# PITCH PERCEPTION OF YOUNG COCHLEAR IMPLANT USERS AND NORMAL-HEARING PEERS

by

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# *Abstract*

This study examines pitch discrimination thresholds in young cochlear-implant users between the ages of 8 and 15. Difference limens (DLs) were determined for fundamental frequency in vowel-like stimuli at three referent fundamental frequencies ($f_0$): 100, 200, and 400 Hz. Two different tasks were employed: pitch discrimination, in which subjects were asked whether two stimuli are same or different, and pitch ranking, in which participants determined which of two stimuli is higher in pitch. Young CI users were found to have much larger difference limens than normal-hearing peers, and did not have significantly different DLs from postlingually deafened adults. Age of implantation did not influence performance for young CI users, although length of CI experience did.

## *List of Abbreviations Used*

| | |
|---|---|
| BM | basilar membrane |
| CAEP | cortical auditory evoked potential |
| CI | cochlear implant |
| DL | difference limen |
| $f_0$ | fundamental frequency |
| NH | normal-hearing |
| pps | pulses per second |

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# Chapter 1

## *Introduction*

### 1.1. IMPORTANCE OF PITCH

Pitch is a crucial component of speech perception. We use pitch as a perceptual aid in the interpretation of linguistic information. In English, pitch helps us to recognize vowels and lexical stress. In tonal languages, such as Chinese, different pitch contours reflect different word meanings. Pitch also conveys affective information that is essential to understanding the full meaning of speech; both emotion and tone are conveyed through the pitch of a person's voice. Furthermore, pitch transmits personal information that helps us determine whether we are hearing a male or female voice, and whether that voice is familiar to us.

However, for cochlear implant (CI) users, pitch information that is transmitted to the central nervous system is not perfect. CI users consequently have greater difficulties perceiving pitch differences than their normal hearing counterparts do. A review of the relevant research into pitch perception, including discussion of the limitations cochlear implants present to the proper encoding of pitch, follows.

### 1.2. WHAT IS PITCH?

Before entering into a review of pitch perception research, it is perhaps important to start with a brief discussion of what is meant by the term *pitch* itself. This is not an easy task, as there are numerous definitions of pitch spanning many years of research. Today, most definitions fall within one of two categories: those that are psychological in nature, and those that are psychophysical in nature.

Psychological definitions are based on the auditory sensation of pitch as opposed to the actual physical characteristics of the sound. One such definition has been proposed by the American National Standard Institute, which in 1973 defined pitch as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high" (ANSI, 1973). It is also common for some psychological definitions to include a reference to the musical scale, for instance "that attribute of sensation whose variation is associated with musical melodies" (Plack & Oxenham, 2005, p.2). Psychophysical descriptions, on the other hand, incorporate both the auditory sensation and the physical sound characteristics. One such example might be: "Pitch is the auditory percept associated with the frequency (f) or, equivalently, the period (T = 1/f) of sound wave vibrations in the audible frequency range (~20–20 kHz)" (Tramo et al, 2005, p.149). In 1994, the American National Standard Institute's definition was amended to include a psychophysical component: "Pitch depends primarily on the frequency content of the sound stimulus, but it also depends on the sound pressure and the waveform of the stimulus" (ANSI, 1994).

There are a number of difficulties one encounters when trying to define pitch. With pure tones, changes in intensity can influence the perceived pitch of a tone (Chatterjee & Zwislocki, 1997). In complex tones, spectral differences can lead to different pitch-like qualities, such as timbre or brightness. For example, some aperiodic sounds can be perceived to have a pitch. De Cheveigné (2005) suggests there may be "multiple pitch-like dimensions" (p.176) that can influence how a person perceives the pitch of complex stimuli. When determining what the smallest detectable pitch difference is for an individual (i.e., obtaining frequency difference limens or DLs), it is therefore difficult to determine whether it is pitch or some other perceptual quality that is playing the most important role in discrimination. Furthermore, there is evidence to suggest that pitch may be listener dependent for some complex tones (Smoorenburg, 1970). All of these findings suggest that pitch may be closely connected with other perceptual attributes, some of which may influence how a tone is perceived by the listener.

For the purposes of the present study, we assume that pitch varies with frequency, and that it can be perceived to be low or high relative to other tones that evoke the sensation of pitch.

## 1.3. THEORIES OF PITCH PERCEPTION

There have historically been two different theories of pitch perception: place theory and temporal theory. Place theory (also known as place-coding, place-rate, or spectral coding) suggests that pitch is determined by the place along the basilar membrane (BM) which exhibits maximal vibration or displacement for a given stimulus. High frequency tones stimulate hair cells at the basal end of the cochlea, and low frequency tones stimulate hair cells towards the apical end of the cochlea. This tonotopic organization of the BM determines the characteristic frequency of inner hair cells and causes them to fire at their highest rate when a specific frequency is present in the incoming signal.

For pure tones, pitch is associated with the place of maximal displacement on the BM. Between 50 and 16,000 Hz, the place of maximal displacement increases monotonically from base to apex; below 50 Hz, the pattern of excitation on the BM does not change. Place theory can therefore not account for pitch perception of frequencies below 50 Hz (Warren, 1999). The place of maximal displacement along the BM can actually be estimated from the incoming frequency using Greenwood's frequency-position function (1990). This function is a useful tool for making acoustic to electric place-pitch comparisons, which will be discussed in more detail later.

Place theory also cannot explain why pitch is not influenced by spectral amplitude. An increase in amplitude of pure tones shifts the location of maximal displacement along the BM. In a study with guinea pigs, Chatterjee and Zwislocki (1997) found that increasing intensity from 30 to 80 dB resulted in a shift of maximal displacement towards the basal end of the cochlea by a distance corresponding to 1-2 octaves. However, this shift in the place of maximal displacement does not result in a significant change in perceived pitch (Warren, 1999).

For complex tones, the cochlea performs a spectral analysis similar to a Fourier transform, separating incoming signals into their component frequencies and stimulating different locations along the BM according to frequency. However, the perceived pitch of complex tones does not always correspond to the place of maximal displacement. The fundamental frequency does not even have to be present in the incoming signal for the pitch corresponding to the period of the complex waveform to be perceived, something that is known as the missing fundamental or residue pitch (Schouten, 1940). Residue pitch can occur when the frequencies present are harmonics (i.e., integer multiples) of the fundamental frequency, or when there are steep spectral peaks of noise which occur periodically (Yost, 2000; Zwicker & Fastl, 1999). The exact manner in which the auditory system encodes residue pitch is not well known, but there are two potential explanations: pattern matching and temporal coding (Winter, 2005).

Pattern matching assumes complex sounds are broken up into their component partials (i.e., individual harmonics are resolved). Pitch is then determined by the pattern of these resolved frequencies. According to Greenwood's function, critical bandwidths corresponding to auditory filters are approximately 1mm wide along the BM in humans. Given that average length of a human BM is approximately 35 mm, this results in nearly 35 critical bands covering the entire range of frequencies humans can perceive (Greenwood, 1990). If harmonic frequencies in the incoming signal are within one critical band, they will not be resolved. Pattern matching requires at least one resolvable harmonic in order for a low, residual pitch to be heard (Moore et al, 2006a).

An alternate explanation to place theory can be provided through temporal theory (also known as rate theory or periodicity). It assumes that pitch is transmitted through the timing of neural action potentials. This is possible through the phase-locking ability of neurons to fire in synchrony with the period of an incoming acoustic signal; the intervals between the action potential spikes from a group of neurons match the frequency of the signal and transmit the pitch information. For pure tones, the rate of transmission matches the frequency of the signal up to approximately 4-5 kHz (Moore, 1997; Plack & Oxenham, 2005). Above this frequency the refractory period of nerve cells is too long for phase-locking to encode the period of the incoming waveform.

For complex tones, pitch is encoded in the temporal pattern of neurons firing at different locations along the BM. Stimuli with harmonics at integer multiples (e.g., 400, 600, 800) have a $f_0$ corresponding to the difference between harmonics (e.g., 200 Hz), even if that frequency is absent in the signal (i.e., residue pitch). The coding of lower harmonics in particular is deemed to be necessary for complex pitch perception (Moore et al, 2006a; Carlyon et al, 2002), although some studies have shown that higher, unresolved harmonics may play a role as well (Houtsma & Smurzynski, 1990).

The obvious limitation to temporal theory is that it does not work for the entire range of frequencies which humans can perceive. At higher frequencies (e.g., above 4-5 kHz) place-coding may therefore play a larger role in pitch perception. At lower frequencies (e.g., 20-50 Hz), temporal coding may play the dominant role in perception. Although it is generally accepted that both place and rate are important for reliable pitch perception, it is still unknown how exactly the two interact, and whether one can compensate for the other when both types of information are not available. These issues become very important when exploring ways to improve pitch perception through cochlear implants.

### 1.4. ENCODING PITCH IN COCHLEAR IMPLANTS

Cochlear implants (CIs) bypass inner hair cells and stimulate the auditory nerve directly. Temporal coding can be provided through rate of electrical stimulation, and place-coding information is provided through electrode placement. As with normal-hearing individuals, both place and temporal coding are seen as important factors in pitch perception for CI users. Fearn et al. (1999) conducted a study with 6 postlingually deafened CI users to assess contributions of rate versus place coding in CIs. They found that at lower frequencies (e.g., 100 to 200 Hz), both rate and place contributed to pitch, but at higher frequencies (e.g., above several hundred Hz) only stimulation place had an effect on pitch. McKay et al. (2000) had subjects detect pitch changes using only rate, only place, or a combination. Results from the combined information were better than for either rate or place alone.

Unfortunately, there are limitations to the amount of spectral and temporal information that CIs can provide. The following section discusses some of the limitations CIs pose to transmitting accurate and complete pitch information.

### *1.4.1. Place-coding Limitations*

One obstacle to accurate place-coding is that CIs have only a limited number of electrodes stimulating the auditory nerve (usually between 4 and 22: Grayden & Clark, 2006) compared to healthy cochleas that have thousands of hair cells to provide more detailed spectral resolution. This reduction in the number of sites of stimulation results in a neural signal that may convey only limited spectral information to the central auditory nervous system. Chatterjee and Shannon (1998) found that excitation patterns in the cochlea for four postlingually deafened CI users were much wider than for normal-hearing individuals, suggesting that frequency selectivity through CIs may be reduced compared to normal-hearing individuals. Furthermore, with each electrode channel being assigned a wide band of frequencies, there is often only one channel stimulating the entire range of fundamental frequencies found in normal speech (e.g., 100 to 220 Hz for adult males and females).

Another limitation to place-coding through CIs is that the electrode array is not inserted over the entire length of the basilar membrane. The depth of insertion of the electrode array is generally 18-26 mm, while even more deeply inserted electrode arrays do not extend beyond 30 mm (Wilson, 2006). CIs therefore do not have access to neurons at the most apical end of the cochlea. This electrode placement mismatch means that the frequency range assigned to a particular electrode does not correspond to the same range of characteristic frequencies along the basilar membrane. As a result, electrodes provide greater stimulation to the basal sections of the BM than would otherwise be stimulated in healthy cochleas. Ketten et al. (1998) found that for 20 CI users, the most deeply inserted electrode was situated at the location for 387 Hz to 2596 Hz (according to the function provided by Greenwood, 1990), yet the electrode was programmed to transmit information for frequencies lower than 240 Hz, leading to a place mismatch of up to 3 octaves or more (Moore and Carlyon, 2005).

Most studies show that, in general, electrode stimulation results in a relative sensation of pitch that is monotonic (i.e., consistently ordered from lowest to highest) and in the same direction as healthy cochleas (high frequencies as the basal end and low frequencies at the apical end of the electrode array; Busby & Clark, 2000a; Zwolan et al, 1997; Collins et al, 1997; Busby et al, 1994). Although Nelson et al. (1995) also found that pitch percepts associated with electrode stimulation were relatively tonotopic, they observed large individual variability in pitch ranking tasks. Some subjects exhibited pitch reversals on certain electrodes (i.e., electrodes that were more basal were judged to have a lower pitch than those that were more apical). However, there was no relationship between absolute location of the electrodes and the presence of pitch reversals. Some subjects showed better place-pitch sensitivity for more electrodes placed on the apical half of the cochlea, whereas others had better place-pitch sensitivity for electrodes in the basal half. Other studies have also found pitch reversals for some subjects (Busby et al, 1994; Collins et al, 1997).

Nerve fibers with characteristic frequencies in the low- and mid-frequency range are found in the upper turns of the cochlea. This frequency range is therefore particularly important for hearing speech sounds. With most implants only being inserted 1-2 turns into the cochlea, there is reduced place-coding in the low-frequency range that is important for pitch perception. However, stimulating the upper turns of the cochlea may not result in better pitch perception in lower frequencies, as the modiolus does not extend as far as the apex of the cochlea and afferent nerve fibres in the upper turns are likely unable to be stimulated anyway (Chen et al, 1999).

### 1.4.2. *Temporal-coding Limitations*

In addition to the place-coding limitations mentioned above, CIs have difficulties transmitting some temporal information as well. Wilson (1997) believes that carrier pulse rates (stimulation rates) need to be four times the frequency of the modulation rate to carry sufficient information regarding the temporal envelope. However, stimulation rates in many CIs are too low to convey detailed temporal information (Green et al, 2004; Moore, 2003). While some CIs have stimulatioin rates around 10,000 pps, the current is spread out over a number of channels. If 8 channels are used, stimulation rates are 1250 pps per channel; if more channels are used, rates for individual channels are even lower. When the per-channel rates are divided by Wilson's factor of 4, 300 Hz is the highest frequency that can be conveyed using temporal coding alone for such CIs. Newer CI models are capable of delivering much higher rates of stimulation—some higher than 5000 pps/channel. Rate of stimulation for these models is less likely to be a factor in poor temporal coding.

Another limitation to temporal coding is that most CI users are in fact unable to discriminate changes in rate-pitch above 300 Hz regardless of actual stimulation rates (Fearn et al, 1999; Zeng, 2002). However, there is great variability between CI users as to upper limit of perceived rate pitch, as well as their ability to discriminate between different rate pitches. McKay (2004) noted that one CI user was unable to perceive differences in rate pitch above 225 Hz on one electrode, and 160 Hz on another electrode, while another subject had an upper limit of 330 Hz on one electrode. Townshend et al. (1987) also observed wide variability in the upper limit of temporal coding for CI users, with one subject unable to perceive rate differences above 200 Hz, and the other two subjects able to perceive differences at 1000 Hz (albeit only very large differences).

### *1.4.3. Other Limitations to Pitch-Coding in Cochlear Implants*

There are other factors which can limit how well CI users are able to perceive pitch. One such factor may be the presence of "dead regions" in the cochlea. It is common for deaf individuals to have some degeneration of the auditory nerve, resulting in dead regions where no nerve fibres are left to be stimulated by the CI (Moore & Carlyon, 2005). Dead regions do not occur in any predictable fashion in the cochlea, and there is large individual variability (Wilson, 2006). CI users can therefore have a perfectly functioning electrode stimulating a region of the cochlea where there are no, or few, surviving nerve cells to transmit the information to.

Another issue affecting the transmission of pitch information is the proximity of the electrode array to the spiral ganglion. The CI electrode array is placed within the cochlea, usually along the medial wall of the scala tympani (Grayden & Clark, 2006). Closer placement of the array to the ganglion cells can improve spatial selectivity, reduce thresholds, and increase the dynamic range of stimulation (Wilson, 2004). However, placement of the array is not always close to the spiral ganglion (Clark, 2003), and it may not be beneficial beyond the basal turn of the cochlea due to the differing paths of the basilar membrane and the spiral ganglion (Wilson, 2004).

Another factor which can influence how well CI users perceive pitch is the length of auditory deprivation they experienced prior to implantation. Research shows that prelingually/congenitally deafened adults have more difficulty with speech and pitch perception through their CIs than those who have experienced shorter periods of deafness (Clark, 2003; Blamey et al, 1996a), although it is unknown whether the timing of the auditory deprivation also plays a role. Busby and Clark (2000b) found that electrode DLs were positively correlated with length of auditory deprivation in prelingually deafened CI users. In another study with the same subjects (Busby and Clark, 2000a), it was shown that only half of participants had a tonotopic order of pitch based on electrode stimulation. One quarter of participants exhibited a "consistent but deviant tonotopic order of pitch" (p.341), and the remaining quarter of participants had no tonotopic organization of pitch. In animal studies, tonotopic organization of pitch in the auditory cortex was mostly absent in animals with long-term deafness (Clark, 2003). Auditory maturation and plasticity in the brain will be discussed in more detail below.

## 1.5. PITCH DISCRIMINATION OF ADULT CI USERS AND NORMAL-HEARING ADULTS

### *1.5.1. Rate-Pitch and Pure-Tone Studies*

Several studies have looked at CI users' ability to perceive differences in rate-pitch over a range of frequencies. Townshend et al. (1987) observed rate pitch DLs in three postlingually deafened CI users. DLs of 10-30% were observed at 150 Hz, 10-20% at 250 Hz, and approximately 25-100% at 400 Hz (DLs are shown as a percentage of the referent frequency; for instance, at 150 Hz DLs were 15 to 45 Hz or 10 to 30% of 150 Hz). Only two of the three subjects could discriminate changes above 200 Hz.

McKay et al. (1994) used a pitch matching task to observe rate-pitch DLs in five CI users. DLs were determined by the 75% correct response ratio during a two-alternative forced choice (2AFC) pitch matching task using amplitude modulated stimuli. Not all subjects could discriminate changes at all test frequencies. DLs were 2-15% at 100 Hz (3 subjects) and 150 Hz (all 5 subjects), 3-30% at 200 Hz (5 subjects), and 7-36% at 400 Hz (3 subjects). Only 3 subjects were able to discriminate changes above 300 Hz. Other studies of rate-pitch show that CI users' perception of rate-pitch deteriorates above 300 Hz (Pfingst, 1994; Tong & Clark, 1985).

Rate-pitch has also been shown to vary substantially between subjects. Moore & Carlyon (2005) reviewed the findings from 5 studies of CI users incorporating 19 subjects (Pfingst et al, 1994; van Hoesel and Clark, 1997; McKay et al, 1999, 2000; Zeng, 2002). They found that the average DL at 100 Hz across all studies was 7.3%, but that DLs ranged from less than 2% to approximately 18%. Moore and Carlyon suggested that although some of the difference could be attributed to different procedures (e.g., roving level vs. not roving level) large differences still existed within single studies.

For normal-hearing adults, pure tone DLs are generally around 0.2% below 1000 Hz (Moore, 1997). Wier et al. (1977) reviewed several studies that looked at frequency DLs of normal-hearing listeners. They found DLs of approximately 0.5% at 125 Hz and 0.2% at 500 Hz. However, acoustic pitch discrimination in normal-hearing individuals allows place-coding cues in addition to temporal cues, whereas rate-pitch studies have CI users distinguish differences based on rate (i.e., temporal cues) alone. Townshend et al. (1987) suggested that a more comparable measure for rate-pitch through CIs might include studies of acoustic nonspectral pitch, where only temporal cues are provided to normal-hearing individuals. With no place cues, normal-hearing listeners generally have DLs of 2-5% at 1000 Hz (Townshend et al, 1987), similar to those found in some CI users.

