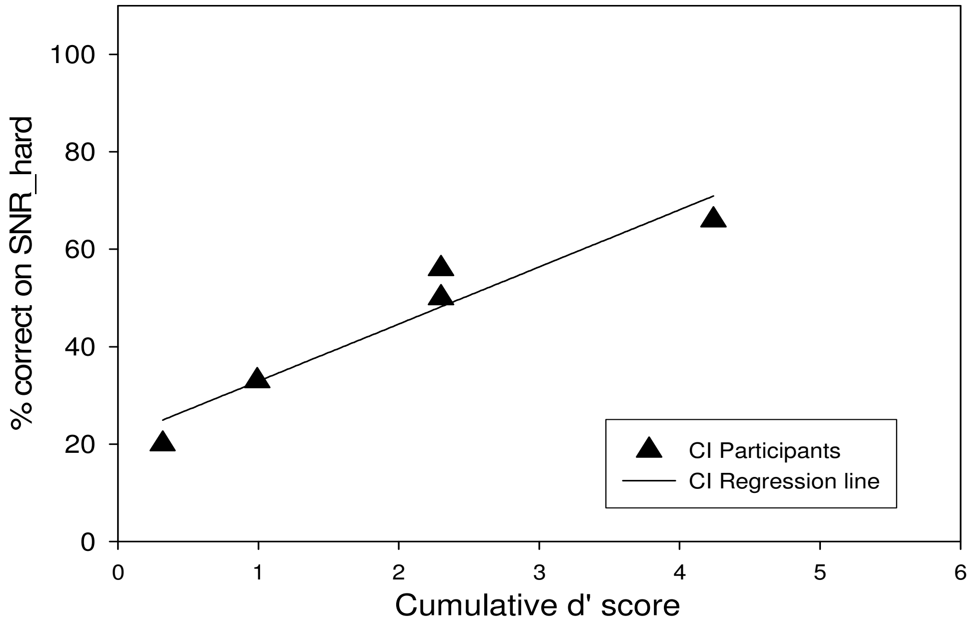


Figure 9: NH group's performance on the intonation recognition task analyzed for effects of the listener's gender. Error bars represent ± 1 S.D.

Relationship Between Intonation Recognition and Listening in Noise

In order to determine if any relationship existed between intonation identification and speech perception in noise capabilities, a Pearson correlation was performed between cumulative d' and SNR70 and cumulative d' and SNR90. Analysis indicated that these correlations were significant for the cochlear implant group in both cases (r=-0.975, p=.025 for SNR70 and r=-0.966, p=.034 for SNR90), but not significant for the NH group (p=.507 and p=.607, respectively). This indicates that as SNR70 on the listening-in-noise task decreases, the participant’s cumulative d' score increases, indicating better performance. The same is true for SNR90. Note, however, that only 4 out the 5 cochlear implant group participants were included in this analysis as the 3-parameter sigmoid function could not be fit to participant I4’s data. An analysis of the relation between cumulative d' and overall percent correct performance on SNR_hard indicated a significant correlation for the cochlear implant group (p=0.0105) but not for the NH group (p=0.9133) (see figure 10). In this analysis, data from all five of the CI participants were included. However, analysis of the relationship between cumulative d' and SNR_all did not indicate any significant relationships for either group. Thus, significant relationships between performance on the two tasks were observed in the CI group in 3 of the 4 analyses conducted. However, these results were obtained with only n=4 or n=5 CI participants and therefore the results should be interpreted with caution.



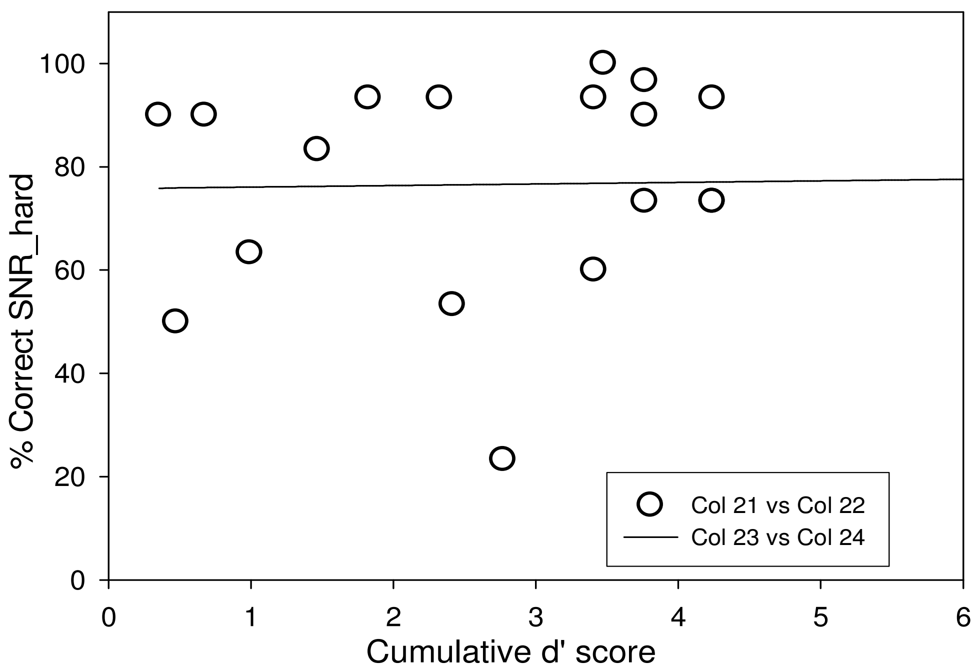


Figure 10: Scatterplot of CI participant group (top panel) and NH participant group (bottom panel) performance on listening in noise task for SNR_hard and cumulative d' score. Regression lines demonstrate a significant relationship between the tasks for the CI group and lack of relationship by NH group.

Dependence on other Variables

Correlations were performed between age in days at testing and NVIQ scores, d' and NVIQ, and d' and age in days at testing. None of the correlations within individual groups were found to be significant for α=.05. See table 4 for Pearson correlation coefficients for each comparison by group. Fisher Z-tests for significant differences in correlations indicated no significant differences between correlations for any of the above combinations (table 4).

