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Long-term cochlear implant characteristics as predictors of speech and language outcomes in children

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LONG-TERM COCHLEAR IMPLANT CHARACTERISTICS AS PREDICTORS OF SPEECH AND LANGUAGE OUTCOMES IN CHILDREN

by

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Abstract: The purpose of the current study was to investigate the longitudinal stability of map characteristics and their relationship with spoken language outcomes for the pediatric population.

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LIST OF ABBREVIATIONS

CI = Cochlear Implant

AOI = Age of Implantation

IQ = Intelligence Quotient

SPEAK = Spectral Peak

ACE = Advanced Combination Encoder

MPEAK = Multiple Peak

Hi-Res = High Resolution

Hi-Res P = High Resolution Paired

Hi-Res P with Fidelity 120 = High Resolution Paired with Fidelity 120

Hi-Res S with Fidelity 120 = High Resolution Sequential with Fidelity 120

MPS = Multiple Pulsatile Sampler

CIS = Continuous Interleaved Sampling

SAS = Simultaneous Analog Stimulation

EDR = Electrical Dynamic Range

IDR = Input Dynamic Range

T level = Threshold Level

C/M level = Comfort/Maximum Level

PPVT – III = Peabody Picture Vocabulary Test – III

PLS – 3 = Preschool Language Scale, Third Edition

PTA = Pure Tone Average

CELF – 4 = Clinical Evaluation of Language Fundamentals, Fourth Edition

EC = Expressive Communication

AC = Auditory Comprehension

BKB-SIN = Bamford- Kowal- Bench Sentence in Noise

S/N = Signal-to-Noise

SRT = Speech Reception Threshold

LNT-50 = Lexical Neighborhood Test at 50 dB SPL

LNT-70 = Lexical Neighborhood Test at 70 dB SPL

NLE = Normal Language Emergence

LLE = Late Language Emergence

PLD = Persistent Language Delay

ANOVA = Analysis of Variance

nC = Nanocoulombs

μA = Microamperes

μs = Microseconds

INTRODUCTION AND LITERATURE REVIEW

It is widely recognized that cochlear implants (CIs) provide substantial benefits for understanding speech and developing spoken language skills for children with severe to profound hearing loss (Davidson, Geers, Blamey, Tobey, & Brenner, 2011; Svirsky, Teoh, & Neuburger, 2004; Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). Many children using CIs acquired early in life eventually achieve age-appropriate scores on spoken language tests (Duchesne, Sutton, & Bergeron, 2009; Leigh, Dettman, Dowell, & Briggs, 2013; Fulcher, Purcell, Baker & Munro, 2012). Specific family-, environmental-, and child-based factors have been investigated and shown to lead to better outcomes for prelingually deafened children who receive CIs at a young age (Boons et al., 2012; Geers & Nicholas, 2013). Characteristics related to the CI device have also been shown to be associated with positive outcomes. Technological advances in speech coding strategies, speech processor upgrades, and map stimulation level optimization by audiologists are among the device-related characteristics that have been associated with improved speech perception skills (Geers, Brenner, & Davidson, 2003).

Family-, Child-, and Environment-Based Factors

Despite the findings that many children who receive CIs are able to achieve age-appropriate speech and language abilities, there is still large variability in achievement across pediatric users (Niparko et al. 2010; Peterson, Pisoni, & Miyamoto, 2010). There are several factors that have been found to help predict the language outcomes for pediatric CI recipients and can be categorized into family-, child-, and environmental-based factors.

Several studies have demonstrated the importance of Age of Implantation (AOI) and speech and language outcomes. Cochlear implantation occurring before the child's second birthday provides optimal opportunity to achieve higher performance levels in receptive and expressive language, academia, and socialization (Nicholas & Geers, 2006). These positive effects on language performance have also been demonstrated to last through elementary school for children implanted during that age range (Geers & Nicholas, 2013).

Boons and colleagues (2012) implemented a cross-sectional, retrospective study that examined 288 prelingually deafened children recruited from five different CI centers in Europe. Aside from AOI, predictors for language skill success were found to be contralateral stimulation (through either bimodality or bilateral CI use) and absence of additional disabilities. Environmental factors including monolingualism, increased parental involvement, and oral communication also increased the child's success rate with speech and language. The largest contribution, however, was from AOI. Data analysis revealed that children who were implanted before two years of age significantly outperformed children implanted at older ages on all speech and language tests administered.

Early identification and intervention, utilization of listening and spoken language, a longer duration of CI use, better pre-implant pure tone averages, being in a general education classroom setting, having a typical nonverbal intelligence quotient (IQ), and no additional disabilities are all predictive of better language outcomes that are closer to normative age-related scores (Boons, et. al, 2012; Nicholas & Geers, 2006).

Speech Coding Strategies and Processor Technology Effects on Speech Perception

The development and implementation of new speech coding strategies for CI devices have been shown to result in improved speech perception abilities when compared to previous generations of strategies in both the adult and pediatric populations (Wilson, Lawson, Finley, & Wolford, 1991; Geers, Brenner, & Davidson, 1999; Manrique et al., 2005). Additionally, Meyer & Svirsky (2000) found that children who were implanted at a younger age and used newer speech coding strategies achieved higher levels of speech perception skills in a shorter amount of time than those utilizing older strategies.

In a nationwide sample of pediatric CI users, Geers et al. (2003) documented that increased utilization of the Spectral Peak (SPEAK) coding strategy with the updated Cochlear Americas' Spectra processor was related to better speech perception skills. Additionally, the benefits of SPEAK over the previous strategy, Multi-Peak (MPEAK), were documented for pediatric CI users listening in background noise (Geers et al., 1999).

This has also been shown to hold true across CI manufacturers. Ostroff and colleagues (2003) evaluated the High-Resolution (Hi-Res) speech coding strategy in Advanced Bionics' Clarion speech processor users. These participants, prior to the study, were utilizing previous generations of speech coding strategies including: Multiple Pulsatile Sampler (MPS), Continuous Interleaved Sampling (CIS), and Simultaneous Analog Stimulation (SAS). The participants not only subjectively preferred the sound quality of the Hi-Res strategy, but results from speech perception testing indicated

significantly better performance with the Hi-Res strategy for all subjects, particularly when listening to speech in background noise.

CI speech processor features also play a large role in the recipient's success in understanding speech. Automatic gain control (AGC) and preprocessing strategies are two of the features that have resulted in greater access and comfort for a variety of speech levels from soft to loud inputs. Both the electrical dynamic range (EDR) and the input dynamic range (IDR) are critical to the process of utilizing these features. The EDR is the difference between threshold (T level) and maximum/most comfortable level (C/M) for electrical stimulation on individual electrodes, while the IDR is the intensity range of acoustic signals coded by the speech processor and delivered to individual channels. Several studies have demonstrated the importance of a wider IDR in CI processors on speech perception. Wider IDRs have been found to be associated with increased vowel, consonant, word and sentence recognition for signals presented at a softer level (Davidson et al., 2009; Holden, Skinner, Fourakis, & Holden, 2007; Santarelli et al., 2009).

Similar to upgrading speech coding strategies, when CI recipients upgrade to newer generations of speech processors, users are able to take advantage of newer technology and features within the processor resulting in an improvement in performance (Davidson, et al., 2011; Geers, Brenner, & Davidson, 2003; Geers, Nicholas, Tobey, & Davidson, 2015). Specifically, Davidson, Geers, & Brenner (2010) investigated a large pediatric sample of long-term Cochlear Americas' Nucleus CI system users and found that children using more recent processors, such as the ESPrit 3G and Freedom, demonstrated better speech perception scores at soft input levels (50 dB SPL) when compared to those using older technology processors, such as the ESPrit 22 and Spectra.

A longitudinal study by Geers, Nicholas, Tobey, & Davidson (2015) was conducted with sixty children who were tested at preschool age and again at elementary school age. The aim of the study was to differentiate language growth trajectories for pediatric CI users who were all implanted at an early age with processor technology among the potential predictive factors. In that study, children who did not achieve age-appropriate language scores by elementary school were more likely to use older speech processor technology. Upgrading speech processors was one of the recommendations made by the authors for positively influencing long-term language outcomes.

Map Characteristics and CI Programming Effects on Speech Perception

In the CI mapping process, audiologists are responsible for individualizing the device based on subjective responses from the patient. Initial measurements that lay groundwork for further optimization of the device include electrical T and C/M levels which are measured on individual electrodes or groups of electrodes. T level is considered the lowest or smallest amount of electric stimulation that elicits the sensation of hearing for the CI recipient and reflects the electrical stimulation level where soft sounds are typically mapped in the EDR. Conversely, C/M levels are considered the highest stimulation level perceived by the CI recipient as loud but comfortable or most comfortable and reflects where moderately loud to loud sounds are mapped in the EDR. The difference between T level and C level is the patient's EDR. The audiologist can further manipulate and optimize the EDR by adjusting the T and/or C/M levels across electrodes with the goal of giving access to soft inputs and comfort to louder inputs. In other words, make soft sound audible and loud sounds loud, but comfortable.