### 1.5.2. *Complex Pitch Studies*

Studies of complex pitch perception in CI users have found responses as variable as those found in rate-pitch studies. Geurts and Wouters (2001) conducted a study of four, postlingually deafened CI users who used the continuous interleaved sampling (CIS) processing strategy. Stimuli used were synthetic vowels (/a/ and /i/) with $f_0$ of 150 Hz and 250 Hz. They found that DLs ranged from 4% to 13% at 150 Hz for all four participants. At 250 Hz responses were more variable; two participants had DLs of 5-8%, whereas the other two participants were found to be "not sensitive" to frequency changes near 250 Hz from a previous experiment and were not tested at this frequency (Geurts & Wouters, 2001).

Laneau et al. (2004) found an even wider range of DLs in four adult CI users. Their study used vowel-like single-formant stimuli ranging in $f_0$ from 133 to 558 Hz, with referent $f_0$ of either 133 and 165 Hz. Subjects were found to have DLs ranging from 6-60%.

In another study by Geurts and Wouters (2004) with four adult CI users, DLs were found using synthetic vowels with $f_0$ from 110 to 189 Hz. DLs ranged from approximately 2% to nearly 100%, although the authors note that "since there was a limit on the largest $f_0$ difference presented, the obtained value is an underestimate of the real noticeable $f_0$ difference" (p.849). Furthermore, it was noted that one subject was asked to indicate the lower, rather than the higher, sound, when it became apparent that a pitch reversal was taking place between two adjacent electrodes (the more deeply inserted electrode produced a higher-pitched sound), suggesting that although he was able to detect stimulus differences, the tonotopic ordering was deviant.

Rogers et al. (2006) looked at pitch-discrimination of vowels within words for adult CI users and normal-hearing listeners. Three, trisyllabic words with middle-stressed vowels ("potato", "sufficient", and "allowance") were read by a male speaker. Fundamental frequency for the middle vowels were measured to be 132, 125 and 91 Hz for each word respectively. The $f_0$ of the middle vowel was increased by 1 Hz increments (up to an increase of 40 Hz) and DLs were measured using a 3-interval, 2AFC procedure. CI users were found to have an average DL (averaged across subjects and words) of 25 Hz, whereas normal-hearing listeners had an average DL of 3.2 Hz. Some CI users were noted to have DLs approaching 40 Hz, suggesting their actual DLs may have been higher due to ceiling effects of the stimulus set.

Other studies of normal-hearing adults have shown that DLs for complex pitch are generally in the same range as for pure tones. Houtsma and Smurzynski (1990) showed that DLs are 1 Hz or less (0.5%) for complex tones with an $f_0$ of 200 Hz with a full harmonic spectrum. Moore and Glasberg (1990) showed that normal-hearing adults have complex pitch DLs of around 0.5% at 100 Hz, improving to around 0.2% at 400 Hz. These are equivalent to pure tone DLs of normal-hearing adults in the same frequency range (Wier et al, 1977).

However, a more recent study conducted with normal-hearing individuals found wider variability in responses. Moore et al. (2006b) used referent tones with fundamental frequencies of 110, 131, 156, 186 and 220 Hz and comparison tones that were either a) the same, b) 75 cents higher, and c) 75 cents lower (75 cents corresponds to a difference of approximately 4.4%). They found considerable variability in the percentage correct scores: normal hearing listeners were correct between 37.7% and 100% of the time.

### *1.5.3. Electric to Acoustic Pitch Studies*

There have been a handful of studies conducted with CI users who have residual hearing in their non-implanted ear. Subjects receive electric sound stimuli through their CI, and acoustic sound stimuli through a hearing aid. In one study, 13 CI users with relatively poor residual hearing (group averages were greater than 85 dB HL at all frequencies tested) were asked to compare the pitch of pure tones through their non-implanted ear to electric sound stimuli through their CIs

(Blamey et al, 1996b). For most subjects it was found that pitch percepts through the CI were lower than expected based on the electrode position within the cochlea. That is, the acoustic pure tones that were matched to electric stimuli stimulated a more basal location on the basilar membrane in the non-implanted ear, than was stimulated by electrodes in the implanted ear. In some cases, the mismatch between location of maximal displacement in the non-implanted ear and location of electrode stimulation in the implanted ear for stimuli with the same perceived pitch corresponded to a difference of 3 octaves.

Boex et al. (2006) had similar findings in a study of six CI users with substantial residual hearing in their non-implanted ear. They too found that the location of stimulation within the cochlea differed greatly between the implanted and non-implanted ear when using Greenwood's (1990) frequency-position function as a basis of comparison. Data from one subject closely followed Greenwood's position function shifted down by one octave, data from three subjects followed Greenwood's position function shifted down by two octaves, and data from two subjects fell even lower. Dorman et al. (2007) also found a downward pitch shift of half an octave to an octave below the Greenwood function in one adult CI user. What these studies show is that pitch percepts generated from electrical stimulation correspond to very different place-to-characteristic-frequency mappings along the basilar membrane than for acoustic hearing. For postlingually deafened CI users, the mismatch may pose a problem since their auditory systems were previously mapped to receive frequency stimulations at different locations on the basilar membrane than are being stimulated following implantation. For prelingually deafened CI users who have little or no experience with acoustic stimulation of the basilar membrane, the mismatch may not be as important. Conversely, Blamey et al. (1996b) suggest that the pitch shift to more basal locations might better allow CI users to perceive low frequency differences:

> "The perceptual effect is fortuitous for speech coding because it allows a more natural coding of low-frequency speech components without the need to insert electrodes into the most apical parts of the cochlea." (p.149)

Pitch shifts over a period of time were revealed in a recent study of hybrid (short-electrode) CI users. Reiss et al. (2007) assessed electric-acoustic pitch comparisons in 18 subjects with hybrid implants. These CIs have shorter electrode arrays that are only implanted in the basal area of the cochlea in an attempt to preserve low-frequency, acoustic hearing. Reiss et al. found that pitch matches changed by as much as two octaves in the five years following implantation, with three of five subjects experiencing a downward pitch shift, and one experiencing an upward pitch shift. Differences of one-half to one-octave were seen in both intra-session and inter-session testing, suggesting substantial individual variation, but not enough to account for pitch shifts of up to two octaves over time. Reiss et al. present a number of reasons why the pitch shift may occur, but suggest central auditory processing may play a larger role than previously thought.

### *1.5.4. Melody Recognition and Other Music Studies*

Although CI users are able to discriminate changes in musical tempo and rhythm quite well, identifying musical melodies with rhythmic cues removed is very difficult (Kong et al, 2004). Likewise, CI users perform better on music listening tasks when lyrics are present as opposed to when songs are purely instrumental. In a study with conventional CI users, hybrid CI users and normal-hearing adults, Gfeller et al. (2006) found that conventional CI users were significantly poorer at identifying melodies without lyrics as well as at identifying musical instruments than either of the other groups. Leal et al. (2003) and Fujita and Ito (1999) also found that CI users rely on verbal cues to recognize familiar melodies.

Pressnitzer et al. (2005) had CI users and NH individuals listen to a four-note melody, then listen to the same melody repeated with one note altered.

Subjects were asked to determine which note had been altered. Normal-hearing subjects had no problems identifying the altered tone, but the task "proved impossible for most implant recipients" (p. 344), even though the altered tone was always larger than each individual's pitch difference limen (i.e., from 2 to 7 semitones).

Gfeller et al. (2002) also assessed pitch discrimination abilities of CI users before asking them to complete a melody recognition task. They found CI users could discriminate an average difference of 7.56 semitones (approximately 55%) using synthesized grand piano notes ranging from 73 to 553 Hz. Normal-hearing listeners had an average detection threshold of 1.13 semitones (approximately 6.7%), however, one semitone was the lowest interval provided. Normal-hearing individuals would typically be able to hear much smaller differences in musical pitch. In the melody recognition task, Gfeller et al. found that CI users performed significantly worse than normal-hearing individuals.

Clearly, CI users are adept at using verbal and rhythmic cues to aid in music recognition. When relying on pitch cues alone, music recognition is very challenging. Musical tone discrimination (e.g., Gfeller et al, 2002; Pressnitzer et al, 2005) appears to be comparable to findings from other studies of complex pitch discrimination in CI users, as discussed above. From the point of view of speech perception, however, these results have profound implications for speakers of tone languages as discussed further below.

### 1.6. AUDITORY MATURATION AND PLASTICITY

For children who are born deaf, the issue of how well they will be able to perceive pitch through a CI depends on several factors including age of implantation and length of auditory deprivation. Closely tied to these are questions of auditory maturation and plasticity, namely, is there a sensitive period of development during which auditory stimulation must occur, and can electric stimuli provide this stimulation?

Animal studies give us some indication of how well neural pathways are preserved and whether or not there is a critical period for development of auditory perception. Clark (2003) reviewed a number of animal studies and found that place coding and temporal coding mechanisms are likely in place by birth, but that early auditory stimulation is necessary to refine neural connections. Studies with cats that have been auditorily deprived show that they have reduced synaptic activity and minimal cochleotopic organization in the primary auditory cortex (Kral et al, 2001). Other studies have shown that there does appear to be a sensitive period of development for animals. Kral et al. (2006) note that:

> "Plasticity of the auditory cortex decreases with increasing age, so that a sensitive period for plastic adaptation can be demonstrated within the second to sixth months of life in the deaf cat." (p.283)

In humans, the period of sensitivity or maximal plasticity in the auditory system is more protracted than in most animals. For typically developing humans, the formation of neuronal synapses occurs during the last trimester of pregnancy and the first two years after birth (Huttenlocher & Dabholkar, 1997), and is followed by a period of synaptic pruning in which neural processes that have not been used are eliminated. In the auditory cortex, synaptic density reaches its peak at just 3 months of age, and synaptic pruning is complete by 12 years of age (Huttenlocher & Dabholkar, 1997). Electrophysiological data (cortical evoked potentials) show that it may take as long as 15 years for latencies to reach adult levels (Eggermont et al, 1997).

Numerous studies have used cortical auditory evoked potentials (CAEPs) as a measure of auditory maturation in children and CI users. Ponton et al. (1996) assessed P1 latency times in young CI users, normal-hearing children, adult CI users and normal-hearing adults. They found that 1) maturation of the P1 latency responses is delayed by roughly the length of deafness in young CI users, 2) stimulation is required for P1 responses to mature, 3) young CI user responses were similar to young NH responses, when hearing history was taken into consideration, and 4) the maturation process continues even after long periods (e.g., up to 9 years) of auditory deprivation (although it is not known if there is a limit, or how auditory deprivation affects other aspects of auditory perception beyond P1 latencies).

A more recent study (Sharma & Dorman, 2006) showed that if children are implanted prior to 3.5 years, the P1 peak of their CAEPs will reach normal levels within 3 to 6 months. If children are implanted after 7 years, their P1 peak is likely to be delayed or abnormal, even after several years of CI experience. For children implanted between these ages, half are likely to reach normal limits and half are likely to have delayed latencies. The authors concluded that central auditory pathways are at their greatest plasticity for only 3.5 years, and that auditory deprivation lasting beyond the first 7 years greatly limits improvement in CI users. This approximate age cut-off is supported by behavioural studies which have found that children implanted prior to 4 years have better speech perception than those implanted at later ages (Lee et al, 2005; Oh et al, 2003; Kirk et al, 2002). Harrison et al. (2005) found that children implanted at 5 years or younger outperformed children implanted at later ages on all tests of speech perception by five years post-implantation. However, the authors note that there is no clearly defined period of time beyond which cochlear implantation is not valuable.

Animal studies and evoked potential studies on children and adults give an idea of the maturation of auditory development in children. Another way of gauging development is through behavioural testing. It is important to note that behavioural measures cannot precisely show where the maturation is occurring; attention, memory, and other cognitive processes are developing along with central and peripheral auditory mechanisms. Results from behavioural studies on normal-hearing and cochlear implanted children follow.

## 1.7. PITCH DISCRIMINATION OF NORMAL-HEARING CHILDREN

### *1.7.1. Pure-Tone Studies*

Numerous studies over the past century have explored pitch discrimination abilities in children using behavioural testing. Kidd and Rivoire (1966) reviewed studies of the development of pitch discrimination in children from the previous 75 years. Their review found that 1) pitch sensitivity improves with age up to approximately 10 years (although no studies looked at children older than 10 years), and 2) training improves performance.

In a study with deaf, hard-of-hearing, and normal-hearing children, Gengel (1969) observed DLs for pure tones of 3 Hz (1.2%) at 250 Hz, and 4 Hz (0.8%) at 500 Hz in normal-hearing children aged 10 to 12 years.

In a study of pure-tone discrimination for children aged 4, 6, 8, 10 and 12 years old, only the 12 year olds had DLs similar to those of adults (Maxon & Hochberg, 1982). At all four frequencies tested (500 Hz, 1000 Hz, 2000 Hz and 4000 Hz), mean DLs decreased with age. At 500 Hz, DLs ranged from 15.86 Hz (3.2%) for 4 year olds to 4.70 Hz (0.9%) for 12 year olds.

Jensen and Neff (1993) conducted a study of 41 children aged 4 to 6 years and 9 adult controls. DLs were gathered using a 440 Hz referent tone. Average DLs by age group were as follows: 65 Hz (14.5%) for 4 year olds, 55 Hz (12.2%) for 5 year olds, 6 Hz (1.3%) for 6 year olds, and 2 Hz (0.45%) for adult controls. Age was found to be negatively correlated with frequency DLs, so younger children tended to have larger DLs than older children.

Thompson et al. (1999) observed DLs of children aged 5, 7, 9, and 11 at 1000 Hz. Tones had a duration of 20, 50 and 200 ms (only 200 ms data will be discussed). Eleven of the 16 participants in the 5 year old group were unable to complete the task. Of the 5 that did, DLs were approximately 25 Hz (2.5%). For 7 year olds DLs improved to approximately 10 Hz (1%), and for children aged 9 and 11, DLs were comparable to the adult control group (5 Hz or less).

Looking at these studies together, pitch discrimination ability for children appears to improve up until around nine to twelve years of age. This is consistent with findings from other studies of psychoacoustic behaviour in children; pure tone thresholds in children are shown to improve with age until approximately 10-13 years (Fior, 1972; Eagles et al, 1967). Of the pitch discrimination studies mentioned above, most used frequencies above the range of voice pitch, so obtaining DLs at lower frequencies (e.g., 200 Hz and below) would be useful. However, given our knowledge of adult pitch discrimination (DLs are generally smallest at, and quite similar between, 500-1000 Hz, and may be slightly higher at lower frequencies; Moore, 1997), we can extrapolate that the above-mentioned scores would likely be similar or slightly larger at lower frequencies (e.g., 100 to 200 Hz).

### 1.7.2. *Complex Pitch Studies*

Fewer studies have explored complex pitch perception in children. Although not directly related to pitch perception, Eguchi (1976) observed DLs for formant frequencies in 10 adults and 90 children aged 7 to 15 years using synthetic vowels. Referent $f_0$ was fixed at 130 Hz, and DLs were obtained for $F_1$ at 300, 500 and 700 Hz ($F_2$, $F_3$, and $F_4$ were fixed for this condition), and for $F_2$ at 1000, 1500 and 2000 Hz ($F_1$, $F_3$ and $F_4$ were fixed for this condition). For adults, mean DLs were 6.0% at 500 Hz and 4.9% at 1500 Hz. For children, mean DLs ranged from 5.0 to 25.7% at 500 Hz, and 5.2 to 24.2% at 1500 Hz. Mean DLs were largest for 7 year olds, and decreased with each year until 12 years old, where they reached adult levels. The frequency DLs in this study are larger than those from other studies of pitch discrimination because they address formant rather than pitch (fundamental frequency) perception. However, the study is useful in that it incorporates a large number of children and clearly shows an improvement in formant frequency discrimination until twelve years old, as was found in pure tone perception studies mentioned above.

Andrews and Madeira (1977) examined how well children aged 6-8 are able to understand pitch discrimination tasks that use relational language (higher, lower, etc.). They presented musical tones one octave apart (262 and 523 Hz) using a pitch pipe, and had the children determine whether the second sound presented was higher or lower than the first. They found that the 6 and 7 year olds were correct only 60% of the time over 5 presentations, and that the 8 year olds were correct approximately 80% of the time. The authors suggested these scores related to a difficulty understanding or completing the task, rather than an inability to discriminate the difference between the two sounds.

Allen and Nelles (1996) played tonal sequences differing in mean $f_0$ to children aged 4 to 7 and adult controls. Participants were asked to identify which sequence was higher in pitch. It was observed that task performance improved with age until age 7, when it approached adult levels.

As with pure tones, discrimination of complex tones appears to improve with age, and may not reach adult levels until approximately twelve years of age. More studies need to be conducted with a wider range of children to gain a better understanding of the development of complex pitch perception.

## 1.8. PITCH DISCRIMINATION ABILITIES OF YOUNG COCHLEAR IMPLANT USERS

Most of the information available on the pitch perception abilities of prelingually deafened CI users comes from studies of children who speak tonal languages (e.g., Cantonese, Mandarin, Vietnamese...). In tonal languages, pitch contours and intonation changes are contrastive and can reflect lexical differences. Individuals who speak these languages must be able to extract pitch information from the incoming signal to determine the appropriate meaning of the word. Most studies show that young CI users have difficulties discriminating between phonemically contrastive tones. Ciocca et al. (2002) conducted a study of 17 CI users aged 4;6 to 8;11. The study employed a 2AFC picture identification task and required children to identify which of the six contrastive Cantonese tones they heard. The tones were produced by a male Cantonese speaker and were presented in pairs to participants, who in turn pointed to a picture corresponding to the word they heard. The fundamental frequency ranged from approximately 80 Hz to 160 Hz across all tones. Only 2 of the 17 children performed above chance levels overall, and on 5 of the 8 paired contrasts, none of the children performed above chance levels. Of the 3 pairs of tones for which children did perform above chance level, $f_0$ differences were quite large (approximately 35-45 Hz difference).

In a different study, Wong (2000) tested the same children as Ciocca et al. (2002). A 2AFC task was also used in this study, but children were asked to choose whether the two sounds were the same or different. The overall group average was 59% correct, with only 4 participants performing significantly above chance level. Wong and Wong (2004) and Lee et al. (2002) have found similar results for young CI users who speak Cantonese.

Other studies have found that young CI users are able to perform significantly above chance levels on a wider range of tonal contrasts. Barry et al. (2002) showed that Cantonese-speaking CI users (aged 3 to 6) performed above chance level on 10 to 12 of 16 tonal contrasts. Children with SPEAK processors were found to perform slightly better than those with ACE processors, although no CI users performed at the overall level of age-matched peers.

Peng et al. (2004) examined Mandarin tone perception in 30 children between 6;0 and 12;6. The overall percent correct was 72.9% (significantly above chance), and six children received scores of 89% or better. However, the authors note that differences in syllable duration which may also cue phonemic tones may aid tone identification in Mandarin, in contrast to Cantonese, where tone discrimination is primarily based on changes of $f_0$. In the Mandarin study, pairs of tones which had the highest correct rate were also the pairs containing Tone 4, which had the shortest duration.

