University of Alberta

Physiological and Acoustic Measures of Speech and Voice Outcomes in Children with Cochlear Implants

by

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ABSTRACT

This descriptive study investigated speech and voice outcomes in five children with cochlear implants. Measurements were taken from each speech subsystem: respiratory; laryngeal; velopharyngeal; oral articulatory; and from the timing and coordination between subsystems. Speech intelligibility was measured as a global index of how well the subsystems combined to allow these children to be understood by unfamiliar listeners. Case studies were presented that give a thorough description of each child's developing speech mechanism. Results indicated that although the children performed outside normative ranges on many of the measurements of the speech subsystems, overall their speech was at least 80% intelligible to unfamiliar listeners. Results also suggested that these children are in the midst of refining their speech-motor systems in response to auditory information provided by cochlear implants.

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1. Introduction

1.1 The relationship between auditory feedback and physiology for the production of speech

Typically developing hearing children learn to use speech to communicate by imitating the speech sounds, or acoustic targets, that they hear. The child attempts to match the acoustic information they hear by using phonation (voicing), and adjusting the configuration of the speech mechanism according to the auditory and sensorimotor feedback that is available to them. Anatomical components of the speech mechanism include the lungs, vocal folds, velopharynx and the oral articulators (tongue, lips, jaw). Each component of the speech mechanism and its physiology (including coordination across mechanisms) can be related to one or more perceptual features that contribute to voice quality and/or speech intelligibility (how well a listener is able to understand a speaker). Functionally, the lungs provide breath support as the source for sound production. The vocal folds, which are housed in the larynx, provide phonation (sound), and are important for the perception of voice quality, voice naturalness, and the voiced/voiceless distinction between consonants. The velopharynx raises and lowers to allow air to pass through the nose or mouth for nasal and non-nasal sounds. The oral articulators move in concert to produce the specific configuration of each speech sound.

When any element of the speech mechanism is compromised, deviations from normal speech may be observed. Improper breath support may lead to decreases in loudness, shortened breath groups and inappropriate pauses in speech. At the level of the larynx, improper vocal fold closure may lead to a voice that sounds breathy and/or hoarse. Inappropriate vocal fold tension may cause the voice to sound harsh, and/or lead to insufficient control of the pitch of the voice, which impacts the prosody (intonation pattern and/or stress of a word) and naturalness of an utterance. Improper opening or closure of the velopharynx leads to non-nasal sounds being produced as nasal sounds (hypernasal) or nasal sounds being produced as non-nasal sounds (hyponasal). When the oral articulators are placed incorrectly (especially the tongue), the speaker may produce a sound that was not intended and the message may be affected negatively. Deviations in the onset of phonation at the vocal folds timed with movement of the oral articulators (or voice onset time) can lead to confusion between speech sounds. Deviations in any or a combination of these factors may result in a disruption in conveying the intended message.

Normal hearing children have the advantage of a fully functioning hearing mechanism that gives them appropriate auditory feedback so that they may adjust their speech mechanism to produce target sounds. Children who are hearing impaired are at a disadvantage because first, they cannot fully hear the acoustic target, and second, they are less able to make physiological adjustments of their speech mechanisms based on auditory feedback, which is necessary to make online adjustments to produce the target sounds. Consequently, speech intelligibility is negatively affected.

1.2 Intelligibility of children with hearing loss

Intelligibility refers to how well a speaker is understood by a listener (Peng, Spencer, & Tomblin, 2004). Intelligibility can be calculated as a percent, which indicates how much of a speaker's message is conveyed to the listener. Intelligibility of children of all ages with pre-lingual hearing loss is extremely variable, but overall, their intelligibility scores are lower than those of hearing children. Normally developing hearing children are 70% intelligible by the time they are 18-24 months of age (Paul, 2001) and show intelligibility that is near-adult-like or adult-like (100%) by age four (Chin, Tsai, & Gao, 2003). A review of the literature revealed that children with various degrees of hearing loss who are unaided (i.e., do not wear an amplification device), regardless of age, have intelligibility scores as low as 20% (Osberger & McGarr, 1982) and as high as 95.7% (Monsen, 1983) when judged by individuals who are unfamiliar with the speech of children with hearing impairment.

1.3 Cochlear implantation

Children who suffer damage to their hearing mechanisms (cochleas) in utero or shortly after birth are at a disadvantage for developing speech through the typical developmental sequence due to a compromised ability to hear the sounds around them. One way to treat hearing loss in children when the hair cells in the cochlea are damaged is to implant a prosthetic device that mimics the function of the hair cells in the cochlea, called a cochlear implant (CI). CIs are recommended for children who have severe to profound sensorineural hearing loss. The pre-implant speech intelligibility of children who are candidates for CIs is often close to zero, as they have not experienced the sounds of their language in a meaningful way, even with amplification via hearing aids. In fact, in a study by Miyamoto et al. (1997), a group of children whose mean age at implantation was 5 years old were tested pre- and post-implantation. The authors found that the pre-implant speech intelligibility of these children was approximately 5%, similar to that of children who demonstrate hearing thresholds over 110 dB HL (a profound hearing loss).

Functional speech outcomes may be related to the age at which a child receives a CI. These speech outcomes may be linked to physiological changes in the speech subsystems that are governed by auditory feedback from the hearing mechanism. When a child receives a CI early in the developmental process, some auditory feedback becomes available, and motor control for speech may be implemented earlier and more efficiently. According to Lohle et al. (1999), children who were implanted early (age 2-4 years) had post-implant intelligibility scores of 60%-90%; children implanted between 5-8 years showed intelligibility scores of 30%-90%; and children who were implanted later (age 9-14 years) had intelligibility scores that were under 40%.

1.4 Intelligibility of children with cochlear implants

Studies that investigated the intelligibility of children with CIs reveal that these children show gradual improvement in intelligibility over time, and that earlier implantation and more experience with the implant leads to more intelligible speech. When the mean age at implant is five years old, they are, on average, approximately 0%-5% intelligible at the time of implant, 10% intelligible after one year with the implant, 15%-20% intelligible after two years experience, 40% intelligible after three years experience, and 70% intelligible after seven years experience (Calmels et al., 2004; Miyamoto, Iler-Kirk, Robbins, Todd, & Riley, 1996; Osberger, McConkey-Robbins, Todd, & Riley, 1994; Peng et al., 2004). Children who are three years old (on average) when they receive an implant are slightly more intelligible, even with less experience with the implant. These children are (on average) close to 0% intelligible at time of implant, 30% - 35% intelligible after two years with the implant, 50%-55% intelligible after three years of experience, and 74% intelligible after four years of experience (Mondain et al., 1997; Svirsky, Sloan, Caldwell, & Miyamoto, 2000). The outcomes of these studies show that speech intelligibility gradually improves over time and suggest that there is a relationship between age at implant, experience with the implant, and the positive effects of auditory feedback on intelligibility in this group of children.

1.5 Measuring physiology for production of speech: The speech subsystems

There are a number of studies that have assessed physiological factors that contribute to speech intelligibility in children with CIs. These factors include: voice onset time;

phonation; vocal fold tension; intonation patterns; pitch and loudness variation; voice quality (e.g., hoarseness, breathiness); amount of velopharyngeal closure (nasalance or resonance); intra-oral pressure; tongue position; and articulation. Some studies have assessed children who received their CIs at age four or older (Higgins, Carney, McCleary, & Rogers, 1996; Higgins, McCleary, Carney, & Schulte, 2003; Higgins, McCleary, & Schulte, 2001; Miyamoto et al., 1996; Perrin, Berger-Vachon, Topouzkhanian, Truy, & Morgan, 1999; Svirsky, Jones, Osberger, & Miyamoto, 1998; Uchanski & Geers, 2003). Other studies include children who are under age four at implantation, but also include older children in their analyses, up to age thirteen (Hocevar-Boltezar, Vatovec, Gros, & Zargi, 2005; Horga & Liker, 2006; Poissant, Peters, & Robb, 2006; Seifert et al, 2002; Van Lierde, Vinck, Baudonck, De Vel, & Dhooge, 2005). The most recent studies are the most relevant to the current study, as the speech processing strategies in the latest CIs have benefited from more advanced technology. What follows is a review of the literature, focusing on the most recent studies that measure the physiology of the speech subsystems in children with CIs.

1.5.1 The Lungs

In order to produce speech, one must have adequate subglottal pressure. According to Netsell and Hixon (1978), adequate subglottal pressure is 5-7 cmH2O. No studies were found that provided norms for typically developing children or measured subglottal pressure in children with CIs.

1.5.2 The Larynx

Hocevar-Boltezar et al. (2005) studied the effect of CIs on children's voices using a single vowel: /ah/. These children were between 2;5 and 13 years of age at the time of implant. The authors of this study divided the participants into two groups based on age at implant; before and after age four. The results of this study showed that the measures of jitter and shimmer (cycle-to-cycle variability in frequency and intensity, respectively), and noise-to-harmonics ratio, or NHR (noise present in the signal) showed significant improvement in the group of children who were implanted before age four. The measures of fundamental frequency (Fo) and shimmer were found to have improved significantly for the children who were implanted after age four (however, the finding of an improved Fo may be influenced by the increased size of the larynx in the older children). The authors concluded that children who receive an implant earlier in life are able to gain better auditory control over their speech and voice productions in a shorter period of time.

Higgins et al. (2003) examined the voices of English-speaking children with CIs. The children in their study received implants between the ages of 5;3 ad 10;7 years. Higher than normal fundamental frequencies (Fo) were found both before and after implantation for the syllables [pa] and [pi].

Van Lierde et al. (2005) compared Fo and jitter of Dutch-speaking female children who used CIs to Dutch-speaking children who used bilateral hearing aids (HA). The CI children ranged in age from 1;7 to 9;6 at the time of implantation. Results indicated that the jitter values for the female children with CI were lower (better) than the norm, but not significantly, and that the jitter values for the HA children were significantly higher (worse) than the norm.

In a study by Horga and Liker (2006), perceptual measures were obtained for Croatian children using CIs, children using HA, and normal hearing controls. The children with CIs were between 3;11 and 11;11 at the time of implant. Results indicated that voice and pronunciation quality were perceived as better in the CI children than in the HA children.

To assess the influence of auditory feedback on the speech of English children with CIs, Poissant et al. (2006) tested acoustic and perceptual measures of speech production in children with CIs when their implants were turned on and off. The children were between the ages of 2;2 and 7;5 at time of implant. The results showed that overall, the children's performance was variable between the on and off conditions. Four out of the six children showed significantly higher Fo in the CI-off condition, and the opposite pattern was observed for the other two children (also significant). The authors concluded that children with CIs do in fact rely on auditory feedback to some extent to monitor their Fo.

Seifert et al. (2002) studied the voices and articulation of German- or Swiss-German-speaking children with CIs. The children in that study were between the ages of 1;5 and 5;3 at age of implantation. They also divided their subjects into two groups based on age at implant; before and after four years, and compared outcomes to a typically developing hearing control group. The results indicated that the children who were implanted earlier were able to gain more control over their Fo. Measures of Fo showed that there was no significant difference between the earlier implanted children and the normal group, but that there was a significant difference between the younger-implanted group and the older-implanted group.

1.5.3 The Velopharynx

Van Lierde et al. (2005) measured the overall resonance of Dutch-speaking children who used CIs, who ranged in age from 1;7 to 11;9 at the time of implantation. Children with CIs had values that were lower than the norms for their age and sex when they produced nasal sentences (i.e., they were hyponasal).

Higgins et al. (2001) examined whether having auditory feedback from a CI had an effect on nasal airflow in two English-speaking children with CIs. Both children were approximately 4 years at implantation. The data were collected first with the CI turned on, and again with the CI turned off. The first child showed statistically significant decreased nasal airflow for /b/; but increased nasal airflow for /p/ in the OFF condition.

Uchanski and Geers (2003) measured acoustic characteristics of the speech of English-speaking children who used CIs. The children in their study were between the ages of 1;8 and 5;4 at the time of implant. Results indicated that only 54% of the CI users were within normal limits (WNL) on values for the nasal manner metric. The values obtained indicated that the CI users were not sufficiently opening their velopharyngeal (VP) port (i.e., they were hyponasal).

1.5.4 Oral Articulators

Consonants

Van Lierde et al. (2005) compared the articulation of Dutch-speaking children who used CIs to Dutch-speaking children who used bilateral hearing aids. Cochlear-implanted children ranged in age from 1;7 to 11;9 at the time of implantation. The children with hearing aids produced significantly more cluster reductions by deletion (most common), stopping of fricatives, and backing. The children with CIs produced significantly more cluster reductions by insertion (mainly due to one participant), and substitutions for /r/. For both groups, distortions were the most common error. Overall, the children with CIs showed fewer phonological processes and articulation errors than did the children who wore hearing aids.

Vowels

Higgins et al. (2001) examined whether having auditory feedback from a CI had an effect on several articulatory behaviours in two English-speaking children with CIs. Both children were approximately 4 years at implantation. The data were collected first with the

CI turned on, and again with the CI turned off. The first child showed statistically significant changes in: decreased jaw opening for /i/; increased F1 for /i/; increased F2 for /a/ in the OFF position. The authors proposed that the increase in F2 may be due to a more forward tongue placement due to decreased auditory feedback. The second child did not exhibit statistically significant differences in formant frequencies.

Seifert et al. (2002) studied the voices and articulation in German- or Swiss-German-speaking children with CIs. The children in this study were between the ages of 1;5 and 5;3 at age of implantation. They divided their subjects into two groups based on age at implant; before and after four years. The results indicated that the children who were implanted earlier were able to gain more control over their speech mechanisms. Measures of the formants F1, F2, and F3 revealed that all children in the study were within the normal limits for their age and sex. Analysis of the F1:F2 ratio revealed that the values of the children implanted early were closer to the values of the normal hearing group, and they were significantly different from the values of the older implanted group.

Uchanski and Geers (2003) measured several acoustic characteristics of the speech of English-speaking children who used CIs. The children in their study were between the ages of 1;8 and 5;4 at the time of implant. Results indicated that the second formant frequencies (F2) for /i/ and /ah/ of the children with CIs were within the normal range of hearing children of the same age.

In a study by Horga and Liker (2006), acoustic and pronunciation measures were obtained in Croatian children using CIs, children using hearing aids, and normal hearing controls. The children with CIs were between 3;11 and 11;11 at the time of implant. Results indicated that the CI children had formant values (F1, F2) on the vowels /i/ and /u/ that were closer to those of the the normal hearing control participants than those of the participants who were using hearing aids. Differences were not shown for the vowel /a/. Vowel intelligibility testing supported the acoustic findings as well.

To assess the influence of auditory feedback on the speech of English children with CIs, Poissant et al. (2006) performed acoustic measures of speech production in children with CIs when their implants were turned on and off. The children were between the ages of 2;2 and 7;5 at time of implant. The results showed that overall, the children's performance was variable between the on and off conditions. One of the six children showed a significantly higher F1-F2 ratio, and two showed a significantly lower ratio in the OFF condition. A higher ratio is an indication of a tongue position that is high and backed. A lower ratio indicates a tongue position that is low and forward. The authors did not note whether the children who were implanted earlier showed different patterns than children who were implanted later, though this would be an interesting comparison.

1.5.5 Timing – Voice Onset Time

Higgins et al. (2001) examined whether having auditory feedback from a CI had an effect on several articulatory behaviours in two English-speaking children with CIs. Both children were approximately 4 years at implantation. The data were collected first with the CI turned on, and again with the CI turned off. The first child showed statistically significant increased voice onset time (VOT) for /b/ in the OFF position. The second child exhibited statistically significant decreased VOT for /p/ in the OFF condition. The authors proposed that the decreases in VOT may be due to the fact that timing was not yet mastered in participant two, and that not having auditory feedback made it even more difficult to produce the difference in timing for /p/ and /b/. This study suggests that auditory feedback plays a role in how well the children were able to adjust their speech mechanism to reach the target speech sounds.

Higgins et al. (2003) examined the voices of English-speaking children with CIs. The children in their study received implants between the ages of 5;3 and 10;7. These children showed both long and short VOT for /p/, both before and after implantation.

In the previously mentioned study by Horga and Liker (2006), voice and pronunciation measures were obtained in Croatian children using CIs who were between 3;11 and 11;11 at the time of implant. Results indicated that there was no significant difference between the CI children and the HA children on the voice onset distinction between /t/ and /d/ (i.e., both groups produced the /t/ as a /d/).

1.5.6 Summary

Few studies have assessed physiologic factors that contribute to the speech and voices of children based on the age at which they were implanted with a CI. Studies that included children who were implanted before their fourth birthday found that they achieved better control over some acoustic aspects of their speech (such as tongue position, pitch and loudness variability, and vocal fold tension) compared to children who were implanted after their fourth birthday (Hocevar-Boltezar et al., 2005; Seifert et al., 2002). These results support the need for early implantation and illustrate that early auditory feedback does play a role in many aspects of speech and voice development. Several of the studies speak to the importance of early implantation to help children avoid aberrant speech habits that may form in the first years of life and to gain better auditory control over their speech and voice productions in a shorter period of time (Higgins et al., 2003; Hocevar-Boltezar et al., 2005, Seifert et al., 2002). In addition, some studies suggest that auditory feedback plays a role in how well children are able to adjust their speech mechanisms to reach target speech sounds and to monitor Fo and vowel formant production (Higgins et al., 2001; Poissant et al., 2006).

Although the speech of hearing-impaired children who wear CIs does not sound like that of typically developing children in all dimensions, according to the research described above, more often than not, they sound more like typically developing children than children with similar levels of hearing loss who wear hearing aids, especially when implanted before age four. When compared to hearing-impaired children who wear hearing aids, children who wear CIs show fewer articulation and pronunciation errors, have improved voice quality, have higher levels of intelligibility, and show measures of Fo and F1 and F2 that are less like the children who wear hearing aids and more similar to normal hearing control children. The auditory feedback that the CI provides allows the child to maintain better control over speech and voice. Measures that support this observation include: increased intelligibility, increased ability to monitor Fo, vowel-formant production, and measures of jitter, shimmer, and noise-to-harmonics ratio (NHR) that are closer to those of typically developing children. When differences between age groups at implantation have been included in analyses, it has been shown that earlier-implanted children use the auditory feedback that they acquire to their advantage, and perform better than later-implanted children on many speech and voice measures.

None of the studies found to date have compiled a comprehensive evaluation of all of the speech subsystems in the same children within this population. Further research in the area of the physiology of speech-motor control in children with CIs is needed to understand how auditory feedback influences motor learning for speech. Knowing how the control of speech subsystems is influenced by the amount and timing of auditory feedback will give clinicians a better idea of which subsystems to target for therapy.