Incorrect manipulation of the EDR can results in adverse effects for speech understanding and perception. T levels that are programmed too low could result in reduced audibility of soft inputs and C/M levels that are set too high could result in decreased tolerance and comfort for louder inputs. The ideal map will have as many active electrodes as allowed, a wide EDR, higher C/M levels, and optimal loudness growth.

Geers et al. (2003) demonstrated that in pediatric CI users, maps characterized by maximum number of active electrodes, wider EDR, and optimal growth of loudness, as measured by a loudness-scaling task, were associated with improved audibility and speech understanding. Studies with adults have yielded similar findings and conclusions. For example, Waltzman, Cohen, and Shapiro (1991) evaluated a group of Nucleus 22 users concluding that better open- set speech recognition was associated with a wider EDR. Robinson and colleagues (2012) found that wider EDRs and higher C levels were associated with better speech perception in quiet and noise for long term pediatric CI recipients.

To achieve these ideal parameters for an optimized fitting and thus improved speech perception, studies suggest that it is necessary for audiologists to employ proper CI mapping protocols, loudness-scaling judgments, and sound-field thresholds for all patients (Skinner, Holden, & Holden, 1997). When these optimized map characteristics are paired with updated speech processors and speech coding strategies, the CI recipient experiences increased success in audibility, speech perception abilities, and even language development (Robinson et al., 2012; Geers et al., 2003).

Longitudinal Changes in Map Characteristics

Several research groups have investigated longitudinal changes of map characteristics, specifically T levels, C/M levels, and EDR, over time in both adult and pediatric populations (Henkin, Kaplan-Neeman, Muchnik, Kronenberg, & Hildesheimer, 2003a, 2003b; Hughes et al., 2001; Kawano, Seldon, Clark, Ramsden, & Raine, 1998; Shapiro & Waltzman, 1995). The origin of longitudinal map characteristic changes have been attributed to anatomical and physiological alterations within the cochlea as well as behavioral changes. Anatomically, post-surgical changes include fibrous tissue and bone growth within the cochlear space (Kawano et al., 1998). Physiological cochlear transformations involve an adjusted number of excitable neurons and altered pathways to the central auditory system (Miller, Morris, & Pfingst, 2000; Xu, Shepherd, Millard, & Clark, 1997). Finally, stimulation levels can change over time due to behavioral changes that occur as the user adjusts to electrical stimulation and behavioral responses during programming sessions become more reliable (Shapiro & Waltzman, 1995). Due to the adjustment period, it is imperative that clinicians have frequent programming sessions within the first year of activation and device use, for both adults and children. Follow-up care after the one year mark remains essential as it is unclear if stabilization periods are permanent or if further changes will occur after long-term use, technology advancements, and speech processor upgrades.

For pediatric CI users, changes in map settings are typically greatest within the first three to six months of use and continue to stabilize through the first year of CI use. Henkin and colleagues in 2003(a) documented electrical stimulation changes over time in 25 prelingual pediatric Nucleus 24M users. The participants were evaluated at activation and at 1, 3, 6, and 12 months post-activation. Results of this study indicated significant

elevations of T and C levels as well as a widened EDR from activation to the 12-months post-activation session. The most dramatic changes occurred within the first 3 to 6 months of use. These authors also evaluated differences in map characteristics based on the cochlear region. T and C levels were found to be significantly lower in the apical segment of the cochlea when compared to their counterparts in the basal segment. In 2006, Henkin and another group of colleagues evaluated the same map characteristics over time in 18 prelingual pediatric Advanced Bionics Clarion users. Again, results indicated the greatest changes for T level, M level, and EDR within the first 3 months of CI use. However, in this study no significant differences were found in placement across the cochlea.

Zwolan et al. (2008) found similar results in a longitudinal evaluation of 188 pediatric CI recipients, from six centers, who utilized devices from all three major CI manufacturers: Med-El, Advanced Bionics, and Cochlear Americas. Mean C/M levels were compared at four different time intervals with the longest being 24 months post-activation. The authors discovered that children using devices by all three manufacturers demonstrated significantly increased C levels between device activation and 24 months post-activation. The most dramatic change in C/M levels took place between activation and 6 months post-activation. Similar to Henkin et al. (2006), no differences between cochlear segments were found. Mean C/M level differences between manufacturers emerged after 6 months of use and continued to 24 months. However, the authors noted that the distribution of devices was not equally allocated across CI centers, thus differences could be based upon mapping procedures across CI centers. Finally, the authors compared electrical stimulation levels in normal cochlea and abnormal cochlea. Results revealed that

pediatric users with cochlear anomalies had significantly higher C/M levels when compared to those with normal anatomy.

Map electrical stimulation levels have also been examined in the adult population and results suggest that levels, although variable, stabilize over the first year of CI use (Waltzman et al., 1991; Hughes et al., 2001). A retrospective review of 26 post-lingually deaf adults using Nucleus devices was conducted to document electrical stimulation shifts over time (Butts, Hodges, Dolan-Ash, & Balkany, 2000). Comparisons were made at the following intervals: initial stimulation, 2 weeks, 3 months, 6 months, and 12 months post-activation, and finally at their most recent programming session. All participants had used their CI device for at least two years. Five participants had 5 or more years of experience, 8 participants had 3 to 5 years of use, and the remaining users had between 2 and 3 years of experience. Results revealed that changes in stimulation level occur gradually over time and researchers did not find any significant changes when comparing consecutive measurements. However, significant changes for both T and C levels were found when the authors compared levels obtained at the initial activation to those obtained at 6 months post activation and the most recent programming levels.

Robinson et al (2012) assessed the stability of electrical stimulation levels of 82 adolescent Nucleus 22 CI recipients by examining maps at two test sessions approximately 7-9 years apart. Participants ranged from 8-9 years of age at session one and 15-18 years of age at session two. The majority of participants upgraded from body worn to ear levels speech processors between test sessions. Map T and C levels were converted from clinical units to charge per phase units in nanocolumbs (nC) to allow for accurate comparison of stimulation levels across different speech processors worn over time. On average, T levels

remained stable over time and C levels decreased by approximately 19 nC. The decrease in C levels was likely due to electrical current reductions imposed by ear level speech processors.

More recently, Mosca, Grassia, and Leone (2014) evaluated 26 profoundly deaf adults (age range 18-58 years) who used Cochlear devices. Participants were evaluated approximately 30 days, 3 months, 6 months, and 12 months post-implantation. Data analysis revealed significantly increasing mean values for both T and C levels up through 6 months post-implantation. Additionally, the authors evaluated changes between cochlear regions. Results suggested that T levels in the basal regions of the cochlea were higher than in other regions. Three of the 5 subjects that had used their CI for longer than 5 years exhibited the greatest change in T and C levels over time. For all subjects, changes in T and C levels for the basal and medial electrodes were significant while changes in the apical region were not.

Study Rationale

Given what is known regarding the variability in performance outcomes for pediatric CI recipients, it has become increasingly more important that audiologists learn what predictive factors and programming manipulations may lead to optimal performance for these children. Addressing this issue presents an excellent opportunity to pose questions that will individualize and improve patient care. Thus, the current study seeks to address the following:

1. Examine the long-term stability of participants' map characteristics (average T level, average C/M level, EDR, and proportion of active

electrodes) over time in a sample of children who had used a CI for an average of six years.

2. Examine the relations among map characteristics and spoken language outcomes at the preschool testing session.
3. Examine the relations among map characteristics and spoken language outcomes at the elementary testing session.
4. Compare map characteristics across different language trajectories.

METHODS

Study Design

This study was a retrospective analysis of data from an ongoing longitudinal study initiated in 2000 (Nicholas & Geers, 2006, 2007; Geers & Nicholas, 2013; Geers et al., 2015). In that study, participants were tested first at 4.5 years of age in their home cities. The children were tested a second time at an average age of 10.5 years of age (range 9-12) in a "Research Camp" setting in St. Louis, Missouri. The data for this retrospective analysis was comprised of audiological records from ages 4.5 and 10.5 and from direct speech perception testing at age 10.5 years. These data will be combined with previously reported spoken language testing at both test ages. In this paper, testing at age 4.5 years will be described as the Preschool Assessment and the age 10.5 testing will be described as Elementary Assessment. This protocol was evaluated and approved by the Human Research Protections Office at the Washington University in St. Louis. The collection of data analyzed in this study was funded by National Institute on Deafness and Other Communication Disorders (NIDCD) Grant R01DC004168.