	NVIQ vs. Age	**NVIQ vs. Cumulative d' prime**	**Cumulative d' prime vs. Age**	**NVIQ vs. SNR_hard**
NH	0.293	0.205	0.301	-0.127
CI	-0.127	0.423	0.768	0.438
Computed Z	0.5745	-0.4355	-1.262	-0.611

Table 4: Pearson correlation coefficients for individual groups and computed Z-scores for Fisher Z-test for differences in correlations.

In order to determine if age was a contributing factor to any of these findings, cumulative d' prime scores and SNR values required to obtain 90% correct were plotted as a function of age at testing and fit with a linear regression line (see figure 11). The regression line was not significant for either group when d' and age were plotted. However, when age and SNR90 were plotted, the regression line was significant for the cochlear implant group (p=.0412), but not significant for the normally-hearing group (p=0.2694).

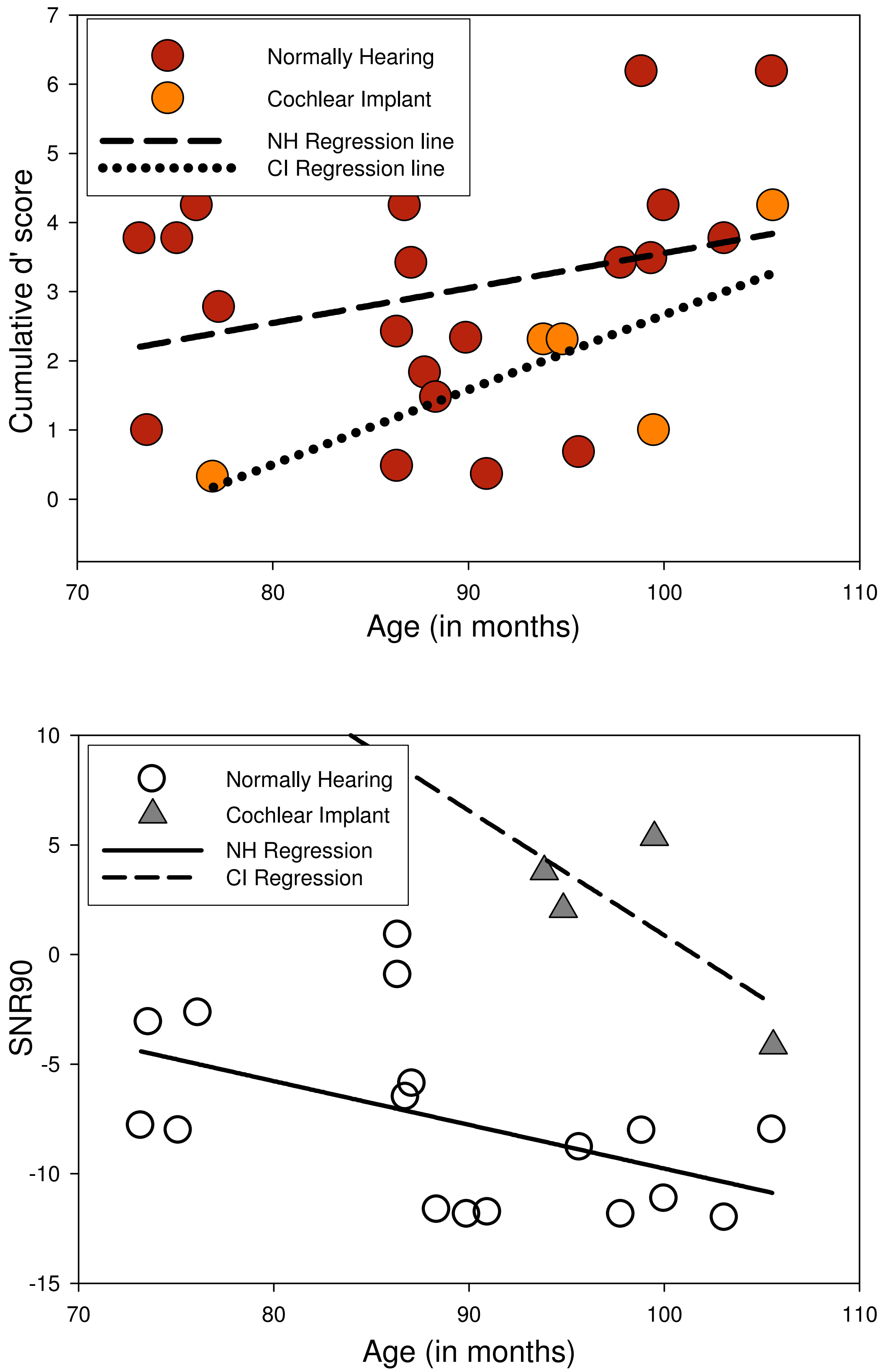


Figure 11: Regression lines showing relationships between age (in months) at testing and cumulative d' scores (top panel) and age and SNR90 (bottom panel).

Group Variations

Sources of differences between participant groups were examined. One variable, non-verbal intelligence quotient (NVIQ), was examined as a possible source of variation between the two groups. Differences in NVIQ were found to be insignificant between the two groups by an independent samples t-test (t=-1.512, p= 0.144) and between genders for each group (t=1.618, p= 0.123 for the hearing group and t=-.011, p= 0.992 for the cochlear implant group).

Age differences were also examined as a possible source of group variations. Independent-samples t-testing revealed no significant differences between groups in terms of age at testing (t=-1.109, p=0.319).

Chapter 6: Discussion

The purpose of this study was to investigate the use of F0 in normally-hearing children and in children with cochlear implants. Given that cochlear implants do not provide the fine frequency resolution achieved by the normal auditory system, the overall hypothesis of this study was that there would be a significant difference between normally-hearing children and children with cochlear implants in their ability to use F0 information. These abilities were tested in a listening-in-noise task and an intonation recognition task. The working hypotheses of this study was that there would be significant differences between the two groups of children in their ability to listen in noise and to use F0 to identify the intonation contour of a sentence.