Overall, studies of tonal pitch perception in young CI users demonstrate that although some children are able to discriminate changes in tones with larger contrasts, most young CI users only perform at or slightly above chance levels.The benefit of tonal pitch studies is that they assess how well young CI users can perceive meaningful pitch differences they encounter in everyday life. The drawback of such studies is that they do not give a good indication of how large pitch differences need to be before CI users can perceive them.

## 1.9. DIFFICULTIES ASSESSING PITCH DISCRIMINATION IN CHILDREN

One reason for the limited information available concerning the pitch discrimination abilities of children is that it is difficult to obtain pitch DLs for children. Traditional psychoacoustic testing procedures pose a number of challenges for researchers working with children. To begin with, children are less likely to sit quietly and listen to stimuli for the long periods of time required to obtain all of the necessary data. Tasks therefore must be able to be completed within a reasonably short time period and be sufficiently interesting to keep the young participant engaged and focused. Even with suitable reinforcements and rewards, researchers are more likely to have numerous, shorter data-gathering sessions rather than fewer, longer sessions as can be done with adults.

Another difficulty in assessing children is that they tend to exhibit strong practice or training effects. In a study of pitch discrimination with hearing impaired and deaf children 10 to 17 years old, Gengel (1969) found a significant training effect across three test sessions. For deaf participants, median DL was half as large on the third day of testing as it was on the first day for all four conditions tested (two different referent frequencies with fixed and variable intensity). For hard-of-hearing children, the training effect was significant for three of four conditions. Soderquist and Moore (1970) assessed training effects in normal-hearing children aged 5 to 9 using a pitch discrimination task. They too found significant decreases in average DLs for all three age groups tested.

Task complexity poses another challenge to effective testing of children. Thompson et al. (1999) tested pitch perception in children using a 2-interval, 2AFC procedure. They found that this format was too difficult for 5 year olds to complete, possibly because the memory demands were too great (children had to listen to 4 tones and make a judgement on them). In addition to demands on memory or attention, the level of language used to describe the task may also impact a child's performance. Andrews and Madeira (1977) suggested that relational language (e.g., high-low, higher-lower) could hinder a child's performance on pitch discrimination tasks. They found that six- to eight-year-olds exhibited better pitch discrimination on a task involving no relational language than tasks requiring a high-low or higher-lower distinction to be made. However, the task not involving relational language did require training to get children to associate different pitches with different animals, therefore, the better performance on this task may have been training-related as opposed to language-related. Soderquist and Moore (1970) also suggested that language could play a role in children's performance. They reported that 5-year-olds found it easier to make absolute judgements (e.g., high vs low) as opposed to relative judgements (e.g., higher/lower), and that children must be able to make relative judgements in order to complete any tasks measuring DLs (i.e., a child must be able to determine which is the higher tone).

Lastly, children have been shown to have a shallower psychometric function than adults (Allen & Wightman, 1994; Nozza et al, 1991) and they tend to "asymptote at levels considerably less than 100% correct performance in a variety of different psychophysical tasks" (p.1065, Thompson et al, 1999). In other words, children are less likely to have a steeply defined difference limen, above which they are very accurate in differentiating stimuli and below which they are incapable of telling stimuli apart.

All of these factors complicate psychoacoustic testing with children, but they do not render it impossible. Indeed, many studies have explored pitch perception in children, some as young as a month or two old. Nevertheless, care must be taken when interpreting behavioural data obtained from psychoacoustic testing, particularly when younger children are concerned.

### 1.10. JUSTIFICATION FOR PRESENT STUDY

While many studies have examined the pitch perception abilities of adult CI users who lost their hearing later in life, very little research is currently available on the pitch perception abilities of cochlear implanted children with prelingual hearing loss. There are several reasons why it might be important to explore pitch perception in young CI users. First, unlike postlingually deafened adults who have previous experience with acoustic pitch perception, individuals with prelinguistic hearing loss are likely to have experienced pitch only through their implants or other electric hearing devices (e.g., hearing aids). These individuals may have little or no pre-existing concept of relative pitch prior to receiving their implants. Postlingually deafened individuals, on the other hand, generally have a "relatively normal tonotopic order of pitch percepts" (Busby & Clark, 2000a, p.548) because of their earlier acoustic experience. This previous acoustic experience may allow them to perform better on pitch perception tasks than prelingually deafened children who have no, or minimal, acoustic knowledge.

Another reason to assess pitch perception in young CI users is that the auditory systems of children continue to mature after birth for up to twelve years (Huttenlocher & Dabholkar, 1997; Fior, 1972), with the first four years being the most crucial to development (Sharma & Dorman, 2006). The auditory system is at its most plastic during this time; therefore input through CIs at this time may actually influence how the auditory system develops. If the electrical stimulation from a CI provides the only incoming auditory signals, the organization and sensitivity of the auditory system may be somewhat different than for individuals with normal hearing. Research has shown that auditory stimulation may be important in maintaining auditory neural pathways and allowing maturation to proceed (Busby & Clark, 2000a). In addition, auditory deprivation is known to prevent maturation and potentially cause degeneration to the auditory system (Clark, 2003). That the period of maximum auditory sensory plasticity also within a critical period of language development for children is further cause for the separate study of pitch perception in children.

Pitch plays a noteworthy role in early language learning. The primary characteristics of child-directed speech (CDS) are the exaggerated pitch contours and higher overall pitch. The use of CDS is thought to be important to language learning in infants and young children (Cooper & Aslin, 1994; Trainor & Desjardins, 2002); therefore, the ability of infants and young children to perceive pitch is also important. Since many CIs are being implanted in children at very young ages, some in children younger than one year old, the quality of pitch information these children receive through their implants is of interest.

Other studies have explored the relationship between early implantation and overall language acquisition and development (e.g., Anderson, 2004; Colletti et al, 2005; Hassanzadeh et al, 2002). They have found that the earlier children are implanted, the earlier they reach developmental milestones in speech and language and the better they can perform in auditory and verbal tasks. Other benefits of early implantation include better literacy development, academic achievement, and social development (Boothroyd & Boothroyd-Turner, 2002). However, one area that has not been fully explored in these or other studies is how early implantation affects pitch perception abilities.

The present study attempts to address this lack of information by addressing three questions: 1) What are the pitch perception abilities of cochlear-implanted children? 2) How are the pitch perception abilities of implanted children different than those of normal-hearing children and adult CI users? and 3) Does age of implantation affect how well CI users can perceive pitch? Testing the pitch perception abilities of implanted children and normal-hearing peers will provide a clearer understanding of how well children of different ages perceive pitch, and may provide evidence of the benefits of early implantation to pitch perception in CI users. In addition, it will provide a quantitative measure of CI users' ability to use extract complex pitch information.

# Chapter 2

## *Methods and Procedures*

### 2.1. PARTICIPANTS

Thirty-five participants took part in this study. Of these, 28 participants were children between the ages of 8 and 15 years old, and 7 participants were adults. The children were divided into two groups: those with cochlear implants (young CI, n=14) and those with normal hearing (young NH, n=14). Young CI participants ranged in age from 8;3 to 15;5 (M=12;3), and young NH participants ranged in age from 8;9 to 15;4 (M=12;1). The 7 adult participants (adult CI) were 29;5 to 71;0 (M=49;10). All participants met the following criteria: (a) spoke English at home; (b) had no known cognitive deficits; and (c) were familiar with personal computers. In addition to these selection criteria, young NH participants were required to have hearing thresholds of 20 dB HL or lower at 1000, 2000 and 4000 Hz, and 25 dB HL or lower at 500 Hz. All CI users were also required to have a minimum of one year of experience using their implant.

CI users were recruited through the Cochlear Implant Program at the Nova Scotia Hearing and Speech Centres. Due to the small population of CI users in Nova Scotia, it was not possible to limit participation to those with the same type of implant, or, for the young CI users, to those who were early implanted (e.g., less than two years old). However, every attempt was made to recruit children who had received their implants at a very young age. Age of implantation for young CI users ranged from 1;10 to 12;4 (M=5;8, median=3;6). Two children were implanted at younger than two years old, and another six were implanted between two and four years old.

Young NH participants were recruited from the Halifax region to match the ages of young CI users. The difference in age between pairs ranged from 1 to

10 months, with a mean difference of 4 months. Ages of young CI users and their normal-hearing matched peers can be seen in Table 2.1.

Adult CI users were all postlingually deafened and had a profound hearing loss prior to implantation. Onset of profound hearing loss for adult CI users ranged from 24 to 44 years, with an average age of 34. All of the young CI users were prelingually deafened (i.e., prior to 18 months) with the exception of three participants, each of whom had a progressive hearing loss leading to profound deafness by age 3 (for C10), age 5 (for C11), and age 7 (for C14). All young CI users had a severe to profound hearing loss prior to implantation, and all adult CI users had a profound hearing loss prior to implantation. More information concerning CI users' age, implant and hearing history can be found in Tables 2.2 and 2.3. Stimulation rates shown in Tables 2.2 and 2.3 were determined by taking the total stimulation rate and dividing it by the number of active channels.

**Table 2.1. Ages of young CI users and normal-hearing age-matched peers.**

| CI users (years) | | NH peers (years) | | Difference in age (months) |
|---|---|---|---|---|
| C1 | 8;3 | N1 | 8;9 | 6 |
| C2 | 9;1 | N2 | 9;1 | 0 |
| C3 | 9;1 | N3 | 9;2 | 1 |
| C4 | 10;9 | N4 | 9;11 | -10 |
| C5 | 11;5 | N5 | 10;9 | -8 |
| C6 | 11;7 | N6 | 10;10 | -9 |
| C7 | 12;5 | N7 | 12;9 | 4 |
| C8 | 12;5 | N8 | 12;10 | 5 |
| C9 | 13;2 | N9 | 13;0 | -2 |
| C10 | 14;1 | N10 | 13;8 | -5 |
| C11 | 14;1 | N11 | 13;8 | -5 |
| C12 | 14;7 | N12 | 14;6 | -1 |
| C13 | 14;9 | N13 | 14;6 | -3 |
| C14 | 15;5 | N14 | 15;4 | -1 |

Table 2.2. Background information for young CI users.

| Subject | Age (years) | Age of implantation (years) | Implant experience (years) | Type of implant | Processor | Stimulation Rate (pps/channel) | Diagnosis of severe-profound hearing loss | Etiology |
|---|---|---|---|---|---|---|---|---|
| C1 | 8;3 | 1;11 | 6;4 | Clarion | PSP | 1444 | Congenital | Unknown |
| C2 | 9;1 | 1;10 | 7;3 | Nucleus 24 | Sprint | 1200 | Congenital | Unknown |
| C3 | 9;1 | 3;11 | 5;2 | Nucleus 24 | Sprint | 1200 | Age 1 | Unknown |
| C4 | 10;9 | 2;7 | 8;2 | Nucleus 24 | 3G | 1200 | Age 18 months | Meningitis |
| C5 | 11;5 | 2;1 | 9;4 | Nucleus 22 | Spectra | 250 | Congenital | Familial |
| C6 | 11;7 | 2;10 | 8;9 | Nucleus 22 | Spectra | 250 | Congenital | Unknown |
| C7 | 12;5 | 5;6 | 6;11 | Clarion | S-series | 11375 | Congenital | Unknown (adopted) |
| C8 | 12;5 | 7;11 | 4;6 | Nucleus 24 | Sprint | 900 | Age 1 | Unknown |
| C9 | 13;2 | 3;2 | 10;0 | Nucleus 22 | 3G | 250 | Congenital | Ushers |
| C10 | 14;1 | 12;4 | 1;9 | Nucleus 24 | 3G | 1200 | Age 3 | EVAS, progressive |
| C11 | 14;1 | 10;5 | 3;8 | Nucleus 24 | 3G | 900 | Age 5 | Familial progressive |
| C12 | 14;7 | 10;10 | 3;9 | Nucleus 24 | 3G | 900 | Congenital | Unknown |
| C13 | 14;9 | 2;11 | 11;10 | Nucleus 22 | Spectra | 250 | Congenital | Familial |
| C14 | 15;5 | 11;11 | 3;6 | 90K Helix | Auria | 5156 | Age 7 | Familial, progressive |

Table 2.3. Background information for adult CI users.

| Subject | Age (years) | Age of implantation (years) | Implant experience (years) | Type of implant | Processor | Stimulation Rate (pps/channel) | Diagnosis of profound hearing loss | Etiology |
|---|---|---|---|---|---|---|---|---|
| A1 | 29;5 | 28;2 | 1;3 | 90K Helix | Auria | 5156 | Age 24 | Familial progressive |
| A2 | 35;6 | 32;11 | 2;7 | Nucleus 24 | 3G | 900 | Age 30 | Autoimmune disease, progressive |
| A3 | 42;4 | 36;0 | 6;4 | Clarion | PSP | 11375 | Age 35 | Skull fracture, progressive |
| A4 | 48;4 | 47;1 | 1;3 | Nucleus | Freedom | 900 | Age 44 | Autoimmune disease, progressive |
| A5 | 53;9 | 46;6 | 7;3 | Clarion | PSP | 813 | Age 30 | Familial progressive |
| A6 | 68;10 | 65;5 | 3;5 | 90K | Auria | 5156 | Age 42 | Familial progressive |
| A7 | 71;0 | 68;3 | 2;9 | Nucleus 24 | Sprint | 900 | Age 30 | Familial progressive |

## 2.2. LISTENING TASKS

The study consisted of two listening tasks: the *pitch discrimination* task, in which participants determined whether two stimuli were the same or different, and the *pitch ranking* task, in which participants determined which of the two stimuli was higher in pitch. Tasks were counterbalanced, with approximately half of participants from each group (young CI, young NH and adult CI) completing the ranking task first, and half completing the discrimination task first. Because the pairing of young CI and young NH participants did not take place until after most data were collected, it was not possible to have both members of the pair complete the tasks in the same order to allow for analysis of order effects. The discrimination and ranking tasks were both employed to discover if participants found it easier to identify two stimuli as being different (i.e., pitch discrimination task), than correctly identifying which one had the higher pitch (i.e., pitch ranking task). With normal-hearing participants, it was expected that DLs from the discrimination and ranking tasks would be nearly the same. Other studies of normal-hearing individuals show that discrimination and ranking tasks produce similar responses. Sek and Moore (1995) found that below 1000 Hz, responses were roughly the same on the two tasks, although they were significantly different at frequencies higher than 4000 Hz. Tramo, Shah and Braida (2002) also found that pitch direction discrimination (equivalent to a ranking task) and pitch change discrimination (equivalent to a discrimination task) were similar when assessing pure tone DLs from normal-hearing listeners between 250 and 1000 Hz. Assigning a relative pitch is therefore not any more difficult than detecting a change in pitch between two stimuli for normal-hearing individuals.

CI users, on the other hand, might not have the same ability to label the relative pitch of the stimuli, even if they are able to detect that two stimuli are not the same. Moore (1973) reported that normal-hearing individuals listening to short-duration tone pulses can often detect a change but not be able to determine which one is higher in pitch. CI users may very well experience a similar difficulty since their implants may provide only weak pitch information. In addition, the stimulation they receive may not be tonotopically consistent with normal-hearing individuals, so they may be able to hear a difference but be unable to correctly identify the sound with the higher pitch. For example, evidence of pitch reversals and poor place-pitch sensitivity in the apical and/or basal ends of the cochlea has been found for some CI users (Nelson et al, 1995). Because of these issues, CI users may be expected to be able to perform better on the discrimination task than on the ranking task.

### 2.3. PSYCHOPHYSICAL PROCEDURE

A two-alternative forced choice (2AFC) paradigm was used within an adaptive staircase procedure to determine pitch difference limens (DLs) for each participant. A 1-up, 2-down framework was used to find the 70.7% point along the psychometric function (Levitt, 1971). Every time a participant made an incorrect response, the next interval was wider, and every time a participant made *two* correct responses on the same interval, the next interval was smaller.

Prior to the initiation of the 1-up, 2-down procedure, step sizes decreased by 4 steps until the participant made his/her first incorrect choice. Step sizes then decreased by 2 steps until the participant made his/her second incorrect choice. This modification was employed to allow participants with better pitch perception abilities to more quickly reach their threshold, while still allowing those participants with weaker pitch perception abilities to start at the same point and progress through the same intervals. Other studies assessing pitch discrimination of adult CI users and NH children have shown that both groups can have quite variable difference limens (e.g., Laneau et al, 2004; Maxon & Hochberg, 1982; Thompson et al, 1999). In the present study, the initial interval needed to be large enough to allow for correct responses for all participants, yet the final interval needed to be small enough to surpass the DL of a normal-hearing listener.

Another reason for the modification was that preliminary testing showed several participants accidentally made one or two incorrect choices early in the task, perhaps due to unfamiliarity with the procedure. It was therefore decided that the first incorrect choice would be considered a "free" error, and that the 1-up 2-down procedure would not be initiated until after the second incorrect decision. Step sizes decreased by 2 steps (rather than 4) following the free error, to allow participants to progress more slowly through the intervals until their second incorrect choice was made. Figures 2.1 and 2.2 show examples of the modified 1-up 2-down procedure for two participants.

Within the adaptive procedure, intervals for each of the three referent stimuli (100, 200 and 400 Hz) were interleaved to provide more variation for subjects. As participants completed the requisite number of reversals for any of the referent stimuli, the trial ended for that referent and the participant continued with the remaining one or two referent stimuli. A different number of reversals were gathered for participants of different ages: adult CI users completed 11 reversals, participants aged 12 to 16 years completed 9 reversals, and participants younger than 12 years completed 7 reversals. As mentioned previously, the first incorrect response during each task did not constitute a reversal. The second incorrect response (the first true reversal) was discarded, leaving the last 10 reversals for adults, 8 reversals for 12 to 16 year olds, and 6 reversals for participants younger than 12 years old to be used in DL calculations. The mean of these reversals was calculated to determine the DL for that referent $f_0$.

The different number of reversals were chosen to accommodate the length of time participants were expected to attend to the task. Adult participants completed the most reversals because they could be expected to attend to the task for a longer period of time than the younger participants. Participants younger than twelve years old only completed 7 reversals since any more reversals would have taken more time and likely resulted in more participants stopping early.