1.5.7 Research Question and Study Rationale

The purpose of this research was to compile a comprehensive evaluation of the speech mechanism in children with cochlear implants. Measurements from each speech subsystem were taken, including respiratory, laryngeal, velopharyngeal, oral articulatory, as well as measures of the timing and coordination of these subsystems. Intelligibility was measured as an overall indicator of the combined contributions of each of the subsystems as the child spoke. Individual case studies will be presented that will provide a picture of each child's speech mechanism.

2. Method

2.1 Participants

The original sample of participants was to consist of two groups of children with cochlear implants who had been implanted either between age 1 and 2, or between age 2 and 3, and who had at least two years of experience with their CI. The children were to have no concomitant disabilities affecting speech, language, or cognition. Seven children were recruited to participate in this study. Of those, two children were excluded from the study due to their young ages (3 years and 3 years, 7 months) and the inability to collect a comprehensive data set from them. One child's comprehension of the tasks was also questioned. Therefore, a convenience sample of five children who received CIs participated in this study. The children and their families were recruited with the assistance of the staff of the Language and Speech Services for the Hearing Impaired Program of the Communication Disorders Department of the Glenrose Rehabilitation Hospital, Edmonton, Alberta, Canada. Speech-language pathologists and Educators of the Deaf were provided with a telephone script with which they contacted parents of children who were on their caseload who fit the selection criteria for this study (see Appendix 8.1 for telephone script). The children ranged in age from 7 years, 4 months to 10 years, 5 months at time of testing. All of the children fell into the profound range of hearing loss (greater than 95 dB bilaterally) and received a CI in the right ear. When it was required, one child used Signed Exact English (SEE2) for speech perception, and two children used SEE2 for both speech perception and production in addition to the auditory information provided by the CI. Two children communicated orally and did not use any form of visual language to augment the auditory information (i.e., they used audition only). All of the children used a personal FM system that plugged into their CI. One child wore a hearing aid on one side, and a CI on the other. The demographics data for the children are presented in Table 1. A parent accompanied each child to each procedure and both the parent and the child consented/assented to participation in the study in accordance with the study's ethics approval by the Health Research Ethics Board, Panel B, at the University of Alberta. (Appendix 8.2). Due to the small number of participants in this research study, group comparisons were not attempted.

2.2 Rationale for the Measurements

Subglottal pressure is used as a measure of lung function because it has been established that it is necessary to have adequate subglottal pressure in order to produce vibrations of the vocal folds to produce sound (voicing) at a normal conversational level (Netsell & Hixon, 1978). Measures of the laryngeal mechanism give information about the quality of the voice. Together, measures of jitter, shimmer, and NHR (cycle-to-cycle variability in pitch and loudness and degree of noise in the vocal signal, respectively) are indications of how "natural" the voice sounds. When the values for these measurements are high, the voice sounds hoarse, harsh, or pressed, and generally sounds deviant. Fo is a measure of vocal fold vibration and is the acoustic correlate of vocal pitch. Measurement of laryngeal airway resistance (Rlaw) evaluates the opposition of the muscles of the vocal folds to airflow from the lungs during phonation. Measures of Rlaw are directly related to perceptions of voice quality (e.g., breathy, strained). At the level of the velopharynx, the integrity of the closure of the velum to the nasopharynx is important in the perception of nasality. Nasalance is an acoustic measure of the integrity of the velopharynx. A high nasalance percentage indicates speech production that sounds more nasal, as more air than usual is escaping through the nose, and a low nasalance percentage indicates speech production that sounds less nasal, as less air is allowed to escape through the nose. Velopharyngeal (VP) area is also an indication of the integrity of the velopharynx, and is a measurement of the extent of the VP opening. Movement of the oral articulators is important for the accuracy of the production of speech sounds. Formants are used to measure resonant frequencies of oral and pharyngeal cavities shaped by the movement of the tongue as vowels are produced, and a standardized test such as the Goldman-Fristoe Test of Articulation gives information about the perceptual results of movement of the articulators in the production of consonants. Measures of VOT measure the coordination of the laryngeal and articulatory systems. This measure is particularly sensitive to when a stop burst is released and vocal fold vibration begins. When the coordination between the burst and vocal fold vibration is not timed appropriately, distinctions between certain obstruent sounds are affected. Finally, intelligibility measures are used to get an overall idea of how well all subsystems work together to produce speech that others can understand.

2.3 Data Collection Procedures

Data were collected from each child in one session that included five different data collection stations.

2.3.1 PERCI Procedures

To measure the integrity of the velopharynx and function of the lungs, measurements of velopharyngeal area (VP area), Rlaw, and subglottal pressure were gathered using the PERCI hardware and software (Microtronics Corp.). Pressure and flow were calibrated as per PERCI manual procedures, and the system was reset to zero preceding each data collection session to compensate for changes in atmospheric pressure in the room.

To measure VP area, a small, sterile, soft cork of appropriate size containing a small, sterile tube was inserted into one nostril to measure nasal pressure. A small sterile tube was inserted into the other nostril to record nasal flow. To measure oral pressure, a small, sterile polyethylene catheter was held inside the participant's mouth, just behind the teeth and not occluded by the tongue. The participants were asked to repeat the syllable /pa/ and the word "hamper".

Rlaw was measured using a pneumotachometer and differential air pressure transducer with PERCI computer software. Each participant was asked to repeat the syllable /pi/ with a sterile, soft plastic PERCI mask covering the mouth and nose, and a small, sterile plastic tube placed between and slightly behind the teeth.

To measure subglottal pressure, the participants wore a sterile nose plug and a small, sterile polyethylene catheter was placed inside the participant's mouth just behind the teeth and not occluded by the tongue. The participant repeated the syllable /pi/ as the researcher held the catheter.

2.3.2 Computerized Speech Laboratory 4500 (Kay Elemetrics) Procedures

Measurements of the first and second formants (F1 and F2), VOT, Fo, jitter, shimmer, and NHR were obtained from digital recordings of the participants using the Computerized Speech Laboratory (CSL) computer software (Main program and MDVP program). Each participant was seated, held a microphone approximately 5 centimeters away from the mouth, and was instructed to use a normal voice.

To obtain F1 and F2, each participant was asked to repeat the carrier phrase "I can say __ today." (Nelson & Hodge, 2000) three times for each of four vowels: /ee/; /u/; /uh/; and /ah/. A carrier phrase was used to yield an accurate measure of the vowel during running speech. The CSL Main program was used to record the F1 and F2 data at a sampling rate of 11025 Hz.

For the collection of VOT, each participant was instructed to produce the consonant-vowel (CV) combinations /ba, pa/; /da, ta/; and /ka, ga/. Each participant produced each CV combination three times. The CSL Main program was used to record the VOT data at a sampling rate of 11025 Hz.

The CSL Main Program was used to measure Fo, jitter and shimmer at a sampling rate of 11025 Hz. Each participant was asked to produce a sustained /ah/ three times at a steady conversational volume and pitch.

For the measurement of NHR, each participant again produced three trials of sustained /ah/, this time using the MDVP program in the CSL to record the voice, with a sampling rate of 50,000 Hz.

2.3.3 Nasometer 6200 (Kay Elemetrics) Procedures

To measure nasalance, each participant produced speech samples while wearing a Nasometer headpiece (Nasometer 6200 - Kay Elemetrics). The headset was calibrated by equalizing the gain of the oral and nasal microphones as sound was played from a source equidistant from both microphones. The headset was placed on the child's head, ensuring that the metal plate was perpendicular to the child's face. The speech samples were taken from The MacKay-Kummer SNAP Test (MacKay & Kummer, 1994), which included two subtests: the Syllable-Repetition Subtest required the child to repeat (CV) syllables and the Picture-Cued Subtest required the child to produce sentences in a carrier phrase. The procedure followed the SNAP Test recommendations for administration, scoring and interpretation of these data.

2.3.4 Goldman-Fristoe Test of Articulation 2 (GFTA-2) Procedures

Each participant was seated in a sound-treated booth and spoke into a microphone that was placed approximately 15 centimeters from the face to record the productions. Each child named pictures as per GFTA-2 procedures.

2.3.5 Intelligibility Procedures

Each participant was seated in a sound-treated booth and spoke into a microphone that was placed approximately 15 centimeters away from the face. Each participant read ten sentences from the Beginner's Intelligibility Test (BIT) (Osberger et al., 1994). The BIT is an intelligibility test that was designed specifically for children with hearing loss. It combines pictures and objects as well as written words to elicit target sentences. The test consists of four lists of sentences, each comprised of ten sentences that are simple in syntactic structure. Each sentence is between two and six words in length, with a total number of words per list that is between 37 and 40. If the child is able to read the sentences, they may do so; if not, the task turns into a repetition task using the pictures and objects to support elicitation of the sentences. The child's productions were recorded and played back with the TOCS+ Record-Playback program (Hodge, Gotzke, & Daniels, 2007) and edited with Adobe Audition 1.5, to be played in random order to naïve student listeners at a later date.

Six naïve student listeners who had minimal or no experience listening to the speech of children with disordered speech were seated in a sound-treated room, underwent a hearing screening, and were then asked to listen to four different children's speech recordings. Each child's recording included two practice sentences and ten sentences from the BIT. Participants typed the words that they heard the children saying into a computer and were permitted to listen to the recordings up to two times. The recordings were played and the listener's responses recorded using the TOCS + Record-Playback software (Hodge & Gotske, 2006). They also rated how well they could understand the child on a scale from 1 to 7 (Appendix 8.9).

2.4 Data Analysis

2.4.1 PERCI Analysis

Measurements of subglottal pressure were taken by placing the cursor to the left of the oral pressure peak with the right arrow key, then pressing the up arrow key to determine the absolute peak. Five peaks were chosen. The first and last peaks and any peaks that surrounded a breath were omitted in order to acquire the most accurate reading. Analyses were run using the PERCI software, and values for subglottal pressure were derived from measures of oral pressure based on the relationship between oral pressure and its estimation of subglottal pressure during production of pressure consonants (i.e., /p/).

Rlaw data were analyzed using PERCI software, and were taken by placing the cursor to the right of the trough in the oral pressure signal, midpoint between two peaks. Three to five points were chosen; more points were chosen when the data allowed it. The first and last peaks and any peaks that surrounded a breath were omitted in order to acquire the most accurate reading. Values for Rlaw were obtained from the PERCI software package based on the relationship of oral pressure and flow and its estimation of Rlaw using certain consonant-vowel tokens.

Measurements of VP area were gathered using PERCI software, and were taken by placing the cursor to the left of each oral pressure peak using the right arrow key, then pressing the up arrow key to determine the absolute peak. Three to five peaks were chosen; more peaks were chosen when the data allowed it. The first and last peaks and any peaks that surrounded a breath were omitted in order to acquire the most accurate reading. Values were obtained using the PERCI software package based on the relationship among oral and nasal pressure and nasal flow for nasal and non-nasal sounds.

2.4.2 Computerized Speech Laboratory 4500 (Kay Elemetrics) Analysis

The CSL Main program was used to analyze the formant (F1 and F2) data. Linear Predictive Coding (LPC) was used as the primary analysis; however, in the event that the formants were not obvious with LPC, Fast Fourier Transform (FFT) power spectra were substituted in order to obtain the most accurate result. LPC calculates the formant values using a formula based on the predictability of speech, and the computer identifies peaks that correspond to the formant frequencies and spectral amplitudes of each vowel. FFT analysis displays a spectrum of the amplitude of the harmonics of the Fo of each vowel in a speech sample. The formant values can be obtained by relating the peaks in the display to the formant values. In general, the peaks of the LPC spectrum and the FFT spectrum fit with each other well (Kent & Read, 1992), however, the FFT analysis allows for a greater degree of precision when the peaks are not evident with LPC coding. Each formant measure was taken from the midpoint of the vowel token to ensure that the formants were on-target, as steady as possible, and the peak vowel amplitude was the greatest. An average of the three productions for each vowel was taken as that participant's F1 and F2 value for that vowel. As a measure of inter-rater reliability, one child was randomly selected (to account for 20% of the data), and the productions were analyzed by a second judge.

The CSL Main Program was used to record and analyze the VOT data. The participants produced each CV combination three times (as stated above), and an average of those was taken as the VOT for that CV combination. Each sample was trimmed and the voice onset was measured from the point of the release of the consonant to the onset of voicing. As a measure of inter-rater reliability, one child was randomly selected, and the productions were analyzed by a second judge (to account for 20% of the data).

The CSL Real-Time Pitch program was used to analyze the Fo, jitter and shimmer data. An average of the measurements from three tokens was taken as the value for each of the measures.

For the measurement of NHR, the participant again produced three trials of sustained /ah/, this time using the MDVP program in the CSL to analyze the voice. An average of measurements from the productions was taken as the value for NHR.

2.4.3 Nasometer 6200 (Kay Elemetrics) Analysis

The samples taken from the Nasometer 6200 (Kay Elemetrics) were trimmed to exclude sounds and other extraneous words that were present at the beginning or end of the passage. The nasalance values were then calculated by selecting "analysis" and then "all data" in the Nasometer 6200 software package. Each value was recorded on the SNAP test score sheet and compared with the normal values.

2.4.4 Goldman-Fristoe Test of Articulation (GFTA-2) Analysis

The GFTA-2 was scored online and was also checked for accuracy and reliability using the recordings described above. As a measure of inter-rater reliability, one child was randomly selected (to account for 20% of the data), and the productions were transcribed by a second listener.

2.4.5 Intelligibility Analysis

Intelligibility of the child speakers' utterances was calculated as the percent of the words in an utterance that were correctly identified by three naïve listeners. The average of the three intelligibility scores was calculated as each child's overall intelligibility score.

2.4.6 Inter-rater Reliability

Twenty percent of the data that required an element of subjective analysis were re-analyzed by a second judge. Reliability of identification of both formant frequencies for vowels was between 0.74 and 0.99 for all vowels except /uh/. The reliability of /uh/ was 0.31 for F2, and the reliability of F1 could not be determined. The low reliability for that particular vowel was due to the production of the vowel and as a result, the peaks for the formants were not well-defined. Reliability of measures of VOT was between 0.57 and 1.0 for all tokens. Because the GFTA score is a single number, reliability statistics could not be performed. Overall, reliability was high between the two judges based on raw score agreement. The difference between the two judges' values was minimal enough to place the participant in the same percentile.

3. Results

Data are presented individually for each participant, followed by group profiles and observations. For each participant, data are presented by speech subsystem, beginning with the respiratory subsystem, then moving to the larynx, the velopharynx, the oral articulatory subsystem, the coordination of laryngeal and oral articulatory subsystems, intelligibility, and finally, a summary of findings for each participant.

3.1 Participant 1

Participant 1 was a female aged nine years, six months who received her implant at age three. She used a Clarion Hi Focus 1.2 and used both a Platinum BTE and a body worn processor. Her unaided auditory thresholds for left and right ears were 103 dB HL and 105 dB HL respectively. Her aided audiogram showed a threshold of 30 dB HL, which falls within an acceptable range for an individual with a CI. Perceptually, P1's speech sounded hypernasal, and she sometimes omitted consonants in words. Her voice did not sound noticeably different from a typically developing child her age. Her primary expressive mode of communication was oral. Receptively, she used auditory information most often, but when required, her educators and parents used SEE 2 to augment the auditory information to ensure her understanding.

3.1.1 Measures of Lung Function and Capacity

Measurement of subglottal pressure is shown in Table 2. Subglottal pressures reflect the driving pressure necessary for sound production. Subglottal pressure values should range between 5-8 cmH_2O in order to produce adequate phonation. No studies were found that have measured subglottal pressure in children who have CIs. Participant 1 (P1) had a subglottal pressure of 13.5 cmH_20 (SD=2.13 cmH_20), which represents adequate to more-than-adequate driving pressure to the vocal folds for sound production.

3.1.2 Measures of Laryngeal Function

The acoustic analyses of laryngeal function and available normative data are shown in Tables 2 and 3. According to Campisi et al. (2002), and Lee, Pontamianos, & Narayanan, (1999), the range of normal values for Fo for children aged 4-11 years is 234 Hz to 300 Hz. Children with CIs have Fo values between 225 Hz and 364.76 Hz (Hocevar-Boltezar et al., 2005; Seifert et al., 2002; Van Lierde et al., 2005). P1's Fo was 276 Hz (SD=8 Hz). According to Campisi et al. (2002), normal laryngeal values for children aged 4-11 years are the following: jitter is 1.24% (SD=.07%); shimmer is 3.35% (SD=.12%); and NHR is 0.11% (0.002%). Studies done with children who have CIs have shown jitter values ranging from 0.45% to 1.41%, shimmer values of 3.23% (SD=1.51) and NHR values of 0.11% (SD=.01%) (Hocevar-Boltezar, 2005; Van Lierde et al., 2005). P1 produced a jitter value of 1.347% (SD=0.42 %), a shimmer value of 0.26% (SD=0.053%), and a NHR value of 0.11% (SD=0.007%). According to Strathopoulos and Sapienza (1997), the normative value for Rlaw that corresponds to P1's sex and age is 79.04 $cmH_20/l/s$ (SD=35.51 $cmH_20/l/s$). No studies were found that measure Rlaw in children who have CIs. P1's Rlaw could not be analyzed due to a leak in the mask. Perceptually, P1 did not present with noticeable voice abnormalities such as strain-strangled or breathy voice quality.

3.1.3 Measures of Velopharyngeal Function

The nasalance measures and the normative data for comparison are shown in Table 4. Measures of VP area and the norms are shown in Table 2. Nasalance norms on the SNAP test for non-nasal sentences are between 6% and 19%; and between 45% and 63% for nasal sentences. P1's nasalance scores for non-nasal sentences were between 13% and 27%, and her score for nasal sentences was 59%. On average, she scored 3 standard deviations above the mean for non-nasal sentences. According to Smith, Patil, Guyette, Brannan, & Cohen (2004), the normal values for VP area in female children ages 9-13 are: for the speech token /pi/, VP area is 0.21 mm^2 (SD=0.22 mm^2), and for the speech token /hamper/, VP area is 0.97

mm^2 (SD=0.86 mm^2). No studies were found that present norms for VP area for the speech token /pa/, or for children who have CIs. P1 had a VP area of 0.013 cm^2 (SD=0.009 cm^2) for the speech token /papa/, and .003 cm^2 (SD=0.002 cm^2) for the speech token /hamper/.