Listening in Noise

As expected, there were significant differences between the participant groups in terms of their ability to listen in noise. Overall percent correct identification in noise was lower for the cochlear implant group than for the normally-hearing group, suggesting that, in listening environments with background noise, children with cochlear implants will not correctly identify as many utterances as their normally-hearing peers in the same environment. Furthermore, there was a significant difference in the SNR values required for the cochlear implant group participants to achieve 70 and 90 percent correct than was required by the normally-hearing group. This indicates that the cochlear-implant recipients in this study needed higher signal-to-noise ratios in order to achieve the same performance as their normally-hearing peers.

These findings may be, in part, a result of the masker used in this investigation. The PSI message-in-competing noise task includes target sentences spoken by a male talker and competing sentences, spoken by a different male talker. The target and competing talkers are different, but may be close in F0. As previously suggested, larger differences in F0 may improve speech perception in the case of two simultaneous incoming messages (Culling & Darwin, 1993; Rossi-Katz & Arehart, 2005). This is particularly true for CI listeners (Stickney et al., 2007; Stickney et al., 2004). The relatively small difference in F0 between the two incoming messages may have made it more difficult for the CI listeners to separate signal from the competing speech. Because the normally-hearing participants were presumably able to use spectral and temporal cues in order to perceive F0 information, the small difference in F0 between the target and masker in the listening-in-noise task may not have created as much difficulty for that participant group.

Furthermore, the use of a competing sentence as a masker sentence may have presented another difficulty for the cochlear implant group. Previous investigations have shown that modulated or interrupted background noise (such as another talker) are more difficult for adult cochlear-implant when listening in noise than is steady-state background noise (Fu & Nogaki, 2004; Nelson et al., 2003; Qin & Oxenham, 2003; Stickney et al., 2004). The inverse is true for normally-hearing listeners (adults and children) who are able to use the "gaps" in modulated background noise to improve their speech perception abilities as compared to steady-state background noise (Stuart, 2005; Stuart, Givens, Walker

& Elangoven, 2006). The listening-in-noise task in this investigation, therefore, would have favored listeners who were able to use modulated maskers to their advantage.

One of the unexpected findings from the listening-in-noise task was the large variability noted in both participant groups. This finding is not in keeping with other studies of speech perception in noise in children, where variability was considerably smaller. Blandy and Lutman (2005) studied speech in noise perception in a large sample of normally-hearing 7-year-olds. Their reported SNR of -3.9 dB required in order to obtain 71% correct on their listening-in-noise task, along with a small standard deviation (SD=1.3) for n=171 is very different from the findings reported in this study. The normally-hearing group in this investigation (n=17), accounting for participants not able to be fit with a 3-parameter sigmoid function) required only a -11.62 dB SNR in order to achieve 70% correct on the listening-in-noise task, but had a much larger standard deviation (SD=5.58). The difference in SNR may be a result of the closed-set response set found on the PSI and the open-set nature of the BKB test. However, aside from variations in overall n, the large variability found in this study is not observed in a different study of normally-hearing children in noise (Blandy & Lutman, 2005).

Stuart (2005) makes a case for the developmental time course of temporal processing capabilities. In a study of the speech perception abilities of normally-hearing children in noise, Stuart (2005) reported that in children ages 6 through 15 years of age, listening-in-noise capabilities were not equal to adult capabilities until age 11. However, listening capabilities in quiet were equivalent to adult capabilities by the age of 8 years. Even though the participants of the present study were of a more restrictive age range (between 6 and 8 years of age) than the Stuart (2005) study, our findings support the suggestion of a developmental time course for listening-in-noise. The regression line observed when age and SNR90 were plotted together (as in figure 10) was significant only for the normally-hearing participant group. This line indicated that as age increased, the SNR90 decreased. This suggests that as age increases, the participant requires less of a difference between target and masker (i.e., less favorable conditions) to listen in noise. This is similar to the findings of Hartley et al. (2000) who observed improvements in listening-in-noise capabilities until the age of 11 years. Their study was conducted on a wider age range than the age range in this investigation. However, since the age ranges included in the present study fall within the age range examined by Hartley and colleagues, the significant effects of age for listening-in-noise are not surprising. It may be that the non-significant findings on this measure for the cochlear implant participants were a result of a small n for that group or the approximately equivalent device use times for all of the cochlear-implant participants.

Both Eisenberg and colleagues (2006) and Wang and colleagues (2008) reported only on their findings on the PSI in quiet, without competing messages as presented in this study. Thus, while direct comparison of PSI results is not possible, both Eisenberg and Wang reported similar ceiling effects by the normally-hearing participants in their study as were noted by the normally-hearing participants in this study. In fact, all participants in the current investigation were administered the PSI material in quiet conditions and all participants, both normally-hearing and cochlear implant, demonstrated perfect performance (100% correct), which is similar to the results reported by Eisenberg and colleagues (2006) with 98-99% correct and Wang et al. (2008) with 94% correct.

The significant differences between the two groups on the listening-in-noise task are even more interesting when we consider the SNRs proposed by Jamieson and colleagues (2004) as being representative of actual classroom conditions. Jamieson and colleagues used SNRs of 0 dB, -6 dB and -12 dB when testing young school-aged children. These SNR values, while not precisely replicated in the current study, are very similar to those used in this investigation (i.e., the current study utilized 0 dB SNR and -12 dB SNR, but did not test -6 dB SNR). The SNR values utilized by Yacullo and Hawkins (1987) were significantly easier than those used by Jamieson et al. (2004) and this study. However, considering that both Jamieson and colleagues and Yacullo and Hawkins describe their conditions as representative of "real world" classroom environments, it is reasonable to assume that the SNR values used in this study are representative of actual classroom environments as well. With this assumption, the finding of significant differences between the two participant groups on listening-in-noise, when placed in the context of a classroom, has significant implications for cochlear-implant users in classrooms. Cochlear-implant users in the classroom may be missing more information in the classroom than even their normally-hearing peers who already demonstrate more stringent requirements for listening-in-noise than adults do. Thus, future efforts to optimize listening conditions in the classroom (where modulate background noise is likely to be found) for this population may result in better functioning. Further, reverberation effects were not accounted for in the present study, whereas they may be a further complicating factor when listening in noisy classrooms.