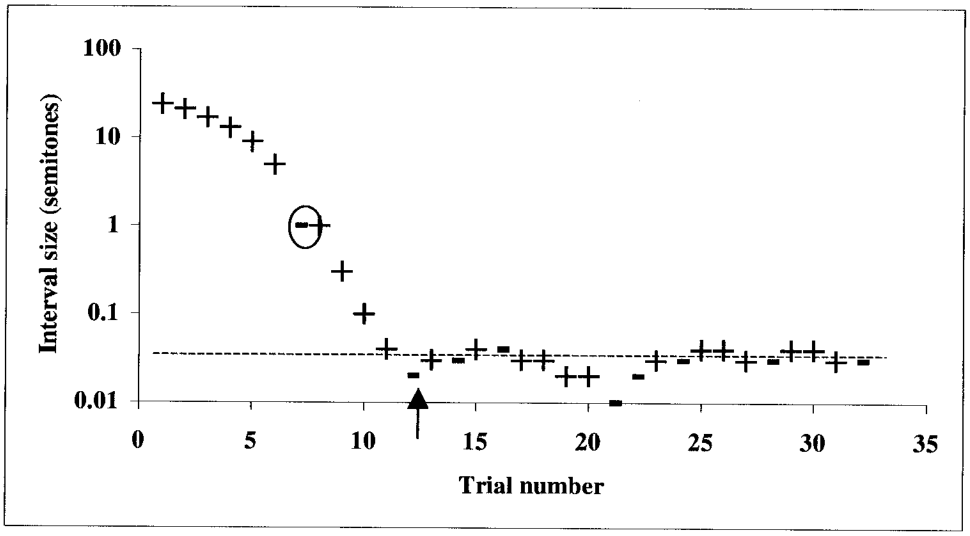

**Figure 2.1. Data from the pitch ranking task (100 Hz) for N6, plotted logarithmically.** The circle shows the "free error", which is notably higher than threshold. This is an example of an accidental response. Prior to the free error, intervals decreased by four steps. Following the free error, intervals decreased by two steps until the second incorrect choice was made (shown by the arrow), at which point the one-up two-down procedure commenced. The dashed line shows the average between reversals (the difference limen).

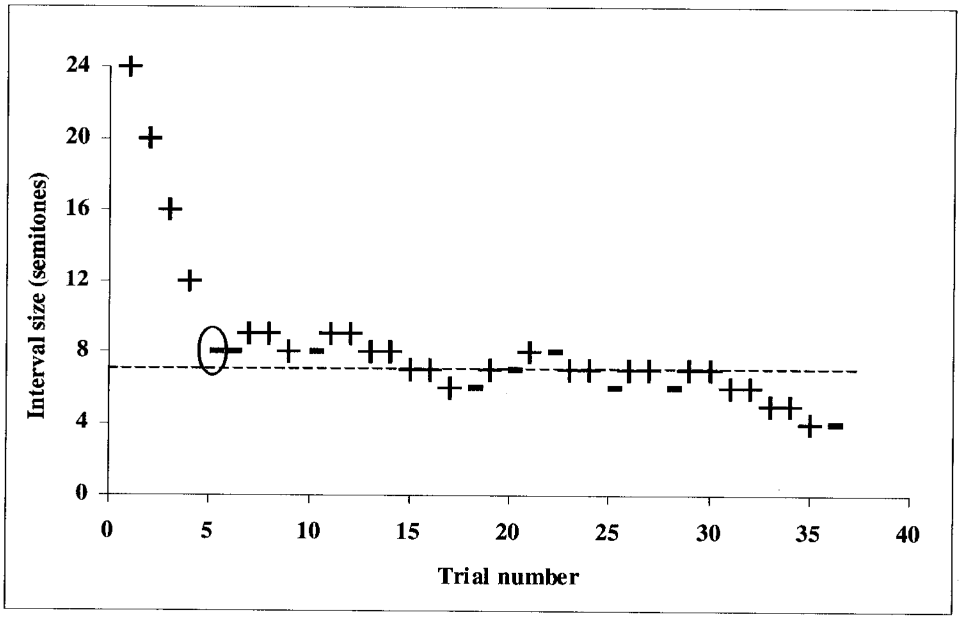

**Figure 2.2. Data from the pitch ranking task (400 Hz) for C12.** The circle marks the free error. In this case, the free error was in fact at threshold for the participant. The incorrect choice immediately following is the first reversal. The dashed line shows the difference limen.

Training was provided for all participants prior to testing. For adult participants and children 12 and older, training took approximately 5 minutes to complete. For participants younger than 12, training took slightly longer (e.g., 7-8 minutes) as it included examples of high- and low-pitched sounds and more practice intervals than for the older participants. Many participants, including most normal-hearing participants, completed the training with 100% accuracy. Some participants made incorrect decisions and had to repeat sections of the training until they were at least 80% successful on the tasks. One young CI user (C2) and two adult participants (A6 and A7) were unable to pass the training portion for the pitch ranking task. These participants will be discussed further in Chapter 3. No feedback was given to participants during the testing, although some participants did request to see their responses after the end of testing.

### 2.4. COMPUTER GAME

For the younger participants (i.e., children between 8 to 12 years old), both listening tasks were incorporated into a computer game to maintain participant attention and keep participants motivated to continue until all reversals were completed. The computer game was developed using Gamemaker 6 software (www.gamemaker.nl) and digitized, hand-drawn animations. Because we wanted to ensure all children, regardless of computer gaming experience, could complete the listening trials, the game was designed so that even those with limited computer experience could play it. Participants used the arrow keys to move a character across the screen in search of his lost spaceship (see Fig. 3.3). Every few seconds the character would have to "send a signal" to locate his ship by listening to pairs of sounds and choosing which sound was higher (for the pitch ranking task, see Fig. 3.4) or whether two sounds were the same or not (for the pitch discrimination task, see Fig. 3.5). The primary motivation for participants to keep playing the game was to find the character's spaceship. Children were also reinforced by the background animation which changed every time the character got to the right edge of the screen. Once participants had finished all of the trials, the character would find his spaceship and fly away. Participants were told they could stop if they did not want to participate any longer, and only one participant (C9) chose to quit the game before completing the minimum number of reversals. Another participant (C4) was unable to complete the second task due to a software failure.

As with the older children and the adult participants, a training session was completed before testing began. An additional training component was built into the beginning of the computer game so participants could become familiar with the game layout and how the sounds would be presented within the game. Any level of the training could be repeated for children who were having difficulties understanding the tasks, but this was rarely required. For C2, his inability to complete the training for the pitch ranking task did not appear to be because of difficulties understanding the task. When he was questioned about understanding what it meant to select the "higher sound", he mentioned the piano as an analogy and said the keys "up here" are higher and the keys "down here" are lower. Even though he did not pass the training portion for this task, he was allowed to attempt the task. This participant will be discussed further in Chapter 3.

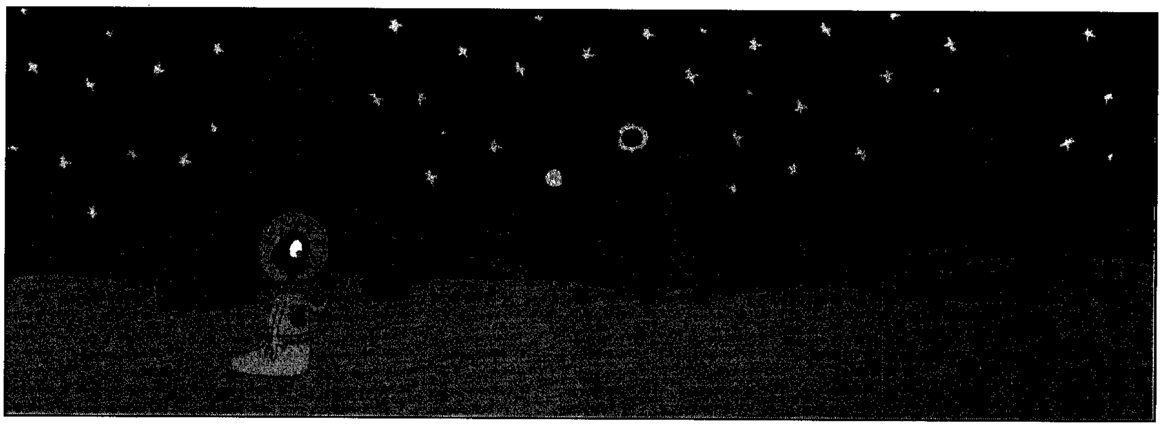

**Figure 2.3. Screen shot from the computer game used to obtain DLs for younger participants.** Participants moved the character across the screen in search of his lost ship, stopping to do listening tasks along the way. When the character reached the right side of the screen, he would enter a new landscape or building with a different background.

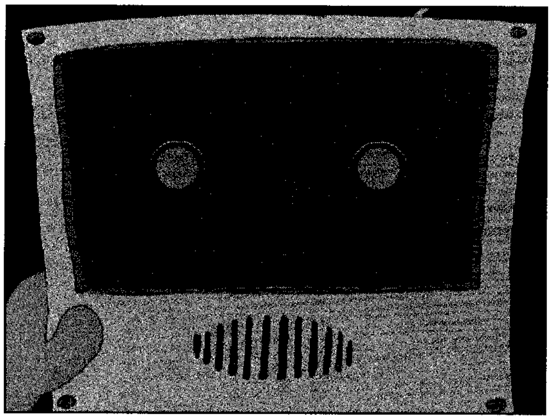

**Figure 2.4. Screen shot from the pitch ranking listening task.** Participants used the computer mouse to click on the button associated with the higher tone. To alert participants when the interval was about to be played, the phrase "Listen for the two sounds" appeared at the top of the screen.

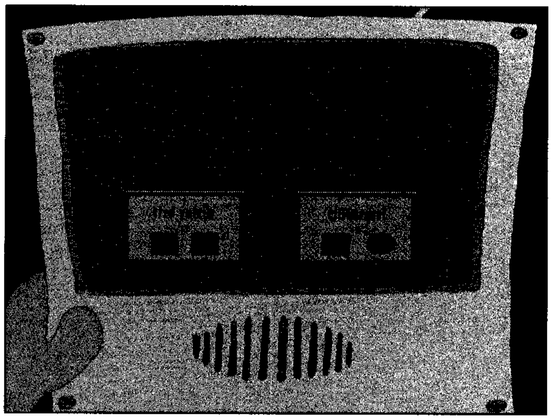

**Figure 2.5. Screen shot from the pitch discrimination listening task.** Participants clicked on either the "same" or "different" rectangle after hearing the interval.

## 2.5. STIMULI

Complex sound stimuli were chosen for two reasons. First, at lower frequencies (e.g, 100-200 Hz) CI users are unable to rely on place-cues because several harmonics will fall within the bandwidth of a single electrode. Since place-coding is not available, it is worth exploring how well temporal coding is able convey the harmonics of complex stimuli in this frequency region. Second, we wanted to explore how well CI users were able to perceive differences in vocal pitch. Sound stimuli were therefore synthetic vowels which were presented to listeners at a sampling rate of 11025 Hz. Vowels were 500 ms long and were synthesized in a manner that mimicked the cascade branch of the Klatt80 speech synthesizer (Klatt, 1980). Three fundamental frequencies ($f_0$) were chosen for referent stimuli: 100, 200 and 400 Hz. These frequencies were selected to represent the normal range of vocal pitch for adults (i.e., 100-200 Hz), and to provide an opportunity to explore complex pitch perception at much higher frequencies (i.e., 400 Hz) where temporal coding becomes more difficult for many CI models (Moore, 1997; Zeng, 2002). Loudness was randomly varied between adjacent stimuli on the $f_0$ continuum so that it was not correlated with frequency.

Formant frequencies were chosen to approximate those for the vowel /ɑ/. For the 100 Hz referent stimuli, formant frequencies for $F_1$ through $F_5$ were 700, 1220, 2600, 3300, 3750 Hz respectively. Formant bandwidths were set to be as wide as possible to avoid large fluctuations in overall amplitude of harmonics in the spectral region of $F_1$ and $F_2$ with changes in fundamental frequency, and yet preserve the quality of the perceived vowel. For 100 Hz referent stimuli, bandwidths for F1 through F5 were 390, 220, 480, 750, 600 Hz respectively. For 200 and 400 Hz reference stimuli, the frequency response spectra resulting from these synthesis parameters were scaled by either a factor of 2 or 4 respectively. This resulted in three sets of stimuli, one for each referent frequency, that differed in spectral envelope. The glottal source was synthesized via sinewave summation up to 5 kHz rather than a simple pulse train because of the numerical problems associated with producing fundamental frequencies that did not correspond to whole-sample periods. See Appendix A for spectra of the three referent stimuli and sample comparison stimuli.

Fundamental frequency of comparison (target) stimuli started at two octaves above the referent and, with correct discrimination or identification, decreased by one semitone (or four or two semitones at the beginning of the 2AFC procedure) until the comparison stimulus had $f_0$ one semitone above that of the referent. At this point the step size halved to 50 cents (one-half semitone) before decreasing by 10 cents (0.1 semitones), then 5 cents (0.05 semitones), and ultimately 1 cent steps (0.01 semitones). The complete list of comparison stimuli used for all three referent frequencies can be seen in Appendix B.

Stimuli were presented on a laptop computer with a Realtek AC97 sound card. The same program used to make the computer game for the younger participants, Gamemaker 6, was used to present the sound stimuli to older children and adult CI participants but without the animation or storyline. For all

CI users, sound stimuli were presented directly from the laptop to the CI processor via a 1/8″ patch cable. For normal-hearing participants, stimuli were presented via supra-aural headphones. All participants were instructed to adjust the volume until it was at a comfortable loudness. Every implant user had different threshold and comfort levels, therefore there was no objective measure of subjective loudness. Because fixing the perceived stimulus level for CI participants was impossible, it was deemed unnecessary to fix the level for normal-hearing participants. Testing took place in a quiet room, either at the participant's house, at the Nova Scotia Hearing and Speech Centres, or at the Dalhousie School of Human Communication Disorders.

# Chapter 3

## *Results*

### 3.1. PITCH RANKING TASK

Complete results for the pitch ranking and pitch discrimination tasks can be found in Appendix C. DLs of greater than 300% mean that the individual was unable to correctly identify the higher sound at two octaves apart (the widest interval presented in this experiment). DLs of less than 0.06% mean that the individual successfully identified the higher sound three successive times when the stimuli were 1 cent apart (the narrowest interval presented). There was wide variability within all three groups, in particular among young CI and adult CI users. Individual results by group as well as pooled data for the pitch ranking task follow.

#### *3.1.1. Young Cochlear Implant Users*

For young CI users, DLs spanned the full range of possible values in the experimental design (i.e., from less than .06% to over 300% of the referent frequency—see Figure 3.1). At the lowest referent frequency (100 Hz), eleven participants had DLs at or below 50%. At the highest referent frequency (400 Hz), only seven participants had DLs at or below 50%. Three participants (C3, C8, C14) showed a sharp increase in DLs between 100 and 400 Hz, and three participants (C7, C10, C13) showed a relatively large decrease in DL size between these referent frequencies. One participant (C2) was unable to correctly identify the higher sound at the initial interval size of two octaves for all three referent frequencies. This was the same participant who was unable to successfully pass the training components for this task.

### *3.1.2. Young Normal-hearing Participants*

Young NH participants had DLs ranging from less than .06% to 15% (see Figure 3.2). Six participants had DLs less than 1% at all three referent frequencies. Across all frequencies, DLs could be evenly divided into three groups: one third of DLs were below 0.5%, one third were between 0.5 and 1%, and the remaining third were greater than 1%.

### *3.1.3. Adult Cochlear Implant Users*

Adult CI users, like young CI users, showed great variability in responses, with DLs ranging from less than 0.6% to greater than 300% (see Figure 3.3). At 100 Hz, 5 of 7 participants had DLs below 50%, whereas only one participant (A1) had a DL below 50% at 400 Hz. Three participants (A3, A4, A5) showed a sharp increase in DLs from 200 to 400 Hz. The two participants who were unable to pass training for this task (A6, A7) were also unable to progress beyond the initial two-octave interval, as with C2.

### *3.1.4. Pooled Data*

Because a number of DLs were >300%, the median was chosen as a measure of central tendency rather than the mean. Median DLs for young CI, young NH and adult CI in the pitch ranking task are shown in Figure 3.4. Median DLs for young NH participants were 0.62%, 0.74% and 0.81% at 100, 200 and 400 Hz respectively. Median DLs for young CI were 30.9%, 71.8% and 71.2% respectively. Adult CI median scores were 13.1%, 50.9% and greater than 300%, showing that at the highest frequency there was, in effect, no measurable median DL. Both young CI and adult CI median DLs were lowest at 100 Hz and showed a modest increase at 200 Hz. However, the median DLs for young CI were roughly equal between 200 and 400 Hz whereas the median DL for adult CI jumped to greater than 300% at the highest frequency.

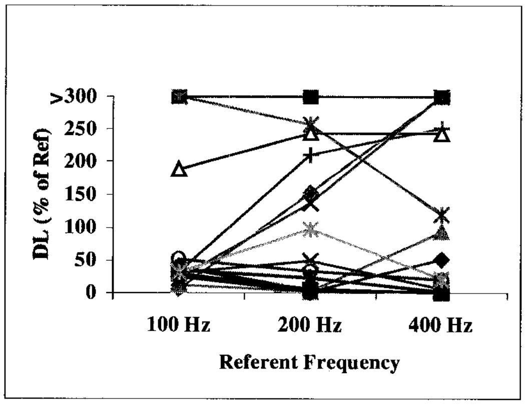

**Figure 3.1.** Results from pitch ranking task for Young CI (n=14). Results shown as a percentage of the referent frequency.

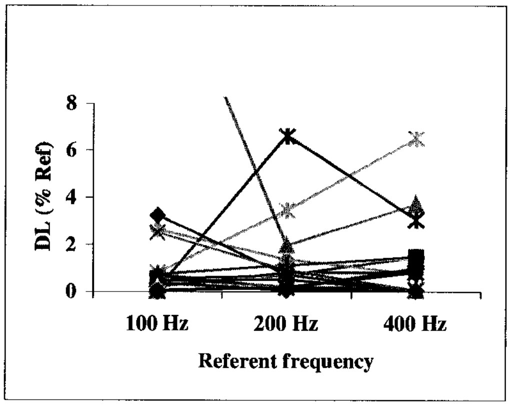

**Figure 3.2.** Results from pitch ranking task for Young NH (n=14).

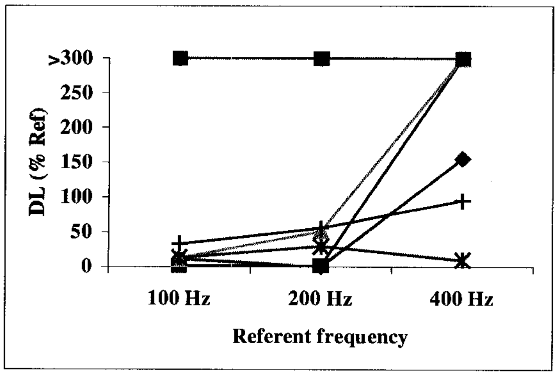

**Figure 3.3.** Results from pitch ranking task for Adult CI (n=7).

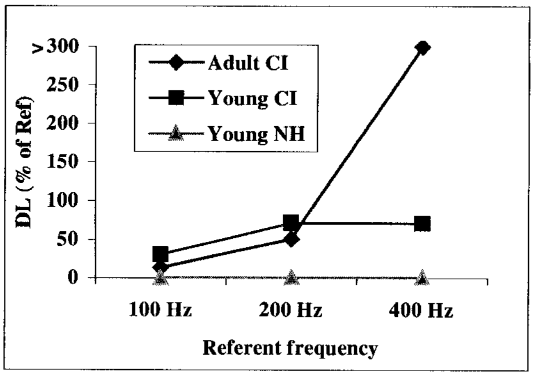

**Figure 3.4.** Group median DLs from the pitch ranking task.

## 3.2. PITCH DISCRIMINATION TASK

### 3.2.1. *Young Cochlear Implant Users*

Twelve young CI users who completed the ranking task also completed the discrimination task. DLs for young CI users ranged from 10.8% to greater than 300% (see Figure 3.5). There were no DLs smaller than 10% in this task, although in the ranking task, there were 9 DLs in this range. At the lowest frequency (100 Hz), only 6 participants had DLs of 50% or less, compared to 11 of 14 participants whose DLs were below 50% in the ranking task. At the highest frequency, nearly half of participants had DLs greater than 300%, compared to 3 of 14 participants in the ranking task. Two participants (C1 and C10) had much higher DLs at 400 Hz in the discrimination task compared to the ranking task. However, the participant who had >300% DLs at all three referent frequencies in the ranking task (C2) showed markedly smaller DLs in the discrimination task: 43.2%, 54.9%, and 72% at 100, 200 and 400 Hz respectively. This participant was therefore able to discriminate changes in pitch at all three frequencies, but was unable to determine which stimulus was higher in pitch. It is possible that this participant was exhibiting a pitch reversal at these frequencies and would have been able to consistently label the stimulus with the lower pitch as having the higher pitch. Unfortunately, this was not assessed in the present study.