3.1.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

The scores on the Goldman-Fristoe Test of Articulation-2 (GFTA-2) are shown in Table 5, and the results of the formant analyses and the norms for those values are presented in Table 6. P1 had a raw score of 10 on the GFTA-2, which means that she was in the 1st percentile for her age and sex. A score in the 1st percentile means that 99% of female children age 9;6 through 9;11 had fewer than 10 errors on the GFTA-2. According to Lee et al. (1999), the following values for F1 have been reported for female children age 9: for the token /ah/, their F1 was 801 Hz (SD=48 Hz); for /i/, F1 was 455 Hz (SD=61 Hz); for /uh/, F1 was 652 Hz (SD=51 Hz); and for /u/, F1 was 505 Hz (SD=44 Hz). According to Campisi et al. et al., (2005), children who have CIs have shown an F1 for /ah/ of 862.8 Hz (SD=43.4 Hz). No other studies with children who have CIs were found that give F1 values for other vowels. P1's values for F1 were: for /ah/, F1 was 996 Hz (SD=82 Hz); for /i/, F1 was 281 Hz (SD=15 Hz); for /uh/ F1 was 874 Hz (SD=34 Hz); and for /u/, F1 was 330 Hz (SD=0 Hz). The F2 data from Lee et al. (1999) showed normative values for the following: for /ah/, F2 was 1658 Hz (SD=144 Hz); for /i/, F2 was 3061 Hz (SD=140 Hz); for /uh/, F2 was 1506 Hz (SD=107 Hz); and for /u/, F2 was 1764 Hz (SD=220 Hz). According to Campisi et al. et al., (2005) and Uchanski and Geers (2003), children with CIs show F2 values for the following vowels: F2 for /ah/ was between 1265 Hz and 1551 Hz, and F2 for /i/ was 3003 (SD=237). No studies were found that assess F2 for other vowels. P1's values for F2 were the following: for /ah/, F2 was 1500 Hz (SD=164 Hz); for /i/, F2 was 3519 Hz (SD=47 Hz); for /uh/, F2 was 1785 Hz (SD=80 Hz); and for /u/, F2 was 1328 Hz (SD=351 Hz).

3.1.5 Coordination of Laryngeal and Oral Articulatory Subsystems

VOT data and norms are presented in Table 7. Normal values for VOT for female children age 9 according to Whiteside and Marshall (2001) are the following: for /d/, VOT was 24.4 ms (SD=9.2ms), for /t/, VOT was 100.4 ms (SD=21.4 ms), was /b/, VOT is 15.9 ms (SD=6.5 ms), and for /p/, VOT was 72.3 ms (SD=20.6 ms). No pediatric studies were found that present VOT values for the tokens /k/ and /g/. There is a limited amount of research that addresses VOT in children who have CIs. Uchanski and Geers (2003) studied VOT of /t/ and /d/ in this population. According to their work, children with CIs had a VOT of 17ms (SD=9 ms) for /d/ and 80 ms (SD=21 ms) for /t/. Higgins et al. (2003) found that the VOT for /p/

was 12.3 for a child with a CI who is age and gender matched to P1. P1's VOT data reveals the following: VOT of /d/ was 15.8 ms (SD=4.3 ms); /t/ was 83.8 ms (SD=15.9 ms); /b/ was 12.8 ms (SD=3.4 ms); /p/ was 55.0 ms (SD=32.3 ms); /g/ was 23.4 ms (SD=7.8 ms); and /k/ was 66.1 ms (SD=21.4 ms).

3.1.6 Intelligibility Measures

Intelligibility scores are shown in Table 8. Children show intelligibility that is near-adult-like or adult-like (100%) by the time they are four years old. P1's intelligibility score averaged across three listeners was 85% (SD=8.19%).

3.1.7 Summary

For P1, the measures that most likely contribute negatively to her intelligibility score are nasalance, the GFTA-2 (articulation), and formant frequencies (F1 and F2). Therefore, the speech subsystems that are most involved for P1 are the velopharynx and the oral articulators.

3.2 Participant 2

Participant 2 was a ten year, five month old female who received her CI at age five years, nine months. She wore a Clarion CII implant with hi-resolution body-worn processor. The unaided auditory threshold for her left ear was >115 dB HL, and no measurable hearing could be detected in her right ear. Her aided threshold was 25 dB HL, within an acceptable range for a child with a CI. Perceptually, her speech sounded hyponasal with some speech-sound errors. Her voice sounded somewhat pressed or strained. She used SEE 2 in addition to audition to understand and communicate.

3.2.1 Measures of Lung Function and Capacity

Measurement of subglottal pressure is shown in Table 2. Subglottal pressures reflect the driving pressure necessary for sound production. Subglottal pressure values should range between 5-8 cmH_2O in order to produce adequate phonation. No studies were found that have measured subglottal pressure in children who have CIs. Participant 2 (P2) had a subglottal pressure of 9.7 cmH_20 (SD=1.85 cmH_20), which represents adequate to more-than-adequate driving pressure to the vocal folds for sound production.

3.2.2 Measures of Laryngeal Function

The acoustic analyses of laryngeal function and the available normative data are shown in Table 3. According to Campisi et al. (2002), and Lee et al. (1999), the range of normal values for Fo for children aged 4-11 years is 234 Hz to 300 Hz. Children with CIs have Fo values between 225 Hz and 364.76 Hz (Hocevar-Boltezar et. al., 2005; Seifert et. al., 2002; Van Lierde et. al., 2005). P2's Fo was 274 Hz (SD=22 Hz). According to Campisi et al. (2002), normal laryngeal values for children aged 4-11 years are the following: jitter is 1.24% (SD=.07%); shimmer is 3.35% (SD=.12%); and NHR is 0.11% (0.002%). Studies done with children who have CIs have shown jitter values ranging from 0.35% to 1.41%, shimmer values of 3.23% (SD=1.51) and NHR values of 0.11% (SD=.01%) (Hocevar-Boltezar, 2005; Van Lierde et al., 2005). P2 produced a jitter value of 1.33%, a shimmer value of 0.23%, and a NHR value of 0.132% (SD=0.16 %). According to Strathopoulos and Sapienza (1997), the normative value for Rlaw that corresponds to P2's sex and age is 79.04 $cmH_20/l/s$ (SD=35.51 $cmH_20/l/s$). No studies were found that measure Rlaw in children who have CIs. P2's Rlaw value was 274.83 $cmH_20/l/s$ (SD=238.91 $cmH_20/l/s$).

3.2.3 Measures of Velopharyngeal Function

The nasalance measures and the normative data for comparison are shown in Table 4. Measures of VP area and the norms are shown in Table 2. Nasalance norms on the SNAP test for non-nasal sentences are between 6% and 19%; and between 45% and 63% for nasal sentences. P2's nasalance scores for non-nasal sentences were between 6% and 17.67%, and her score for nasal sentences was 6%. On average, she scored 5 standard deviations below the mean for nasal sentences. According to Smith et al. (2004), the normal values for VP area in female children ages 9-13 are: for the speech token /pi/, VP area is 0.21 mm^2 (SD=0.22 mm^2), and for the speech token /hamper/, VP area is 0.97 mm^2 (SD=0.86 mm^2). No studies were found that present norms for VP area for the speech token /pa/, or for children who have CIs. P2 had a VP area of 0.004 cm^2 (SD=0.00 cm^2) for the speech token /papa/, and .004 cm^2 (SD=0.00 cm^2) for the speech token /hamper/.

3.2.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

The scores on the Goldman-Fristoe Test of Articulation-2 (GFTA-2) are shown in Table 5, and the results of the formant analyses and the norms for those values are presented in Table 6. P2 had a raw score of 17 on the GFTA-2, which means that her score falls below the 1st percentile for her age and sex. A score in or below the 1st percentile means that 99% (or more) of female children age 10;0 through 10;5 had less than 17 errors on the GFTA-2. According to Lee et al. (1999), the following values for F1 have been reported for female children age 10: for the token /ah/, their F1 was 791 Hz (SD=79 Hz); for /i/, F1 was 472 Hz (SD=45 Hz); for /uh/, F1 was 636 Hz (SD=51 Hz); and for /u/, F1 was 496 Hz (SD=54 Hz). According to Campisi et al. et al., (2005), children who have CIs have shown an F1 for /ah/

of 862.8 Hz (SD=43.4 Hz). No other studies with children who have CIs were found that give F1 values for other vowels. P2's values for F1 were: for /ah/, F1 was 1018 Hz; for /i/, F1 was 366 Hz ; for /uh/ F1 was 804 Hz; and for /u/, F1 was 445 Hz. The F2 data from Lee et al. (1999) showed normative values for the following: for /ah/, F2 was 1748 Hz (SD=118Hz); for /i/, F2 was 2969 Hz (SD=134 Hz); for /uh/, F2 was 1689 Hz (SD=240 Hz); and for /u/, F2 was 1747 Hz (SD=280 Hz). According to Campisi et al. et. al., (2005) and Uchanski and Geers (2003), children with CIs show F2 values for the following vowels: F2 for /ah/ was between 1265 Hz and 1551 Hz, and F2 for /i/ was 3003 (SD=237). No studies were found that assess F2 for other vowels. P2's values for F2 were the following: for /ah/, F2 was 1319 Hz; for /i/, F2 was 3020 Hz (SD=124.32 Hz); for /uh/, F2 was 1224 Hz; and for /u/, F2 was 1134 Hz.

3.2.5 Coordination of Laryngeal and Oral Articulatory Subsystems

VOT data and norms are presented in Table 7. Normal values for VOT for female children age 11 according to Whiteside and Marshall (2001) are the following: for /d/, VOT was 20.6 ms (SD=4.8 ms), for /t/, VOT was 89.0 ms (SD=14.9 ms), was /b/, VOT is 15.5 ms (SD=4.9 ms), and for /p/, VOT was 47.4 ms (SD=11.9 ms). No pediatric studies were found that present VOT values for the tokens /k/ and /g/. There is a limited amount of research that addresses VOT in children who have CIs. Uchanski and Geers (2003) studied VOT of /t/ and /d/ in this population. According to their work, children with CIs had a VOT of 17ms (SD=9 ms) for /d/ and 80 ms (SD=21 ms) for /t/. Higgins (2003) found that the VOT for /p/ was 8.7 for a child with a CI who is age and gender matched to P2. P2's VOT data reveals the following: VOT of /d/ was 21.4 ms (SD=12.5 ms); /t/ was 62.1 ms (SD=29.7 ms); /b/ was 21.1 ms (SD=4.5 ms); /p/ was 78.2 ms (SD=9.6 ms); /g/ was 59.4 ms (SD=31.1ms); and /k/ was 123.7 ms (SD=10.4 ms).

3.2.6 Intelligibility Measures

Intelligibility scores are shown in Table 8. Children show intelligibility that is near-adult-like or adult-like (100%) by the time they are four years old. P2's intelligibility score averaged across three listeners was 83.3% (SD=3.82%).

3.2.7 Summary

For P2, the measures that most likely contribute negatively to her intelligibility score are VOT, jitter, NHR, nasalance, the GFTA-2 (articulation), and formant frequencies (F1 and F2). Therefore, the speech subsystems that are most involved for P2 are the larynx, velopharynx, timing of the oral articulators with the larynx, and the oral articulators.

3.3 Participant 3

Participant 3 is an eight year, three month old female who received her implant at age five years, three months. She used an Advanced Bionics 90k CI with an Auria BTE hi-resolution processor. She also wore an Oticon Sumo XP digital hearing aid in her left ear. P3's unaided auditory thresholds for left and right ears were 102 dB HL and >110 dB HL respectively, and her aided threshold was within the acceptable range for a child with a CI, at 30 dB HL. Perceptually, her voice sounded appropriate, and her speech sounded fairly clear and understandable, with intermittent articulation errors. Her primary mode of expressive communication was oral, with occasional use of SEE 2, and receptively, she used oral plus SEE 2.

3.3.1 Measures of Lung Function and Capacity

Measurement of subglottal pressure is shown in Table 2. Subglottal pressures reflect the driving pressure necessary for sound production. Subglottal pressure values should range between 5-8 cmH_2O in order to produce adequate phonation. No studies were found that have measured subglottal pressure in children who have CIs. Participant 3 (P3) had a subglottal pressure of 13.2 cmH_20 (SD=2.39 cmH_20), which represents adequate to more-than-adequate driving pressure to the vocal folds for sound production.

3.3.2 Measures of Laryngeal Function

The acoustic analyses of laryngeal function and the available norms are shown in Table 3. According to Campisi et al. (2002), and Lee et al. (1999), the range of normal values for Fo for children aged 4-11 years is 234 Hz to 300 Hz. Children with CIs have Fo values between 229 Hz and 364.76 Hz (Hocevar-Boltezar et. al., 2005; Seifert et. al., 2002; Van Lierde et. al., 2005). P3's Fo was 291 Hz (SD=15 Hz). According to Campisi et al. (2002), normal laryngeal values for children aged 4-11 years are the following: jitter is 1.24% (SD=.07%); shimmer is 3.35% (SD=.12%); and NHR is 0.11% (0.002%). Studies done with children who have CIs have shown jitter values ranging from 0.35% to 1.41%, shimmer values of 3.23% (SD=1.51) and NHR values of 0.11% (SD=.01%) (Hocevar-Boltezar, 2005; Van Lierde et al., 2005). P3 produced a jitter value of 1.08% (SD=n/a), a shimmer value of 0.56% (SD=n/a), and a NHR value of 0.113% (SD=0.017%). According to Strathopoulos and Sapienza (1997), the normative value for Rlaw that corresponds to P3's sex and age is 105.51 $cmH_20/l/s$ (SD=43.47 $cmH_20/l/s$). No studies were found that measure Rlaw in children who have CIs. P3's Rlaw was 173.05 $cmH_20/l/s$ (SD=33.42 $cmH_20/l/s$).

3.3.3 Measures of Velopharyngeal Function

The nasalance measures and the normative data for comparison are shown in Table 4. Measures of VP area and the available norms are shown in Table 2. Nasalance norms on the SNAP test for non-nasal sentences are between 6% and 19%; and between 45% and 63% for nasal sentences. P3's nasalance scores for non-nasal sentences were between 8.3% and 10%, and her score for nasal sentences was 49.67%. Overall, P3 was within the range of normal values for all sentences. According to Smith et al. (2004), the normal values for VP area in female children ages 5-8 are: for the speech token /pi/, VP area is 0.15 mm^2 (SD=0.12 mm^2), and for the speech token /hamper/, VP area is 0.44 mm^2 (SD=0.61 mm^2). No studies were found that present norms for VP area for the speech token /pa/, or for children who have CIs. P3 had a VP area of 0.001 cm^2 (SD=0 cm^2) for the speech token /papa/, and 0.001 cm^2 (SD=0.001 cm^2) for the speech token /hamper/.

3.3.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

The scores on the Goldman-Fristoe Test of Articulation-2 (GFTA-2) are shown in Table 5, and the results of the formant analyses and the norms for those values are presented in Table 6. P3 had a raw score of 8 on the GFTA-2, which means that she was in the 6th percentile for her age and sex. A score in the 6th percentile means that 94% of female children age 8;3 through 8;5 had less than 8 errors on the GFTA-2. According to Lee et al. (1999), the following values for F1 have been reported for female children age 8: for the token /ah/, their F1 was 848 Hz (SD=60 Hz); for /i/, F1 was 428 Hz (SD=46 Hz); for /uh/, F1 was 1450 Hz (SD=90 Hz); and for /u/, F1 was 426 Hz (SD=80 Hz). According to Campisi et al. et al., (2005), children who have CIs have shown an F1 for /ah/ of 862.8 Hz (SD=43.4 Hz). No other studies with children who have CIs were found that give F1 values for other vowels. P3's values for F1 were: for /ah/, F1 was 1167 Hz (SD=40); for /i/, F1 was 333 Hz (SD=28 Hz); for /uh/ F1 was 1109 Hz (SD=59 Hz); and for /u/, F1 was 412 Hz (SD=51 Hz). The F2 data from Lee et al. (1999) showed normative values for the following: for /ah/, F2 was 1693 Hz (SD=109 Hz); for /i/, F2 was 2997 Hz (SD=201 Hz); for /uh/, F2 was 1450 Hz (SD=90 Hz); and for /u/, F2 was 1539 Hz (SD=165 Hz). According to Campisi et al. et. al., (2005) and Uchanski and Geers (2003), children with CIs show F2 values for the following vowels: F2 for /ah/ was between 1265 Hz and 1551 Hz, and F2 for /i/ was 3003 (SD=237). No studies were found that assess F2 for other vowels. P3's values for F2 were the following: for /ah/, F2 was 1691 Hz (SD=37 Hz); for /i/, F2 was 3568 Hz (SD=57 Hz); for /uh/, F2 was 1584 Hz (SD=242 Hz); and for /u/, F2 was 1134 Hz (SD=111 Hz).

3.3.5 Coordination of Laryngeal and Oral Articulatory Subsystems

VOT data and norms are presented in Table 7. Normal values for VOT for female children age 7 according to Whiteside and Marshall (2001) are the following: for /d/, VOT was 28.6 ms (SD=6.5ms), for /t/, VOT was 96.0 ms (SD=17.6 ms), for /b/, VOT was 13.8 ms (SD=6.5 ms), and for /p/, VOT was 84.2 ms (SD=28.3 ms). No pediatric studies were found that present VOT values for the tokens /k/ and /g/. There is a limited amount of research that addresses VOT in children who have CIs. Uchanski and Geers (2003) studied VOT of /t/ and /d/ in this population. According to their work, children with CIs had a VOT of 17ms (SD=9 ms) for /d/ and 80 ms (SD=21 ms) for /t/. Higgins (2003) found that the VOT for /p/ was 10.1 for a child with a CI who is age and gender matched to P3. P3's VOT data reveals the following: VOT of /d/ was 16.8 ms (SD=5.3 ms); /t/ was 130.0 ms (SD=18.9 ms); /b/ was 23.5 ms (SD=3.2 ms); /p/ was 36.0 ms (SD=10.7 ms); /g/ was 28.7 ms (SD=13.0 ms); and /k/ was 101.4 ms (SD=59.6 ms).

3.3.6 Intelligibility Measures

Intelligibility scores are shown in Table 8. Children show intelligibility that is near-adult-like or adult-like (100%) by the time they are four years old. P3's intelligibility score averaged across three listeners was 89% (SD=1.4%).

3.3.7 Summary

For P3, the measures that most likely contribute negatively to her intelligibility score are VOT, NHR, the GFTA-2 (articulation), and formant frequencies (F1 and F2). A higher overall Fo and lower VP area on the speech token /hamper/ may also contribute, but to a lesser degree. Therefore, the speech subsystems that are most involved for P3 are the larynx, velopharynx and the oral articulators.

3.4 Participant 4

Participant 4 was a nine year old male who was implanted at age three. He used the Clarion Hi-focus 2 CI with Platinum Series Processor. P4's unaided auditory thresholds for left and right ears were 105 dB HL and 100 dB HL respectively. His aided threshold was 25 dB HL, within the acceptable range for a child with a CI. Perceptually he had excellent speech and voice. He used oral communication both receptively and expressively (i.e., he did not use SEE 2 or other type of visual language).