Intonation Recognition

The expectation that both participant groups would be able to use the F0 cue in order to classify the stimuli as a question or a statement was supported. Regression lines, fit over the plots of averaged group performances were significant for both groups indicating that, overall, both participant groups were able to reliably use F0 information without the benefit of other prosodic cues, to determine the communicative intent of a sentence. As the amount of octave change becomes greater and the direction of octave change becomes positive, participants in both groups identified the word as a question more often, suggesting that they were able to use the F0 cue to determine whether or not an word was a statement or a question.

However, individual plots fitted with regression lines did not show a significant relationship for every participant. Six participants in the NH group and 3 participants in the cochlear implant group were not able to use the F0 cue reliably. These cases do not necessarily indicate an inability to use prosody to determine the communicative intent of a sentence. In these instances, it may be simply that the participant was unable to use F0 information *alone* to make judgments about the stimuli. If given other intonation cues that vary with F0, such as intensity and duration information, these participants may be able to use intonation to make judgments about the communicative intent of the sentence.

Although both groups demonstrated significant use of the F0 cue in intonation recognition, the working hypothesis of significant differences between the two groups on the intonation recognition task was not supported. There were no significant differences between the participant groups in ability to identify a "popcorn" stimuli as a statement or a question based on individual calculations of cumulative d'. This finding supports the idea that while the two participant groups may have different access to F0 information, this difference is not impacting their ability to identify the intonation contour of an word, at the word level. (Note that contextual cues from longer utterances, such as a sentence are not contributing any further information in this task).

These findings are somewhat surprising in light of other studies investigating the perceptual limits of pitch changes in adult cochlear-implant users. Pitch perception has finite limits in cochlear implant coding (McKay & Carlyon, 1999; McDermott & McKay, 1997). It may be that the overall changes to F0 in this study remained within the limits of perception for the cochlear implant group and thus did not help differentiate them from their peers. Chatterjee and Peng (2008) observed that adult CI listeners performed more poorly, on average, than adult NH listeners on the same intonation recognition task. Age at implantation may also play a significant role in the differences in findings between the present study and Chatterjee and Peng (2008). Comparisons between normally-hearing adults and adult cochlear-implant recipients should be viewed in a different light than comparisons between similar populations in children (as in the present study) because of differences in language learning. Adult-cochlear implant recipients may be more likely to be post-lingually deafened and have experience with language whereas pediatric cochlear implant recipients may not have any prior experience with language. The present study has taken care to include only cochlear-implant recipients who were pre-lingually deafened but early-implanted and thus still able to take advantage of greater brain plasticity for language learning and adapt to their new means of language access. Post-lingually deafened adult cochlear-implant recipients may be beyond the "critical period" of highest brain plasticity and thus may be at a greater disadvantage for language learning and speech perception with a cochlear implant, whereas evidence has shown that children implanted at an earlier age have better speech and language outcomes as compared to children implanted at an older age (Svirksy, Teoh & Neuburger, 2004).

The study by Peng, Tomblin and Turner (in press) differed from the present study in (1) age range of participants, (2) stimuli used and (3) length of device use by the CI group. These differences are presumably largely responsible for the difference in findings between the present study and Peng and colleagues. The age range investigated by Peng and colleagues (6-19 years of age) was much larger than the one examined in the present study. Given that temporal-resolution abilities require time to develop in normally-hearing children (Hartley et al., 2000; Stuart, 2005), the NH participants in the present study and the participants in Peng et al. may not be comparable on the basis of differences in maturity in temporal resolution. The normally-hearing participants in the Peng et al. study included participants who were at an appropriate age (between 6 and 19 years of age) to have adult-like temporal processing capabilities. The normally-hearing group in the present study was much younger than those in the Peng et al. study that their immature auditory systems may have been underdeveloped enough to put them more on par with their implanted peers in terms of temporal resolution. Furthermore, as noted by Doherty et al. (1999), intonation recognition in speech is not fully mature in normally-hearing children until the age of 8.5 years, which is slightly beyond the age range of the present study. Since Peng and colleagues included much older normally-hearing participants (mean 11.52 years), many of the participants in that study may have demonstrated adult-like intonation recognition, particularly in comparison to the implant participants. The study by Peng and colleagues further differed from the present study in terms of stimuli. The intonation recognition stimuli used by Peng and colleagues were sentence length natural utterances with co-varying prosodic cues and was not an intonation recognition task based on changes in F0 alone, as in the present study.

Another major difference between this study and that of Peng and colleagues that may contribute to the different outcomes may be different periods of device use. While both investigations enrolled only persons who had been pre-lingually deafened, the periods of device use in the Peng study (mean=10.04 years) were much longer than those found in this study (mean=4.12 years). When considering that device use time represents the period of best language access in cochlear-implant recipients, than the cochlear-implant users with longer device use time may have a significantly older "language age" and thus, have developed better skills for processing complex auditory tasks, such as those presented in the current study and in Peng and colleagues. However, the children in the Peng et al. study performed significantly poorer than their NH peers, suggesting that the longer duration of use with the device did not help them to the fully desired extent.

Other studies that have demonstrated decrements in intonation recognition capabilities also did so with stimuli in which all prosodic cues were present and co-varying (i.e., increased voice pitch may be present and co-varying in the stimuli with decreasing duration and intensity, etc.) (Doherty et al., 1999; Green et al., 2005; Richardson et al., 1997). In such cases, the difference in performance may not be because of F0 only, but instead, may be a result of other prosodic cues or a combination thereof.