### 3.2.2. *Young Normal-hearing Participants*

For young NH participants, DLs ranged from less than 0.6% to 41.2% (see Figure 3.6). DLs were more consistent between referent frequencies than for young CI; 10 participants had DLs that ranged by less than 1% between all three frequencies. Compared to the ranking task, DLs in the discrimination task were slightly larger, with only three DLs less than 0.5% (compared to fourteen in the ranking task) and twelve DLs from 0.5- 1% (compared to fourteen in the ranking task). Only 3 participants had DLs less than 1% at all 3 frequencies (compared to 6 participants in the ranking task). One participant obtained DLs greater than 30% in the discrimination task. This participant also had relatively large DLs in the ranking task (2-15%) compared to other young NH participants.

### 3.2.3. *Adult Cochlear Implant Users*

DLs for adult CI users ranged from 1.4% to greater than 300% (see Figure 3.7). Participants had noticeably smaller DLs at 400 Hz in the discrimination task compared to the ranking task. Only one participant (A5) had a DL greater than 300% at the highest frequency in the discrimination task, compared to four participants who had DLs greater than 300% in the ranking task. Although A5 also had a DL of >300% in the ranking task, he showed a significant increase in DLs in the discrimination task at the lower two frequencies. DLs for A5 were below 2% at 100 and 200 Hz in the ranking task, yet in the discrimination task his DLs at these frequencies were 203% and >300%.

As was seen with C2, the two participants who had >300% DLs in the ranking task (A6 and A7) showed smaller DLs in the discrimination task. For A7, the biggest difference was seen at 100 Hz where her DL in the discrimination task was 15%. For A6, DLs were much smaller across all three frequencies and actually smallest at the two higher frequencies: 46.2%, 5.1%, 7.7% at 100, 200 and 400 Hz respectively. The ability of these two participants to perform much better in the discrimination task than in the ranking task suggests that they too may be experiencing pitch reversals at the frequencies tested.

### *3.2.4. **Pooled Data***

Median DLs for young NH, young CI and adult CI in the pitch discrimination task are shown in Figure 3.8. Median scores for young NH were roughly equal across frequencies: 1.4%, 1.4% and 1.2%. These scores are slightly higher than median scores from the ranking task (0.6-0.8%). Young CI median scores for the discrimination task were 51.7%, 81.7% and 158%, also higher than for the ranking task (30.9-71.8%). For adult CI users, median scores were 20.6%, 36.7% and 78.4% which reflected lower scores at the higher two frequencies than in the ranking task (50.9% and >300%). Median DLs on both the pitch ranking and pitch discrimination tasks therefore showed differences between young CI, young NH and adult CI. Young NH had the lowest median DLs and young CI had the highest. The exception to this distribution was at 400 Hz on the ranking task, where adult CI had the highest median DL.

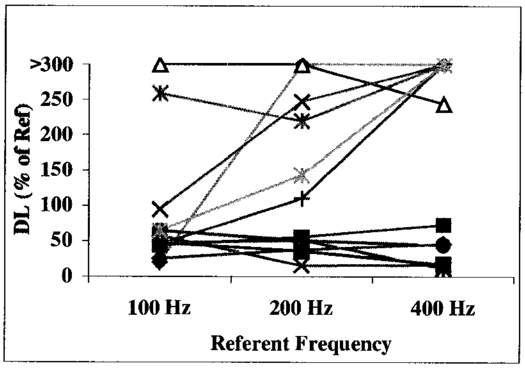

**Figure 3.5.** **Results from pitch discrimination task for Young CI (n=12).** Two participants that completed the ranking task did not complete the discrimination task.

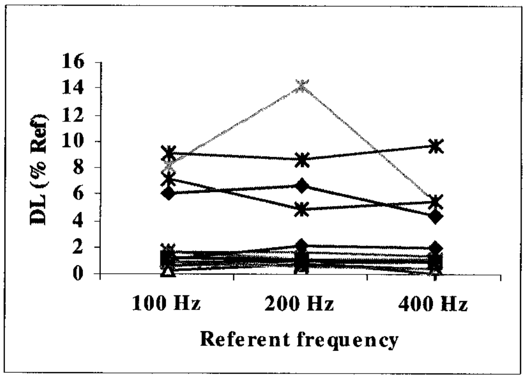

**Figure 3.6.** **Results from pitch discrimination task for Young NH (n=14).** One participant had DLs above 30% for all three frequencies and is not

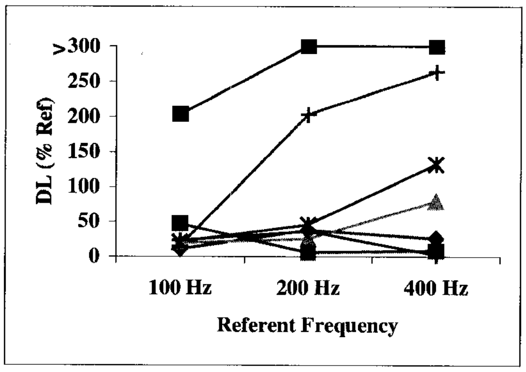

**Figure 3.7.** **Results from pitch discrimination task for Adult CI (n=7).**

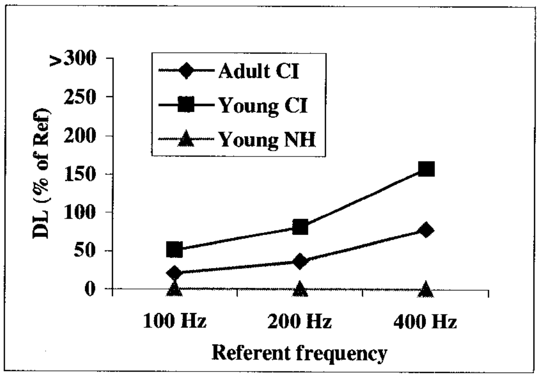

**Figure 3.8. Group median DLs from the pitch discrimination task.**

## 3.3. COMPARISON BETWEEN PAIRS: YOUNG CI AND YOUNG NH

A repeated measures analysis of variance (ANOVA) was conducted with task, hearing and frequency as within-subjects (or matched-subjects) factors. Order of task administration was not included in the analysis because the way in which subjects were recruited and the experimental design made it impossible. The ANOVA revealed no significant effect for task or frequency, but, not surprisingly, a significant effect for hearing ($p$=.001), confirming that young CI users had significantly higher DLs than young NH participants. DLs greater than 300% were entered as 300 in the analysis, even though actual DLs may in fact be larger than 300%. To ensure findings were still significant at higher values for these data points, the ANOVA was repeated with >300% scores entered as 400. The second ANOVA also revealed a significant difference between young NH and young CI (*p*=.001).

### 3.4. COMPARISON BETWEEN GROUPS: YOUNG CI AND ADULT CI

An ANOVA with frequency and task as within-subjects factors, and group and order of task administration as between-subjects factors was conducted with young CI and adult CI groups. There was no significant effect for task, group or order. The ANOVA was repeated with >300% scores entered as 400 to ensure findings were valid; there remained no significance for these three factors. The ANOVA did reveal that there was an effect for frequency (*p*=.01). This effect was still significant when >300% scores were entered as 400 (*p*=.02). Post-hoc analysis using a Bonferroni adjustment for multiple comparisons showed that DLs at 400 Hz were significantly larger than those at 100 and 200 Hz, but that there was no significant difference between DLs at the two lower frequencies.

### 3.5. COMPARISONS WITH OTHER STUDIES

#### 3.5.1. *Young Cochlear Implant Users*

The lack of previous pitch discrimination data for CI users in this age range makes it impossible to compare present findings with other studies of CI users. DLs for young CI users in the present study show large inter-subject variability, something which has also been seen in many studies with postlingually deafened adult CI users. Previous research has shown that DLs for adult CI users can range from 2 to 100% across similar frequencies (Moore & Glasberg, 1990; Geurts & Wouters, 2001, 2004; Laneau & Wouters, 2004). DLs for young CI users in the present study, however, covered a much wider range (<0.6% to >300%). For the ranking task, DLs were both smaller and larger than for adult CI users, whereas for the discrimination task, DLs were larger in general, with most DLs being higher than 20% and the lowest being 10.8%. Compared to normal-hearing children, DLs were much higher and much more variable. The following section discusses DLs for normal-hearing children.

### 3.5.2. *Young Normal-hearing Participants*

Studies have shown that children's auditory discrimination may not reach adult levels until approximately 12 years of age (Maxon & Hochberg, 1982). Results from young NH were therefore divided into two groups for comparison with other studies: participants under 12 years of age (n=6) and participants 12 years and older (n=8). The mean DL for the under 12 group, across both tasks, was 6.7%. With the one outlier removed from the group, the mean DL became 3.6%. This mean DL is still higher than what has been observed in studies assessing pure tone perception in young listeners. Because there are not previously reported DLs for complex pitch with NH children, pure tone DLs were used as a basis of comparison. Thompson et al. (1999) obtained pure tone DLs at 1000 Hz for 5, 7, 9, and 11 year olds. The mean DL averaged across data from the 7, 9, and 11 year olds was 6 Hz or .6%. Maxon and Hochberg (1982) examined pure tone DLs in children aged 4 to 12. The mean DL from the 8 and 10 year olds was 6.2 Hz (1.2%) at 500 Hz, and 5.7 Hz (0.57%) at 1000 Hz. However, both of these studies used higher frequencies than the present study and used pure tones instead of complex stimuli. Pure tone DLs at 1000 Hz are generally slightly lower than DLs at lower frequencies (Moore, 1997), as was seen in the Maxon & Hochberg findings above. Gengel (1969) observed pure tone DLs for children aged 10 to 12 at slightly lower frequencies. He found average DLs of 1.2% at 250 Hz and 0.8% at 500 Hz. These studies of pure tone DLs can give an indication of what we might expect complex tone DLs to be for children between 8 and 12 (i.e., around 1%), but make direct comparisons with the present study difficult.

The mean DL for NH children 12 years and older across both tasks was 1.1% (n=8). This is somewhat larger than DLs found in normal-hearing adults, who generally have DLs of .5% or less for complex tones in this frequency region (Houtsma & Smurzynski, 1990; Moore & Glasberg, 1990).

Looking at DLs across all young NH participants, there appears to be more variability in responses than has been observed in other studies. Standard deviations ranged from 1.8% to 10.7% across frequencies for young NH. In the Thompson et al. (1999) study, standard deviations for DLs from 7 to 11 year olds were all less than 0.5%. In the Maxon and Hochberg (1982) study, standard deviations of DLs for 8 to 10 year olds were even smaller (less than 0.3%).

### 3.5.3. *Adult Cochlear Implant Users*

As with previous studies, adult CI users in the present study showed large variability in complex waveform DLs. However, like for young CI users, the range of DLs for adult CI users in the present study is much greater than previously recorded. Geurts and Wouters (2004) found DLs of 2 to 100%, whereas Laneau et al. (2004) observed a smaller range of DLs (6 to 60%) and Geurts and Wouters (2001) observed an even smaller range (4 to 13%). The range of DLs in the present study was <0.06 to >300%. Reasons for the wider range of scores in the present study will be discussed in Chapter 4.

## 3.6. CORRELATIONS

Bivariate correlation analyses (Spearman, two-tailed) were conducted for young CI, young NH and adult CI. For all groups, factors tested included:

- age
- average of pitch ranking DLs (Task 1)
- average of pitch discrimination DLs (Task 2)
- average of DLs in both tasks

For young CI and adult CI, other factors tested were:

- age of implantation
- years CI experience
- length of auditory deprivation
- rate of stimulation

Length of auditory deprivation was determined using the diagnosis date of the profound hearing loss (or severe loss for some young CI users), and the date of implantation.

### 3.6.1. *Young Cochlear Implant Users*

For young CI users, there was a moderately strong negative correlation between years CI experience and Task 1 ($r$=–.62, $p$=.019), and a strong negative correlation between years CI experience and both Task 2 ($r$=–.825, $p$=.001) and the average of both tasks ($r$=–.818, $p$=.001). These findings suggest that the longer young CI users have their implants, the lower their DLs are on both tasks. Therefore, early (e.g., congenital) deafness may prolong the period over which CI experience can have an effect. However, there was no correlation between age of implantation and task performance, so young CI users who received their implants at an early age did not have lower DLs than those who were later-implanted. There was also no correlation between task performance and age, length of auditory deprivation or stimulation rate. A moderately strong correlation was found between Task 1 and Task 2 ($r$=.72, $p$=.008), something which was not seen in young NH or adult CI.

### 3.6.2. *Young Normal-hearing Participants*

For young NH participants, there was a moderate negative correlation between age and the average of both tasks ($r$=–.559, $p$=.038), signifying that younger NH children had higher DLs than older NH children. This was not seen in young CI users. Surprisingly, there was no correlation between Task 1 and Task 2.

Participants' performance on the discrimination task was therefore not predictive of their performance on the ranking task, or vice versa.

### *3.6.3. **Adult CI***

As with young NH, there was no correlation between Task 1 and Task 2 for adult CI users. There was a strong correlation between age and Task 1 (*r*=.919, *p*=.003), and age and the average of both tasks (*r*=.821, *p*=.023), suggesting that the older adult CI users found it more difficult to make pitch ranking decisions than younger CI users. There was also a strong correlation between length of auditory deprivation and the average of both tasks (*r*=.929, *p*=.003), signifying that the longer participants were deprived of auditory input, the higher their average DLs were. The correlation between age and auditory deprivation just missed significance (*r*=.75, *p*=.052).

Another strong correlation was found between age of implantation and Task 1 (*r*=.955, *p*=.001) but not Task 2 (*r*=.071, *p*=.879); a correlation between both tasks and age of implantation just missed significance (*r*=.75, *p*=.052). Although a later age of implantation resulted in higher DLs in the pitch ranking task, years of CI experience had no effect on task performance. This is opposite to findings from young CI users, where more years of CI experience resulted in lower DLs, and age of implantation had no effect. Rate of stimulation was not found to influence performance.

## 3.7. SUMMARY OF FINDINGS

To sum up, the major findings of the study are as follows:

- Young CI users performed significantly worse on both tasks than young NH
- Young CI users did not have significantly different DLs than adult CI users

- For young CI, age did not influence task performance. For young NH and for adult CI, age was correlated with task performance although in different ways. Young NH showed a moderate negative correlation between age and DLs, whereas adult CI showed a strong positive correlation between age and DLs.
- No correlation was found between performance on the ranking and discrimination tasks for adult CI and young NH, although there was a moderately strong correlation between tasks for young CI.
- For young CI, increased length of CI experience improves DLs, but age of implantation does not.
- For adult CI, age of implantation improves performance on Task 1, but length of CI experience has no effect
- There was large individual variability present in all three groups tested.

# Chapter 4

## *Discussion*

### 4.1. LARGER RANGE OF DLS THAN PREVIOUSLY RECORDED

For all three groups tested (young CI, young NH, adult CI), mean DLs obtained were larger than those found in previous studies. For young NH, the difference can only partially be explained by the one outlier whose average DL between tasks was over 14%. Excluding the outlier's data lowers the mean DL from 6.7% to 3.6%, but still leaves the mean DL larger than expected; pure tone studies show average DLs are approximately 0.6-1.2% for children in this age range (Thompson et al, 1999; Maxon & Hochberg, 1982; Gengel, 1969). There is no known reason to suspect that complex waveform DLs should be any larger than those found in pure tone studies. Research with normal-hearing adults shows that DLs are roughly equivalent for pure-tone and complex tones in this frequency range (Houtsma & Smurzynski, 1990; Moore & Glasberg, 1990; Wier et al, 1977).

One explanation for the larger scores for young NH could be that the mean DL may not provide the best point of comparison with other studies. The variability between subjects and the presence of outliers suggest that a better measure of middle performance might be a non-parametric estimate of central tendency such as the median score. For young NH, the overall median score between both tasks was 0.95%. This score falls within the range of mean DLs previously recorded (0.6-1.2%). Unfortunately this still does not account for why there was so much variability within young NH and why a number of young NH participants had much larger DLs in the present study. One possibility is that musical experience may have had an influence.

Training effects may provide another explanation for the discrepancy between DLs in the present study and those previously recorded. Children's performance on pitch discrimination tasks is shown to improve significantly with practice (Soderquist & Moore, 1970; Gengel, 1969). Most studies involving pitch discrimination tasks for children employ multiple testing sessions and, in some cases, more training than in the present study. Given that children's performance on pitch discrimination tasks has been shown to improve by as much as 50% over several sessions (Soderquist & Moore, 1970; Gengel, 1969), it is reasonable to suggest that mean DLs for young NH could have improved to comparable levels with increased training and multiple testing sessions. Although training in the present study was sufficient to allow young NH and young CI participants to complete the tasks, further training and repeated testing may have produced even smaller DLs. Additional training could conceivably influence the performance of young CI users as well, but with such large between- and within-subject variability it might be harder to detect improvement between sessions.

For young CI and adult CI users, comparisons with previous research show that both groups have larger mean DLs than found in other studies of adult CI users. This holds true even if median scores are instead used as a basis of comparison. There are a number of reasons why this may be the case. First, no effort was made to limit participation in the present study to those with better pitch perception. Other studies would likely have observed a wider range of DLs if they had not chosen to work with frequencies where participants were known to have good pitch discrimination (e.g., McKay et al, 2000), used subjects who had extensive psychophysical testing experience (e.g., Zeng, 2002), or limited participation to those with good sensitivity to pitch (e.g., McKay et al, 1999; Geurts & Wouters, 2001). Although these studies used such restrictions to gain further insight into pitch perception mechanisms for CI users, they make straightforward comparisons with the present study difficult. Still, previous research has found wide variability in responses; Geurts and Wouters (2004) found DLs of approximately 2 to 100% and noted that 100% was likely an underestimate since it was the largest interval presented. In the present study, 36% of DLs for adult CI users were between 100 and 300%, so roughly one-third of the trials needed a starting interval that was larger than one octave, the largest interval presented in the Geurts and Wouters (2004) study.