3.4.1 Measures of Lung Function and Capacity

Measurement of subglottal pressure is shown in Table 2. Subglottal pressures reflect the driving pressure necessary for sound production. Subglottal pressure values should range between 5-8 cmH_2O in order to produce adequate phonation. No studies were found that have measured subglottal pressure in children who have CIs. Participant 4 (P4) had a subglottal pressure of 6.9 cmH_20 (SD=0.4 cmH_20), which represents adequate driving pressure to the vocal folds for sound production.

3.4.2 Measures of Laryngeal Function

The acoustic analyses of laryngeal function and the available norms are shown in Table 3. According to Campisi et al. (2002), and Lee et al. (1999), the range of normal values for Fo for children aged 4-11 years is 234 Hz to 300 Hz. Children with CIs have Fo values between 225 Hz and 364.76 Hz (Hocevar-Boltezar et. al., 2005; Seifert et. al., 2002; Van Lierde et. al., 2005). P4's Fo was 258 Hz (SD=6 Hz). According to Campisi et al. (2002), normal laryngeal values for children aged 4-11 years are the following: jitter is 1.24% (SD=.07%); shimmer is 3.35% (SD=.12%); and NHR is 0.11% (0.002%). Studies done with children who have CIs have shown jitter values ranging from 0.35% to 1.41%, shimmer values of 3.23% (SD=1.51) and NHR values of 0.11% (SD=.01%) (Hocevar-Boltezar, 2005; Van Lierde et al., 2005). P4 produced a jitter value of 0.820% (SD=0.085%), a shimmer value of 0.185% (SD=0.007), and a NHR value of 0.096% (SD=0.020%). According to Strathopoulos and Sapienza (1997), the normative value for Rlaw that corresponds to P4's sex and age is 87.02 $cmH_20/l/s$ (SD=50.63 $cmH_20/l/s$). No studies were found that measure Rlaw in children who have CIs. P4's Rlaw was 92.67 $cmH_20/l/s$ (SD=26.83 $cmH_20/l/s$).

3.4.3 Measures of Velopharyngeal Function

The nasalance measures and the normative data for comparison are shown in Table 4. Measures of VP area and available norms are shown in Table 2. Nasalance norms on the SNAP test for non-nasal sentences are between 6% and 19%; and between 45% and 63% for nasal sentences. P4's nasalance scores for non-nasal sentences were between 13% and 15%, and his score for nasal sentences was 66%. According to Smith et al. (2004), the normal values for VP area in male children ages 9-13 are: for the speech token /pi/, VP area is 0.21 mm^2 (SD=0.22 mm^2), and for the speech token /hamper/, VP area is 0.97 mm^2 (SD=0.86 mm^2). No studies were found that present norms for VP area for the speech token /pa/, or for children who have CIs. P4 had a VP area of 0.006 cm^2 (SD=0.001 cm^2) for the speech token /papa/, and 0.005 cm^2 (SD=0 cm^2) for the speech token /hamper/.

3.4.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

The scores on the Goldman-Fristoe Test of Articulation-2 (GFTA-2) are shown in Table 5, and the results of the formant analyses and the norms for those values are presented in Table 6. P4 had a raw score of 4 on the GFTA-2, which means that he was in the 13th percentile for his age and sex. A score in the 13th percentile means that 87% of male children age 9;0 through 9;5 had less than 4 errors on the GFTA-2. According to Lee et al. (1999), the following values for F1 have been reported for male children age 9: for the token /ah/, their F1 was 793 Hz (SD=75 Hz); for /i/, F1 was 2979 Hz (SD=147 Hz); for /uh/, F1 was 626 Hz (SD=54 Hz); and for /u/, F1 was 471 Hz (SD=73 Hz). According to Campisi et al. et al., (2005), children who have CIs have shown an F1 for /ah/ of 862.8 Hz (SD=43.4 Hz). No other studies with children who have CIs were found that give F1 values for other vowels. P4's values for F1 were: for /ah/, F1 was 849 Hz (SD=45); for /i/, F1 was 310 Hz (SD=15 Hz); for /uh/ F1 was 867 Hz (SD=43 Hz); and for /u/, F1 was 309 Hz (SD=16 Hz). The F2 data from Lee et al. (1999) showed normative values for the following: for /ah/, F2 was 1529 Hz (SD=137 Hz); for /i/, F2 was 2979 Hz (SD=147 Hz); for /uh/, F2 was 1472 Hz (SD=124 Hz); and for /u/, F2 was 1603 Hz (SD=225 Hz). According to Campisi et al. et. al., (2005) and Uchanski and Geers (2003), children with CIs show F2 values for the following vowels: F2 for /ah/ was between 1265 Hz and 1551 Hz, and F2 for /i/ was 3003 (SD=237). No studies were found that assess F2 for other vowels. P4's values for F2 were the following: for /ah/, F2 was 1348 Hz (SD=121 Hz); for /i/, F2 was 3328 Hz (SD=124 Hz); for /uh/, F2 was 1707 Hz (SD=29 Hz); and for /u/, F2 was 1707 Hz (SD=137 Hz).

3.4.5 Coordination of Laryngeal and Oral Articulatory Subsystems

VOT data and norms are presented in Table 7. Normal values for VOT for male children age 9 according to Whiteside and Marshall (2001) are the following: for /d/, VOT was 33.9 ms (SD=18.7ms), for /t/, VOT was 109.6 ms (SD=32.0 ms), for /b/, VOT was 15.4 ms (SD=4.1 ms), and for /p/, VOT was 76.9 ms (SD=30.4 ms). No pediatric studies were found that present VOT values for the tokens /k/ and /g/. There is a limited amount of research that addresses VOT in children who have CIs. Uchanski and Geers (2003) studied VOT of /t/ and /d/ in this population. According to their work, children with CIs had a VOT of 17ms (SD=9 ms) for /d/ and 80 ms (SD=21 ms) for /t/. Higgins (2003) found that the VOT for /p/ was 8.7 for a child with a CI who is age and gender matched to P4. P4's VOT data reveals the following: VOT of /d/ was 11.6 ms (SD=4.4 ms); /t/ was 160.0 ms (SD=36.0 ms); /b/ was 18.8 ms (SD=1.2 ms); /p/ was 157.4 ms (SD=29.3 ms); /g/ was 42.0 ms

(SD=41.4 ms); and /k/ was 120.5 ms (SD=32.6 ms).

3.4.6 Intelligibility Measures

Intelligibility scores are shown in Table 8. Children show intelligibility that is near-adult-like or adult-like (100%) by the time they are four years old. P4's intelligibility score averaged across three listeners was 99% (SD=1.7%).

3.4.7 Summary

For P4, the measures that most likely contribute negatively to his intelligibility score are VOT, the GFTA-2 (articulation), and formant frequencies (F1 and F2). Therefore, the speech subsystems that are most involved for P4 are the timing of oral articulators with the pharynx, and the oral articulators themselves.

3.5 Participant 5

Participant 5 was a seven year, four month old male who received his CI at age one year, two months. He used the Clarion CII implant with the Platinum Series Hi-Res body worn Processor. P5's unaided auditory thresholds showed no measurable hearing bilaterally. His aided threshold was 20 dB HL, which is within the acceptable range for children with CIs. Perceptually, P5's speech was understandable; however his voice sounded unusually tight, or pressed, and his pitch sounded low. P5 used oral communication both receptively and expressively (i.e., he did not use visual language such as SEE 2).

3.5.1 Measures of Lung Function and Capacity

Measurement of subglottal pressure is shown in Table 2. Subglottal pressures reflect the driving pressure necessary for sound production. Subglottal pressure values should range between 5-8 cmH_2O in order to produce adequate phonation. No studies were found that have measured subglottal pressure in children who have CIs. Participant 5 (P5) had a subglottal pressure of 6.7 cmH_20 (SD=1.16 cmH_20), which represents adequate driving pressure to the vocal folds for sound production.

3.5.2 Measures of Laryngeal Function

The acoustic analyses of laryngeal function and available normative data are shown in Table 3. According to Campisi et al. (2002), and Lee et al. (1999), the range of normal values for Fo for children aged 4-11 years is 234 Hz to 300 Hz. Children with CIs have Fo values between 225 Hz and 364.76 Hz (Hocevar-Boltezar et. al., 2005; Seifert et. al., 2002; Van Lierde et. al., 2005). P5's Fo was 196 Hz (SD=24 Hz). According to Campisi et al. (2002), normal laryngeal values for children aged 4-11 years are the following: jitter is 1.24%

(SD=.07%); shimmer is 3.35% (SD=.12%); and NHR is 0.11% (0.002%). Studies done with children who have CIs have shown jitter values ranging from 0.35% to 1.41%, shimmer values of 3.23% (SD=1.51) and NHR values of 0.11% (SD=.01%) (Hocevar-Boltezar, 2005; Van Lierde et al., 2005). P5 produced a jitter value of 1.698% (SD=0.369%), a shimmer value of 0.493% (SD=0.100), and a NHR value of 0.146% (SD=0.011%). According to Strathopoulos and Sapienza (1997), the normative value for Rlaw that corresponds to P5's sex and age is 78.30 $cmH_20/l/s$ (SD=28.66 $cmH_20/l/s$). No studies were found that measure Rlaw in children who have CIs. P5's Rlaw was 329.18 $cmH_20/l/s$ (SD=20.08 $cmH_20/l/s$).

3.5.3 Measures of Velopharyngeal Function

The nasalance measures and the normative data for comparison are shown in Table 4. Measures of VP area and available norms are shown in Table 2. Nasalance norms on the SNAP test for non-nasal sentences are between 6% and 19%; and between 45% and 63% for nasal sentences. P5's nasalance scores for non-nasal sentences were between 4% and 4.67%, and his score for nasal sentences was 37%. Overall, P5's nasalance scores were below the normal values for all sentences. According to Smith et al. (2004), the normal values for VP area in male children ages 5-8 are: for the speech token /pi/, VP area is 0.15 mm^2 (SD=0.12 mm^2), and for the speech token /hamper/, VP area is 0.44 mm^2 (SD=0.61 mm^2). No studies were found that present norms for VP area for the speech token /pa/, or for children who have CIs. P5 had a VP area of 0.003 cm^2 (SD=0.001 cm^2) for the speech token /papa/, and 0.011 cm^2 (SD=0.007 cm^2) for the speech token /hamper/.

3.5.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

The scores on the Goldman-Fristoe Test of Articulation-2 (GFTA-2) are shown in Table 5, and the results of the formant analyses and the norms for those values are presented in Table 6. P5 had a raw score of 4 on the GFTA-2, which means that he was in the 28th percentile for his age and sex. A score in the 28th percentile means that 72% of male children age 7;3 through 7;5 had less than 4 errors on the GFTA-2. According to Lee et al. (1999), the following values for F1 have been reported for male children age 7: for the token /ah/, their F1 was 815 Hz (SD=94 Hz); for /i/, F1 was 425 Hz (SD=46 Hz); for /uh/, F1 was 624 Hz (SD=66 Hz); and for /u/, F1 was 449 Hz (SD=82 Hz). According to Campisi et al. et al., (2005), children who have CIs have shown an F1 for /ah/ of 862.8 Hz (SD=43.4 Hz). No other studies with children who have CIs were found that give F1 values for other vowels. P5's values for F1 were: for /ah/, F1 was 1005 Hz (SD=31); for /i/, F1 was 374 Hz (SD=8 Hz); for /uh/ F1 was 733 Hz (SD=59 Hz); and for /u/, F1 was 309 Hz (SD=16 Hz). The F2 data from Lee et al. (1999) showed normative values for the following: for /ah/, F2 was 1642 Hz (SD=148 Hz); for /i/, F2 was 3002 Hz (SD=191 Hz); for /uh/, F2 was 1542 Hz (SD=136 Hz); and for /u/, F2 was 1700 Hz (SD=236 Hz). According to Campisi et al. et. al., (2005) and Uchanski and Geers (2003), children with CIs show F2 values for the following vowels: F2 for /ah/ was between 1265 Hz and 1551 Hz, and F2 for /i/ was 3003 (SD=237). No studies were found that assess F2 for other vowels. P5's values for F2 were the following: for /ah/, F2 was 1355 Hz (SD=45 Hz); for /i/, F2 was 3191 Hz (SD=145 Hz); for /uh/, F2 was 1380 Hz (SD=237 Hz); and for /u/, F2 was 915 Hz (SD=51 Hz).

3.5.5 Coordination of Laryngeal and Oral Articulatory Subsystems

VOT data and norms are presented in Table 7. Normal values for VOT for male children age 7 according to Whiteside and Marshall (2001) are the following: for /d/, VOT was 27.5 ms (SD=10.3ms), for /t/, VOT was 96.3 ms (SD=15.3 ms), for /b/, VOT was 10.9 ms (SD=4.5 ms), and for /p/, VOT was 63.0 ms (SD=20.9 ms). No pediatric studies were found that present VOT values for the tokens /k/ and /g/. There is a limited amount of research that addresses VOT in children who have CIs. Uchanski and Geers (2003) studied VOT of /t/ and /d/ in this population. According to their work, children with CIs had a VOT of 17ms (SD=9 ms) for /d/ and 80 ms (SD=21 ms) for /t/. Higgins (2003) found that the VOT for /p/ was 26.4 for a child with a CI who is age and gender matched to P5. P5's VOT data reveals the following: VOT of /d/ was 10.3 ms (SD=2.4 ms); /t/ was 30.1 ms (SD=11.4 ms); /b/ was 14.3 ms (SD=6.5 ms); /p/ was 23.3 ms (SD=13.3 ms); /g/ was 20.6 ms (SD=2.3 ms); and /k/ was 48.5 ms (SD=12.9 ms).

3.5.6 Intelligibility Measures

Intelligibility scores are shown in Table 8. Children show intelligibility that is near-adult-like or adult-like (100%) by the time they are four years old. P5's intelligibility score averaged across three listeners was 98% (SD=1.7%).

3.5.7 Summary

For P5, the measures that most likely contribute negatively to his intelligibility score are VOT, Fo, jitter, nasalance, the GFTA-2 (articulation), and formant frequencies (F1 and F2). Therefore, the speech subsystems that are most involved for P5 are the larynx, velopharynx, timing of the onset of voicing with the oral articulators, and the oral articulators themselves.

4. Discussion

The purpose of this study was to describe the speech mechanism in five children who were implanted with CIs in order to compile a comprehensive evaluation of all the speech subsystems in the same children. The discussion of each participant will be presented individually, followed by a general discussion. Each discussion will follow the speech mechanism, beginning with the respiratory subsystem, followed by the laryngeal, velopharyngeal, and articulatory subsystems, then moving to the timing of the laryngeal and articulatory subsystems, and finally overall intelligibility.

4.1 Participant 1

4.1.1 Measures of Lung Function and Capacity

Overall, P1 has adequate subglottal pressure for speech.

4.1.2 Measures of Laryngeal Function

P1's values for laryngeal function reveal that she demonstrates vocal pitch (Fo) in the average range, lower (better) cycle-to-cycle variability in pitch and loudness (jitter and shimmer, respectively), and is within normal limits on how much noise is in the signal (NHR) for female children her age. P1's Fo and jitter values were within the range of values of other children with CIs. P1's shimmer value was lower and her NHR value was within the ranges of the children who have CIs.

4.1.3 Measures of Velopharyngeal Function

P1's productions on the SNAP test show that she produces normal nasalance on nasal sentences but she shows higher nasality on sentences that are non-nasal (i.e., she was hypernasal). Analysis of VP area data show values that are within the normal range for the speech token /pa/, but lower than the normal range for the speech token /hamper/ (i.e., decreased area corresponds to hyponasality). The differences between nasality measures and the VP area measures may be due to the different speech tokens that were used to gather the data. Sentences are used in the SNAP test, whereas a single syllable (/pa/) or a single word ('hamper') was used to gather the VP area data. Practice effects and/or the ability to better prepare the motor control system when producing a single syllable or word during the collection of VP area may contribute to small differences between the VP area data and the SNAP test sentences. It is also possible that P1 is variable in the use of her velopharynx because she has not yet refined the use of that system in response to the auditory information that is available to her. It appears that she has not mastered the fine movements of the velum that are necessary to correctly produce nasal and non-nasal sounds consistently. Those times that she is not producing the correct nasality in words, she may be overcompensating with her velum. This is evidenced by the values indicating that she is holding her velum in a more open position on non-nasal sentences (hypernasality), and in a more closed position for nasal sentences (hyponasality).

4.1.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

P1's score on the GFTA-2 indicated that she did not always exhibit accurate articulation for consonant sounds, in fact, 99% of normally developing children her age had fewer errors on the GFTA-2 than she exhibited. Her errors included nasalization, denasalization, devoicing of /z/, substitution of /d/ for /th/ (voiced)/, and turbulence when producing /s/. The GFTA-2 looks for specific sounds in specific words, but some errors were produced on sounds that were not specifically being targeted. Therefore, incidental errors were also seen that were not addressed in the test per say, but that are present in P1's speech. These errors included addition and/or substitution of /s/ word-finally, substitution of /ch/ for /sh/, and other instances of deletion or addition of nasal sounds. P1's errors could largely be explained by her inability to sufficiently control her velum in response to nasal and non-nasal sounds, as well as insufficient auditory feedback to precisely guide her articulators.

P1 was outside the normal range for F1 and F2 on all vowels tested. When the F1 value is higher than the norm, it means that the tongue is being held lower in the oral cavity, and when the value is lower than the norm, it means the tongue is being held in a higher position than normal. When the F2 value is higher than the norm, it means that the tongue is being positioned more forward, and when the F2 value is lower than the norm, it means that the tongue is being positioned farther back in the oral cavity than normal. P1's F1 values were higher than the norm for /uh/ and /ah/ (she was holding her tongue in a lower position), and her F1 values were lower than the norms for /u/ and /i/ (she was holding her tongue in a higher position). Her F2 values were higher than the norm for /uh/ and /i/ (she was holding her tongue more forward), but were lower than the norms for /ah/ and /u/ (she was holding her tongue farther back in her oral cavity). Interestingly, these data suggest that P1 was overshooting the target frequencies of all the vowels. For example, when producing high front vowels (e.g., /i/), she held her tongue even higher and farther forward; when producing low back vowels (e.g., /ah/), she held her tongue even farther back and lower than the norms. When compared to other children with CIs, her F1 value for /ah/ was higher than the upper limit of the range obtained by Campisi et al. (2005). Her F2 value for /ah/ was higher than the upper limit of the range defined by Campisi et al. (2005), however it was within the range defined by Uchanski and Geers (2003). Her F2 value for /i/ is higher than the range defined by Uchanski and Geers (2003). Consistent with other children with CIs, P1 overshot the target vowel position for F1, but for F2, her tongue position was more central than other children with CIs.