When examining the intonation task data obtained in the present study, large amounts of response variability might be expected around $\Delta F0=0$. In this case, there are no changes in F0, either up or down, to indicate that the word is a statement or a question, and performance may drop to chance levels (50%). However, in this study, the variability around $\Delta F0=0$ is no greater or smaller than the variability about any other $\Delta F0$ values, negative or positive. Chatterjee and Peng (2008) noted a sharply increasing monotonic function at $\Delta F0=0$ when plotting the performance of their normally-hearing participants listening to unprocessed intonation task stimuli and noted that this function grew shallower as spectral information was reduced through the use of a noise-band vocoder (with 4 and 8 spectral channels of information). Personal communication with the authors has allowed for a plotting of the results of the intonation recognition task (with the identical “popcorn” stimuli) from their adult participants with the results from the current investigation with the normally-hearing participants (figure 12). Note that the range of stimuli used by Chatterjee and Peng (2008) was larger than in the present study, and included stimuli that had systematically varying duration and intensity cues. The data included in figure 12, however, only show participants’ performance with those stimuli that were identical to the ones used in the present study. Visual inspection of figure 12 suggests that the normally-hearing children in this study did not demonstrate the sharply increasing monotonic function at $\Delta F0=0$ as did the normally-hearing adults in Chatterjee and Peng (2008). This again provides evidence for a possible developmental time course for intonation recognition abilities in speech, as suggested by Doherty and colleagues (2000). It may also be that children are inherently more variable in their response patterns than adults are and that this difference between data sets is not entirely representative of the inability of children to use the F0 cue as reliably as adults.

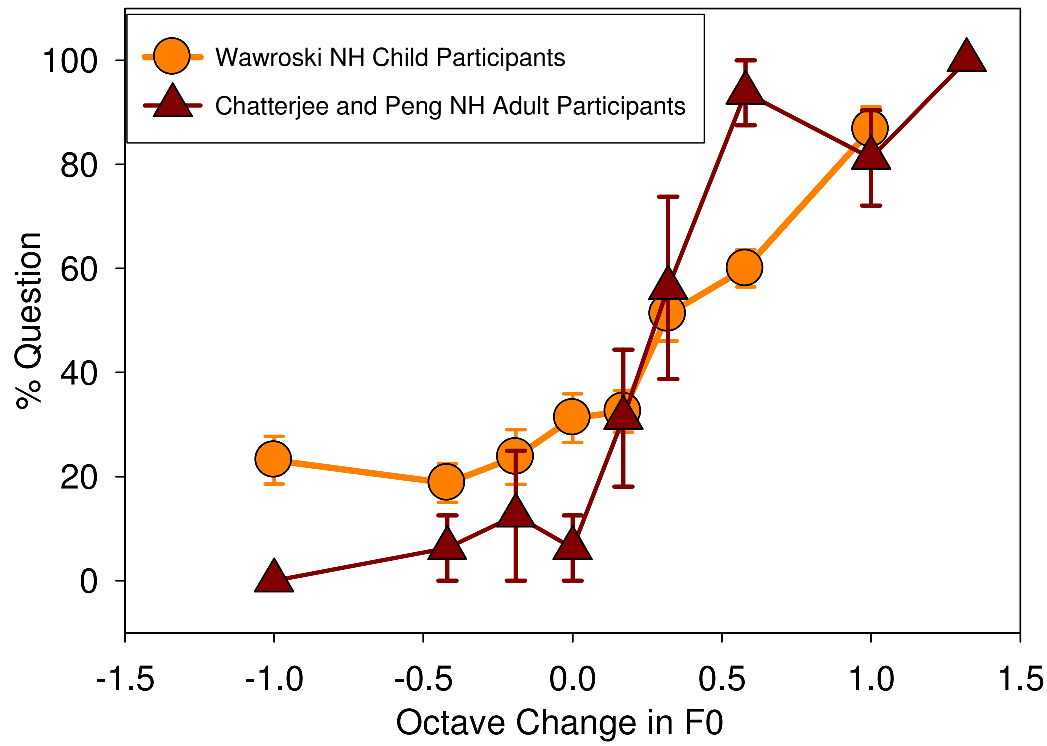


Figure 12: Comparison of intonation task performance between adult NH listeners (n=4) from Chatterjee and Peng (2008) and the NH children from the current investigation (n=20). Error bars represent ±1 S.E.

Relationship between Variables

It was expected that there would be a significant positive relationship between performance on the intonation task and the listening-in-noise task for both groups. This working hypothesis was only partially supported by the findings of the present study. A significant relationship (r=-0.975, p=.025 for SNR70 and r=-0.966, p=.034 for SNR90) was noted between tasks for the cochlear implant group only. Pearson correlations between cumulative d' scores and SNR70 and SNR90 were performed in order to make judgments about the relationship between these variables. While both groups demonstrated a positive correlation between the variables, these correlations were only significant for one participant group. The fact that this significant relationship existed for the cochlear implant group only is somewhat surprising. This suggests that even though the normally-hearing participants may perform better in noise as compared to their peers with cochlear implants, they will not necessarily be better at the intonation recognition task. This may be an effect of "language experience". Consider that the normally-hearing children in this study have had 6-8 years of language experience. However, when we consider that the cochlear implant participants were pre-lingually deafened and that their device use time represents their best language access, we can see that the cochlear-implant users may still be developing auditory skills that are already mature in the normally-hearing listeners. In other words, the normally-hearing participants may be demonstrating mature listening-in-noise skills and thus, further improvements in listening-in-noise are not expected. However, they may still be improving their use of prosody for judgments of communicative intent. The cochlear implant participants may still be developing in both areas of auditory skills; this may explain why they demonstrated a significant positive relationship in this analysis. It is also possible that the normally-hearing children had greater access to the many redundant cues in speech, and were able to use them to their advantage to listen in noise. In contrast, the children with cochlear implants might have access to a more limited set of cues, which they must use for all listening tasks: thus, their performance in one task is directly related to their performance in another.