Participants

The 60 participants in the present study received a CI between 12 and 38 months of age. All participants received their first CI between 1998 and 2003 and were originally identified as meeting study inclusion/exclusion criteria by auditory-oral preschools and speech therapy practices across North America. All children were evaluated at age 4.5 years (Preschool) after they had used their CI between 19 and 45 months and were conducted at the child's school or speech therapy center. There were 30 female and 30 male participants in this study.

Participants met the following criteria: (a) Age of Implantation (AOI) less than 38 months, (b) English as the primary language spoken at home, (c) enrollment in spoken language instruction since implantation, (d) copies of MAPs available for each test session, and (e) a user of either a Cochlear Americas or Advanced Bionics device.

Candidate participants were excluded if: (a) interruption of CI use for more than 30 days, (b) diagnosis of a disability that may interfere with communication, (c) below-average nonverbal learning abilities as tested in preschool, and (d) any known period of hearing prior to cochlear implantation.

The sample was broadly distributed geographically and school grades completed at the Elementary assessment were: third grade (25%), fourth grade (55%), fifth grade (17%), and sixth grade (3%). For extended detail regarding these Research camps and participant recruitment, see Geers and Nicholas (2013).

The educational setting for the majority of these students changed significantly from age 4.5 years to age 10 years. In preschool, 47 of the students (78%) were in a special

education setting. By age 10, the majority of the students, 51 of 60 (85%), attended school in a general education setting. At the Elementary assessment, all but four students attended school in regular classrooms with hearing age-mates for at least 85% of the full school day. All children continued using speech as their primary communication mode, although one child was rated as using “occasional signs” and moved from an oral to a total communication classroom in second grade.

About half of the sample (n = 29) received a second CI between the ages of 4.5 and 10.5 years and used bilateral CIs for an average of 3 years at the Elementary test session. Two of the unilateral CI users continued using a hearing aid in the other ear. In order to examine the effects of speech processor upgrades on language development, processors were rank ordered by generation of technology for analysis, with higher rankings indicating newer technologies (i.e., from the oldest to most recent). Forty-one of the children received an upgrade to newer speech processor technology in at least one ear between the test sessions, and 31 of them used the most recent processor available at the Elementary test session. For this sample, two CI manufacturer’s were represented, Cochlear Americas (n = 37) and Advanced Bionics (n = 23).

Equipment and Test Environment

For each test session, the participant was seated 1 meter at a 0 degree azimuth from the loudspeaker. Speech perception stimuli were routed through a Grason Stadler GSI 61 audiometer and sound-field loudspeaker. For calibration of the speech stimuli, a type 2

sound level meter was placed at the level of the child's implant microphone and levels were measured in dB SPL (A weighted). Participants utilized their personal hearing device settings for all test measures. An experienced pediatric audiologist completed testing at each session.

Preschool Assessment

Formal language testing was conducted at age 4.5 years to assess receptive vocabulary and global language development relative to hearing age-mates (see Geers & Nicholas, 2013; Nicholas & Geers, 2007). All participants were administered the following assessments: *Peabody Picture Vocabulary Test- III* (PPVT-III; Dunn & Dunn, 1997)—The PPVT is a norm-referenced test of receptive vocabulary in which the examiner says a word and the child is required to point to one of 4 pictures that best depicts that word, and the *Preschool Language Scale–Third Edition (*PLS-3; Zimmerman, Steiner, & Pond, 2002)—The PLS-3 provides scores for Auditory Comprehension (receptive language) and Expressive Communication (expressive language) to give an overall language score. Both the PPVT and the PLS-3 provide standard scores with a mean of 100 and a standard deviation of 15.

Elementary Assessment

Follow-up testing was conducted at a mean age of 10.5 years (range = 9.1–12.7 years). The battery included the following language and audition tests. *Aided Soundfield Thresholds*—Aided soundfield thresholds were obtained for each child utilizing frequency

modulated (FM) tones at octave frequencies from 250 to 4000 Hz. An aided pure-tone average (PTA) was calculated from the obtained thresholds at 0.5, 1, and 2 kHz. *Peabody Picture Vocabulary Test- III* (PPVT; Dunn & Dunn, 1997) – This test was repeated to maintain a consistent measure from the preschool assessment. *Clinical Evaluation of Language Fundamentals, Fourth Edition* (CELF-4; Semel, Wiig, & Secord, 2003)— The CELF-4 is a norm-referenced test of language with an Expressive Communication (EC) scale and an Auditory Comprehension (AC) scale, which measures receptive skills. The EC scale includes the following subtests for this age group: Recalling Sentences, Formulated Sentences and Word Classes-Expressive. The AC scale for this age group includes: Concepts and Following Directions, and Word Classes-Receptive. *Bamford-Kowal-Bench Sentence in Noise* (BKB-SIN; Bamford & Wilson, 1979) Test—The BKB-SIN is an open set sentence audition test, which consists of 36 lists with 10 sentences each and three to four key words per sentence. The 36 lists are paired to create 18 predetermined list-pairs that are matched for difficulty level. The BKB-SIN is designed for a first grade reading level and is comprised of short, highly redundant, and simple sentences. The sentences are spoken by a male talker and presented in four-talker babble with varying Signal-to-Noise (S/N) ratios. The S/N ratios range from +21 to -6 dB in 3 dB increments. For each sentence, the number of key words correctly repeated by the participant was recorded. The participant's test performance is expressed in terms of the S/N ratio required to obtain 50% of the key words spoken correctly—the speech reception threshold (SRT). A lower SRT indicates higher performance in more adverse S/R ratio conditions. *Lexical Neighborhood Test* (LNT; Kirk, Pisoni & Osberger, 1995)—The LNT consists of 50 monosyllabic words per list; 25 of which are high frequency words with limited lexical

neighbors (labeled "easy") and 25 that are lower frequency words with many lexical neighbors (labeled "hard"). The LNT word list was administered in quiet at 70 dB SPL (LNT-70) and in quiet at 50 dB SPL (LNT-50). The child was instructed to repeat what he or she heard, and responses were transcribed phonetically. The score represents the percentage of phonemes produced that matched the corresponding phoneme in the target word. Phoneme rather than whole-word scoring minimizes the impact of vocabulary on speech perception scores.

Categories of Language Emergence

The children in the study were categorized into three groups according to the relationship between language performance at the preschool and elementary-age testing points. In other words, they were categorized based on the pattern of emergence of spoken language. Those receiving a standard score of 85 or above on a comprehensive language test at both test ages were considered to have Normal Language Emergence (NLE). Those who were initially delayed (scored below 85 at preschool age) but then caught up were characterized as experiencing Late Language Emergence (LLE) and those who scored below 85 (1 SD below the mean) at both ages were categorized as having Persistent Language Delay (PLD). These categories will be referred to as Language Emergence Groups.

Participants were fairly equally distributed among the NLE (n=19), LLE (n=22) and PLD (n = 19) groups. The average AOI for the NLE group was 18.53 months (SD = 7.37, Range = 12-38), 24.55 months for the LLE group (SD = 7.46, Range = 12-35), and for the PLD group the average was 24.89 months (SD = 6.84, Range = 16-35). Analysis of

variance was employed to test differences between the NLE, LLE, and PLD groups in AOI. There was a significant difference between the groups ($F(2,57) = 4.74$, $p = 0.01$).

MAP Characteristics and Speech Processors

At each testing session, the participant's speech processor and map characteristics were documented. The CI processor technology type was documented and ranked from 4 (most recent) to 0 (oldest). CI map characteristics included the coding strategy, proportion of active electrodes, map T and C/M levels, EDR, stimulation rate, and pulse width. Manufacturer clinical map units were converted to a charge-per-phase unit in nanocoulombs (nC) to allow for appropriate comparisons of the T levels, C/M levels, and across different manufacturers and speech processors. The EDR for each electrode was calculated by subtracting T levels from the C/M levels. Conversions to charge-per-phase units were made available by utilizing tables provided by Cochlear Americas and Advanced Bionics.

The current value (μA) was dependent on internal device and pulse width. Current (μA) was then converted to charge-per-phase (nC) using the formula provided by the specific manufacturer. For Cochlear users, nC was calculated by multiplying the current level (μA) by the pulse width (μs), then dividing the total by 1000 ((μA x μs)/1000=nC). Advanced Bionics provided two separate formulas depending on what programming software the user was mapped in. For users mapped in SCLIN 2000, nC was calculated similar to Nucleus users by multiplying the clinical M level (μA) by the pulse width (μs) and then dividing by 1000 ((μA x μs)/1000). For users mapped in Soundwave software,

the clinical unit was divided by 0.0128 and then again by 1000 (Clinical HiRes or Soundwave unit/ 0.0128/1000).

Based on each variable and analysis requirements, only children with complete records for that analysis were included in statistical computation. For example, if a participant's T levels could not be converted for some reason he or she would be excluded from the longitudinal analysis of T levels.