4.1.5 Coordination of Laryngeal and Oral Articulatory Subsystems

The VOT data show that P1 was within the range of available normal VOT data for normally developing female children age 9 (data available for /b, p, d, and t/). She also was within the range defined by Higgins et al. (2003) for /d/ and /t/ for children who have CIs.

4.1.6 Intelligibility Measures

P1's intelligibility score was lower than expected for her age, as unfamiliar listeners were able to understand only 85% of what she said. Intelligibility can be affected by any single measure or a combination of the measures described above, however the speech subsystems that are most involved for P1 are the velopharynx and the oral articulators.

4.1.7 Summary

P1 does not demonstrate any issues with breath support or laryngeal function. Her decreases in intelligibility are mainly due to issues with nasalance, VOT, and articulation. She overshoots tongue placement for vowels, but perceptually, her vowel articulation is not a large contributor to decreases in her intelligibility. Based on the intelligibility data, her errors were largely due to velopharyngeal function. Overall, nasalance errors resulted in the most confusion for the listeners (7/9 errors were errors of nasalance), however, she was variable in her production of nasalance, as 4 of those 7 errors showed hypernasality and 3 of the 7 showed hyponasality. This variability supports the incongruity in the velopharyngeal data as well. P1 clearly has not mastered control of her velopharynx. Her other two errors were due to addition errors at the end of words. She added /s/ where one was not expected, nor grammatically correct. It is interesting to note that the errors P1 made on the GFTA-2 were mainly errors of VOT and nasalance. She substituted /s/ for /z/, two consonants that were not included in the analysis of VOT in this study.

Clinically, the focus for treatment may be to correct errors in nasality. Goals may include training to increase her awareness of nasal and non-nasal sounds, and give her skills to know how and when to produce nasals and non-nasals. It also may be beneficial to teach her to pronounce the sounds that she does not hear by training her to "feel" where the articulators should be placed for certain sounds (for example, /s/) and the associated airflow.

4.2 Participant 2

4.2.1 Measures of Lung Function and Capacity

Overall, P2 has adequate subglottal pressure for speech.

4.2.2 Measures of Laryngeal Function

P2's values for laryngeal function reveal that she demonstrates vocal pitch (Fo) that is within the normal range and within the range of values collected on children with CIs. Her value for how much noise is in the signal (NHR) is within normal limits for typical children and other children with CIs. Her value for cycle-to-cycle variability in loudness (shimmer) was higher (worse) than the norms for her sex and age and was slightly lower (better) than the range of shimmer values of other children with CIs. She demonstrates cycle-to-cycle variability in pitch (jitter) that is higher (worse) for the norms for her sex and age, but that is within the range for other children with CIs. P2's average value for Rlaw was higher than the norm. Her flow values were low, and her oral pressure values were high, indicating that her voice was strained, which corresponded to the perceptual quality of her voice. According to the Rlaw data, P2's laryngeal system may be somewhat deviant; however the two other voice parameters that were outside the normal range (jitter and shimmer) did not deviate substantially, nor were they corroborated by an abnormal NHR, which would be expected if the voice were deviant. She may have a mildly strained voice quality, however she did have a cold the day of testing, and mucous production and/or a persistent cough may have contributed to the score. Further testing to rule out the effects of the cold is warranted before a definitive conclusion regarding her voice can be reached.

4.2.3 Measures of Velopharyngeal Function

P2's productions on the SNAP test show that she has normal nasalance on non-nasal sentences but she shows much lower nasality scores than expected on nasal sentences, meaning she was hyponasal (5 standard deviations below the mean). P2's VP area values support the SNAP test findings. Her values for /pa/ (non-nasal) are within the normal range; however her value for the speech token /hamper/ (nasal) is below the normal range, indicating that she is holding her velum in a more closed position. This would correspond to less nasality (hyponasality) on nasal words and sentences. It is of note that P2 did present with a cold the day of testing, and the presence of nasal mucous could have affected her scores on these tests, making her appear more hyponasal than she may actually be. Further testing of P2's VP function when she does not have a cold is warranted before this speech subsystem is targeted for treatment.

4.2.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

P2's score on the GFTA-2 indicated that she did not always exhibit accurate articulation for consonant sounds, in fact, 99% (or more) of normally developing children her age had fewer errors on the GFTA-2 than she exhibited. Common errors included denasalization, substitution of /s/ for /sh/, devoicing (/s/ for /z/ and /t/ for /d/). The GFTA-2 looks for specific sounds in specific words, but some errors were produced on sounds that were not specifically being targeted. Therefore, incidental errors were also seen that were not addressed in the test per say, but that are present in P2's speech. These errors included addition and/or substitution of /s/ word-finally, final sound deletion (especially nasal sounds), medial sound deletion (especially nasal sounds), voicing errors (/b/ for /p/), and other instances of deletion/substitution of nasal sounds. The pattern of errors that P2 shows could be largely explained by insufficient auditory feedback to precisely guide her articulators.

P2 was inside the normal range for F1 and F2 on two formants: F1 for the vowel /u/, and F2 for the vowel /i/. For all other vowels, she was either lower or higher than the normal range. Refer to P1 for a description of tongue placement for F1 and F2. P2's F1 values were higher than the norm for /uh/ and /ah/ (she was holding her tongue lower), and her F1 values were lower than the norms for /i/ (she was holding her tongue higher). Her F2 values were lower than the norms for /ah/, /uh/, and /u/ (she was holding her tongue farther back in the oral cavity). Interestingly, these data suggest that when P2 produced a vowel outside the normal range, she was overshooting the target frequencies of all the vowels except F2 of /uh/. For example, when producing high front vowels (e.g., /i/), she held her tongue even higher and farther forward; when producing low back vowels (e.g., /ah/), she held her tongue even farther back and lower than the norms. When producing the vowel /uh/, instead of overshooting the F2 frequency and holding her tongue too far forward, she held her tongue too far back in the oral cavity. When compared to other children with CIs, her F1 value for /ah/ was higher than the upper limit of the range obtained by Campisi et al. (2005). Her F2 value for /ah/ was lower than the lower limit of the range defined by Campisi et al. (2005), however it was within the range defined by Uchanski and Geers (2003). Her F2 value for /i/ is within the range defined by Uchanski and Geers (2003). Consistent with other children with CIs, P2 overshot the target vowel positions according to the available norms data on children with CIs.

4.2.5 Coordination of Laryngeal and Oral Articulatory Subsystems

The VOT data show that P2's time for /d/ was within the range of available normal VOT data for normally developing female children age 11 (data available for /b, p, d, and t/); however her times for /b/ and /p/ were longer than the normal range, and her time for /t/ was shorter the normal range. P2 was within the range defined by Higgins et al. (2003) for /d/ and /t/ for children who have CIs. P2's VOT errors could be attributed to insufficient auditory feedback information to allow her to monitor the timing of the onset of voicing, resulting in diminished voice-voiceless cognate distinctions.

4.2.6 Intelligibility Measures

P2's intelligibility score was lower than expected for her age, as unfamiliar listeners were able to understand only 83% of what she said. Intelligibility can be affected by any single measure or a combination of the measures described above, however the speech subsystems that appear to be the most involved for P2 are the larynx, velopharynx, timing of the oral articulators with the larynx, and the oral articulators.

4.2.7 Summary

P2 does not demonstrate any issues with breath support for speech. She does display some deviation from the norms on the voice characteristics of jitter and shimmer; however, as is discussed in the general discussion section, norms for children's voices are not well-established with large groups of children, and as a group, children are extremely variable in voice production. Her value for Rlaw indicates a strained voice quality. P2 overshoots tongue placement for most vowels, but perceptually, her vowel production does not drastically affect her intelligibility. According to a review of the errors that led to misinterpretations by the student listeners and errors from the GFTA-2, the decreases in intelligibility that P2 displays are due to issues with nasalance, articulation, and VOT. Common articulation errors are sound deletion and addition, fronting of velars, sound substitution, and cluster reduction. She demonstrates consistent hyponasality, but this may or may not be due to blockage in her nasal passages due to mucous production secondary to having a cold. The cold may also have impacted the Rlaw values. Further testing is required to rule out this possibility.

Clinically, the focus for treatment might be articulation. She demonstrated many different types of articulatory errors, but consonant deletion and substitution were the most common patterns observed both during standardized testing and incidentally. Goals may include training to increase her awareness of sounds at the end and in the middle of words, and to consistently and correctly produce those sounds. It also may be beneficial to teach her to pronounce the sounds that she does not hear by training her to "feel" where the articulators should be placed for certain sounds (for example, /f/) and the associated airflow.

4.3 Participant 3

4.3.1 Measures of Lung Function and Capacity

Overall, P3 has adequate subglottal pressure for speech.

4.3.2 Measures of Laryngeal Function

P3's values for laryngeal function reveal that she is within the normal range for vocal pitch (Fo) compared to other children her age and sex, and for children with CIs. She showed lower (better) cycle-to-cycle variability in pitch (jitter) than the norms, and her jitter values were within the range for children who have CIs. She also showed lower (better) cycle-to-cycle variability in loudness (shimmer) than the norms and than the range of other children with CIs. P3's value for how much noise is in the signal (NHR) is higher (worse) than the norms for her sex and age and the ranges of the children who have CIs. P3's values for Rlaw were higher than the normal range, however, like P2, her productions were variable, and at least one production is within the normal range. Overall, P3's laryngeal system is functioning adequately. The acoustic parameter that was outside the normal range (NHR) did not deviate substantially, and when taking the SD in account, she was within the normal limit for at least one of three productions. Her NHR also was not corroborated by an abnormal jitter and shimmer, which would be expected if the voice were deviant.

4.3.3 Measures of Velopharyngeal Function

P3's productions on the SNAP test show that she has normal nasalance on nasal and non-nasal sentences. VP area data show that her values for the speech token /pa/ are within the normal range, but her values for the speech token /hamper/ are lower than the normal range (hyponasality). As previously discussed, the differences between nasality measures and the VP area measures may be due to the different speech tokens that were used to gather the data. When the system is required to approximate a VP movement for sentences, the requirements of the system are different than when producing syllables or words. During running speech, P3 may be making other adjustments that make her speech more nasal when required. It is also possible that like P1, P3 has not yet refined the use of that system in response to the auditory information that is available to her. It appears that she has not mastered the fine movements of the velum that are necessary to correctly produce nasal and non-nasal sounds consistently. Those times that she is not producing the correct nasality in words, she may be overcompensating with her velum. This is evidenced by the values indicating that she is holding her velum in a position that is more closed than is appropriate for nasal sounds (hyponasality).

4.3.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

P3's score on the GFTA-2 indicated that she did not always exhibit accurate articulation for consonant sounds, in fact, 94% of normally developing children her age had fewer errors on the GFTA-2 than she exhibited. Her errors included substitution, final consonant deletion, cluster reduction, and addition of a sound in a cluster. The GFTA-2 looks for specific sounds in specific words, but some errors were produced on sounds that were not specifically being targeted. Therefore, incidental errors were also seen that were not addressed in the test per say, but that are present in P3's speech. These errors included other instances of final consonant deletion, addition of /s/ word-finally, and substitution of nasal sounds for non-nasal sounds or non-nasal sounds for nasal sounds. P3's errors could largely be explained by her inability to sufficiently control her velum in response to nasal and non-nasal sounds, as well as insufficient auditory feedback to precisely guide her articulators

P3 was within the normal range for two formants: F1 for /u/, and F2 for /ah/. For all other vowels, she was either lower or higher than the normal range. P3's F1 values were higher than the norm for /ah/ (she was holding her tongue lower), and her F1 value was lower than the norms for /i/ and /uh/ (she was holding her tongue higher). Her F2 values were higher than the norm for /uh/ and /i/ (she was holding her tongue farther forward in her oral cavity), but were lower than the norms for /u/ (her tongue was farther back). Interestingly, these data suggest that when P3 produced a vowel outside the normal range, she was overshooting the target frequencies of all the vowels except F1 and F2 of /uh/. For example, when producing high front vowels (e.g., /i/), she held her tongue even higher and farther forward; when producing low back vowels (e.g., /ah/), she held her tongue even farther back and lower than the norms. When producing the vowel /uh/, instead of overshooting the F2 frequency and holding her tongue too far forward, she held her tongue too far back in the oral cavity. When compared to other children with CIs, her F1 value for /ah/ was higher than the upper limit of the range obtained by Campisi et al. (2005). Her F2 value for /ah/ was higher than the upper limit of the ranges defined by Campisi et al. (2005) and Uchanski and Geers (2003). Her F2 value for /i/ is higher than the range defined by Uchanski and Geers (2003). Consistent with other children with CIs, P1 overshot the target vowel positions for F1 of /ah/

and F2 of /i/, but for F2 of /ah/, her tongue position was more central than other children with CIs.

4.3.5 Coordination of Laryngeal and Oral Articulatory Subsystems

The VOT data show that P2 was not within the range of available normal VOT data for normally developing female children age 7 (data available for /b, p, d, and t/). Her times for /b/ and /t/ were longer than the normal range, and her values for /p/ and /d/ were shorter the normal range. P2's time for /d/ was within the range for children who have CIs, but her time for /t/ was longer than the range as defined by Higgins et al. (2003). Like P2, P3's VOT errors could be attributed to insufficient auditory feedback information to allow her to monitor the timing of the onset of voicing, resulting in diminished voice-voiceless cognate distinctions.

4.3.6 Intelligibility Measures

P3's intelligibility score was lower than expected for her age, as unfamiliar listeners were able to understand only 89% of what she said. Intelligibility can be affected by any single measure or a combination of the measures described above, however the speech subsystems that are most involved for P3 are the larynx, velopharynx and the oral articulators.

4.3.7 Summary

P3 does not demonstrate any issues with breath support. Her values for laryngeal function reveal better production of cycle-to-cycle variability in pitch and loudness (jitter and shimmer, respectively), and normal average pitch (Fo), but a higher than normal amount of noise in her vocal signal (NHR). P2 overshoots tongue placement for most vowels, but perceptually, her vowel production does not consistently affect her intelligibility (but may occasionally). According to a review of the errors that led to misinterpretations by the student listeners, her errors on intelligibility are due to nasality (both hypo- and hypernasality), final consonant deletion, substitution errors due to VOT, addition of /s/ word-finally, and one instance of vowel substitution (/a/ for /E/). Overall, VOT errors resulted in the most confusion for the listeners, as she most often produced a voiceless sound when a voiced sound was the target (/k/ for /g/ and /f/ for /v/). Her errors on the GFTA-2 were mainly due to final consonant deletion, nasalance errors, and addition of /s/ word-finally.

Clinically, the focus of treatment might be to target final consonant deletion and errors in voicing. Goals may include training to increase her awareness of sounds at the end of a word, and to produce the required differences in VOT. It also may be beneficial to teach her to pronounce the sounds that she does not hear by training her to "feel" where the articulators should be placed for certain sounds (for example, /s/) and the associated airflow.

4.4 Participant 4

4.4.1 Measures of Lung Function and Capacity

Overall, P4 has adequate subglottal pressure for speech.

4.4.2 Measures of Laryngeal Function

P4's values for laryngeal function reveal that he demonstrates vocal pitch (Fo) that is in the average range, lower (better) cycle-to-cycle variability in pitch and loudness (jitter and shimmer, respectively) than the norms, and is within normal limits with regard to how much noise is in the signal (NHR). P4's Fo, jitter and shimmer values were within the range of the values of other children with CIs. His NHR value was lower (better) than the ranges of the children who have CIs. P4's Rlaw values were within normal limits. Therefore, there are no concerns with the function of P4's laryngeal system.

4.4.3 Measures of Velopharyngeal Function

P4's productions on the SNAP test show that he has normal nasalance on nasal sentences but he shows slightly higher nasality on sentences that are non-nasal (hypernasality). P4's VP area values for /pa/ (non-nasal) are within the normal range; however his value for the speech token /hamper/ (nasal) is below the normal range, indicating that he is holding his velum in a more closed position. This would correspond to less nasality (hyponasality) on nasal words and sentences. The differences between nasality measures and the VP area measures again may be due to the different speech tokens that were used to gather the data. It is also possible that P4 is variable in the use of his velopharynx because he has not yet refined the use of that system in response to the auditory information that is available to him. It appears that he has not mastered the fine movements of the velum that are necessary for consistently correct production of nasal and non-nasal sounds. Those times that he is not producing the correct nasality in words, he may be overcompensating with his velum. This is evidenced by the values indicating that he is positioning his velum in a more open position than is required on non-nasal sentences (hypernasality), and in a more closed position for nasal sentences (hyponasality).

4.4.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

P4's score on the GFTA-2 indicated that he did not always exhibit accurate articulation for consonant sounds, in fact, 87% of normally developing children his age had fewer errors on the GFTA-2 than he exhibited. His errors were all substitution errors; one substitution of /t/ for /th/, and all other errors were substitutions of /w/ for either /l/ or /r/ within a consonant cluster (e.g., /kw/ for /kr/). P4's errors could largely be explained by insufficient auditory feedback to guide his articulators to precise placements.

P4 was inside the normal range for F1 and F2 on two formants: F1 for the vowel /ah/, and F2 for the vowel /u/. For all other vowels, he was either lower or higher than the normal range. P4's F1 value was higher than the norm for /uh/ (his tongue was being held lower in the oral cavity), and his F1 values were lower than the norms for /u/ and /i/ (he was holding his tongue higher). His F2 values were higher than the norms for /uh/ and /i/ (he was holding his tongue more forward in the oral cavity), but were lower than the norms for /ah/ (his tongue was farther back in the oral cavity). Interestingly, these data suggest that when P4 produced a vowel outside the normal range, he was overshooting the target frequencies of all vowels. For example, when producing high front vowels (e.g., /i/), he held his tongue even higher and farther forward; when producing low back vowels (e.g., /ah/), he held his tongue even farther back and lower than the norms. When compared to other children with CIs, his F1 value for /ah/ was within the range obtained by Campisi et al. (2005). His F2 value for /ah/ was within the ranges defined by Campisi et al. (2005), and Uchanski and Geers (2003). His F2 value for /i/ is higher than the range defined by Uchanski and Geers (2003). Consistent with other children with CIs, P4 is overshooting his tongue position for both formants of /ah/, however, for F2 of /i/, his tongue position was more central than other children with CIs.

4.4.5 Coordination of Laryngeal and Oral Articulatory Subsystems

The VOT data show that P4 was within the range of available normal VOT data for normally developing male children age 9 (data available for /b, p, d, and t/) for /b/; however his times for /t/ and /p/ were longer than the normal range, and his value for /d/ was shorter than the normal range. His time was within the range defined by Higgins et al. (2003) for children who have CIs for /d/, but his time for /t/ was higher than the range. Like P2, and P3, P4's VOT errors could be attributed to insufficient auditory feedback information to allow him to monitor the timing of the onset of voicing, resulting in diminished voice-voiceless cognate distinctions.