Other factors that may have led to higher DLs in the present study are associated with the way in which data waere collected. Due to issues of timing and convenience, participants were not assessed in sound-attenuated rooms. Rather, participants were assessed in quiet rooms either in their own home, at the Nova Scotia Hearing and Speech Centres clinic in Halifax, or at the Dalhousie School of Human Communication Disorders. Sometimes, despite best efforts, there were occasional interruptions or background noise that could have impacted participants' performances. Research has shown that Mandarin tone recognition for CI users is poorer in the presence of background noise (Wei et al, 2007); a signal-to-noise ratio of 10 dB can result in a 20% drop in tone recognition compared to results taken in quiet conditions. Background noise in the present study (e.g., phone ringing, someone talking in the next room) may have contributed to higher DLs for participants whose listening environments were less than optimal.

In addition, lack of attention or motivation as well as fatigue effects may have influenced responses for some participants, particularly towards the end of the testing session, as some subjects became visibly restless and anxious to finish the task. This was observed in some children and, surprisingly, in some adult participants, although most participants appeared attentive through to the end of both tasks. Testing sessions for some participants were longer than expected, with some children taking over an hour to complete both tasks. In other studies with children, testing is generally broken up into multiple, shorter sessions which would conceivably have helped prevent fatigue and lack of motivation. Even with shorter sessions, children may experience fatigue or lack of interest in listening to successive intervals. In their study of pure-tone DLs in five- to eleven-year-old children, Thompson et al. (1999) found that some of the children got frustrated "when too many trials that are close to threshold occur and they are not sure of what they are hearing" (p.1063).

For young CI and adult CI users, the most likely source of such wide variation in responses is the lack of uniformity within each group. CI users had different types of implants with different processors, rates of stimulation and type of stimulation (e.g., monopolar versus bipolar). However, because there were so many variables and relatively few subjects, not all of these factors were able to be correlated with performance. CI users also had different hearing loss etiologies, lengths of auditory deprivation, ages of implantation, and onsets of hearing loss. Although not formally assessed, young CI users also appeared to have different levels of speech perception and production. Some participants required sign support to communicate well, others understood speech well only when face-to-face with the speaker, and some communicated so well (both speaking and listening) that a stranger might not even know they had a CI. Clearly, these are issues that other studies have to deal with as well. However, other studies often have larger sample sizes or are able to restrict some of the variables (e.g., only choosing subjects who were implanted earlier than 2, or only choosing subjects with the same type of implants). The limited population of young and adult CI users in Nova Scotia made both of these options impossible.

It is worth noting that even though mean DLs were larger in the present study compared to previous research, some young CI and adult CI participants had lower DLs than previously observed. Five DLs recorded from young CI and 4 DLs from adult CI were smaller than 2%. It is possible, although unlikely, that the two individuals who obtained <0.06% responses (C13 and A3) may actually have slightly larger DLs since the full number of reversals were not completed at that referent frequency (after three consecutive correct responses on the final interval, the trial ended). Because of the modified psychophysical procedure, A3 progressed through the steps four at a time right up until the final interval, which he then heard and correctly responded to three consecutive times. As a result, A3 heard only 5 intervals that were smaller than 2% of the referent. His low DL may be slightly underestimated because of the lower limit on intervals. However, the actual threshold would have to be very close to this value because of the low likelihood of getting very many correct responses by chance. For example, the likelihood of obtaining five correct answers at intervals lower than the actual threshold is approximately 3%. This suggests that there was only a 3% likelihood that this individual's thresholds were actually greater than 2%.

### 4.2. PITCH PERCEPTION OF CI USERS COMPARED TO NORMAL-HEARING CHILDREN

As was expected, young CI users had significantly poorer DLs than young NH participants. In fact, many young and adult CI users demonstrated profound deficits in ability to extract adequate pitch information, as evidenced by their large mean (and median) scores. Limitations to place-coding and temporal coding as discussed in Chapter 1 are all possible reasons for the relatively poor performance of CI users. In particular, poor place-coding at the apical (low-frequency) end of the cochlea and a limited ability to use temporal cues above 300 Hz likely played a large role. Possible physiological limitations such as poor neuronal survival may also have impacted performance.

Higher rates of stimulation have been shown to improve pitch perception for some, but not all, CI users (Fu et al, 2004). In a study of 8 Mandarin-speaking CI users aged 7 to 11, it was found that children with lower pulse rates (250 pps/channel) had significantly poorer speech recognition (i.e. tone recognition) than those with stimulation rates at or above 900 pps/channel (Hsu et al, 2003). Stimulation rates for young CI and adult CI users in the present study ranged from 250 to 11375 pps/channel. Four young CI users and 1 adult CI user had stimulation rates of less than 900 pps/channel (see participant background information in Tables 2.2 and 2.3 for stimulation rates). Despite the wide variation in stimulation rates in the present study, a higher rate of stimulation was not correlated with lower DLs for CI users. However, the three participants with the lowest stimulation rates (250 pps) also had some of the longest CI experience (8;9 to 11;10 years). It is possible that increased CI experience allowed these three participants to perform better on the tasks than they otherwise would have with such low stimulation rates. These findings suggest that lower stimulation rates may not limit pitch perception for young CI users over time.

Other studies have shown that increased length of auditory deprivation is associated with poorer performance on speech and language tasks (Clark, 2003) and abnormal cortical auditory evoked potentials (Sharma & Dorman, 2006) for CI users. In the present study, length of auditory deprivation was not correlated with task performance for young CI users, although it was for adult CI users. This may be because the mean length of auditory deprivation was longer for adult CI users (12.8 years) compared to young CI users (4.2 years). One adult participant had 23 years of auditory deprivation, and another experienced nearly 40 years of auditory deprivation, whereas the longest a young CI user went without auditory input was 10 years. Another possible explanation is that auditory plasticity could counteract the effects of auditory deprivation in young CI users, whereas for adult CI users this would not be the case.

### 4.3. YOUNG CI DID NOT PERFORM SIGNIFICANTLY BETTER THAN ADULT CI

The lack of significant difference between young CI and adult CI scores implies that being implanted as a child does not improve pitch perception compared to being implanted as a postlingually deafened adult. It was thought that plasticity in the auditory system might improve performance for those who received their implants during childhood. The auditory system does not reach maturity until approximately 12 years of age (Huttenlocher & Dabholkar, 1997), therefore children who are implanted during this time may have more success with their CIs than those who are later implanted. Early-implanted children are known to perform better on speech recognition tasks and have better overall success with their CIs than prelingually deafened individuals who were implanted as adolescents or adults (Teoh et al, 2004). However, in the present study no benefit was seen for young CI users who were early-implanted.

One possible explanation might be that any benefit prelingually deafened individuals receive by being implanted as children, is countered by early acoustic experience in postlingually deafened adults. That is, the acoustic stimulation adult CI users received during their early years of life may have laid the groundwork for better electric hearing later in life. All adult CI users in the present study received acoustic stimulation during their early years (e.g., first 12 to 15 years). This experience may have helped their auditory system mature in a presumably typical fashion (at least moreso than for prelingually deafened individuals) until they either passed the age of auditory maturation (12-15 years) or until they developed a significant hearing loss.

Young CI users, on the other hand, experienced little, if any, acoustic stimulation. Over half were born with a congenital hearing loss, and only three participants had not been diagnosed with a severe to profound loss by 18 months of age. Most of these participants have had to rely exclusively on electric stimulation to provide the sensory input needed to help their auditory system mature. Even though many of them received their implants at young ages and received electrical auditory stimulation for much of their childhood, they did not perform any better on pitch discrimination tasks than postlingually deafened adults who received their implants much later in life.

One factor that may have prevented young CI from having lower mean DLs is that some of our young CI participants received their CIs as late as ten years after the onset of severe-to-profound hearing loss; five young CI users were implanted after 7 years of age. Not only did these participants have a later age of implantation, something which has been found to produce delayed or abnormal P1 latencies (Sharma & Dorman, 2006), they also experienced longer periods of auditory deprivation and fewer years CI experience, all factors that have been associated with decreased CI performance (Clark, 2003). As such they might be expected to have larger DLs. A discussion of the role of age of implantation and length of CI experience follows.

### 4.4. EARLY IMPLANTATION AND LENGTH OF CI EXPERIENCE

Although early implantation has been shown to improve performance in measures of speech and language for CI users (e.g., Anderson et al., 2004; Colletti et al., 2005; Hassanzadeh et al, 2002; Tomblin et al, 2005), there was no evidence in the present study that pitch perception improves with early implantation. Further data are needed to support this finding, especially considering that only 2 young CI users in the present study were implanted at less than 2 years of age. Much of the available research on early implantation shows benefits for those implanted at younger than 2 years of age compared to those implanted at later ages (O'Donoghue, 1996, 1999; Connor et al, 2006). Even so, 8 participants in this study were implanted prior to 4 years of age, and there is ample evidence that children who receive their implants at 5 and younger receive substantial benefits with speech and language compared to those implanted at later ages (e.g., Lee et al, 2005; Kirk et al, 2002; Harrison et al, 2005).

Better performance of early-implanted CI users on speech and language tasks does not appear to translate into better pitch perception performance. Tonal language studies with young CI users support these findings. Wu and Yang (2003) explored the effects of early implantation on speech perception in young, Mandarin-speaking CI users. They found that spondee, vowel, phrase and sentence tests all showed a moderate negative correlation with age of implantation, but that there was no such correlation with tone tests. Peng et al. (2004) found that early implantation was not correlated with tone perception, although it did have a significant negative correlation with tone production. Early-implanted children were therefore better able to produce Mandarin tones than later-implanted children, but there was no significant difference between the two groups on tasks of tone perception. The discrepancy between tone and speech perception for young CI users suggests that either CIs are incapable of conveying adequate pitch information, or pitch perception takes longer to develop than speech perception following implantation.

Although age of implantation did not affect tone perception in the Peng et al. (2004) study, it was found that tone perception was positively correlated with length of CI experience. Children who had their CIs longer therefore did better on tone perception tasks. This observation coincides with findings from the present study, where length of CI experience was negatively correlated with both tasks. In other words, the longer children had their CIs, the better they could perceive differences of pitch. These findings are also consistent with studies of cortical auditory evoked potentials (CAEPs) that show electrical stimulation allows maturation to proceed for CI users, even after periods of auditory deprivation lasting up to nine years (Ponton et al, 1996). It is therefore likely that pitch perception can take years to develop for young CI users.

### 4.5. EVIDENCE OF AUDITORY MATURATION AND PLASTICITY

A moderate negative correlation was observed between age and DLs for young NH, proving pitch perception improved with age between 8 and 15 years. Although there were not enough participants at different ages to be able to draw conclusions (e.g., there were no 11-year-olds and most other years had only 1-3 participants), the findings show that ceiling performance may be reached around 12 years of age. This is in keeping with other behavioural (Maxon & Hochberg, 1982) and electrophysiological studies (Huttenlocher & Dabholkar, 1997).

Pitch DLs did not improve with age for young CI users, although they did improve with increased CI experience. For most young CI users in the present study, length of CI experience was roughly equivalent to hearing age. Chronological age was therefore not a determining factor in pitch perception for young CI users, but hearing age was. In other words, our findings show that electrical stimulation appears to allow auditory maturation to proceed for young CI users, just as acoustic stimulation drives auditory maturation in young NH listeners. Ponton et al. (1996) observed that electric stimulation allowed CAEPs to mature at the same rate as normal-hearing children, even after extended periods of deafness (up to 9 years). They found that when hearing age was taken into account, P1 latencies for CI users were similar to their NH peers. Although the present study shows young CI users are not on par with their normal-hearing counterparts even when hearing age is considered, the findings seem to prove that auditory maturation is at least proceeding with electrical stimulation.

There was no correlation observed between length of CI experience and DLs for adult CI users. One possible explanation is that central plasticity in young CI users might give them greater potential for improvement. Speech recognition studies have shown that young CI users have a longer period of improvement compared to adults. Oh et al. (2003) found that young prelingually deafened CI users showed continual improvements in speech recognition over a period of at least four years. Since assessments were only carried out for the four years following implantation, and since ceiling levels of performance were not reached for young CI users, it is likely that the period of improvement is even longer for young CI users. Postlingually deafened adults, on the other hand, did not show improved performance beyond two years of CI experience.

Just as adult CI users show a shorter period of improved speech perception than young CI users, they may also reach asymptotic levels of pitch perception sooner than young CI users. Electrophysiological studies have found that P1 latencies improved as late as 9 years following implantation for young CI users (Ponton et al, 1996). In the present study, over half of young CI users had at least 6 years experience with their CIs, and 3 participants had over 9 years experience. It is therefore reasonable to suggest that the period of improvement for young CI users may be quite protracted.

Another reason that adult CI users did not show an improvement with length of CI experience may be that, as a group, they did not have their CIs long enough for bigger changes in pitch discrimination to be observed. The mean length of CI experience for adult CI users was 3.5 years, compared to 6.5 years for young CI users. With further CI experience, adult CI users may have shown improvements in their DLs. Postlingually-deafened hybrid CI users have been shown to exhibit pitch shifts over a 3 to 5 year period following implantation, although it is possible that this shift is due to an acoustic-electric pitch mismatch which the brain is trying to correct (Reiss et al, 2007). Without obtaining more longitudinal information concerning pitch DLs in traditional CI users, it is difficult to know how long improvements continue for postlingually deafened adults.

## 4.6. COMPARISON OF DISCRIMINATION AND RANKING TASKS

It was hypothesized that CI users might have higher DLs on the ranking task than the discrimination task. However, median scores showed that young CI actually had lower DLs on the ranking task across all three frequencies. Adult CI users had a lower median DL only at the lowest frequency in the ranking task; median scores at 200 and 400 Hz were lowest in the discrimination task. Despite apparently better performance on the ranking task for young CI and young NH, and better overall performance on the discrimination task for adult CI, there did not turn out to be any statistically significant difference between the two tasks for any group. The lack of difference between tasks suggests that assigning a relative pitch (e.g., choosing the higher tone) is no more difficult for CI users or young NH listeners than detecting a difference between two stimuli. It was previously noted that normal-hearing adults have similar scores between ranking and discrimination tasks for lower frequency sounds (Sek & Moore, 1995; Tramo, Shah & Braid, 2002), so the findings for young NH are perhaps not surprising. What is surprising is that DLs from the ranking task were not significantly higher for young CI or adult CI users, especially considering three CI users in the present study were unable to rank pitch at all, and other studies have shown wide variation in pitch ranking abilities of adult CI users (Nelson et al, 1995; Collins et al, 1997). One possible explanation is that differences between tasks were simply masked by large within- and between-subject variability.

Another possible explanation may be that the ranking task could actually encourage slightly smaller DLs. The discrimination task allows participants to decide two sound stimuli are alike enough that they could be judged to be the same, whereas the ranking task forces participants to always choose a higher sound, even if the two stimuli sound identical to the listener. By forcing the participant to choose the higher sound (whether or not they hear a difference), the ranking task may encourage listeners to make narrower perceptual judgements than they do in the discrimination task. Although Tramo, Shah and Braida (2002) found no significant difference between the discrimination and ranking tasks for normal-hearing listeners, the average DL for the ranking task (0.7%) was slightly lower than for the discrimination task (1%). Likewise in the present study, the median pitch ranking scores of young CI users and young NH users are lower than median discrimination scores. Young CI had an overall group median score of 35.8% in the ranking task, compared to 59.9% in the discrimination task; young NH had an overall median score of 0.7% in the ranking task, compared to 1.3% in the discrimination task. The same trend was not seen in adult CI users, suggesting that adult participants are less likely to judge that two sounds are "alike enough" to be labeled the same. If the ranking task did encourage slightly smaller DLs for young participants, it could balance out some of the deficits CI users have to pitch ranking and bring scores on this task closer in line with discrimination scores.

Analysis of discrimination and ranking scores revealed another surprising finding: for young NH and adult CI users, there was no correlation between the two tasks. This was an unexpected finding, as previous research shows these tasks are highly correlated (Sek & Moore, 1995). Again, the lack of correlation between the two may be due to large variability among participants, or the relatively small sample sizes used (n=7 for adult CI, n=14 for young NH). It might also be related to practice or fatigue effects for the second task.

## 4.7. EFFECTS OF FREQUENCY

Numerous studies have shown that most CI users find it very difficult to perceive changes in pitch above 300 Hz (as discussed in Chapter 1). The present study shows that this not only holds true for postlingually deafened CI users, but also for young CI users. Both young CI and adult CI users had significantly larger DLs at 400 Hz compared to the two lower frequencies. A number of CI users also exhibited considerably higher DLs at 200 Hz. For instance, A7 had a DL of 15% at 100 Hz in the discrimination task, but her DLs were 202% and 263% at 200 and 400 Hz respectively. Likewise, C3 had a DL of 4.9% at 100 Hz, but 153% and 300% at 200 and 400 Hz. Other CI users showed similar trends (C1, C8, C14), although not always on both tasks. It would seem that these participants have a lower saturation point for pitch than others.

## 4.8. CONCLUSION

Previous research has shown that most postlingually deafened CI users are unable to extract adequate pitch information through their implants to perceive small differences in pitch that are common in speech and music. Young CI users appear to face the same challenges to pitch perception as postlingually deafened CI users, although this study shows they have the potential to improve over longer periods of time. Age of implantation does not appear to affect performance on pitch perception tasks, however, more research is needed to verify this. The large individual variability seen in responses from both young and adult CI users suggests that other factors play a large role in pitch perception.

### 4.9. FUTURE DIRECTIONS

Given the lack of research into how young CI users perceive complex pitch, this study is meant to provide an initial estimate of pitch perception abilities and to generate further study. It is clear that the diversity of responses from CI users makes it difficult to draw conclusions about the benefits of early implantation to pitch perception. It would therefore be beneficial to assess complex pitch difference limens in a larger sample of normal-hearing and implanted children so as to observe maturational effects more clearly. To do so, more NH subjects at each age would need to be recruited (e.g., twelve 10-year-olds, twelve 11-year-olds, etc.). Younger children (i.e., 4-7 year olds) might also be included since changes to pitch perception are known to improve during these years (Jensen & Neff, 1993) and since children this age should be able to attend to simple psychophysical tasks with appropriate training.[1] Obtaining DLs from a larger sample of 4- to 15-year-olds could potentially show the full maturation of pitch perception mechanisms, and provide an excellent basis of comparison for CI children. In addition to recruiting larger numbers of NH children, more early-implanted CI users would need to be recruited to better examine early-implantation effects. In particular, there should be more children implanted younger than 2 years old, since this age-group was under-represented in the present study.

Because there is evidence that pitch perception can improve in CI users over long periods of time, more information needs to be gathered from young CI users at regular periods following implantation. This could be accomplished through a longitudinal study examining pitch perception and speech recognition in young CI users and normal-hearing peers. Complex pitch DLs could be

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[1] The present study initially planned on including children as young as four, but with only one potential subject available in this age range, it was decided to focus our attention on 8-15 year olds.

obtained shortly after activation and every few months for the first year, then every year for several further years. Including tasks of speech recognition would allow us to see if pitch perception does take longer to develop than speech recognition, as has been suggested by Wu and Yang (2003). Comparisons could be made with normal-hearing children based on hearing age and chronological age to see whether CI users' perception of speech, language and complex pitch are hearing-age appropriate, even if they may not be age-appropriate.