Statistical Analysis

Speech perception results, map T and C/M levels, EDR and proportion of active electrodes were compared for each subject at preschool and elementary assessments using analysis of variance (ANOVA). Correlational analyses were used to examine relations between processor/map variables and spoken language outcome measures. SPSS Statistics software was utilized for all statistical analysis.

RESULTS

Longitudinal Stability of CI Characteristics from Preschool to Elementary Assessments

Between the preschool and elementary assessments, 41 out of 52 participants (79%) upgraded their speech processors to newer technology updates (e.g., from Sprint to Freedom for Cochlear or Platinum Series to Harmony for Advanced Bionics). Only 52 participants were counted in this measure due to lack of information at their elementary school audiological record.

Recall that the CI processor technology rating was documented and ranked from 4 (most recent) to 0 (oldest). For participants utilizing Advanced Bionics speech processors,

the average technology rating at preschool age was 1.11 (SD = 0.68, Range = 0 - 3) and 2.17 at the elementary assessment (SD = 1.43, Range = 0 - 4). For Cochlear participants, the average technology rating at the preschool assessment was 2.94 (SD = 0.25, Range = 2 - 3) and 3.81 (SD = 0.40, Range = 3 - 4) at the elementary assessment.

Speech coding strategies utilized by Cochlear participants at preschool age included Advanced Combination Encoder (ACE; n = 34) and Spectral Peak (SPEAK; n = 2). By the elementary assessment, all Cochlear participants were using the ACE speech coding strategy. Speech coding strategies utilized by the Advanced Bionics participants included a variety of available strategies. At preschool ages Advanced Bionics participants were programmed with Continuous Interleaved Sampling (CIS, n = 5), High Resolution Paired (HiRes-P, n = 6), Multiple Pulsatile Sampler (MPS, n = 4), and Simultaneous Analog Sampling (SAS, n = 8). At the elementary assessment ages CIS, HiRes-P, and HiRes-P with Fidelity 120 all had 3 participants each who were utilizing that speech coding strategy. Other strategies used by Advanced Bionics participants at the elementary assessment included: High Resolution Sequential with Fidelity 120 (HiRes-S with Fidelity 120, n = 4), MPS (n = 2), and SAS (n = 5) (See Table 2).

T level, C/M level, were collected from maps at both preschool and elementary assessments for each participant. The EDR was calculated by subtracting the T levels from the C/M level at each electrode. The T, C/M and EDR values were summed and averaged across electrodes for all participants. The group average T level at the preschool assessment was 8.32 nC (SD = 5.75; Range = 0.96-28.91) and the average C/M level was 24.17 nC (SD = 13.90; Range = 6.95-52.35). The average T and C/M levels at the elementary assessment age were 7.44 nC (SD = 5.00; Range = 1.15-16.54) and 21.46 nC (SD = 10.05;

Range = 6.95-52.35) respectively. No significant differences were found for T levels ($F(1,43) = 2.24$, $p = 0.14$) or C levels ($F(1,43) = 2.51$, $p=0.12$) across the two assessment ages. The average EDR at preschool age for the group was 17.77 nC (SD = 11.12; Range = 3.88-50.04) and at elementary age, the EDR was 14.03 nC (SD = 6.32; Range = 4.64-35.81). The change in EDR between the assessment ages was significant ($F(1,43) = 5.29$; $p = 0.03$).

The proportion of active electrodes in each participant's map was also noted at both assessment ages. A proportion of 1.0 would indicate that all of that participant's electrodes within their array were active. Statistical analysis revealed the average proportion at preschool age was 0.97 (SD = 0.05; Range = 0.75-1.0) and 0.96 (SD = 0.06; Range = 0.38-1.0) at elementary age. No significant differences in the proportion active of electrodes for the participants' CI maps were noted across the two assessment ages ($F(1,51) = 0.03$, $p = 0.85$).

Each participant's individual CI device characteristics, map characteristics, and Language Emergence Group categorization at both assessments can be found in Appendix A and spoken language scores in Appendix B.

Speech Perception and Language Scores at Preschool and Elementary Assessments

During the preschool evaluation, participants were administered the PPVT-III and PLS-3. At the participants' elementary assessment, the PPVT-III, CELF-4, LNT-50, LNT-70, BKB-SIN, and aided PTA were evaluated. Table 3 lists average spoken language scores

for the group at both preschool and elementary age.

Correlation Analysis of Map Characteristics as Predictors

Correlations between map characteristics and spoken language score outcomes can be found in Table 4 (preschool) and Table 5 (elementary). At preschool age, a significant correlation was found between EDR and PPVT-III at preschool ($r = 0.30$; $p = 0.04$) as well as the PLS-4 scores ($r = 0.49$; $p = 0.00$). When the participants returned for testing at elementary age, T levels were correlated with the CELF-4 ($r= 0.42$, $p = 0.00$) and LNT-50 ($r = 0.30$, $p = 0.04$). The correlation between T levels and BKB-SIN scores did not reach significance, however there was a trend for higher T levels to be associated with better BKB-SIN scores ($r = - 0.28$, $p = 0.05$). C/M levels were only correlated with CELF-4 scores ($r = 0.37$, $p = 0.01$). Notably, significant correlations between aided PTA and all of the spoken language assessments were found at the elementary test age. These correlations between aided PTA and spoken language outcomes were as follows: PPVT-III at elementary ($r = -0.45$, $p = 0.00$), CELF-4 ($r = -0.51$; $p = 0.00$), LNT-50 ($r = -0.70$, $p = 0.00$), LNT-70 ($R = -6.1$, $p=0.00$), and BKB-SIN ($R = 0.66$, $p = 0.00$). There was a trend for the lower (better) aided PTA to be associated with higher map T levels, however the correlation did not reach significance ($r = - 0.26$, $p = 0.07$).

Language Emergence Groups

T levels, C/M levels, EDR, and proportion of active electrodes were collected from audiological records at preschool. At the elementary assessment, aided PTA was also collected. The average results for T levels, C/M levels, EDR and proportion of active

electrodes for each Language Emergence Group at the preschool and elementary test ages are shown in Table 6. Aided PTA at the elementary age is included as well.

Language Emergence Group Comparisons

Preschool Assessment: Average T levels, C/M levels, EDR, and proportion of active electrodes were compared across the language emergence groups. T levels ($F(2,48) = 1.34$, $p = 0.27$), C/M levels ($F(2,48) = 1.57$, $p = 0.22$), and proportion of active electrodes ($F(2,56) = 2.05$, $p = 0.14$) were not significantly different across the groups. However, there was a significant difference found across the groups for the EDR ($F(2,48) = 4.95$, $p = 0.01$). Post-hoc analyses revealed that the NLE group had significantly wider EDR than the other two groups (LLE $p = 0.04$; PLD $p = 0.02$).

Elementary Assessment: Differences across the language groups at the elementary test sessions were not seen for EDR ($F(2,45) = 1.58$, $p = 0.22$) or proportion of active electrodes ($F(2,50) = 0.81$, $p = 0.45$). However, differences were noted across the groups for the average T level ($F(2,45) = 4.03$, $p = 0.03$) and C/M level ($F(2,45) = 3.29$, $p = 0.04$). Post-hoc analyses revealed that T levels for the PLD group were significantly lower than the LLE group ($p = 0.02$). Similarly, the C/M levels for the PLD were significantly lower than the LLE group ($p = 0.04$). Finally, there were significant differences across the groups' aided PTA ($F(2,57) = 9.21$, $p = 0.00$). The PLD group had significantly worse aided PTA than both the NLE and LLE groups (NLE $p = 0.00$; LLE $p = 0.01$).

SAS versus Non-SAS

The conversion tables provided by both Cochlear Americas and Advanced Bionics to convert the clinical map units to nC assume that the speech coding strategy is utilizing

a biphasic pulse. However, the SAS speech coding strategy generates digitally reconstructed analog waveforms and delivers it simultaneously along the electrode sites in the cochlea at relatively high rates. This specific speech coding strategy does not employ biphasic pulses or set pulse widths and therefore cannot be converted to charge-per-phase units using the standard conversion tables.

Due to the inability to convert T and C/M levels for children utilizing the SAS speech coding strategy, they were taken out of longitudinal map characteristic analysis and will be described and compared to the rest of the group here. Due to the small number of participants using this strategy, only trends and descriptive statistics will be discussed. Out of the 8 participants starting with SAS in preschool, 3 upgraded their speech processor as well as their speech coding strategy. This information can be found in Table 7.

The AOI was later for 3 out of the 5 participants (33, 34, and 35 months) who remained in the SAS group at the elementary assessment. Notably the SAS speech coding strategy was introduced and in use in 1999, the year that these children received their CI.

Language Emergence Group was determined for each of the SAS participants. Of the 8 participants utilizing SAS at either preschool or elementary school, 5 were classified as PLD, 1 as LLE, and 2 as NLE. The two NLE upgraded their speech processor and coding strategy between the first and second assessments.