4.4.6 Intelligibility Measures

P4's intelligibility score was only slightly lower than is expected for his age, as unfamiliar listeners were able to understand 99% of what he said. Intelligibility can be affected by any single measure or a combination of the measures described above, however the speech subsystems that are most involved for P4 are the timing of oral articulators with the larynx, and the oral articulators themselves.

4.4.7 Summary

P4 does not demonstrate any issues with breath support or laryngeal function. His decreases in intelligibility are mainly due to articulation errors. He does overshoot tongue placement for some vowels, but these are not noticeable enough to interfere with how well unfamiliar listeners can understand him. According to a review of the errors that led to misinterpretation by the listeners, the decrease in intelligibility was due to a final consonant deletion. In this case it is possible that the listener made an error typing the word into the computer, as only one of three listeners indicated that the final sound of that word was not present. This was P4's only error on the intelligibility test. According to the results of the GFTA-2, his errors were largely due to the substitution of /w/ for /l/ and /r/, and one instance of substitution of /t/ for /th/ (unvoiced) word-initially only. He did not exhibit any other incidental errors during the test. Although the tests of VP competence showed some hyponasality, perceptually, P4 did not show drastic hyponasality in his speech.

Because P4 has good intelligibility, treatment may or may not be warranted. Clinically, the focus for P4's treatment might be to correct gliding of liquids /l/ and /r/.

4.5 Participant 5

4.5.1 Measures of Lung Function and Capacity

Overall, P5 has adequate subglottal pressure for speech.

4.5.2 Measures of Laryngeal Function

P5's values for laryngeal function reveal that he demonstrated vocal pitch (Fo) that is higher than expected for his age and sex. He also demonstrated higher (worse) cycle-to-cycle variability in pitch (jitter), lower (better) cycle-to-cycle variability in loudness (shimmer) than the norms, and normal values of how much noise is in the signal (NHR). P5's Fo and jitter values were higher than the values of other children with CIs. P5's shimmer and NHR values were lower (better) than the values collected on children with CIs. P5's values for Rlaw were higher than the normal range. His values for flow were low, and values for oral pressure were adequate, indicating that his voice was "pressed". The quality of his voice perceptually supports this finding. Overall, P5's laryngeal system is somewhat deviant. Perceptually, his voice sounded pressed, and the Rlaw data support the perceptual findings. Although the other two parameters that were outside the normal range (Fo and jitter), did not deviate substantially, nor were they corroborated by an abnormal shimmer and NHR, their values may be an indication that P5 does not have good control of his laryngeal musculature.

4.5.3 Measures of Velopharyngeal Function

P5's productions on the SNAP test indicate that he shows much lower nasality scores than expected on both nasal sentences and non-nasal sentences (hyponasality). P5's VP area values for /pa/ (non-nasal) were lower than the norms for his age, but his value for the speech token /hamper/ (nasal) was within normal range, indicating that he is holding his velum in a more closed position for non-nasal words. This would correspond to less nasality (hyponasality) on non-nasal words and sentences. Overall, P5 seems to hold his velum in a more closed position, which results in hyponasal-sounding speech. In general, the findings from the SNAP test support the findings from the test of VP area, except for the /hamper/ token finding. It is also possible that P5 has not mastered the use of the VP subsystem in response to the auditory information that is available to him, which may lead to variability in the nasality outcomes.

4.5.4 Oral Articulation Measures – GFTA-2 and Formants (F1, F2)

P5's score on the GFTA-2 indicated that he did not always exhibit accurate articulation for consonant sounds, in fact, 72% of normally developing children had fewer errors on the GFTA-2 than he exhibited. His errors were all /r/ substitution errors (/l/ or /w/ for /r/, and t for /th/ - unvoiced). The GFTA-2 looks for specific sounds in specific words, but some errors were produced on sounds that were not specifically being targeted. Therefore, incidental errors were also seen that were not addressed in the test per say, but that are present in P1's speech. These errors included other instances of substitution of /w/ for /r/, vowel misarticulation, and a "slushy" sounding /s/. P5's errors could largely be explained by insufficient auditory feedback to precisely guide his articulators.

Values on formant frequencies show that P5 was inside the normal range for F2 for the vowel /i/. For all other vowels, he was either lower or higher than the normal range. P5's F1 values were higher than the norm for /uh/ and /ah/ (he was holding his tongue lower), and his F1 values were lower than the norms for /u/ and /i/ (he was holding his tongue in a higher position). His F2 values were lower than the norms for /uh/, /ah/ and /u/ (he was holding his tongue farther back in the oral cavity). Interestingly, these data suggest that when P5 produced a vowel outside the normal range, he was overshooting the target frequencies of all the vowels except F2 of /uh/. For example, when producing high front vowels (e.g., /i/), he held his tongue even higher and farther forward; when producing low back vowels (e.g., /ah/), he held his tongue even farther back and lower than the norms. When producing the vowel /uh/, instead of overshooting the F2 frequency and holding his tongue too far forward, he held his tongue too far back in the oral cavity. When compared to other children with CIs, his F1 value for /ah/ was higher than the upper limit of the range obtained by Campisi et al. (2005). His F2 value for /ah/ was within the ranges defined by Campisi et al. (2005), and Uchanski and Geers (2003). His F2 value for /i/ is within the range defined by Uchanski and Geers (2003). Consistent with data from other children with CIs, P5 overshot the target tongue positions for /ah/, and he did so even more for F1 of /ah/.

4.5.5 Coordination of Laryngeal and Oral Articulatory Subsystems

The VOT data show that P5 was within the range of available normal VOT data for normally developing male children age 7 (data available for /b, p, d, and t/) for /b/. His times for /p/, /t/, and /d/ were shorter than the normal range. His values were within the range defined by Higgins et al. (2003) for /d/, but were shorter than the range for /t/ for children who have CIs.

Like P2, P3, and P4, P5's VOT errors could be attributed to insufficient auditory feedback information to allow him to monitor the timing of the onset of voicing, leading to subtle differences in the timing for the voiced and voiceless cognates.

4.5.6 Intelligibility Measures

P5's intelligibility score was only slightly lower than is expected for his age, as unfamiliar listeners were able to understand 98% of what he said. Intelligibility can be affected by any single measure or a combination of the measures described above, however the speech subsystems that are most involved for P5 are the larynx, velopharynx, timing of the onset of voicing with the oral articulators, and the oral articulators themselves.

4.5.7 Summary

P5 did not demonstrate any issues with breath support for speech. He demonstrated a higher-than-expected value for average vocal pitch (Fo) for his age and sex, as well as increased (worse) cycle-to-cycle variability in pitch (jitter). His value for cycle-to-cycle variability in loudness (shimmer) was better than the norms, and he was within normal limits on the amount of noise in the vocal signal (NHR). P5 overshoots tongue placement for most vowels, and occasionally his intelligibility is affected by misarticulating vowels. The decreases in intelligibility that P2 displays are primarily due to issues with vowel substitution and medial consonant deletion. Errors that P5 made on the GFTA-2 both during the standardized portion and through informal observation during the test were primarily due to consonant and vowel substitution errors. Although P5 did display some inconsistency in VP control according to the VP data, his overall intelligibility was not affected negatively as a result.

Clinically, even though P5's overall intelligibility is quite high, the focus for treatment may be articulation therapy, specifically for /r/. Some treatment for the articulation of vowels may also be warranted. The findings for his laryngeal subsystem also indicate that he may benefit from voice treatment to reduce the pressed quality of his voice.

4.6 Overall Findings - Group

All of the children in this study had aided pure-tone audiograms between 20 and 30 dB HL, which is the accepted range for individuals with CIs. The purpose of the aided CI pure-tone audiogram is only to ensure a flat audiogram as a measure of whether or not the CI programming is suitable. The aided audiogram is therefore only used to ensure that there is equal stimulation across frequencies. It is not an indication of the auditory perception of the child (what the child can hear). To measure the auditory perception of the child, speech perception testing is used. The child is asked to identify whether they can hear different speech sounds (the Ling 6 sounds) at varying distances. The Ling sounds are used because these 6 speech sounds include frequencies across the spectrum used in speech. This gives a better indication of the child's auditory perception than does pure-tone audiometry. It is likely that all of the children in this study can hear all speech sounds in a quiet environment through speech perception testing.

Overall, none of the children in this study displayed issues with lung function as measured by subglottal pressure. They all had adequate to more-than-adequate subglottal pressure for speech. This is an exciting finding, as traditionally, children with hearing impairments who wore hearing aids were found to have less control over their breath support for speech (Itoh, Horii, Daniloff, & Binnie, 1982). The investigation conducted by Itoh, et al. (1982) used tasks such as running speech, tidal breathing, sustained phonation, and reading. In the current study, the question was more focused and only queried whether or not these participants could generate enough subglottal pressure to drive the larynx but did not include measures of sustained subglottal pressure. However, in all of the current cases, perceptual parameters of the respiratory subsystem (loudness, breath group length, speed of inspirations and general breathiness) were not apparent.

As a group, the children were variable in their voice productions, more so on measures of cycle-to cycle variability and noise in the vocal signal than for vocal pitch. Four out of five children had average pitch (Fo) that was in the normal range, and the other child produced average pitch that was higher than expected for his sex and age. Compared to the Higgins et al. (2003) study, where it was found that the children produced fundamental frequencies that were consistently higher than the norm, four of the children in the current study produced average Fo. On the remaining measures of voice, three children had better jitter values than the norm, and the other two had jitter values that were higher (worse) than the norms. Four of the children produced better shimmer and NHR values than the norms, whereas only one child presented with a value that was worse than the norms. Two of the children displayed Rlaw values that were higher than the means, and those values were supported by perceptual observation of strained and pressed vocal qualities. The other three children did not display voice characteristics that would be considered perceptually deviant.

In terms of velopharyngeal function, all of the children exhibited some deviation from normal ranges on one or more measure. In terms of nasality measured by the Nasometer, three of the five children produced normal nasalance on nasal sentences, and two produced normal nasalance on non-nasal sentences. Two children produced hyponasal speech on nasal sentences. Two children produced hypernasal speech and one child produced hyponasal speech on non-nasal sentences. For measurements of VP area, four of the children were within normal limits, and one was holding his velum more closed (hyponasal) on the speech token /pa-pa/. For the speech token /hamper/, only one child was within normal limits, whereas the other four showed hyponasalance, holding the velum in a more closed position than was appropriate for producing nasal sounds. In addition to some productions that were within the normal range, two of the children showed both hypo- and hypernasality. The other three children produced hyponasal speech as well as some productions that were within normal limits. The variability of hyponasality and hypernasality surrounding islands of normal nasality in these children demonstrates that this subsystem is not managed appropriately in this group of children. In order to correctly produce nasal and non-nasal sounds consistently, it is necessary to master the fine movements of the velum in response to auditory feedback. The results of the current study differ slightly from other studies of children with CIs. In the studies discussed previously, children with CIs were found to be either hyponasal or they were within normal limits (Van Lierde et al., 2005; Uchanski & Geers, 2003). It is important to note that although the children in those studies are similar to the children in the current study, the Uchanski and Geers (2003) study used a different measurement of nasality (nasal manner metric), which may affect the ability to compare between studies. In the current study, the children showed variability in VP opening, with two of the children showing both hypo- and hypernasality, and three children producing both normal and hyponasal speech.

Consonant production was a particular area of difficulty for all five children. The most common error patterns were (in order of occurrence from most to least common): consonant substitution; voicing errors (either devoiced or voiced); nasalization or denasalization; addition/substitution of final /s/; final consonant deletion; and turbulent /s/ production.

Vowel production data produced an interesting result. Only one child was outside the normal range on all vowels. The other four children were within normal limits for at least one formant on one vowel. All of the children presented with the same overall pattern of vowel production. When the children were not within the normal range for both F1 and F2, all of them tended toward overshooting the target frequencies, meaning that instead of centralizing the vowels by minimally moving the tongue, they positioned their tongues toward the correct direction, but they moved them too much. Two children deviated from this pattern for F2 of /uh/, and one child deviated from the pattern for F1 of /uh/. When producing /uh/, instead of overshooting the F2 frequency and holding the tongue too far forward, they both held their tongue in the opposite position; too far back. The child who deviated on F1 of /uh/ was holding her tongue too high. Both children showed the same pattern of overshooting the formant frequencies as the other children for all other vowels. Traditionally, children with hearing impairments who wore hearing aids tended to centralize vowels, that is, they were not moving their tongues enough (Monsen, 1976; Angelocci, Kopp, & Holbrook, 1964). The pattern observed in the Angelocci et al. (1964) study was that the deaf participants' formants were lower for the hearing impaired children than the normal controls. The current study revealed the opposite pattern, that these children's formant values are higher than the norms. These children are not just moving their tongues to get to the vowel target; they are actually moving their tongues too far. Unfortunately for the children in the current study and other children with CIs (Campisi et al., 2005; Uchanski & Geers, 2003), overshooting vowel frequencies could be interpreted as both an advantage and a disadvantage. While overshooting tongue placement allows the child and the listener to distinguish differences between vowels, it is a less economical movement as the child moves from one sound target to the next. It means that the child's tongue must move farther to reach the appropriate co-articulatory placements, and as a result, may mean that the child misses a place of articulation for a consonant after producing the vowel. The result may be an overall decrease in intelligibility.

Analysis of VOT data revealed that four of the children showed some deviation from the normal ranges, while one child was within normal limits. VOT normative data is only available on /p, b, t, d/, therefore the information on /k,g/ is difficult to interpret relative to what is typical. The four children in this study who were not within the normal range produced variable productions on the distinction between voiced and voiceless sound pairs. Two children produced the voiceless sound /p/ and the voiceless sound /t/ with a shorter VOT and two produced it with a longer VOT. Three children produced the voiced sound /d/ with a shorter VOT, and two produced it within the normal range. Three children produced the voiced sound /b/ within normal limits, and two produced it with a longer VOT. When VOT is too long or short, the distinction between voiced and voiceless cognates becomes blurry, and the resulting production may not be what the speaker intended. These data support the theory discussed by Higgins et al. (2001), which suggests that having appropriate auditory feedback promotes adequate monitoring of the coordination of the articulatory and laryngeal subsystems. This could be taken to mean that the monitoring of the auditory signal allows the speaker to make small adjustments of the coordination of the speech mechanism to reach target speech sounds. When auditory information is missing, large adjustments may still be made (such as place of articulation), but the small precise adjustments necessary to distinguish between sounds that differ only in the onset of voicing are more difficult to make. Despite the lack of a robust set of auditory information, these children still manage to adjust their systems well enough most of the time to be understood more often than not.

All of the children in this study were over 82% intelligible, with two children 98% intelligible and above. This result demonstrates that even though these children may be outside the normal limits on many of the measures described in this study, they still manage to be heard and understood quite well by unfamiliar listeners. The child's ability to approximate the target speech sounds, combined with the listener's cognitive ability to synchronize different types of information including: contextual information; stored knowledge regarding the structure of the language system (e.g., word order); and the knowledge of the structure and acoustic patterns of words in the language contribute to how well the listener will understand what the speaker is saying. It is probable that to familiar listeners (i.e., parents, teachers, siblings, etc.), these children are even more intelligible, as the listeners become more familiar with the specific patterns of the child's approximations of speech targets.

4.7 General Discussion

The comprehensive evaluation of all of the speech subsystems in the same children with CIs is what makes this study unique. In order to understand how auditory feedback influences motor learning for speech, it is important to gather information about the physiology of speech-motor control in these children. During the process of speech development, the child's goal is to learn how to fine-tune the movements and coordination of the speech subsystems with increasing accuracy and economy of effort to produce the acoustically distinguishable contrasts of the sounds of their language. The sensory systems that contribute to the feedback for speech-motor control include auditory (sound), kinesthetic (movement sensation), and mechanoreceptive (e.g., pressure of tongue to alveolar ridge), which provide sensory information that is integrated and used for producing and monitoring speech. However, these data may suggest that motor planning for the more finely-tuned production of speech largely depends more on acoustic targets than on other sensory inputs.

Children with hearing loss possess intact speech-motor systems; that is, there are no issues with the structures themselves. Rather, they have an imprecise speech-motor target because they cannot hear it, and in addition, they have limited access to auditory feedback. When a child who is profoundly hearing impaired receives a CI or a hearing aid, more auditory information becomes available to him or her. Although CIs restore some auditory information, the sound that they provide is not the same as having normal hearing. CI technology has made dramatic advancements, and the acoustic information that CIs provide is better than ever; however, there are limits to what the technology can provide presently. Limitations in information exist for frequency, amplitude and especially timing. Speech carries copious amounts of acoustic cues, including spectral and timing cues. According to Nie, Barco, and Zeng (2006), modern CIs only crudely encode these types of cues, especially timing cues. Therefore, it may be inferred that CI users may miss important timing cues at the perceptual level and subsequently inaccurately produce some acoustic speech targets. This issue becomes exaggerated even more when the CI user is listening in noise, a common listening situation (Nie & Zeng, 2004). Some CI users can achieve high levels of speech recognition in quiet but have great difficulty listening in noise (Nie et al., 2006; Nie & Zeng, 2004). The children in this study were found to have issues with several measures that require precise timing between subsystems, such as nasalance and VOT measures. Small adjustments in VOT can cause listeners to make errors in perceiving certain phonemes (i.e., ba vs. pa). In general, the values for voiced stops range from -20 ms to 20 ms, and voiceless stops range from 25 ms to as much as 100 ms (Kent & Read, 1992). The boundary region for voiced and voiceless stops is therefore between 20 ms and 25 ms, where the distinction between sounds becomes blurry (Kent & Read, 1992). Small adjustments in VOT surrounding this boundary area are therefore difficult to make and are vulnerable to misinterpretation by the listener. Measurements of VOT from the children in this study suggest that timing from the processor to cochlea stimulation may not be as refined as that of typical hearing and may, in part, contribute to aberrant VOT for certain obstruent productions.

Discriminating sounds in noise may also be an issue for these children. Sounds such as /s/, /f/, and /th/ are acoustically quieter and are also produced at a higher frequency than voiced sounds such as vowels and voiced consonants. Therefore the less intense, higher frequency sounds may get overpowered by the louder, lower frequency sounds that surround them (a concept known as masking) (Bess & Humes, 2003). This phenomenon occurs in normal hearing individuals, but the effect is more pronounced in an individual with hearing loss. Soft sounds in general are not as salient as loud sounds to a listener, and are even less salient in every-day noisy listening environments. These sounds are therefore the most at-risk to be acquired optimally, and may not be used consistently by individuals with a CI. This is due in part to the fact that CI users are hearing and monitoring these sounds through a device that may not be providing the optimal listening and feedback conditions and a brain that has not had the chance to encode the characteristics of speech that distinguish different speech sounds. In essence, the auditory signal is not optimal, which puts an increased demand on the brain to make sense of the signal and to process and extract auditory information. Despite these seemingly unfavorable conditions, and although the speech and voices of the children in this study deviate from the norms on many of the measures described, they still manage to achieve levels of intelligibility that are remarkably high.