Group Variations

Participant groups were analyzed for differences in non-verbal intelligence quotient scores. No significant differences were found between groups for average NVIQ. This suggests that the significant differences found for listening-in-noise between the two participant groups cannot be explained by intelligence abilities and lends strength to the assumption that the differences noted between the two groups are a result of differences in their spectral and temporal-resolution abilities. However, given this assumption, it might be expected that the groups would differ in their abilities on the intonation recognition task, which was not the case. This suggests that other variables (e.g., differences in audibility and processing or differences in language experience) that may be influencing listening-in-noise that do not influence intonation recognition but were beyond the scope of this investigation.

Practical Implications

In spite of the limited scope of this study, the findings have considerable practical implications. The results indicate that children with cochlear implants require higher SNR values in order to achieve the same performance as their normally-hearing peers. The presence of modulated background noise, which normally-hearing children may be able to adapt to quite easily, is present in many environments that children with cochlear implants find themselves in, such as classrooms. The findings of the present study indicate that children with cochlear implants exhibit significant deficits in this sort of environment and therefore need appropriate accommodations. It may be that children with cochlear implants are quite successful in quiet, and teachers and parents may not be aware that even small deficits exist and may have a great impact on their classroom experience. This is particularly true in oral settings, where special care must be taken to position the child appropriately in order to maximize SNRs in potentially noisy classrooms. The child must be seated close to any sources of instruction and away from any sources of noise.

Strengths and Limitations of the Present Study

An important feature of the present study was that all of the cochlear implant participants were early implanted and pre-lingually deafened. Early implantation has been shown to be more beneficial to language outcomes in pediatric cochlear-implant recipients as opposed to later implantation ages (Svirsky, Teoh & Neuburger, 2004). This helped to ensure that the pediatric implant recipients included in the current study were representative of the cochlear implant population that has had the fewest obstacles to language learning, and perhaps to reduce the potential variability in the data.

The narrow age range included in the present study may been seen as a limitation to the present study, but instead, should be viewed as a strength. By including a narrow range of ages, we have limited some of the variability in responses and eliminated some potentially confounding developmental effects from the findings. Additionally, the addition of the K-BIT to the testing protocol in order to assess NVIQ has ensured that a potentially major confounding variable has been systematically controlled. Because all of the participants in the present study demonstrated, at the very least, average non-verbal intelligence, we can be reasonably sure that any differences between groups or any outlying results are not the result of the confounding variable of intelligence, a non-linguistic factor that may significantly impact performance on the tasks in this study.

The stimuli for the intonation recognition task were an added strength. By including stimuli that were carefully controlled and varied only in terms of F0, we were assured that we were examining participants' true ability to utilize the F0 cue and not their ability to utilize F0 along with other prosodic cues. This helped us to examine any potential root causes of differences between the cochlear implant and normally-hearing populations.

One of the major limitations of this study is the overall small n of the cochlear implant participant group. For the purposes of statistical analyses, Levene's test for equality of variances indicated that both groups demonstrated homogeneity of variance and thus, the two groups were appropriate for statistical comparison. However, given the different findings of Peng, Tomblin and Turner (in press) with more CI participants and more equal groups (26 CI and 17 NH), the addition of more CI participants may have yielded different results.

The choice of a bi-syllabic stimulus word with no carrier phrase and no other contextual cues provided may not be as representative of actual interactive conversations. In most "real-world" listening situations where children are asked to apply prosodic information, contextual cues would also be available to aid in the overall interpretation. Additionally, the prosodic contours of the utterance would occur over an entire sentence or segment of speech instead of simply over a bi-syallbic word, in most cases. However, the “popcorn” stimuli were chosen as a way of isolating any other cues to prosody. Since duration and intensity were controlled and no other contextual cues provided, the findings of this study can be reasonably attributed to differences in F0 perception only. However, the real-world applicability of the “popcorn” stimuli may not be so far-fetched. Chatterjee and Peng (2008) demonstrated a strong positive correlation ($r=0.861$, $p<0.01$) between performance on an intonation recognition task with naturally produced utterances where prosodic cues occurred together and occurred naturally, and performance on an intonation recognition task where prosodic cues were systematically roved, including F0 contour. This finding indicates that a participant with better performance on the controlled stimuli task might also be expected to perform better on the intonation task with the naturally produced stimuli, suggesting that singular prosodic cues in isolation may provide sufficient intonation information on their own merit. Peng and Chatterjee (2008) also demonstrated a strong positive correlation in performance between a temporal detection task and the intonation task utilizing the “popcorn” stimuli, suggesting that the intonation recognition task is closely related to a persons temporal-resolution capabilities.

The closed-set nature of the listening-in-noise task may also have presented a challenge to interpretation of the present study. The unilateral cochlear-implant recipients in the present study demonstrated considerably more difficulty with the listening-in-noise task than their normally-hearing peers.

Many of the normally-hearing participants demonstrated ceiling effects that may not have existed with a more difficult or open set listening-in-noise task. However, the dilemma presented here is that the CI participants would likely have struggled further with a listening-in-noise task that was more challenging to their peers. Furthermore, the masker in the PSI presents a somewhat limited scope of the real-world auditory challenges found in classrooms. The PSI utilizes a single male talker as a masker to a different male talker. Different maskers that include larger differences in F0 between stimulus and masker or maskers that include backgrounds of multiple talkers may be more representative of the auditory challenges presented to the populations examined in the present study.

Implications for Future Studies

Certainly, future studies into the use of F0 in both normally-hearing and pediatric cochlear implant populations should include larger numbers of cochlear implant participants, particularly in studies that seek to examine the relationship between these two populations. Further studies may investigate the effects of different types of maskers, including steady-state, multi-talker and maskers that provide greater separation of F0 between target and masker. Intonation recognition investigations may attempt to further identify any sources of variation between these two populations by including roved stimuli or studying only the contribution of duration and intensity to prosody recognition. Special care must be taken to carefully control for pre- and post-lingually deafened cochlear implant participants and device use time. Comparisons between unilateral and bilateral cochlear-implant recipients may also reveal further differences in the processing of intonation and speech perception in listening-in-noise.