Average values for audiologic and spoken language scores (LNT-50, LNT-70, BKB-SIN, and Aided PTA) for both the SAS group and the non SAS group can be found in Table 8. Overall, the participants mapped with SAS tended to perform poorer on all speech perception assessments at elementary age and had poorer aided PTAs when

superficially compared to the group who did not utilize the SAS strategy.

DISCUSSION

Objective 1: Examine the long-term stability of participants' map characteristics (average T level, average C/M level, EDR, and proportion of active electrodes) over time.

The first objective of the current study was to examine the stability of the participants' map characteristics over the time period between preschool and elementary age, which was approximately 6 years. Past studies have demonstrated significant changes in electrical stimulation levels for both the adult and pediatric population (Zwolan et. al., 2008; Henkin et al., 2003a, 2003b; Hughes et al., 2001; Kawano et al., 1998; Shapiro & Waltzman, 1995), however, these studies only examined changes over a 1 to 2 year period. These studies revealed that the greatest changes in map characteristics are typically greatest within the first three to six months after activation and continue to stabilize up until the first year of device use.

This study aimed to evaluate changes in T levels, C/M levels, EDR, and proportion of active electrodes over a much longer period of time. No significant changes in T levels, C/M levels, or proportion of active electrodes were found. However, statistical analysis revealed a significant change in EDR from preschool assessment to elementary assessment. For this group of participants, in between the time of preschool and elementary age the EDR became slightly narrower. The average C/M levels for the group did decrease from 24.17 nC at preschool age to 21.46 nC, but the difference was not statistically significant. This difference in C/M levels is likely affects the narrowing of the EDR.

These findings are similar to those of Robinson et. al. (2012) who examined the stability of electrical stimulation levels in adolescent participants utilizing Cochlear devices exclusively. No significant changes in T level electrical requirements were observed, however, a significant lowering of the C levels and narrowing of the EDR was detected. They noted that these changes may be due to the evolution of CI technology with participants upgrading into BTE devices or other new speech processors and speech coding strategies. Newer technology typically requires that electrical stimulation levels remain lower overall in order to reduce power needs and maintain usable battery life. Since the participants in this study upgraded to newer processors between the two assessment ages, it seems likely that the same factors noted in the Robinson study may be applicable for these participants. Since mapping protocols from each audiologist were not provided, it is not possible to determine whether differences in mapping techniques played a significant role in longitudinal changes

Another possibility that should be considered is that these changes involve the participants' accuracy in behavioral responding during programming sessions. At preschool age, audiologists may be setting C/M levels higher in order to provide the children an adequate EDR as long as it is comfortable for the user. Children at this age may not be as accurate with categorical loudness scaling and other programming techniques required to set electrical levels. As children got older and reached the elementary assessment, they were more capable of performing these programming tasks. This maturation of behavioral responses and increased accuracy allows an audiologist to refine the participant's EDR and electrical requirements. All of these factors (technology advancements, programming protocol differences, and behavioral maturation for

programming) could interact and play a role in the differences observed in map characteristics between preschool and elementary age.

Objective 2: Examine the relations among map characteristics and spoken language outcomes at the preschool testing session.

Secondly, this study aimed to examine the relationship between CI map characteristics and spoken language outcomes at the preschool age. At this assessment, the participants had been using their devices between 19 and 45 months. The spoken language outcome measures at preschool included the PPVT-III and PLS-3. Speech perception was not measured at this age. The map EDR was positively correlated with both PPVT-III and PLS-3. Participants with wider EDR's performed better on both the vocabulary assessment and had greater overall language scores.

Several studies have yielded similar findings in that a wider EDR is highly correlated with higher performance on spoken language outcome measures (Robinson et al., 2012; Geers et al., 2003; Waltzman et al., 1991). Optimized maps containing wider EDRs allow for a more salient speech signal to be delivered to the CI recipient. A wider EDR permits the CI user a greater range of speech intensities from very soft to loud. When the map is set properly, audibility and comfort over the full range of speech is obtainable. Although speech perception measures were not administered at the preschool assessment, it is reasonable to assume that ability to overhear and comfortably perceive speech at levels from soft to loud will be important factors for a child's vocabulary and overall language performance. Past studies have consistently shown that speech perception, vocabulary, and

language skills are highly correlated (Blamey et al., 2001; Davidson et al., 2001; Geers et al., 2015).

Objective 3: Examine the relations among map characteristics and spoken language outcomes at the elementary testing session.

The outcome measures at the elementary age were PPVT-III, CELF-4, LNT-50, LNT-70, BKB-SIN. In addition to examining T, M/C and EDR, aided PTA was included as a device characteristic at the elementary age. At this assessment, T level and C/M level were predictive of overall language ability, which was evaluated by the CELF-4. Unlike at the preschool age, the user's EDR was not significantly correlated with language.

At the elementary assessment age higher electrical T and C/M levels, not wider EDR, were associated with spoken language abilities. As discussed previously, as children mature in age their ability to reliability perform tasks that require accurate reporting of loudness is likely to improve. EDR may have played a more critical role in spoken language outcomes at preschool ages because clinicians were not able to condition the child to provide reliable information regarding electrical T and C/M levels. Instead, at preschool age, the goal was to optimize the child's map by providing a widened EDR and to provide as much speech information as possible to initiate and maximize the development of spoken language. Children who are inexperienced with hearing electrical signals from their CI's are not as reliable with behavioral responses for categorical loudness scaling. Loudness judgments have been documented in several studies as an imperative measure in CI programming sessions (Robinson et al., 2012; Geers et al., 2003; Skinner, Holden, & Holden, 1997).

With extended use of the CI, participants are better able to perform these loudness judgment tasks and audiologists can refine the users electrical levels and EDR based on their behavioral responses, which is ideal. At the elementary age, these behaviorally-set T and C/M levels, which dictate where the speech signal is being placed into the EDR, are predictive of overall language rather than the EDR.

Speech perception, evaluated by the LNT at 50 dB SPL, represents the child's ability to hear soft speech. This ability to hear speech at soft levels is thought to represent the ability to over-hear words and conversations in real-life listening situations. Results from this study revealed that participants with higher map T levels performed better on speech perception at soft levels. This may be related to the fact that the higher the speech is placed within the EDR, the more salient the signal will be for the child. LNT at 70 dB SPL (conversational speech) were not related to map T levels due to the fact that louder sounds will be placed well above the map T levels in the EDR. Studies from Skinner and colleagues have found that setting map T levels slightly above first hearing or detection for Cochlear recipients resulted in better aided soundfield thresholds and recognition of speech at soft levels (Skinner et al., 1997, 1999; Holden et al. 2013). Later, Holden, and colleagues (2011) provided guidelines to optimize perception of soft speech for Advanced Bionics users. The investigators found that aided thresholds were lowest when T levels were set higher than the recommended 10% of M level and with either the 80 or 65 dB IDR.

At the elementary assessment, children attended a camp at St. Louis where aided PTA could be collected and included as a device variable. Aided PTA represents the participant's audibility with their device as a whole, not just their electrical levels. Children with lower (or better) aided thresholds had better overall audibility with the device. Results

from this study revealed that better aided PTAs are highly related to vocabulary, language, and every speech perception measure employed at the elementary assessment.

Aided thresholds represent a measure that extends beyond how the map electrical current levels are set. It is a combination of how the electrical levels, microphone technology, and preprocessing strategies provide audibility for the speech signal. As CI technology has improved, audiologists have been able to achieve better aided thresholds through both mapping and adjusting AGC, speech processing and microphone characteristics. For example, several studies have shown the benefit of low aided thresholds and increased IDR (Davidson et al., 2009; Dawson, Decker, & Psarros, 2004; Holden, Skinner, Fourakis, & Holden, 2007). IDR represents what the CI is picking up and how it is placed within the EDR. Preprocessing, adjusting the AGC, and widening the IDR can all increase the child's ability to detect soft speech. While the relationship between map T levels and aided thresholds did not reach statistical significance, the combination of both play a role in offering optimal audibility. The aided PTA represents the level of soft sounds that are processed by the CI system while the electrical levels in the map determine the overall saliency and loudness level of these sounds for electrical hearing. Thus the audiologist must be cognizant of both electrical levels and aided thresholds when setting and making programming adjustments.

Unanticipated Findings: SAS vs Non-SAS

Due to the inability to convert the electrical levels of participants who were utilizing SAS, they were not included in any statistical analysis in which T level, C/M level, or EDR was needed. From this small group several trends were apparent. Participants in the SAS

group continued to use older speech processors and were implanted at later ages. They tended to have poorer audibility, which was reflected in their aided PTA measurements. Lastly, they tended to perform worse across all spoken language measures compared to the larger group.