4.8 Limitations

Although it was the goal of this research study to be thorough and measure each speech subsystem in all of the children, there were other measures that could have also been recorded and related to a subsystem. For example, a sustained /ah/ could have easily been gathered, and would have provided more information about the respiratory system and its ability to produce adequate subglottal pressure relative to a changing lung volume. In addition, other measures that could capture the interaction of respiration, phonation, and articulation such as sustained phonation, spontaneous speech tasks, and reading could have been used to get even more information about the interaction of the speech subsystems of children with CIs. It may be desirable for future research to tackle this issue and complete an even more comprehensive evaluation, utilizing other techniques for gathering information about the speech subsystems in children with CIs.

In order to acquire the most accurate representation of the children's productions, it would be desirable to have the children come for testing more than once, and to produce a greater amount of tokens per task. This would increase the chance that the child's productions are typical of their everyday speech patterns, and decrease the chance that the child's productions are influenced by situational incidences (i.e., having a cold; anxiety).

It is always desirable to include as many participants as possible in research such as this. Unfortunately, the timeframe and scope of this project were somewhat limited. This research was completed as a research component of the requirements of a Masters thesis, and it was imperative that it was a manageable project for a two and a half year program. Had there been more flexibility in the timeframe and scope, more participants may have been recruited. If this was the case, more trends in the data may have emerged, and the participants may have been divided into groups based on age at implant and type of communication program. Instead, the data are presented as individual case studies with general overall observations of the participants as a group of children with CIs. Finally, the participants whose parents were interested in participating in the study were somewhat closely grouped in age (ages 7-10). It would be desirable to have an even larger age range, especially children ages 4-6 who were implanted early (before age 3), and have been using their implants for more than 2 years.

A worrisome limitation of the research in this area is the lack of child norms for many of these measurements. When normative data is available, it is questionable at best due to both the small numbers of children included, as well as a high variability of many of the measures in children. A large database (>100) of normative information of the speech subsystems in typically developing children is desperately needed, particularly for VOT, vowel formants, and measures of Rlaw and VP area. In the comparisons for this study, the following norms were age and gender matched: VOT; Rlaw; and one of the norms for Fo.

The following norms were group norms, where the group N was 21: Fo; Jitter; Shimmer; and NHR. The VP norms (/pi/ and /hamper/) were group norms where the N was 8-10. The group norms for F1 and F2 were taken from an N of 20-39 for the male norms and 14-38 for the female norms (there were different Ns for different age groups).

5. Future Research

It would be interesting to know if there are similar changes in the speech mechanism in children with similar levels of hearing loss (and lesser degrees of hearing loss) who wear hearing aids. With programs such as newborn infant hearing screening becoming available to parents, children with hearing loss are being detected earlier, and the opportunity for earlier implementation of hearing devices including hearing aids and CIs is being provided.

There is some indication (from this study and from previous research) that children who rely more heavily on auditory input and who do not use visual languages (e.g., American Sign Language; Signed Exact English) have greater intelligibility scores than children who are exposed to some sort of visual language input in addition to audition. The explanation for this observation requires further research, perhaps utilizing brain imaging technology to understand the type of input in relation to neural plasticity and motor planning for speech.

It would be beneficial for future research to examine the speech subsystems of children with CIs with larger numbers of participants so trends that might emerge in the data may be statistically confirmed. Future research in this area that includes a greater range in age will also add information about the relationship between age at implant, auditory feedback, and the development of speech motor control in children with CIs.

6. Conclusion

Describing the speech subsystems of children with CIs contributes information about the role that auditory feedback plays in the development of the speech mechanism in this group. The data from this research suggest that these children are in the midst of refining their speech-motor systems in response to the auditory information provided by their CIs. Knowing the outcomes of the speech of children with CIs and with hearing aids will contribute information to assist parents when they are faced with difficult decisions for their infant with hearing loss. In addition, knowing what speech subsystems may be involved the most for children with CIs and hearing aids may guide clinicians to know what subsystem(s) to test first, what subsystem(s) may be targeted initially in therapy, and what to expect in terms of speech outcomes for these children.

7. Tables

Table 1: Demographics Data

P #	Sex	Age at testing	Age at implant (when processor turned on)	Duration of CI use as of Sept 2007	Type of Implant	Processing strategy	Unaided auditory thresholds		Post implant aided auditory threshold averages
							Left Ear	Right Ear	
1	f	9;6	3:0 (22 days) right side	7 years	Clarion Hi Focus 1.2: platinum series ear level device	SAS speech processing strategy	103 dB HL	105 dB HL	30 dB HL
2	f	10;5	5:3 (18 days) right side	5 yrs 9 mos	Advanced Bionics II with positioner	30-70 mixing ratio – Hi-Res Strategy since Aug '02	>115 dB HL	no measurable hearing	25 dBHL
3	f	8;3	5:3 (29 days) right side	3yrs 5 mos	Advanced Bionics 90k	Hi-Res Paired programming mode	102 dB HL	>110 dB HL	30 dB HL
4	m	9;0	3:0 (24 days) right side	6 yrs 6 mos	Clarion Hi Focus II	PSP with SAS speech processing strategy (body worn)	105 dB HL	100 dB HL	25 dB HL
5	m	7;4	1:2 (9 days) right side	6 yrs 5 mos	Clarion CII with positioner (Advanced Bionics)	Hi-Res with Platinum series processor (body worn)	no measurable hearing	no measurable hearing	20 dB HL

Table 2: Aerodynamic Measures (PERCI) and Norms

Participant #	SubG Press (cmH$_2$0) (SD)	Rlaw (cmH$_2$0/l/s) (SD)	VP area - /papa/ (cm^2) (SD)	VP area - /hamper/ (cm^2) (SD)
1	**13.5 (2.13)**	*	**0.013 (0.009)**	**0.003 (0.002)**
Strathopoulos & Sapienza (97) F age 10		79.04 (35.51)		
Smith et al., 2004 M and F age 9-13			.21 mm^2 (.22 mm^2)	.97 mm^2 (.86 mm^2)
2	**9.7 (1.85)**	**274.83 (238.91)**	**0.004 (0)**	**0.004 (0)**
Strathopoulos & Sapienza (97) F age 10		79.04 (35.51)		
Smith et al., 2004 M and F age 9-13			.21 mm^2 (.22 mm^2)	.97 mm^2 (.86 mm^2)
3	**13.2 (2.39)**	**173.05 (33.42)**	**0.001 (0)**	**0.001 (0.001)**
Strathopoulos & Sapienza (97) F age 8		105.51 (43.47)		
Smith et al., 2004 M and F age 5-8			.15 mm^2 (.12mm^2)	.44 mm^2 (.61 mm^2)
4	**6.9 (0.40)**	**92.67 (26.83)**	**0.006 (0.001)**	**0.005 (0)**
Strathopoulos & Sapienza (97) M age 10		87.02 (50.63)		
Smith et al., 2004 M and F age 9-13			.21 mm^2 (.22 mm^2)	.97 mm^2 (.86 mm^2)
5	**6.7 (1.16)**	**329.18 (20.08)**	**0.003 (0.001)**	**0.011 (0.007)**
Strathopoulos & Sapienza (97) M age 8		78.30 (28.66)		
Smith et al., 2004 M and F age 5-8			.15 mm^2 (.12mm^2)	.44 mm^2 (.61 mm^2)

*missing data due to a leak in the mask

** norm data for VP area (non-nasal) collected with /pi/ (not /pa/)

Table 3: Acoustic Measures: Fo, Jitter, Shimmer, NHR and Norms

Participant #	Fo /ah/ (Hz) (SD)	Jitter (%) (SD)	Shimmer (%) (SD)	NHR (%) (SD)
1	**276 (8)**	**1.347 (0.420)**	**0.260 (.053)**	**0.110 (0.007)**
Norm (4-11) (Campisi et al., 02)	279.05 (5.79)	1.24 (.07)	3.35 (.12)	.11 (.002)
Strathopoulos & Sapienza (97) F age 10	245.75 (29.24)			
Lee et al., (1999) F age 9	267 (33)			
CI kids Seifert et al. (02) – /ah/ F age 10;2	225			
CI kids Hocevar-Boltezar et.al., (05) - 24 mos post - M and F	315.07 (49.69)	0.88 (0.53)	3.23 (1.51)	0.11 (0.01)
CI kids Van Lierde et al., (05) Mand F	296.83 (38.4)	0.55 (0.10)		
2	**274 (22)**	**1.33 (n/a)**	**0.23 (n/a)**	**0.132 (0.16)**
Norm (4-11) (Campisi et al., 02)	279.05 (5.79)	1.24 (.07)	3.35 (.12)	.11 (.002)
Strathopoulos & Sapienza (97) F age 10	245.75 (29.24)			
Lee et al., (1999) F age 9	267 (33)			
CI kids Seifert et al., (02) – /ah/ F age 10;2	225			
CI kids Hocevar-Boltezar et al., (05) - 24 mos post - M and F	315.07 (49.69)	0.88 (0.53)	3.23 (1.51)	0.11 (0.01)
CI kids Van Lierde et al., (05) Mand F	296.83 (38.4)	0.55 (0.10)		
3	**291 (15)**	**1.080 (n/a)**	**0.560 (n/a)**	**0.113 (0.017)**
Norm (4-11) (Campisi et al., 02)	279.05 (5.79)	1.24 (.07)	3.35 (.12)	.11 (.002)
Strathopoulos & Sapienza (97) F age 8	258.46 (15.03)			
Lee et al., (1999) F age 9	267 (33)			
CI kids Seifert et al., (02) – /ah/ F age 8;2	229			
CI kids Hocevar-Boltezar et al., (05) - 24 mos post - M and F	315.07 (49.69)	0.88 (0.53)	3.23 (1.51)	0.11 (0.01)
CI kids Van Lierde et al., (05) Mand F	296.83 (38.4)	0.55 (0.10)		

Table 3 con't...

Participant #	Fo /ah/ (Hz)	Jitter (%)	Shimmer (%)	NHR (%)
4	**258 (6)**	**0.820 (.085)**	**0.185 (0.007)**	**0.096 (.020)**
Norm (4-11) (Campisi et al., 02)	279.05 (5.79)	1.24 (.07)	3.35 (.12)	.11 (.002)
Strathopoulos & Sapienza (97) M age 10	230.12 (17.07)			
Lee et al., (1999) M age 9	253 (40)			
CI kids Seifert et al., (02) – /ah/ M age 9	240			
CI kids Hocevar-Boltezar et al., (05) - 24 mos post - M and F	315.07 (49.69)	0.88 (0.53)	3.23 (1.51)	0.11 (0.01)
CI kids Van Lierde et al., (05) Mand F	296.83 (38.4)	0.55 (0.10)		
5	**196 (24)**	**1.698 (0.369)**	**0.493 (0.100)**	**0.146 (0.011)**
Norm (4-11) (Campisi et al., 02)	279.05 (5.79)	1.24 (.07)	3.35 (.12)	.11 (.002)
Strathopoulos & Sapienza (97) M age 8	278.45 (42.38)			
Lee et al., (1999) M age 7	264 (40)			
CI kids Seifert et al., (02) – /ah/ M age 7;4	165			
CI kids Hocevar-Boltezar et al., (05) - 24 mos post M and F	315.07 (49.69)	0.88 (0.53)	3.23 (1.51)	0.11 (0.01)
CI kids Van Lierde et al., (05) Mand F	296.83 (38.4)	0.55 (0.10)		

Table 4: Nasalance and Norms

Passage	Norm Mean(SD)	P1	P2	P3	P4	P5
		score	score	score	score	score
Oral Passages						
A	11 (5)	13	17.67	8.3	13.33	4
B	11 (5)	26.67	17	7.67	13	4.33
C	13 (6)	24.33	15.67	9.5	13.33	4
D	12 (5)	19.67	6	10	15	4.67
Nasal Passage						
E	54 (9)	58.67	6	49.67	66	37

A – Bilabial Plosives - Pick up the… (book, pie, baby).
B – Lingual-Alveolar Plosives - Take a… (turtle, tire, teddy bear).
C – Velar Plosives - Go get a… (cookie, car, cake).
D – Sibilant Fricatives - Suzy sees the… (scissors, horse, dress).
E – Nasals - Mama made some… (mittens, muffins, lemonade).

Table 5: GFTA-2 Scores

Participant #	Age	Score on GFTA-2
1	9;6	10 (1 %ile)
2	10;5	17 (<1 %ile)
3	8;3	8 (6 %ile)
4	9;0	4 (13 %ile)
5	7;4	4 (28 %ile)

Table 6: F1 and F2 Participant data and norms

Participant #	/uh/ F1 (Hz) (SD)	/uh/ F2 (Hz) (SD)	/ah/ F1 (Hz) (SD)	/ah/ F2 (Hz) (SD)	/u/ F1 (Hz) (SD)	/u/ F2 (Hz) (SD)	/i/ F1 (Hz) (SD)	/i/ F2 (Hz) (SD)
1	**874 (34)**	**1785 (80)**	**996 (82)**	**1500 (164)**	**330 (0)**	**1328 (351)**	**281 (15)**	**3519 (47)**
difference	higher	higher	higher	lower	lower	lower	lower	higher
F age 9 Lee et al. (99)	652 (51) 601-703	1506 (107) 1399-1613	801 (48) 753-849	1658 (144) 1514-1802	505 (44) 461-549	1764 (220) 1544-1984	455 (61) 394-516	3061 (140) 2921-3201
CI kids Campisi et al. (05)			862.8 (43.4)	1399.6 (60.7)				
CI kids Uchanski & Geers (03)				1408 (143)				3003 (237)
2	**804 (n/a)**	**1224 (n/a)**	**1018 (n/a)**	**1319 (n/a)**	**445 (n/a)**	**1134 (n/a)**	**366 (6)**	**3020 (124)**
difference	higher	lower	higher	lower	in range	lower	lower	in range
F age 10 Lee et al. (99)	636 (51) 585-687	1689 (240) 1449-1929	791 (79) 712-870	1748 (118) 1630-1866	496 (54) 442-550	1747 (280) 1467-2027	472 (45) 427-517	2969 (134) 2835-3103
CI kids Campisi et al. (05)			862.8 (43.4)	1399.6 (60.7)				
CI kids Uchanski & Geers (03)				1408 (143)				3003 (237)

Table 6 con't...

Participant #	/uh/ F1 (Hz) (SD)	/uh/ F2 (Hz) (SD)	/ah/ F1 (Hz) (SD)	/ah/ F2 (Hz) (SD)	/u/ F1 (Hz) (SD)	/u/ F2 (Hz) (SD)	/i/ F1 (Hz) (SD)	/i/ F2 (Hz) (SD)
3	**1109 (59)**	**1584 (242)**	**1167 (40)**	**1691 (37)**	**412 (51)**	**1134 (111)**	**333 (28)**	**3568 (57)**
difference	higher	higher	higher	in range	in range	lower	lower	higher
F age 8 Lee et al. (99)	664 (77) 587-741	1450 (90) 1360-1540	848 (60) 788-908	1693 (109) 1584-1802	426 (80) 346-506	1539 (165) 1374-1704	428 (46) 382-474	2997 (201) 2796-3198
CI kids Campisi et al. (05)			862.8 (43.4)	1399.6 (60.7)				
CI kids Uchanski & Geers (03)				1408 (143)				3003 (237)
4	**867 (43)**	**1707 (29)**	**849 (45)**	**1348 (121)**	**309 (16)**	**1707 (137)**	**310 (15)**	**3328 (124)**
difference	higher	higher	in range	lower	lower	in range	lower	higher
M age 9 Lee et al. (99)	626 (54) 572-680	1472 (124) 1348-1596	793 (75) 718-868	1529 (137) 1392-1666	471 (73) 398-544	1603 (225) 1378-1828	382 (62) 320-444	2979 (147) 2832-3126
CI kids Campisi et al. (05)			862.8 (43.4)	1399.6 (60.7)				
CI kids Urch&G(03)				1408 (143)				3003 (237)
5	**733 (59)**	**1380 (237)**	**1005 (31)**	**1355 (45)**	**309 (16)**	**915 (51)**	**374 (8)**	**3191 (145)**
difference	higher	lower	higher	lower	lower	lower	lower	in range
M age 7 Lee et al. (99)	624 (66) 558-690	1542 (136) 1406-1678	815 (94) 721-909	1642 (148) 1494-1790	449 (82) 367-531	1700 (236) 1464-1936	425 (46) 379-471	3002 (191) 2811-3193
CI kids Campisi et al. (05)			862.8 (43.4)	1399.6 (60.7)				
CI kids Uchanski & Geers (03)				1408 (143)				3003 (237) 2766-3240

Table 7: VOT Participant data and norms

Participant #	VOT /ba/ (ms) (SD)	VOT /pa/ (ms) (SD)	VOT /da/ (ms) (SD)	VOT /ta/ (ms) (SD)	VOT /ka/ (ms) (SD)	VOT /ga/ (ms) (SD)
1	**12.8 (3.4)**	**55.0 (32.3)**	**15.8 (4.3)**	**83.8 (16.0)**	**66.1 (21.4)**	**23.4 (7.8)**
Whiteside & Marshall (01) F age 9	15.9 (6.5) 9.4-22.4	72.3 (20.6) 51.7-92.9	24.4 (9.2) 15.2-33.6	100.4 (21.4) 79-121.8		
CI kids Uchanski & Geers (03)			17 (9) 8-26	80 (21) 59-101		
Higgins et al. (03) F age 10;2		12.3				
2	**21.1 (4.5)**	**78.2 (9.6)**	**21.4 (12.5)**	**62.1 (29.7)**	**123.7 (10.4)**	**59.4 (31.1)**
Whiteside & Marshall (01) F age 11	15.5 (4.9) 10.6-20.4	47.4 (11.9) 35.5-59.3	20.6 (4.8) 15.8-25.4	89.0 (14.9) 74.1-103.9		
CI kids Uchanski & Geers (03)			17 (9) 8-26	80 (21) 59-101		
Higgins et al. (03) F age 10;4		8.7				
3	**23.5 (3.2)**	**36.0 (10.7)**	**16.8 (5.3)**	**130.0 (18.9)**	**101.4 (59.6)**	**28.7 (13.0)**
Whiteside & Marshall (01) F age 7	13.8 (6.5) 7.3-20.3	84.2 (28.3) 55.9-112.5	28.6 (6.5) 22.1-35.1	96.0 (17.6) 78.4-113.6		
CI kids Uchanski & Geers (03)			17 (9) 8-26	80 (21) 59-101		
Higgins et al. (03) F age 8;2		10.1				
4	**18.8 (1.2)**	**157.4 (29.3)**	**11.6 (4.4)**	**160.0 (36.0)**	**120.5 (32.6)**	**42.0 (41.4)**
Whiteside & Marshall (01) M age 9	15.4 (4.1) 11.3-19.5	76.9 (30.4) 46.5-107.3	33.9(18.7) 15.2-52.6	109.6 (32.0) 77.6-141.6		
Urch & Geers (03) CI kids			17 (9) 8-26	80 (21) 59-101		
Higgins et al. (03) M age 9;1		8.7				
5	**14.3 (6.5)**	**23.3 (13.3)**	**10.3 (2.4)**	**30.1 (11.4)**	**48.5 (12.9)**	**20.6 (2.3)**
Whiteside & Marshall (01) M age 7	10.9 (4.5) 6.4-15.4	63.0 (20.9) 42.1-83.9	27.5 (10.3) 17.2-37.8	96.3 (15.3) 81-111.6		
Urch & Geers (03) CI kids			17 (9) 8-26	80 (21) 59-101		
Higgins et al. (03) M age 7;5		26.4				

Table 8: Intelligibility Scores

Participant #	Percent Intelligibility
1	85% (8.2)
2	83% (3.8)
3	89% (1.4)
4	99% (1.7)
5	98% (1.7)

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9. Appendices

9.1 Phone Script

Script for contacting parents of children with cochlear implants for Carrie Timgren's research study titled, *Physiological Measures of Speech and Voice Outcomes in Children with Cochlear Implants.*

Hi, this is _________from the Glenrose Hospital calling. How are you doing? Is now a good time to talk? Today I am phoning on behalf of a student named Carrie Timgren who is working on her Masters degree in Speech-Language Pathology at the University or Alberta. She is conducting a study to better understand how cochlear implants affect speech development in young children. The research that Carrie is doing is very exciting, and will add lots of information to our knowledge of how children with hearing loss who wear cochlear implants learn to talk. I'm calling you because your son or daughter has a cochlear implant and is eligible for the study. If you would be willing to consider participating in the study, I can send you an information letter that describes the study in more detail. In general, Carrie will be taking measurements of the different speech structures while your child is talking. These structures include the lungs, vocal folds, velopharynx (which controls the air coming out of the nose) and movements of the lips, jaw and tongue. The activities involve looking at pictures and working on computers, and most children find these tasks enjoyable. Carrie is also interested in measuring how well your child is understood by others. She is trying to see whether the age at which a child receives a cochlear implant influences any or some combination of these measures. You will receive a written report on the results of your child's assessment for your own information and use. This study and others like it will help us learn more about how to provide treatment to children of different ages who have received implants at different times.