Summary

Normally-hearing children between the ages of 6 and 8 years typically demonstrate good speech perception when listening to speech in the presence of a single talker masker. By comparison, their peers with cochlear implants demonstrate significant deficits in listening-in-noise and require greater SNRs to achieve comparable speech perception results. These findings may partially be a result of differences in spectral and temporal resolution capabilities but may also be reflective of immature auditory skills in the implant population, considering that their overall “hearing age” is much “younger”. When it comes to using F0 information to identify the intonation contours of a word, both populations demonstrate an overall ability to use the cue, but this finding is subject to much individual variability. Unlike their listening-in-noise abilities, 6 to 8-year old normally-hearing children and early-implanted children with cochlear implants do not differ on their intonation recognition abilities. However, given the small sample size of the cochlear implant group, these results should be regarded as preliminary and interpreted with caution.

Appendix A: Sentence stimuli for the Pediatric Speech Intelligibility Test

Response Card A

A bear is combing his hair.
A horse is eating an apple.
A bear is brushing his teeth.
The rabbit is putting on his shoes.
A rabbit is painting an egg.

Response Card B

A rabbit is reading a book.
The fox is roller skating.
A rabbit is kicking a football.
The bear is drinking milk.
A bear is eating a sandwich.

Appendix B: Informed Assent and Consent Forms

Informed Assent Form for Participants Ages 5-12

Speech Understanding in People with Cochlear Implants

I am about to do a research study. A research study is a special way to find out about something. The scientists are trying to find out how children with cochlear implants understand what people say. The scientists also want to see how children with normal hearing understand what people say.

In this study, I will be told to point to a picture on a page that will have a lot of different pictures on it. I will be told by a person or a speaker which picture to point to. Sometimes, it might be hard for me to hear which picture to point to because someone else will be talking or there is other noise in the room. Also, I will listen to a word or sentence and have to say whether the word or sentence is "asking" me something or "telling" me something. The scientists are going to measure whether or not I answer correctly. All of this will take between one and two visits that are about one hour long.

There are some things about this study that I should know. The main thing is that I can stop at any time if I don't want to continue. When they are done with this study, the scientists are going to write a report about what they find out. They won't use my name in the report.

_____ I agree to be in this study. ____

(print your name here)

<u>CONSENT FORM</u>

Project Title	***Speech Perception and Suprasegmental Perception in Children with Cochlear Implants***
Why is this research being done?	*This is a research project being conducted by Lauren Wawroski and Monita Chatterjee at the University of Maryland, College Park. We are inviting your child to participate in this research project because your child has a cochlear implant or normal hearing. The purpose of this research project is to examine the relationship between speech perception and the parts of speech that do not convey concrete information (suprasegmental information) in children with cochlear implants in quiet and in background noise. Both children with cochlear implants and children who have normal hearing sensitivity will be tested in this experiment.*
What will my child be asked to do?	*The procedures involve 1-2 testing sessions that are approximately one hour in length. If your child has not had a hearing test in the past year, testing may take slightly longer and your child will be given a brief auditory evaluation before testing begins. This auditory evaluation involves looking into your child's ear canal, conducting a brief test to measure the mobility of the ear drum and middle ear system, asking your child to repeat some words that are very soft and asking them to indicate when they have heard a tone. During the experiment, your child will be seated in a sound-treated booth and asked to listen to words and sentences that are presented through a loudspeaker. Your child will be asked to point to a picture on a laminated card in response to an auditory prompt, such as "Show me the bear." The words and sentences presented to your child may be difficult to understand because there may be background noise added. Your child will also be presented with a word or sentence and will be asked whether the word/sentence was "asking" or "telling" something. Testing may take place at your child's school during regular school hours if your child attends the River School. If your child does not attend the River School, you and your child will be invited to the University of Maryland Audiology Clinic for testing. Your child will be rewarded at the end of the testing session with a small piece of candy or small toy. Parents of the participants who travel to the Audiology Clinic on the campus of the University of Maryland, College Park, Maryland will be reimbursed a fixed, one time fee for their travel expenses.*
What about confidentiality ?	*We will do our best to keep your child's personal information confidential. To help protect your child's confidentiality, he or she will be identified by a participant number and this number will be kept separate from the participants name and other personal information. The name of the participant or other personal or specific identifiers will not be associated with the data collected from each participant. Data that are collected will be stored in a locked filing cabinet in a locked office in the principal investigator's lab. Only the investigators in the study will have access to this filing cabinet. The data from this study will be kept for a period of 5 years after the end of this study and will be destroyed by shredding at the end of this time period. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.*

Does my child have to be in this research? **May my child stop participating at any time?**	*Your child's participation in this research is completely voluntary. You may choose for your child not to take part at all. If you decide that your child may participate in this research, you may stop your child's participation at any time. If you and your child decide not to participate in this study or if you or your child stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.*
Is any medical treatment available if my child is injured?	*The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.*
What if I have questions?	*This research is being conducted by Dr. Monita Chatterjee in the Department of Hearing and Speech Sciences at the University of Maryland, College Park. If you have any questions about the research study itself, please contact Dr. Chatterjee at: 0100 LeFrak Hall, College Park, MD, 20742, or by calling (301) 405-7716 or by e-mail at mchatterjee@hesp.umd.edu.* *If you have questions about your rights as a research subject or wish to report a research-related injury, please contact:* **Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742;** **(e-mail) irb@deans.umd.edu; (telephone) 301-405-0678** *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*

<table>
<tr><td>Project Title</td><td colspan="3">Speech Perception and Suprasegmental Perception in Children with Cochlear Implants</td></tr>
<tr><td></td><td colspan="3"></td></tr>
<tr><td>Statement of Age of Person Providing Consent</td><td colspan="3">Your signature indicates that:
you are at least 18 years of age;,
the research has been explained to you;
your questions have been fully answered;
and you freely and voluntarily choose to have your child participate in this research project.</td></tr>
<tr><td></td><td colspan="3"></td></tr>
<tr><td rowspan="3">Signature and Date</td><td colspan="2">NAME OF PARENT</td><td></td></tr>
<tr><td colspan="2">SIGNATURE OF PARENT</td><td></td></tr>
<tr><td>DATE</td><td></td><td></td></tr>
</table>

Is it all right if we reward your child with a small piece of candy for their participation?
_____ yes _______no

(check one)

Name of Child:____

Appendix C: Recruiting Letter

April 16, 2007

To the parents of :

My name is Lauren Wawroski and I am a graduate student in Audiology at the department of Hearing and Speech Sciences at the University of Maryland, College Park. I am currently conducting a study on the speech perception abilities of children with cochlear implants.