Objective 4: Compare map characteristics across different language trajectories.

Finally, this paper aimed to compare CI map characteristics across different Language Emergence Groups. Results from the current paper have shown that map and device characteristics are correlated with spoken language outcomes. Thus we were interested in examining how children in the Language Emergence Groups compared across theses variables. Based on past studies demonstrating the positive effects of AOI **(**Nicholas & Geers, 2013; Boons et al., 2012; Nicholas & Geers, 2006**),** it was not unexpected that the NLE group tended to be implanted earlier than the LLE and PLD groups. Recall that the LLE group catches up in spoken language, but the PLD group remains delayed at the elementary assessment. There was no significant difference in AOI between the LLE and the PLD groups, suggesting that AOI did not play a role in distinguishing between children who caught up with age mates between the pre-school years and elementary years and those that did not.

Knowing that AOI is not a significant factor differentiating the initially delayed children who will and won't catch up over time, what predicts if a child will fall into the PLD group versus the LLE group? The PLD group had poorer audibility demonstrated by lower aided PTA. At the preschool assessment, EDR was narrower for the PLD group. At the elementary age results revealed that the PLD group had lower T and C/M levels than

the other groups. The child's ability to hear the speech signal, and to hear it at all levels comfortably, may be limited early on by the narrow EDR and as they get older they are not hearing soft speech as well because their T levels may not be optimized. These results suggest that audibility and intelligibility of speech may be a limiting factor for the PLD group.

For the children remaining in the SAS speech coding strategy at elementary school, 4 of the 5 were categorized as PLD. The use of an older speech coding strategy (SAS) and use older speech processor may be a factor in children remaining in the PLD group. Finally, the children using SAS who fell into the PLD group had poorer aided PTA. Some combination of these factors combined to put these children in the PLD group and unable to catch up in spoken language to their hearing peers.

Conclusions

These results have important implications for audiologists who serve young children with CIs. The clinician should optimize the child's map audibility and comfort of speech ranging from soft to loud. This may include careful manipulation of map T level, C/M levels, EDR, in order to achieve aided thresholds better than or equal to 20 dB HL. Categorical loudness scaling should be utilized as the child ages to refine the electrical requirements and to allow the user proper audibility through their device. In addition, the audiologist should encourage upgraded speech processor technology to provide the child the greatest opportunity to achieve their fullest potential.

It is possible that these findings may be influenced by characteristics of the children and families choosing to participate in the study. Participating children received early

listening and spoken language intervention along with a CI by their third birthday. The mean parental education and income levels were higher than the average for the general American population and the mean nonverbal IQ (105) was slightly higher than the normative mean (100). It will be important to replicate these findings with children from more heterogeneous backgrounds, who may better represent the population of children receiving CIs in North America today.

Future Research

There is a lot of variability in programming protocols across CI centers and manufacturer recommendations for setting electrical levels. Currently there is no standardized protocol for programming and optimizing CIs children utilizing these devices. These standards should be researched and implemented in order to provide best practice for this population. Findings from this paper show the importance of an optimized map and appropriate aided thresholds. These protocols would augment the child's experience with their device and propel them towards successful CI use and possibly enhanced speech and language.

With regard to the Language Emergence Groups, future researchers should investigate factors beyond the mapping characteristics alone, such as cochlear nerve integrity, how the electrodes are placed within the cochlea via imaging and how the electrodes are interacting with the spiral ganglion neurons. The predictors examined in the present study address just the 'surface level' -- of detection and comfort – and several other levels of possible predictive value exist that may help clinicians understand and predict a child's overall audibility capacity. Future studies might also incorporate children's'

cognitive abilities to consider how they may interact in conjunction with auditory abilities.

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Table 1. Processor Ratings.

Rating	Processor
0	MSP, AB S-Series
1	Spectra, AB PSP
2	ESPrit 22, AB BTE Platinum
3	Sprint, ESPrit 3G, AB Auria BTE
4	Freedom, Nucleus 5, AB Harmony BTE

MSP = Mini Speech Processor
AB = Advanced Bionics
PSP = Platinum Speech Processor
BTE = Behind-the-Ear

Table 2. Speech processor strategies.

PRESCHOOL: Speech Coding Strategy Distribution

		Manufacturer		**Total**
		AB	Cochlear	
Strategy				
	ACE	0	34	**34**
	CIS	5	0	**5**
	HiRes-P	6	0	**6**
	MPS	4	0	**4**
	SAS	8	0	**8**
	SPEAK	0	2	**2**
Total		23	36	59

*Advanced Combination Encoder (ACE); Continuous Interleaved Sampling (CIS); High Resolution Paired (HiRes-P); Multiple Pulsatile Sampler (MPS); Simultaneous Analog Stimulation (SAS); Spectral Peak (SPEAK)

ELEMENTARY: Speech Coding Strategy Distribution

		Manufacturer		**Total**
		AB	Cochlear	
Strategy	Not Reported	3	4	**7**
	ACE	0	32	**32**
	CIS	3	0	**3**
	HiRes-P	3	0	**3**
	HiRes-P with Fidelity 120	3	0	**3**
	HiRes-S with Fidelity 120	4	0	**4**
	MPS	2	0	**2**
	SAS	5	0	**5**
Total		23	36	59

*Advanced Combination Encoder (ACE); Continuous Interleaved Sampling (CIS); High Resolution Paired (HiRes-P); High Resolution Paired with Fidelity 120 (HiRes-P with Fidelity 120); High Resolution Simultaneous with Fidelity 120 (HiRes-S with Fidelity 120); Multiple Pulsatile Sampler (MPS); Simultaneous Analog Stimulation (SAS)

Table 3. Average scores on spoken language assessments at preschool and elementary.

Preschool Assessment (n = 60)

Assessment	*Average Score*	*SD*	*Range*
PPVT-III	83.73	18.77	40-112
PLS	76.23	20.74	50-126

Elementary Assessment (n = 60)

Assessment	*Average Score*	*SD*	*Range*
PPVT-III	95.62	22	44-142
CELF-4	89.18	20.19	42-132
LNT-50	52.07	25.96	0-94
LNT-70	76.67	18.71	0-96
BKB-SIN	9.81	4.61	3.5-22.5

*Peabody Picture Vocabulary Test - III (PPVT – III); Preschool Language Scale, Third Edition (PLS – 3); Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF – 4); Lexical Neighborhood Test at 50 dB SPL (LNT – 50); Lexical Neighborhood Test at 70 dB SPL (LNT – 70); Bamford – Kowal – Bench Sentence in Noise (BKB-SIN)

**Children using the SAS speech coding strategy were eliminated from these calculations.

Table 4. Correlations among predictor and outcome variables at preschool assessment.

		Prop. Active Elect	T level (nC)	C/M level (nC)	EDR (nC)	AOI (months)	PPVT-4	PLS-4	LNT-50	LNT-70	BKB-SIN
Proportion of Active Electrodes	Pearson Correlation	1	.139	.209	.222	-.106	.001	-.007	.121	.066	-.119
	Sig. (2-tailed)		.369	.173	.147	.450	.995	.961	.388	.641	.396
	N	53	44	44	44	53	53	53	53	53	53
T level (nC)	Pearson Correlation	.139	1	.897**	.636**	-.109	.057	.144	.100	-.070	-.031
	Sig. (2-tailed)	.369		.000	.000	.448	.691	.313	.483	.626	.831

	N	44	51	51	51	51	51	51	51	51	51
C level (nC)	Pearson Correlation	.209	.897**	1	.773**	-.087	.114	.257	.153	.075	-.132
	Sig. (2-tailed)	.173	.000		.000	.542	.425	.069	.284	.603	.354
	N	44	51	51	51	51	51	51	51	51	51
EDR (nC)	Pearson Correlation	.222	.636**	.773**	1	-.238	.296*	.488**	.261	.246	-.315*
	Sig. (2-tailed)	.147	.000	.000		.092	.035	.000	.064	.082	.024
	N	44	51	51	51	51	51	51	51	51	51
AOI (months)	Pearson Correlation	-.106	-.109	-.087	-.238	1	-.360**	-.441**	-.190	-.231	.290*
	Sig. (2-tailed)	.450	.448	.542	.092		.005	.000	.145	.076	.025

	N	53	51	51	51	60	60	60	60	60	60
PPVT-4	Pearson Correlation	.001	.057	.114	.296*	-.360**	1	.798**	.591**	.655**	-.669**
	Sig. (2-tailed)	.995	.691	.425	.035	.005		.000	.000	.000	.000
	N	53	51	51	51	60	60	60	60	60	60
PLS-4	Pearson Correlation	-.007	.144	.257	.488**	-.441**	.798**	1	.447**	.474**	-.549**
	Sig. (2-tailed)	.961	.313	.069	.000	.000	.000		.000	.000	.000
	N	53	51	51	51	60	60	60	60	60	60
LNT-50	Pearson Correlation	.121	.100	.153	.261	-.190	.591**	.447**	1	.735**	-.746**
	Sig. (2-tailed)	.388	.483	.284	.064	.145	.000	.000		.000	.000