So, if you are interested, we will send you the information letter, and then you can call Carrie and speak with her to learn more details about what your child will be doing with her. You and your child will be invited to visit Corbett Hall on the U of A campus, and your parking and other travel expenses will be covered. You will be with your child at all times. Carrie is excited to work with children with cochlear implants and she looks forward to hearing from you. If you have any questions, or want more information about the study, you can contact her and she will call you back. The laboratory number is: 780-492-7256.

Thank you.

9.2 Recruitment Letter to Parents

UNIVERSITY OF ALBERTA

Dear Parent,

My name is Carrie Timgren, and I am a graduate student at the University of Alberta. I am pursuing my Masters degree in the Speech-Language Pathology and Audiology program. I am writing to invite you and your child to participate in a research study. This study is about speech development in children with cochlear implants. You and your child are eligible to be in this study because your child has been fitted with a cochlear implant.

I am studying how cochlear implantation affects speech development in young children. I want to understand the factors that play a role in how well a child is understood. These are things like tongue placement for sounds, control of the air coming out of the mouth and nose, vocal fold behavior, and the breath support for speaking. Another factor may be the child's age when implanted. These things may play an important role in how well other people can understand them.

We will be measuring these factors to find out how each system develops for speech in children with cochlear implants. The systems we are looking at are: oral; air control out of the nose and mouth; vocal folds; and breath support.

If you are interested in participating in this study, please contact Carrie Timgren at 492-7256. More information about the procedures will be provided.

Thank you,

Carrie Timgren
MSc-SLP thesis student

9.3 Ethics Approval

January 22, 2007

Dr. Melanie Campbell
Speech Language Pathology
2-70 Corbett Hall

File# B-101006

Re: Physiological and Acoustic Measures of Speech and Voice Outcomes in Children with Cochlear Implants

Dear Dr. Campbell:

Thank you for your correspondence received November 28, 2006, and January 12, 2007, which addressed the requested revisions to the above-mentioned study. These changes have been reviewed and approved on behalf of the Research Ethics Board. Your approval letter is attached.

In order to comply with the Health Information Act, a copy of the approval form is being sent to the Office of the Information and Privacy Commissioner.

Next year, a few weeks prior to the expiration of your approval, a Progress Report will be sent to you for completion. If there have been no major changes in the protocol, your approval will be renewed for another year. All protocols may be subject to re-evaluation after three years.

For studies where investigators must obtain informed consent, signed copies of the consent form must be retained, and be available on request. They should be kept for the duration of the project and for a full calendar year following its completion.

Approval by the Health Research Ethics Board does not encompass authorization to access the patients, staff or resources of Capital Health or other local health care institutions for the purposes of research. Enquiries regarding Capital Health administrative approval, and operational approval for areas impacted by research, should be directed to the Capital Health Regional Research Administration office, #1800 College Plaza, phone 407-6041.

Sincerely,

Charmaine N. Kabatoff
Administrative Coordinator
Health Research Ethics Board (Panel B)

9.4 Information Letter – Parent/Child

UNIVERSITY OF ALBERTA

Parent Information Letter

Project Title: *Physiological and acoustic measures of speech and voice outcomes in children with Cochlear Implants.*
Investigator (s):
Co-Supervisors: Drs. Carol Boliek and Melanie Campbell
Carrie Timgren, BA; MSc-SLP thesis candidate

Throughout this information sheet the words "you" and "your" refer to the research participant.

Purpose of Study

You and your child are being asked to participate in a research study. This study is investigating how cochlear implantation affects speech development in young children. We want to understand the factors that play a role in how well a child is understood when talking to others. These are things like tongue placement for sounds, control of the air coming out of the mouth and nose, what is happening at the level of the child's vocal folds, and the child's breath support. Another factor affecting speech may be the child's age when he/she got their implant. During this study, Carrie Timgren (a Master's Degree Student at the University of Alberta in the Department of Speech Pathology and Audiology) will be taking indirect measurements of the different speech structures. These include the lungs, vocal folds, velopharynx (control of air coming out of the nose), and movements of the lips, jaw and tongue. We are trying to see whether the age at which a child receives a cochlear implant (CI) influences these measures.

Procedure:

You and your child will be invited to Corbett Hall on the University of Alberta campus. We will then begin the procedures for measuring speech production. The procedures will take between one and two hours to complete. In addition to these measures, an assigned member of the Glenrose staff will extract pertinent information about the implant your child received; including: your child's date of birth; date at implantation; duration of CI use; most recent auditory thresholds; and his/her speech perception and speech production measurements. This information will be placed under your child's assigned subject number only and not by his or her name.

Lungs

In order to measure the functioning of the lungs for speaking, we will first get your child to blow into a U-tube manometer. This is just a small U-shaped glass tube filled with water. This procedure will be similar to blowing into a straw, and will allow us to measure the amount of pressure coming out of the lungs. We will ask your child to take a big breath of air in and say "ah" for as long as he or she can.

We also will take a measure of how the vocal folds work with breathing for speech. This measure is related to how a person's voice sounds (e.g., breathy, strained). To take this measure, we will use a soft face-mask that covers the mouth and nose, and we will place a small tube between and behind the lips. Your child will be asked to say syllables such as /pi/ while wearing the mask and tube. Children can watch a computer screen as they make these sounds which helps make this task seem like a game.

Larynx (vocal folds)

To measure function of the vocal folds, we will make several audio recordings as your child speaks into a microphone. We will measure how high and how low your child can produce sounds, how loud he/she can talk, and his/her voice quality (e.g., hoarse or breathy).

Velopharynx (where the soft part of the roof of the mouth meets the back of the throat)

To assess the function of the velopharynx, we will use two different measures. One is nasalance, which is used to measure sound which tells us how much air is coming out of the nose for certain words. To measure this, we will ask your child to wear a headset with a metal piece attached to it that separates the nose and mouth. The second measure is the area of the velopharynx. We will obtain this measurement by placing two small corks (each with a small hole in it) into the nasal openings, and a tube in the mouth. Your child will be able to breathe regularly through his/her nose and mouth during this task. We will ask your child to say some speech sounds and words while watching his/her breathing on a computer screen.

Movements of the tongue and lips

To measure the function of the tongue and lips, we will give a standardized articulation test. This will involve looking at and naming some pictures. In addition to this, we will ask your child to speak into a microphone to get measurements of how the tongue moves for different sounds. Some children will read a passage, while others will repeat words and sentences, depending on age and skill level.

We expect the entire experimental procedure to take between 1 and 2 hours. You and your child can take a break at any time. All of the tasks will be presented through game-like activities which children typically enjoy. We will assist you with parking and reimburse you for your parking fees.

Should your child become anxious or experience fatigue, we will stop the procedures and take a break. We will only continue if and when your child expresses that they would like to carry on with the procedures. We inspected all equipment for safety. There are no direct personal benefits to participating in this experiment. However, you will become familiar with speech systems. You will receive a written report at the end of the study that will give you information about your child's speech. You may choose to share this information with other health professionals who are involved in your child's speech and language development.

In addition to this, through your efforts, we hope to be able to find out if there are differences in speech motor control depending on when a child receives a cochlear implant. This may benefit children and their parents who are faced with this decision in the future.

Confidentiality:

All of the information obtained during this study will be kept confidential. The identities of you and your child will be known only to the researchers directly involved in this study. The audio recordings of the sessions and any other related data will be locked in Dr. Carol Boliek's lab, which can be accessed only by her and her research assistants, Ms. Timgren and Dr. Campbell. The tapes and data files will be labeled with a number code to ensure the privacy of you and your child. We will not use these tapes for educational purposes unless we get your permission first. These data will be stored for at least seven years as per University of Alberta guidelines.

If requested, you will be informed of any publication of the information obtained in this study.

Withdrawal:
Participation in the study is voluntary. You and your child will be free to discontinue the project at any time. You do not need to give a reason.

Contact:
Thank you for taking the time to contact us and read this letter. If you have any questions that have not been answered in this letter please feel free to call Carrie Timgren or Drs. Boliek and Campbell at (780) - 492-7256. You may e-mail Carrie Timgren at ctimgren@ualberta.ca, Dr. Carol Boliek at carol.boliek@ualberta.ca, or Dr. Melanie Campbell at melanie.campbell@ualberta.ca. Should you have any concerns about the study you can contact Dr. Paul Hagler, Associate Dean, Graduate Studies and Research, Faculty of Rehabilitation Medicine, (780-492-9674).

9.5 Information Letter – Student Listener

UNIVERSITY OF ALBERTA

Information Letter – Graduate Student Listener

Title: *Physiological and acoustic measures of speech and voice outcomes in children with Cochlear Implants.*

Investigator (s):

Co-supervisors: Carol Boliek, PhD and Melanie Campbell, PhD
Carrie Timgren, BA; MSc-SLP thesis candidate

Throughout this information sheet the words "you" and "your" refer to the research participant.

Purpose of Study

You are being asked to participate in a research study. This study is investigating how children's voices sound, as well as how well they are understood by a listener.

Procedure:

During this study, Carrie Timgren (a Master's Degree Student at the University of Alberta in the Department of Speech Pathology and Audiology) will be playing recordings of children's speech to you. First, she will perform a hearing screening with you. If you do not pass the hearing screening, it will be suggested that you schedule an appointment with an audiologist to get a full hearing test. Next, you will be sitting in front of a computer in a sound treated booth and the recordings of children's speech will be played to you. The children you hear may have difficulties with voice and speech production. You will type what you hear the child say into the computer. You will also rate how intelligible the speech was on a scale from 1-7. Finally, you will rate certain aspects of the quality of their voice.
We expect the entire experimental procedure to take no longer than one hour.

There are no foreseeable risks or dangers associated with this experiment. There are no direct personal benefits for participating in this experiment. You will be helping to further research in the area of voice and intelligibility in children.

Confidentiality:

All of the information obtained during this study will be kept confidential. Your identity will only be known to the researchers directly involved in this study. A number will be assigned to your response record and kept separate from your name. Your responses will be kept in Carol Boliek's lab. This lab can only be accessed by the researchers and Carol Boliek's research assistants. These data will be stored for at least seven years as per University of Alberta guidelines.
You will be informed of any publication of the information obtained in this study if you wish.

Withdrawal:

You are free to discontinue the project at any time for any reason.

Contact:
Thank you for taking the time to contact us and read this letter. If you have any questions that have not been answered in this letter please feel free to call Carrie Timgren, Drs. Boliek and Campbell at (780) - 492-7256. You may also e-mail Carrie Timgren at ctimgren@ualberta.ca, Dr. Carol Boliek at carol.boliek@ualberta.ca, or Dr. Melanie Campbell at melanie.campbell@ualberta.ca. If you have any concerns about the study you can contact Dr. Paul Hagler, Associate Dean, Graduate Studies and Research, Faculty of Rehabilitation Medicine, (780-492-9674).

9.6 Consent Form –Parent

UNIVERSITY OF ALBERTA

Consent Form – Parent

Title of Project: *Physiological and acoustic measures of speech and voice outcomes in children with Cochlear Implants.*

Principal Investigator(s):

Co-supervisors: Carol Boliek, PhD and Melanie Campbell, PhD
Carrie Timgren, BA; MSc-SLP thesis candidate
Contact Number: (780) 492- 7256.

Throughout this consent form the words "you" and "your" refer to the research subject.

	Yes	No
Do you understand that you have volunteered to be in a research study?	☐	☐
Have you read and received a copy of the attached information sheet?	☐	☐
Do you understand the benefits and risks involved in taking part in this research study?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Do you understand that you are free to withdraw from the study at any time without penalty?	☐	☐
Has the issue of confidentiality been explained to you? Do you understand who will have access to your records/information including personally identifiable health information?	☐	☐
Do you understand that the session will be audiotaped for the purpose of later analysis?	☐	☐

By signing the consent form you give permission to the appropriate Glenrose staff to access any personally identifiable health information. The staff will extract information specific to your child's implant and results from hearing and speech tests. Information will be coded by your child's participation number only and not by name.

This study was explained to me by: ______________________________

I agree to take part in this study with my child.

Signature of Research Participant (parent) Child's name Date

Witness

____

Printed Name (parent)

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

____________________________ ____________________

Signature of Investigator Date

9.7 Assent Form – Child

UNIVERSITY OF ALBERTA

Assent Form

Project Title: *Physiological and acoustic measures of speech and voice outcomes in children with Cochlear Implants.*

Investigator(s):

Co-supervisors: Carol Boliek, PhD and Melanie Campbell, PhD
Carrie Timgren, BA; MSc-SLP thesis candidate

Why have you been asked to do this:

You have a cochlear implant. We want to find out how speech develops in children with cochlear implants.

How long will this take:

It will take between one and two hours to complete all the tasks.

What will you have to do:

First, you will look at and name some pictures from some books. You will wear a microphone so that we can record your voice onto a tape recorder.

Second, you will blow into a tube that has water in it. We will try to see if you can get the water up to a certain level. Then we will ask you to take in a big breath of air and say "ah" as long as you can.

Third, you will put on a headband with a plastic piece going between your nose and mouth. You will read or repeat some words and sentences from a book while wearing the headband. We will record your voice while you are doing this. You can watch your voice on a computer screen while you do this.

Fourth, you will talk into a microphone. We will have you say some words and also some sounds like "ah", "e", and "oo". We will record these sounds into a computer.

Then, you will wear a soft plastic mask over your nose and mouth and put a plastic tube between your lips. You will say funny words like "pa pa" while wearing the mask. We will record your voice while you are doing this and you can watch your voice on the computer screen.

Finally, we will put some small soft corks in your nose that will have tubes on the end of them. We will also ask you to place a small tube in your mouth at the same time. This will help us see where the air in your mouth is going when you talk. You can see a picture of your air on a computer screen when you are talking.

The time it will take to do all of these activities is between 1 and 2 hours. You can have a break when you need one.

Will it help?
By helping us out in this study we will find out how children who have cochlear implants like you learn how to talk.

Will it hurt?
Nothing we are asking you to do will hurt. The tubes in your nose and the face mask might feel funny, but you can breathe normally and they don't have to be in for very long. Everything else is easy and will not be hard for you to do.

Can you quit?
You don't have to take part in the study at all and you can quit at any time. If you want to quit, you can tell your parents or the researchers.

Who will know?
No one except your parents and the researchers will know you're taking part in the study unless you want to tell them. Your name and your information will not be seen by anyone except the researchers during the study.

Your signature:
We would like you to sign this form to show that you agree to take part. Your mom or dad will be asked to sign another form agreeing for you to take part in the study.

Do you have any questions?

You can ask your mom or dad about anything you don't understand. You can also talk to Carrie, Carol, or Melanie.

I agree to take part in the study.

______________________________ ____________________
Signature of Research Participant Date

______________________________ ____________________
Signature of Investigator Date

9.8 Consent Form – Student Listener

UNIVERSITY OF ALBERTA

Consent Form – Graduate Student Listener

Title of Project: *Physiological and acoustic measures of speech and voice outcomes in children with Cochlear Implants.*

Principal Investigator(s):
Co-supervisors: Carol Boliek, PhD and Melanie Campbell, PhD
Carrie Timgren, BA; MSc-SLP thesis candidate
Contact number: (780)-492-7256.

Throughout this consent form the words "you" and "your" refer to the research participant.

	Yes	No
Do you understand that you have volunteered to be in a research study?	☐	☐
Have you read and received a copy of the attached information sheet?	☐	☐
Do you understand the benefits and risks involved in taking part in this research study?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Do you understand that you are free to withdraw from the study at any time without penalty?	☐	☐
Has the issue of confidentiality been explained to you? Do you understand who will have access to your study records/information?	☐	☐

This study was explained to me by: ______________________________
I agree to take part in this study.

Signature of Research Participant   Date   Witness

____
Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

______________________________   ____________________
Signature of Investigator   Date

9.9 Listener Rating Form

How much of what this child said could you understand?

I couldn't understand any words	I could understand half of what the child said	I could understand everything

1---------------- 2 ------------- 3 -------------- 4 ---------------- 5 ------------- 6 -----------------7

Describe your impressions of how this child sounds.