Your child, is a potential participant for my study. His/Her name was given to me by Dr. Jennifer Mertes. Your child was considered a potential participant based on his/her use of a cochlear implant or normal hearing status, age, language abilities and current enrollment in the River School.

Briefly, I am attempting to examine the relationship between speech perception abilities and suprasegmental identification in children with cochlear implants. "Suprasegmental information" is a feature of speech that conveys information to the listener without explicit words. For example, when you ask your child a question, you probably raise the pitch of your voice slightly at the end of the question to indicate to your child that a response is required. This change in the pitch of your voice is called suprasegmental information in speech. For this study, I am looking for two groups of children – those with normal hearing and those who have cochlear implants.

In my study, your child will be seated in a sound-treated booth and asked to listen to words and sentences that are presented through a loudspeaker. Your child will be asked to point to a picture on a laminated card in response to an auditory prompt, such as "Show me the bear." The words and sentences presented to your child may be difficult to understand because there may be background noise added. Your child will also be presented with a sentence and asked whether the sentence was "asking" or "telling" something or if the speaker was a "man" or a "woman".

Your child will be rewarded at the end of the testing session with a small piece of candy or small toy. The study procedures involves one testing session that is approximately one half hour to an hour in length. If your child has not had a hearing test in the past year, testing may take slightly longer. Testing will take place on the grounds of your child's school during regular school day hours or, in some cases, you and your child may be invited to the University of Maryland Audiology Clinic for testing.

Before your child participates in this study, you will need to review and sign an informed consent form. (Your child will also need to sign an informed assent form so that he/she is well-informed before participating. If your child cannot read, the assent form will be read to him/her by the examiner and he/she will be asked to "sign" it, though the child's mark on the paper will be all that is necessary.) Please note that your child is not required to participate in this study and that your refusal to sign the informed consent form or have your child participate will in no way have an impact upon the services that you receive from the River School. No testing will be done on your child if you do not sign the informed consent form. You also have the freedom to withdraw your child from my study at any time after the study has begun, even if you have already signed the informed consent form. Again, this will not impact the services that your child receives at the River School.

If you decide that you would like to have your child participate in my study, please fill out and return the attached brief questionnaire to Dr. Mertes, along with the attached informed consent form.

Should you have any questions or wish to discuss your child's participation in this study, please do not hesitate to contact me, Lauren Wawroski at (717) 439-9107 or by e-mailing me at lwisman@hesp.umd.edu. The primary investigator working on this study is my advisor, Dr. Monita Chatterjee and can be contacted by calling (301) 405-7716 or by e-mailing mchatterjee@hesp.umd.edu.

Thank you for your time and consideration.

Sincerely,

Lauren R. Wawroski

Name of Child:_____________________________________

Please take a moment to respond to these questions regarding your child's hearing and hearing history.

1) *In your opinion, does your child currently hear well* <u>*without*</u> *the use of cochlear implants or hearing aids? (circle one)*

YES **NO**

2) *Does your child currently wear a hearing aid(s)?*

YES **NO**

3) *Does your child currently wear a cochlear implant?*

YES (see part A) **NO**

a) *If you answered YES, please provide the following information:*

Age at which your child's hearing loss was identified:______________________

Age at which your child received their cochlear implant:____________________

Has your child been using their cochlear implant for at least one year?

YES **NO**

Thank you for your time and your participation.

Appendix D: Permission to Access Audiometric Records Form

University of Maryland, College Park
Department of Hearing and Speech Sciences
Cochlear Implants and Psychophysics Laboratory

Permission to access audiometric and language records

Title of Project: *Speech Perception and Suprasegmental Perception in Children with Cochlear Implants*

Principal Investigator: *Monita Chatterjee, Ph.D.*
(301) 405-7715
mchatterjee@hesp.umd.edu
Student Investigator: *Lauren R. Wawroski*
(717) 439-9017
lwisman@hesp.umd.edu

For the purposes of our study, we would like to access some of your child's previous audiometric records and/or language testing records. These records may be available through your school audiologist or speech pathologist. The information that we are looking for can be found on audiograms from previous test sessions, cochlear implant mapping records and language testing sessions. This information includes hearing threshold levels, speech reception thresholds, word recognition scores, cochlear implant map information and language test scores. Again, this information will only be used by the above-named investigators for the purposed of our study. If you do not wish for the investigators to access these records, your child's services will be not affected in any way.

By signing this form, you are granting us (Dr. Monita Chatterjee and Lauren Wawroski) permission to access previous audiometric records that your school audiologist or speech pathologist may have.

Please do not hesitate to contact the examiners if you have any questions or concerns.

____________________________________ ____________________

Signature Date

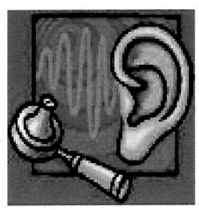
____

Your child's name (please print)

Appendix E: General Recruitment Flier

I need your help!

My name is Lauren Wawroski and I am a graduate student from the University of Maryland. I am conducting a research study on children with cochlear implants. The success of my research is dependent upon children with cochlear implants and children with normal hearing who are willing to participate.



- Does your child have a cochlear implant?
  - Have they had their implant for at least one year?

...or...

- Does your child have normal hearing?

- Are they at least 4-years-old?
- Would you like to know more about your child's speech perception abilities?

For more details or if you would like to participate, please contact Lauren:
By e-mailing lwisman@hesp.umd.edu
By calling (717) 439-9107

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