Another area which could be explored in further depth is the relationship between pitch perception and a) type of education (e.g., mainstream, use of an ASL interpreter), b) type of rehabilitation (e.g., auditory-verbal, oral), c) primary mode of communication (e.g., oral, total communication), d) expressive language and speech abilities, and e) receptive language and speech abilities. This could provide insight into how pitch is correlated with speech and language, and what sort of environment is optimal for fostering better pitch perception.

It is important to consider training effects when planning future studies of pitch perception in children. If too much training is provided, or too little, results may not accurately reflect the everyday perceptive abilities of participants. It is likely a good idea to assess children over multiple, brief sessions in order to maintain attention, and to use a sound-attenuated room to prevent background noise, since background noise is known to influence tone perception for CI users more than normal hearing listeners (Wei et al, 2007). Although the computer game in the present study was able to keep most young participants engaged in the tasks, it could have benefited from stronger reinforcements. Using a different computer program in the future may allow more reinforcements to be built right into the task (e.g., mini-games, gathering coins to collect prizes). Another solution is to give participants tokens after a number of trials, which they could then exchange for toys or other treats at the end of the session.

Finding appropriate ways of gathering psychophysical data for young CI users can certainly be challenging, but the payoff is in learning more about how their brains adapt to a new form of sensory stimulation, during a period of time which normally sees huge growth and development. Understanding what exactly young CI users are able to hear and how their perception changes with time is the first step to improving CI performance, either through earlier implantation, better rehabilitation, or advances in technology.

## *References*

Allen, P., & Nelles, J. (1996). Development of auditory information integration abilities. *Journal of the acoustical society of America, 100*(2), 1043-1051.

Allen, P., & Wightman, F. (1994). Psychometric functions for children's detection of tones in noise. *Journal of speech and hearing research, 37*(1), 205-215.

Anderson, I., Weichbold, V., D'Haese, P. S., Szuchnik, J., Quevedo, M. S., Martin, J., et al. (2004). Cochlear implantation in children under the age of two--what do the outcomes show us? *International journal of pediatric otorhinolaryngology, 68*(4), 425-431.

Andrews, M. L., & Madeira, S. S. (1977). The assessment of pitch discrimination ability in young children. *The Journal of speech and hearing disorders, 42*(2), 279-286.

ANSI. (1973). *Psychoacoustic terminology* (S3:20 ed.). New York: American National Standards Institute.

ANSI. (1994). *American national standard acoustical terminology.* New York: American National Standards Institute.

Barry, J. G., Blamey, P. J., Martin, L. F., Lee, K. Y., Tang, T., Ming, Y. Y., et al. (2002). Tone discrimination in cantonese-speaking children using a cochlear implant. *Clinical linguistics & phonetics, 16*(2), 79-99.

Blamey, P., Arndt, P., Bergeron, F., Bredberg, G., Brimacombe, J., Facer, G., et al. (1996a). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiology & Neuro-Otology, 1*(5), 293-306.

Blamey, P. J., Dooley, G. J., Parisi, E. S., & Clark, G. M. (1996b). Pitch comparisons of acoustically and electrically evoked auditory sensations. *Hearing research, 99*(1-2), 139-150.

Boex, C., Baud, L., Cosendai, G., Sigrist, A., Kos, M. I., & Pelizzone, M. (2006). Acoustic to electric pitch comparisons in cochlear implant subjects with residual hearing. *Journal of the association for research in otolaryngology : JARO, 7*(2), 110-124.

Boothroyd, A., & Boothroyd-Turner, D. (2002). Postimplantation audition and educational attainment in children with prelingually acquired profound deafness. *The Annals of otology, rhinology & laryngology. Supplement, 189*, 79-84.

Busby, P. A., & Clark, G. M. (2000a). Electrode discrimination by early-deafened subjects using the cochlear limited multiple-electrode cochlear implant. *Ear and hearing, 21*(4), 291-304.

Busby, P. A., & Clark, G. M. (2000b). Pitch estimation by early-deafened subjects using a multiple-electrode cochlear implant. *Journal of the acoustical society of America, 107*(1), 547-558.

Busby, P. A., Whitford, L. A., Blamey, P. J., Richardson, L. M., & Clark, G. M. (1994). Pitch perception for different modes of stimulation using the cochlear multiple-electrode prosthesis. *Journal of the acoustical society of America, 95*(5), 2658-2669.

Carlyon, R. P., van Wieringen, A., Long, C. J., Deeks, J. M., & Wouters, J. (2002). Temporal pitch mechanisms in acoustic and electric hearing. *Journal of the acoustical society of America, 112*(2), 621-633.

Chatterjee, M., & Shannon, R. V. (1998). Forward masked excitation patterns in multielectrode electrical stimulation. *Journal of the acoustical society of America, 103*(5 Pt 1), 2565-2572.

Chatterjee, M., & Zwislocki, J. J. (1997). Cochlear mechanisms of frequency and intensity coding. I. the place code for pitch. *Hearing research, 111*(1-2), 65-75.

Chen, J. M., Farb, R., Hanusaik, L., Shipp, D., & Nedzelski, J. M. (1999). Depth and quality of electrode insertion: A radiologic and pitch scaling assessment of two cochlear implant systems. *American journal of otology, 20*(2), 192-197.

Ciocca, V., Francis, A. L., Aisha, R., & Wong, L. (2002). The perception of cantonese lexical tones by early-deafened cochlear implantees. *Journal of the acoustical society of America, 111*(5 Pt 1), 2250-2256.

Clark, G. (2003). *Cochlear implants: Fundamentals and applications*. New York: Springer-Verlaig.

Colletti, V., Carner, M., Miorelli, V., Guida, M., Colletti, L., & Fiorino, F. G. (2005). Cochlear implantation at under 12 months: Report on 10 patients. *The Laryngoscope, 115*(3), 445-449.

Collins, L. M., Zwolan, T. A., & Wakefield, G. H. (1997). Comparison of electrode discrimination, pitch ranking, and pitch scaling data in postlingually deafened adult cochlear implant subjects. *Journal of the acoustical society of America, 101*(1), 440-455.

Connor, C. M., Craig, H. K., Raudenbush, S. W., Heavner, K., & Zwolan, T. A. (2006). The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: Is there an added value for early implantation? *Ear and hearing, 27*(6), 628-644.

Cooper, R. P., & Aslin, R. N. (1994). Developmental differences in infant attention to the spectral properties of infant-directed speech. *Child development, 65*(6), 1663-1677.

de Cheveigne, A. (2005). Pitch perception models. In C. Plack, A. Oxenham, R. Fay & A. Popper (Eds.), *Pitch: Neural coding and perception* (pp. 169-233). New York: Springer.

Dorman, M. F., Spahr, T., Gifford, R., Loiselle, L., McKarns, S., Holden, T., et al. (2007). An electric frequency-to-place map for a cochlear implant patient with hearing in the nonimplanted ear. *Journal of the association for research in otolaryngology, 8*(2), 234-240.

Eagles, E. L., Wishik, S. M., & Doerfler, L. G. (1967). *Hearing sensitivity and ear disease in children: A prospective study*. St. Louis: The Laryngoscope.

Eggermont, J. J., Ponton, C. W., Don, M., Waring, M. D., & Kwong, B. (1997). Maturational delays in cortical evoked potentials in cochlear implant users. *Acta Oto-Laryngologica, 117*(2), 161-163.

Eguchi, S. (1976). Difference limen for the formant frequencies: Normal adult values and their development in children. *Journal of the American audiology society, 1*, 145-149.

Fearn, R., Carter, P., & Wolfe, J. (1999). The dependence of pitch perception on the rate and place of stimulation of the cochlea: A study using cochlear implants. *Acoustics Australia, 27*, 41-43.

Fior, R. (1972). Physiological maturation of auditory function between 3 and 13 years of age. *Audiology, 11*(5), 317-321.

Fu, Q. J., Hsu, C. J., & Horng, M. J. (2004). Effects of speech processing strategy on chinese tone recognition by nucleus-24 cochlear implant users. *Ear and hearing, 25*(5), 501-508.

Fujita, S., & Ito, J. (1999). Ability of nucleus cochlear implantees to recognize music. *Annals of otology, rhinology, and laryngology, 108*(7 Pt 1), 634-640.

Gengel, R. W. (1969). Practice effects in frequency discrimination by hearing impaired children. *Journal of speech and hearing research, 12*, 847-856.

Geurts, L., & Wouters, J. (2001). Coding of the fundamental frequency in continuous interleaved sampling processors for cochlear implants. *Journal of the acoustical society of America, 109*(2), 713-726.

Geurts, L., & Wouters, J. (2004). Better place-coding of the fundamental frequency in cochlear implants. *Journal of the acoustical society of America, 115*(2), 844-852.

Gfeller, K., Turner, C., Mehr, M., Woodworth, G., Fearn, R., Knutson, J. F., et al. (2002). Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear implants international, 3*(1), 29-53.

Gfeller, K. E., Olszewski, C., Turner, C., Gantz, B., & Oleson, J. (2006). Music perception with cochlear implants and residual hearing. *Audiology & neuro-otology, 11 Suppl 1*, 12-15.

Grayden, D. B., & Clark, G. M. (2006). Implant design and development. In H. Cooper, & L. C. Craddock (Eds.), *Cochlear implants: A practical guide* (2nd ed., pp. 1-20). Chichester: Whurr Publishers.

Green, T., Faulkner, A., & Rosen, S. (2004). Enhancing temporal cues to voice pitch in continuous interleaved sampling cochlear implants. *Journal of the acoustical society of America, 116*(4 Pt 1), 2298-2310.

Greenwood, D. D. (1990). A cochlear frequency-position function for several species--29 years later. *Journal of the acoustical society of America, 87*(6), 2592-2605.

Harrison, R. V., Gordon, K. A., & Mount, R. J. (2005). Is there a critical period for cochlear implantation in congenitally deaf children? Analyses of hearing and speech perception performance after implantation. *Developmental psychobiology, 46*(3), 252-261.

Hassanzadeh, S., Farhadi, M., Daneshi, A., & Emamdjomeh, H. (2002). The effects of age on auditory speech perception development in cochlear-implanted prelingually deaf children. *Otolaryngology and head and neck surgery, 126*(5), 524-527.

Hsu, C.-J., Shiao, S.-H., & Chen, Y.-S. (2003). Effects of speech-coding strategies on speech perception performance in Mandarin-speaking children with Nucleus 24 cochlear implants. *4th Congress of Asia Pacific Symposium on Cochlear Implant*, Taipei, Taiwan.

Houtsma, A. J. M., & Smurzynski, J. (1990). Pitch identification and discrimination for complex tones with many harmonics. *Journal of the acoustical society of America, 87*(1), 304-310.

Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *The Journal of comparative neurology, 387*(2), 167-178.

Jensen, J. K., & Neff, D. L. (1993). Development of basic auditory discrimination in preschool children. *Psychological Science, 4*(2), 104-107.

Ketten, D. R., Skinner, M. W., Wang, G., Vannier, M. W., Gates, G. A., & Neely, J. G. (1998). In vivo measures of cochlear length and insertion depth of nucleus cochlear implant electrode arrays. *The Annals of otology, rhinology & laryngology.Supplement, 175*, 1-16.

Kidd, A. H., & Rivoire, J. L. (Eds.). (1966). *Perceptual development in children.* New York: International Universities Press.

Kirk, K. I., Miyamoto, R. T., Lento, C. L., Ying, E., O'Neill, T., & Fears, B. (2002). Effects of age at implantation in young children. *The Annals of otology, rhinology & laryngology.Supplement, 189*, 69-73.

Klatt, D. H. (1980). Software for a cascade/parallel formant synthesizer. *Journal of the acoustical society of America, 67*, 971-995.

Kong, Y. Y., Cruz, R., Jones, J. A., & Zeng, F. G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear and hearing, 25*(2), 173-185.

Kral, A., Hartmann, R., Tillein, J., Heid, S., & Klinke, R. (2001). Delayed maturation and sensitive periods in the auditory cortex. *Audiology & neuro-otology, 6*(6), 346-362.

Kral, A., Tillein, J., Heid, S., Klinke, R., & Hartmann, R. (2006). Cochlear implants: Cortical plasticity in congenital deprivation. *Progress in brain research, 157,* 283-313.

Laneau, J., Wouters, J., & Moonen, M. (2004). Relative contributions of temporal and place pitch cues to fundamental frequency discrimination in cochlear implantees. *Journal of the acoustical society of America, 116*(6), 3606-3619.

Leal, M. C., Shin, Y. J., Laborde, M. L., Calmels, M. N., Verges, S., Lugardon, S., et al. (2003). Music perception in adult cochlear implant recipients. *Acta oto-laryngologica, 123*(7), 826-835.

Lee, H. J., Kang, E., Oh, S. H., Kang, H., Lee, D. S., Lee, M. C., et al. (2005). Preoperative differences of cerebral metabolism relate to the outcome of cochlear implants in congenitally deaf children. *Hearing research, 203*(1-2), 2-9.

Lee, K. Y., van Hasselt, C. A., Chiu, S. N., & Cheung, D. M. (2002). Cantonese tone perception ability of cochlear implant children in comparison with normal-hearing children. *International journal of pediatric otorhinolaryngology, 63*(2), 137-147.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the acoustical society of America, 49*(2), Suppl 2:467+.

Maxon, A. B., & Hochberg, I. (1982). Development of psychoacoustic behavior: Sensitivity and discrimination. *Ear and hearing, 3,* 301-308.

McKay, C. M. (2004). Psychophysics and electrical stimulation. In F. Zeng, A. N. Popper & R. R. Fay (Eds.), *Cochlear implants: Auditory prostheses and electric hearing* (pp. 286-333). New York: Springer-Verlaig.

McKay, C. M., & McDermott, H. J. (2000). Place and temporal cues in pitch perception: Are they truly independent? [Electronic version]. *Acoustics Research Letters Online, 1*(1), 25-30.

McKay, C. M., McDermott, H. J., & Clark, G. M. (1994). Pitch percepts associated with amplitude-modulated current pulse trains in cochlear implantees. *Journal of the acoustical society of America, 96*(5 Pt 1), 2664-2673.

McKay, C. M., O'Brien, A., & James, C. J. (1999). Effect of current level on electrode discrimination in electrical stimulation. *Hearing research, 136*(1-2), 159-164.

Moore, B. C. J., & Carlyon, R. P. (2005). Perception of pitch by people with cochlear hearing loss and by cochlear implant users. In C. J. Plack, A. J. Oxenham, R. Fay & A. N. Popper (Eds.), *Pitch: Neural coding and perception* (pp. 234-277). New York: Springer.

Moore, B. C. (1973). Frequency difference limens for short-duration tones. *The Journal of the Acoustical Society of America, 54*(3), 610-619.

Moore, B. C. (1997). *An introduction to the psychology of hearing* (4th ed.). London: Academic Press.

Moore, B. C. (2003). Coding of sounds in the auditory system and its relevance to signal processing and coding in cochlear implants. *Otology & neurotology, 24*(2), 243-254.

Moore, B. C., & Glasberg, B. R. (1990). Frequency discrimination of complex tones with overlapping and non-overlapping harmonics. *The Journal of the acoustical society of America, 87*(5), 2163-2177.

Moore, B. C., Glasberg, B. R., Flanagan, H. J., & Adams, J. (2006a). Frequency discrimination of complex tones; assessing the role of component resolvability and temporal fine structure. *Journal of the acoustical society of America, 119*(1), 480-490.

Moore, R. E., Keaton, C., & Watts, C. (2006b). The role of pitch memory in pitch discrimination and pitch matching. *Journal of voice: official journal of the Voice Foundation,* [E-pub ahead of print].

Nelson, D. A., Van Tasell, D. J., Schroder, A. C., Soli, S., & Levine, S. (1995). Electrode ranking of "place pitch" and speech recognition in electrical hearing. *The Journal of the acoustical society of America, 98*(4), 1987-1999.

Nozza, R. J., Miller, S. L., Rossman, R. N., & Bond, L. C. (1991). Reliability and validity of infant speech-sound discrimination-in-noise thresholds. *Journal of speech and hearing research, 34*(3), 643-650.

O'Donoghue, G. M. (1996). Cochlear implants in children: Principles, practice and predictions. *Journal of the Royal Society of Medicine, 89*(6), 345P-7P.

O'Donoghue, G. M. (1999). Hearing without ears: Do cochlear implants work in children? *BMJ (Clinical research ed.), 318*(7176), 72-73.

Oh, S. H., Kim, C. S., Kang, E. J., Lee, D. S., Lee, H. J., Chang, S. O., et al. (2003). Speech perception after cochlear implantation over a 4-year time period. *Acta oto-laryngologica, 123,* 148-153.

Peng, S. C., Tomblin, J. B., Cheung, H., Lin, Y. S., & Wang, L. S. (2004). Perception and production of mandarin tones in prelingually deaf children with cochlear implants. *Ear and hearing, 25*(3), 251-264.

Pfingst, B. E., Holloway, L. A., Poopat, N., Subramanya, A. R., Warren, M. F., & Zwolan, T. A. (1994). Effects of stimulus level on nonspectral frequency discrimination by human subjects. *Hearing research, 78*(2), 197-209.

Plack, C., & Oxenham, A. (2005). The psychophysics of pitch. In C. Plack, A. Oxenham, R. Fay & A. Popper (Eds.), *Pitch: Neural coding and perception* (pp. 7-55). New York: Springer.

Ponton, C. W., Don, M., Eggermont, J. J., Waring, M. D., Kwong, B., & Masuda, A. (1996). Auditory system plasticity in children after long periods of complete deafness. *Neuroreport, 8*(1), 61-65.

Pressnitzer, D., Bestel, J., & Fraysse, B. (2005). Music to electric ears: Pitch and timbre perception by cochlear implant patients. *Annals of the New York Academy of Sciences, 1060,* 343-345.

Reiss, L. A., Turner, C. W., Erenberg, S. R., & Gantz, B. J. (2007). Changes in pitch with a cochlear implant over time. *Journal of the association for research in otolaryngology, 8*(2), 241-257.

Rogers, C. F., Healy, E. W., & Montgomery, A. A. (2006). Sensitivity to isolated and concurrent intensity and fundamental frequency increments by cochlear implant users under natural listening conditions. *Journal of the acoustical society of America, 119*(4), 2276-2287.

Schouten, J. (1940). The residue and the mechanism of hearing. *Proc. K. Ned. Akad. Wet, 43,* 991-999.

Sek, A., & Moore, B. C. (1995). Frequency discrimination as a function of frequency, measured in several ways. *Journal of the acoustical society of America, 97*(4), 2479-2486.

Sharma, A., & Dorman, M. F. (2006). Central auditory development in children with cochlear implants: Clinical implications. *Advances in oto-rhino-laryngology, 64,* 66-88.

Smoorenburg, G. F. (1970). Pitch perception of two-frequency stimuli. *Journal of the acoustical society of America, 48*(4), 924-942.