	N	53	51	51	51	60	60	60	60	60	60
LNT-70	Pearson Correlation	.066	-.070	.075	.246	-.231	.655**	.474**	.735**	1	-.829**
	Sig. (2-tailed)	.641	.626	.603	.082	.076	.000	.000	.000		.000
	N	53	51	51	51	60	60	60	60	60	60
BKB-SIN	Pearson Correlation	-.119	-.031	-.132	-.315*	.290*	-.669**	-.549**	-.746**	-.829**	1
	Sig. (2-tailed)	.396	.831	.354	.024	.025	.000	.000	.000	.000	
	N	53	51	51	51	60	60	60	60	60	60

*Correlation is significant at the 0.01 level; (2-tailed).
** Proportion of Active Electrodes (Prop. Active Elec); Threshold Level (T level); Maximum/Comfort Level (C/M level); Electrical Dynamic Range (EDR); Age of Implantation (AOI); Peabody Picture Vocabulary Test - III (PPVT – III); Preschool Language Scale, Third Edition (PLS – 3); Lexical Neighborhood Test at 50 dB SPL (LNT – 50); Lexical Neighborhood Test at 70 dB SPL (LNT – 70); Bamford – Kowal – Bench Sentence in Noise (BKB-SIN)

Table 5. Correlations among predictor and outcome variables at elementary assessment.

		Prop. Active Elect	T level (nC)	C/M level (nC)	EDR (nC)	AOI (months)	Aided PTA	PPVT-4	CELF-4	LNT-50	LNT-70	BKB-SIN
Proportion of Active electrodes	Pearson Correlation	1	.121	.038	-.037	-.106	-.124	-.175	.024	.121	.066	-.119
	Sig. (2-tailed)		.411	.796	.801	.450	.377	.210	.867	.388	.641	.396
	N	53	48	48	48	53	53	53	53	53	53	53
T level (nC)	Pearson Correlation	.121	1	.852**	.549**	-.108	-.264	.127	.416**	.301*	.170	-.282
	Sig. (2-tailed)	.411		.000	.000	.466	.069	.388	.003	.037	.247	.052

	N	48	48	48	48	48	48	48	48	48	48	48
C/M level (nC)	Pearson Correlation	.038	.852**	1	.905**	-.072	-.103	.065	.369**	.116	.006	-.102
	Sig. (2-tailed)	.796	.000		.000	.628	.485	.661	.010	.434	.969	.491
	N	48	48	48	48	48	48	48	48	48	48	48
EDR (nC)	Pearson Correlation	-.037	.549**	.905**	1	-.027	.050	.000	.251	-.060	-.129	.067
	Sig. (2-tailed)	.801	.000	.000		.855	.735	1.000	.085	.683	.381	.651
	N	48	48	48	48	48	48	48	48	48	48	48

AOI (months)	Pearson Correlation	-.106	-.108	-.072	-.027	1	.225	-.318*	-.393**	-.190	-.231	.290*
	Sig. (2-tailed)	.450	.466	.628	.855		.084	.013	.002	.145	.076	.025
	N	53	48	48	48	60	60	60	60	60	60	60
Aided PTA	Pearson Correlation	-.124	-.264	-.103	.050	.225	1	-.453**	-.513**	-.703**	-.608**	.664**
	Sig. (2-tailed)	.377	.069	.485	.735	.084		.000	.000	.000	.000	.000
	N	53	48	48	48	60	60	60	60	60	60	60
PPVT-4	Pearson Correlation	-.175	.127	.065	.000	-.318*	-.453**	1	.835**	.395**	.426**	-.446**

	Sig. (2-tailed)	.210	.388	.661	1.000	.013	.000		.000	.002	.001	.000
	N	53	48	48	48	60	60	60	60	60	60	60
CELF-4	Pearson Correlation	.024	.416**	.369**	.251	-.393**	-.513**	.835**	1	.557**	.549**	-.628**
	Sig. (2-tailed)	.867	.003	.010	.085	.002	.000	.000		.000	.000	.000
	N	53	48	48	48	60	60	60	60	60	60	60
LNT-50	Pearson Correlation	.121	.301*	.116	-.060	-.190	-.703**	.395**	.557**	1	.735**	-.746**
	Sig. (2-tailed)	.388	.037	.434	.683	.145	.000	.002	.000		.000	.000
	N	53	48	48	48	60	60	60	60	60	60	60

LNT-70	Pearson Correlation	.066	.170	.006	-.129	-.231	-.608**	.426**	.549**	.735**	1	-.829**
	Sig. (2-tailed)	.641	.247	.969	.381	.076	.000	.001	.000	.000		.000
	N	53	48	48	48	60	60	60	60	60	60	60
BKB-SIN	Pearson Correlation	-.119	-.282	-.102	.067	.290*	.664**	-.446**	-.628**	-.746**	-.829**	1
	Sig. (2-tailed)	.396	.052	.491	.651	.025	.000	.000	.000	.000	.000	
	N	53	48	48	48	60	60	60	60	60	60	60

*Correlation is significant at the 0.01 level; (2-tailed).
** Proportion of Active Electrodes (Prop. Active Elec); Threshold Level (T level); Maximum/Comfort Level (C/M level); Electrical Dynamic Range (EDR); Age of Implantation (AOI); Aided Pure Tone Average (Aided PTA); Peabody Picture Vocabulary Test - III (PPVT – III); Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF – 4); Lexical Neighborhood Test at 50 dB SPL (LNT – 50); Lexical Neighborhood Test at 70 dB SPL (LNT – 70); Bamford – Kowal – Bench Sentence in Noise (BKB-SIN)

Table 6. Language emergence groups and map characteristics at preschool and elementary assessments

	PRESCHOOL			**ELEMENTARY**		
NORMAL LANUAGE EMERGENCE (NLE)	*Average*	*SD*	*Range*	*Average*	*SD*	*Range*
Threshold (T) level	9.08	6.31	1.75 - 28.91	7.25	4.16	1.18 - 15.14
Comfort/Maximum (C/M) level	27.04	16.15	9.31 - 78.95	21.74	8.1	9.57 - 42.44
Electrical Dynamic Range (EDR)	22.92	13.69	5.95 - 50.04	14.5	5.18	6.73 - 27.3
Proportion of Active Electrodes	0.95	0.05	0.86 - 1.00	0.93	0.16	0.38 - 1.00
Aided Pure Tone Average (PTA)	Not Collected			17.98	5.57	8.30 - 28.3
LATE LANGUAGE EMERGENCE (LLE)	*Average*	*SD*	*Range*	*Average*	*SD*	*Range*
Threshold (T) level	8.66	5.77	1.6 - 22.72	8.64	5.99	1.65 - 26.64
Comfort/Maximum (C/M) level	23.3	13.58	7.58 - 58.32	23.67	12.06	10.67 - 52.35
Electrical Dynamic Range (EDR)	14.54	8.38	5.88 - 36.09	15.02	7.57	5.09 - 35.81
Proportion of Active Electrodes	0.96	0.06	0.75 - 1.00	0.96	0.08	0.69 - 1.00
Aided Pure Tone Average (PTA)	Not Collected			20.08	4.97	10 - 28.83
PERSISTENT LANGUAGE DELAY (PLD)	*Average*	*SD*	*Range*	*Average*	*SD*	*Range*
Threshold (T) level	5.91	4.38	0.96 - 18.45	3.74	2.61	1.15 - 8.08
Comfort/Maximum (C/M) level	18.4	6.7	7.25 - 28.12	14.94	5.14	6.95 - 25.76
Electrical Dynamic Range (EDR)	12.5	5.59	3.88 - 25.32	11.19	4.31	4.64 - 18.21
Proportion of Active Electrodes	0.99	0.03	0.91 - 1.00	0.97	0.04	0.88 - 1.00
Aided Pure Tone Average (PTA)	Not Collected			26.58	13.30	13.30 - 48.30

*All values are in nanocoulombs (nC)

Table 7. Participants with simultaneous analog stimulation speech coding strategy

Participants with SAS at both Preschool & Elementary Assessments

Participant Number	*AOI (months)*	*Ear Implanted*	*Language Emergence Group*
8	35	R	PLD
11	33	L	PLD
21	34	L	PLD
39	18	R	PLD
72	14	R	LLE

Participants with SAS at Preschool Only

Participant Number	*AOI (months)*	*Ear Implanted*	*Language Emergence Group*
23	35	R	PLD
29	24	R	NLE
64	12	R	NLE

* Normal Language Emergence (NLE); Late Language Emergence (LLE); Persistent Language Delay (PLD)

Table 8. Average spoken language scores and aided pure tone average at elementary age for the simultaneous analog stimulation (SAS) and non-SAS groups.