Soderquist, D. R., & Moore, M. J. (1970). Effect of training on frequency discrimination in primary school children. *Journal of auditory research, 10,* 185-192.

Teoh, S. W., Pisoni, D. B., & Miyamoto, R. T. (2004). Cochlear implantation in adults with prelingual deafness. part I. clinical results. *The Laryngoscope, 114*(9), 1536-1540.

Thompson, N. C., Cranford, J. L., & Hoyer, E. (1999). Brief-tone frequency discrimination by children. *Journal of speech, language, and hearing research : JSLHR, 42*(5), 1061-1068.

Tomblin, J. B., Barker, B. A., Spencer, L. J., Zhang, X., & Gantz, B. J. (2005). The effect of age at cochlear implant initial stimulation on expressive language growth in infants and toddlers. *Journal of speech, language, and hearing research : JSLHR, 48*(4), 853-867.

Tong, Y. C., & Clark, G. M. (1985). Absolute identification of electric pulse rates and electrode positions by cochlear implant patients. *Journal of the acoustical society of America, 77*(5), 1881-1888.

Townshend, B., Cotter, N., Van Compernolle, D., & White, R. L. (1987). Pitch perception by cochlear implant subjects. *Journal of the acoustical society of America, 82*(1), 106-115.

Trainor, L. J., & Desjardins, R. N. (2002). Pitch characteristics of infant-directed speech affect infants' ability to discriminate vowels. *Psychonomic bulletin & review, 9*(2), 335-340.

Tramo, M. J., Cariani, P. A., Koh, C. K., Makris, N., & Braida, L. D. (2005). Neurophysiology and neuroanatomy of pitch perception: Auditory cortex. *Annals of the New York Academy of Sciences, 1060,* 148-174.

Tramo, M. J., Shah, G. D., & Braida, L. D. (2002). Functional role of auditory cortex in frequency processing and pitch perception. *Journal of neurophysiology, 87*(1), 122-139.

van Hoesel, R. J., & Clark, G. M. (1997). Psychophysical studies with two binaural cochlear implant subjects. *Journal of the acoustical society of America, 102*(1), 495-507.

Warren, R. M. (1999). *Auditory perception: A new analysis and synthesis.* Cambridge: Cambridge University Press.

Wei, C., Cao, K., Jin, X., Chen, X., Zeng, F-G. (2007). Psychophysical performance and mandarin tone recognition in noise by cochlear implant users. *Ear and hearing, 28*(2 Supplement), 62-65.

Wier, C. C., Jesteadt, W., & Green, D. M. (1977). Frequency discrimination as a function of frequency and sensation level. *Journal of the acoustical society of America, 61*(1), 178-184.

Wilson, B. (2006). Speech processing strategies. In H. Cooper, & L. C. Craddock (Eds.), *Cochlear implants: A practical guide* (2nd ed., pp. 21-69). Chichester: Whurr Publishers.

Wilson, B. S. (2004). Engineering design of cochlear implants. In F. Zeng, A. N. Popper & R. R. Fay (Eds.), *Cochlear implants: Auditory prostheses and electric hearing* (pp. 14-52). New York: Springer-Verlag.

Wilson, B. S. (1997). The future of cochlear implants. *British journal of audiology, 31*(4), 205-225.

Winter, I. M. (2005). The neurophysiology of pitch. In C. Plack, A. Oxenham, R. Fay & A. Popper (Eds.), *Pitch: Neural coding and perception* (pp. 99-146). New York: Springer.

Wong, A. (2000). *Tone perception performance of prelingually hearing impaired cantonese speaking children with cochlear implants.* Unpublished M.Sc., University of Hong Kong.

Wong, A. O., & Wong, L. L. (2004). Tone perception of cantonese-speaking prelingually hearing-impaired children with cochlear implants. *Otolaryngology--head and neck surgery, 130*(6), 751-758.

Wu, J. L., & Yang, H. M. (2003). Speech perception of mandarin chinese speaking young children after cochlear implant use: Effect of age at implantation. *International journal of pediatric otorhinolaryngology, 67*(3), 247-253.

Yost, W. (2000). *Fundamentals of hearing: An introduction* (4th ed. ed.). San Diego: Academic Press.

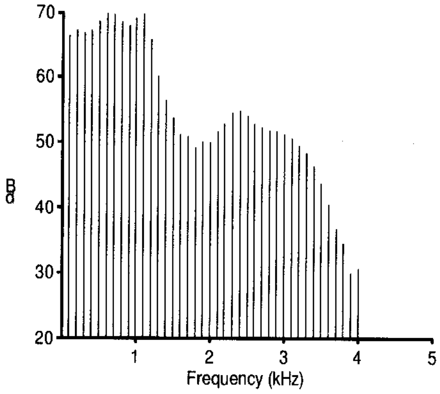
Zeng, F. G. (2002). Temporal pitch in electric hearing. *Hearing research, 174*(1-2), 101-106.

Zwicker, E., & Fastl, H. (1999). *Psychoacoustics: Facts and models* (2nd ed.). Heidelberg: Springer.

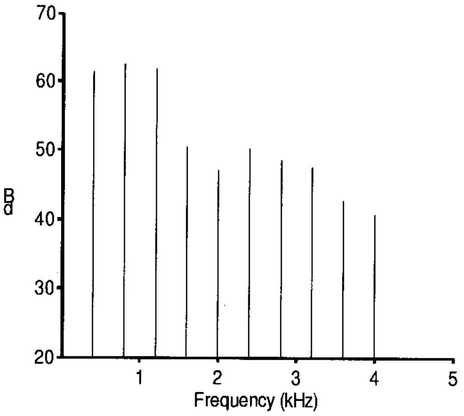
Zwolan, T. A., Collins, L. M., & Wakefield, G. H. (1997). Electrode discrimination and speech recognition in postlingually deafened adult cochlear implant subjects. *Journal of the acoustical society of America, 102*(6), 3673-3685.

# Appendix A

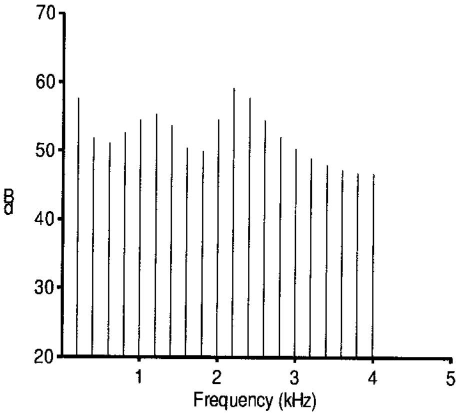
## *Spectra of Referent Stimuli and Sample Comparison Tones*



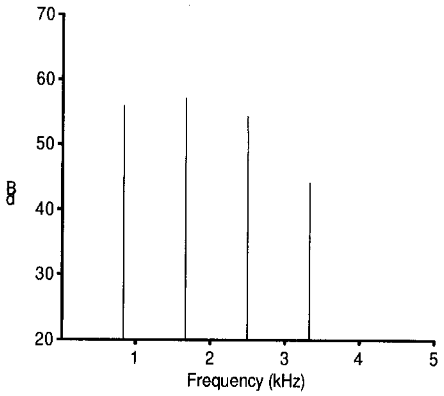
100 Hz Referent Tone



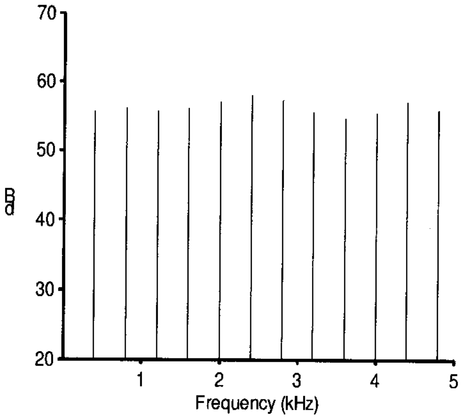
400 Hz Comparison Tone



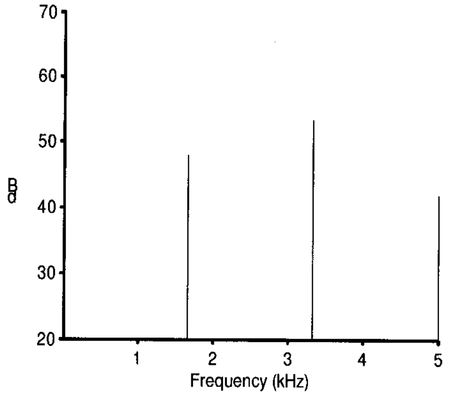
200 Hz Referent Tone



800 Hz Comparison Tone



400 Hz Referent Tone



1600 Hz Comparison Tone

**Figure A.1. Spectra of Referent Stimuli and 3 Comparison Tones**

# Appendix B

## *List of Stimuli*

**Table A.1. List of Stimuli Used in Pitch Ranking and Discrimination Tasks**

| Distance Above Referent Tone | Interval | Comparison Tones for Referent 1 (Hz) | Comparison Tones for Referent 2 (Hz) | Comparison Tones for Referent 3 (Hz) |
|---|---|---|---|---|
| **2 octaves** | 1 | 300.00 | 600.00 | 1200.00 |
| **23 semitones** | 2 | 277.55 | 555.10 | 1110.20 |
| **22 semitones** | 3 | 256.36 | 512.72 | 1025.44 |
| **21 semitones** | 4 | 236.36 | 472.72 | 945.43 |
| **20 semitones** | 5 | 217.48 | 434.96 | 869.92 |
| **19 semitones** | 6 | 199.66 | 399.32 | 795.65 |
| **18 semitones** | 7 | 182.84 | 365.69 | 731.37 |
| **17 semitones** | 8 | 166.97 | 333.94 | 667.87 |
| **16 semitones** | 9 | 151.98 | 303.97 | 607.94 |
| **15 semitones** | 10 | 137.84 | 275.68 | 551.37 |
| **14 semitones** | 11 | 124.49 | 248.99 | 497.97 |
| **13 semitones** | 12 | 111.89 | 223.79 | 447.57 |
| **1 octave** | 13 | 100.00 | 200.00 | 400.00 |
| **11 semitones** | 14 | 88.78 | 177.55 | 355.10 |
| **10 semitones** | 15 | 78.18 | 156.36 | 312.72 |
| **9 semitones** | 16 | 68.18 | 136.36 | 272.72 |
| **8 semitones** | 17 | 58.74 | 117.48 | 234.96 |
| **7 semitones** | 18 | 49.83 | 99.66 | 199.32 |
| **6 semitones** | 19 | 41.42 | 82.84 | 165.69 |
| **5 semitones** | 20 | 33.48 | 66.97 | 133.94 |
| **4 semitones** | 21 | 25.99 | 51.98 | 103.97 |
| **3 semitones** | 22 | 18.92 | 37.84 | 75.68 |
| **2 semitones** | 23 | 12.25 | 24.49 | 48.99 |
| **1 semitones** | 24 | 5.95 | 11.89 | 23.79 |
| **50 cents** | 25 | 2.93 | 5.86 | 11.72 |
| **40 cents** | 26 | 2.34 | 4.68 | 9.35 |
| **30 cents** | 27 | 1.75 | 3.50 | 6.99 |
| **20 cents** | 28 | 1.16 | 2.32 | 4.65 |
| **10 cents** | 29 | 0.58 | 1.16 | 2.32 |
| **5 cents** | 30 | 0.29 | 0.58 | 1.16 |
| **4 cents** | 31 | 0.23 | 0.46 | 0.93 |
| **3 cents** | 32 | 0.17 | 0.35 | 0.69 |
| **2 cents** | 33 | 0.12 | 0.23 | 0.46 |
| **1 cent** | 34 | 0.06 | 0.12 | 0.23 |

# Appendix C

## *Difference Limens Obtained for All Participants*

**Table A.2. Difference Limens for Young CI.** DLs are shown as a percentage of the referent frequency.

| | Ranking task (Task 1) | | | Average of Task 1 | Discrimination task (Task 2) | | | Average of Task 2 | Average of both tasks |
|---|---|---|---|---|---|---|---|---|---|
| | *100 Hz* | *200 Hz* | *400 Hz* | | *100 Hz* | *200 Hz* | *400 Hz* | | |
| **C1** | 31.43 | 96.36 | 20.23 | 49.34 | 64.19 | 141.92 | 300.00 | 168.70 | 109.02 |
| **C2** | 300.00 | 300.00 | 300.00 | 300.00 | 43.22 | 54.92 | 72.00 | 56.71 | 178.36 |
| **C3** | 4.91 | 152.54 | 300.00 | 152.48 | 19.52 | 300.00 | 300.00 | 206.51 | 179.49 |
| **C4** | 10.82 | 0.72 | 91.95 | 34.50 | - | - | - | - | - |
| **C5** | 33.76 | 22.59 | 1.17 | 19.17 | 45.79 | 50.00 | 10.82 | 35.53 | 27.35 |
| **C6** | 29.12 | 47.27 | 4.60 | 27.00 | 56.11 | 14.53 | 15.58 | 28.74 | 27.87 |
| **C7** | 37.90 | 3.50 | 0.24 | 13.88 | 63.64 | 49.51 | 43.63 | 52.26 | 33.07 |
| **C8** | 30.32 | 208.91 | 250.08 | 163.10 | 42.90 | 108.40 | 300.00 | 150.43 | 156.77 |
| **C9** | 50.90 | 32.20 | 19.16 | 34.09 | - | - | - | - | - |
| **C10** | 300.00 | 256.27 | 118.44 | 224.90 | 258.19 | 218.83 | 300.00 | 259.00 | 241.95 |
| **C11** | 187.98 | 243.95 | 243.26 | 225.06 | 300.00 | 300.00 | 243.93 | 281.31 | 253.19 |
| **C12** | 23.94 | 0.71 | 50.38 | 25.01 | 24.74 | 36.70 | 45.48 | 35.64 | 30.33 |
| **C13** | 28.96 | 5.15 | 0.06 | 11.39 | 47.34 | 34.91 | 17.40 | 33.22 | 22.30 |
| **C14** | 21.82 | 136.92 | 300.00 | 152.91 | 93.99 | 247.51 | 300.00 | 213.83 | 183.37 |

**Table A.3. Difference Limens for Young NH.** DLs are shown as a percentage of the referent frequency.

| | Ranking task (Task 1) | | | Average of Task 1 | Discrimination task (Task 2) | | | Average of Task 2 | Average of both tasks |
|---|---|---|---|---|---|---|---|---|---|
| | *100 Hz* | *200 Hz* | *400 Hz* | | *100 Hz* | *200 Hz* | *400 Hz* | | |
| **NH1** | 0.80 | 3.44 | 6.50 | 3.58 | 8.16 | 14.16 | 5.39 | 9.23 | 6.41 |
| **NH2** | 0.56 | 0.67 | 1.49 | 0.91 | 0.92 | 0.87 | 0.87 | 0.89 | 0.90 |
| **NH3** | 2.64 | 1.36 | 0.73 | 1.57 | 1.61 | 1.61 | 1.36 | 1.52 | 1.55 |
| **NH4** | 15.14 | 1.95 | 3.69 | 6.93 | 32.77 | 35.98 | 41.15 | 36.63 | 21.78 |
| **NH5** | 0.06 | 6.60 | 3.05 | 3.24 | 9.10 | 8.66 | 9.61 | 9.12 | 6.18 |
| **NH6** | 0.18 | 0.77 | 0.78 | 0.58 | 7.16 | 4.79 | 5.49 | 5.81 | 3.19 |
| **NH7** | 0.68 | 0.12 | 0.97 | 0.59 | 0.68 | 1.12 | 0.92 | 0.90 | 0.75 |
| **NH8** | 0.69 | 1.09 | 1.46 | 1.08 | 0.57 | 0.87 | 0.06 | 0.50 | 0.79 |
| **NH9** | 0.36 | 0.06 | 0.06 | 0.16 | 5.99 | 6.58 | 4.36 | 5.64 | 2.90 |
| **NH10** | 0.52 | 0.18 | 0.09 | 0.27 | 1.68 | 1.13 | 1.09 | 1.30 | 0.78 |
| **NH11** | 0.49 | 0.51 | 0.06 | 0.35 | 0.35 | 0.79 | 0.43 | 0.52 | 0.44 |
| **NH12** | 3.25 | 0.71 | 0.03 | 1.33 | 1.09 | 2.05 | 1.90 | 1.68 | 1.50 |
| **NH13** | 0.06 | 0.18 | 0.84 | 0.36 | 1.24 | 1.09 | 0.91 | 1.08 | 0.72 |
| **NH14** | 2.53 | 0.89 | 0.06 | 1.16 | 0.91 | 0.56 | 0.51 | 0.66 | 0.91 |

**Table A.4. Difference Limens for Adult CI.** DLs are shown as a percentage of the referent frequency.

| | Ranking task (Task 1) | | | Average of Task 1 | Discrimination task (Task 2) | | | Average of Task 2 | Average of both tasks |
|---|---|---|---|---|---|---|---|---|---|
| | *100 Hz* | *200 Hz* | *400 Hz* | | *100 Hz* | *200 Hz* | *400 Hz* | | |
| **A1** | 13.09 | 29.29 | 9.43 | 17.27 | 20.58 | 45.03 | 132.14 | 65.92 | 44.47 |
| **A2** | 32.54 | 54.92 | 94.67 | 60.71 | 22.03 | 35.54 | 1.40 | 19.66 | 50.30 |
| **A3** | 11.14 | 0.06 | 155.15 | 55.45 | 11.10 | 36.70 | 25.46 | 24.42 | 49.18 |
| **A4** | 11.47 | 50.85 | 300.00 | 120.77 | 19.04 | 23.91 | 78.41 | 40.45 | 100.74 |
| **A5** | 1.60 | 1.40 | 300.00 | 101.00 | 203.20 | 300.00 | 300.00 | 267.73 | 201.20 |
| **A6** | 300.00 | 300.00 | 300.00 | 300.00 | 46.19 | 5.07 | 7.67 | 19.64 | 209.82 |
| **A7** | 300.00 | 300.00 | 300.00 | 300.00 | 15.03 | 202.66 | 263.57 | 160.42 | 280.21 |

# Appendix D

## *Electronic Files on Enclosed CD*

### GAMEMAKER 6 PROGRAM FILES

The following files are the GameMaker 6 program files that contain the source code for the final program. These GameMaker files include all of the graphics and sound stimuli used in the computer game and in the adult and teen versions of the tasks. GameMaker 6 must be installed on the computer in order for these files to be opened.

- Child Task 1 GM
- Child Task 1 Instructions GM
- Child Task 2 GM
- Child Task 2 Instructions GM
- Teen Task 1 GM
- Teen Task 2 GM
- Adult Task 1 GM
- Adult Task 2 GM

### EXECUTABLE GAMEMAKER FILES

The following files are the executable GameMaker files that can be run on most computers. These were the files used to gather data for Task 1 (pitch ranking) and Task 2 (pitch discrimination). The instructions for the Teen and Adult tasks were included in the main executable files.

- Child Task 1
- Child Task 1 Instructions
- Child Task 2
- Child Task 2 Instructions
- Teen Task 1

- Teen Task 2
- Adult Task 1
- Adult Task 2