	SAS (n=5)			**Non-SAS (n=47)**		
	Average	*SD*	*Range*	*Average*	*SD*	*Range*
LNT-50	24.80	15.79	12 - 48	56.34	24.95	0 - 94
LNT-70	64.80	21.34	30 - 86	79.87	13.86	30 - 94
BKB-SIN	14.70	5.30	9.5 - 22	9.15	4.03	3.5 - 21.5
Aided PTA	27.00	8.77	13.3 - 36.7	20.50	6.37	8.3 - 36.7

*Simultaneous Analog Stimulation (SAS); Lexical Neighborhood Test at 50 dB SPL (LNT - 50); Lexical Neighborhood Test at 70 dB SPL (LNT - 70); Bamford – Kowal – Bench Sentence in Noise (BKB - SIN); Aided Pure Tone Average (Aided PTA)

**Non-SAS group contains participants utilizing strategies other than SAS. These speech coding strategies include: Advanced Combination Encoder (ACE); Continuous Interleaved Sampling (CIS); High Resolution Paired (HiRes-P); High Resolution Paired with Fidelity 120 (HiRes-P with Fidelity 120); High Resolution Simultaneous with Fidelity 120 (HiRes-S with Fidelity 120); and Multiple Pulsatile Sampler (MPS)

Table 9. Speech coding strategies represented in each language emergence group at elementary age.

	Normal Language Emergence (NLE, n = 19)	**Late Language Emergence** (LLE, n = 22)	**Persistent Language Delay** (PLD, n = 19)
ACE	68.40	63.64	31.58
CIS	0	9.09	5.26
HiRes-P	5.26	4.55	5.26
HiRes-P with Fidelity 120	0	4.55	10.53
HiRes-S with Fidelity 120	10.53	4.55	5.26
MPS	0	4.55	5.26
SAS	0	4.55	21.05
Not Reported	15.79	4.55	15.79

APPENDIX A

All Participants: Values for Map Characteristics at Preschool Assessment

Participant ID	***AOI (months)***	***Ear Implanted***	***Manufacturer***	***Speech Processor***	***Speech Coding Strategy***	***T level***	***C level***	***EDR***	***Proportion of Active Electrodes***
EISFU02	30	RE	Cochlear	SPrint	ACE	4.80	18.90	14.09	1.00
EISFU03	18	LE	Cochlear	SPrint	ACE	6.99	16.35	9.37	1.00
EISFU04	*26*	LE	Advanced Bionics	Platinum BTE	CIS	7.24	20.36	13.13	1.00
EISFU06	21	RE	Cochlear	SPrint	ACE	4.95	16.33	11.38	1.00
EISFU08	35	RE	Advanced Bionics	Clarion Platinum	SAS				1.00
EISFU09	18	LE	Cochlear	SPrint	ACE	8.58	14.53	5.95	0.86
EISFU10	19	RE	Cochlear	SPrint	SPEAK	5.01	11.87	6.85	0.91
EISFU11	33	LE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU12	21	LE	Advanced Bionics	Clarion S-Series	CIS	5.69	14.86	9.18	1.00
EISFU13	26	RE	Advanced Bionics	Clarion S-Series	CIS	7.24	17.95	10.71	1.00
EISFU14	19	RE	Cochlear	ESPrit	ACE	8.00	30.47	22.47	0.86
EISFU18	21	RE	Cochlear	ESPrit	SPEAK	6.31	13.00	6.70	0.91
EISFU19	19	RE	Advanced Bionics	SP S-Series	MPS	7.34	18.18	10.84	1.00
EISFU20	20	RE	Advanced Bionics	Platinum Series	MPS	4.775	18.225	13.45	1.00

EISFU21	34	LE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU22	21	RE	Cochlear	SPrint	ACE	13.23	35.29	22.06	1.00
EISFU23	35	RE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU24	31	RE	Cochlear	ESPrit 3G	ACE	15.21	30.26	15.04	0.91
EISFU25	17	RE	Cochlear	SPrint	ACE	8.93	20.69	11.76	1.00
EISFU28	16	RE	Cochlear	SPrint	ACE	7.80	26.11	18.31	1.00
EISFU29	29	RE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU31	33	RE	Cochlear	SPrint	ACE	9.64	17.37	7.73	0.95
EISFU32	17	RE	Cochlear	SPrint	ACE	7.32	30.11	22.79	0.95
EISFU33	32	LE	Cochlear	SPrint	ACE	2.36	9.31	6.95	0.95
EISFU34	18	RE	Advanced Bionics	Platinum Series	CIS	3.38	7.25	3.88	1.00
EISFU35	19	RE	Cochlear	ESPrit 3G	ACE	15.43	44.91	29.48	0.91
EISFU36	28	LE	Cochlear	SPrint	ACE	18.45	26.89	8.44	0.91
EISFU38	21	RE	Cochlear	SPrint	ACE	9.21	21.35	12.14	0.95
EISFU39	18	RE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU40	21	RE	Cochlear	SPrint	ACE	28.91	78.95	50.04	1.00
EISFU42	14	RE	Cochlear	SPrint	ACE	21.81	57.91	36.09	1.00
EISFU44	18	LE	Cochlear	SPrint	ACE	6.19	20.38	14.19	1.00
EISFU45	18	RE	Advanced Bionics	Platinum Series	HiRes-P	1.7	7.575	5.875	0.75
EISFU49	12	RE	Cochlear	ESPrit 3G	ACE	11.57	28.57	17.00	0.91
EISFU52	35	RE	Cochlear	SPrint	ACE	22.72	58.32	35.60	0.91

EISFU53	22	LE	Advanced Bionics	Platinum Series	HiRes-P	2.80	28.12	25.32	1.00
EISFU54	18	RE	Advanced Bionics	Platinum Series	MPS	14.96	38.84	23.88	1.00
EISFU55	14	RE	Advanced Bionics	Platinum Series	MPS	8.74	27.90	19.16	1.00
EISFU57	30	RE	Advanced Bionics	Platinum Series	CIS	1.60	15.93	14.33	1.00
EISFU59	12	RE	Cochlear	ESPrit 3G	ACE	4.57	14.99	10.42	0.91
EISFU60	27	RE	Cochlear	SPrint	ACE	6.66	25.69	19.03	1.00
EISFU61	*12*	RE	Cochlear	ESPrit 3G	ACE	5.05	13.73	8.68	0.91
EISFU62	12	RE	Cochlear	SPrint	ACE	6.65	16.84	44.37	1.00
EISFU63	34	RE	Advanced Bionics	Platinum Series	HiRes-P	0.96	9.71	8.74	1.00
EISFU64	12	RE	Advanced Bionics	Platinum Series	SAS				1.00
EISFU65	23	RE	Advanced Bionics	Platinum Series	HiRes-P	1.28	12.70	11.42	1.00
EISFU66	17	RE	Cochlear	ESPrit 3G	ACE	11.91	27.83	40.89	0.95
EISFU67	12	RE	Cochlear	SPrint	ACE	12.10	28.14	41.11	0.91
EISFU68	22	LE	Med-El	TEMPO+ ROM 6.0	CIS+				0.92
EISFU69	30	RE	Cochlear	SPrint	ACE	7.16	14.78	7.63	1.00
EISFU70	21	RE	Cochlear	SPrint	ACE	4.28	16.55	12.27	1.00
EISFU71	15	RE	Cochlear	SPrint	ACE	7.51	25.52	18.01	1.00
EISFU72	*14*	RE	Advanced Bionics	Platinum BTE	SAS				1.00
EISFU74	12	RE	Cochlear	SPrint	ACE	7.39	25.21	17.82	1.00
EISFU75	31	LE	Cochlear	ESPrit 3G	ACE	4.96	16.45	11.49	0.91

EISFU76	35	RE	Cochlear	Sprint	ACE	8.00	25.34	17.34	1.00
EISFU77	23	LE	Advanced Bionics	Platinum	HiRes-P	3.62	11.55	7.93	1.00
EISFU79	35	RE	Cochlear	SPrint	ACE	4.83	16.75	11.93	1.00
EISFU80	31	LE	Cochlear	SPrint	ACE	5.40	23.56	18.16	1.00
EISFU81	38	LE	Advanced Bionics	Auria	HiRes-P	1.75	17.67	15.92	0.94

*Age of Implantation (AOI); Right Ear (RE); Left Ear (LE); Advanced Combination Encoder (ACE); Continuous Interleaved Sampling (CIS); High Resolution Paired (HiRes-P); Multiple Pulsatile Sampler (MPS); Simultaneous Analog Stimulation (SAS); Spectral Peak (SPEAK); Threshold Level (T level); Comfort/Maximum Level (C/M level); Electrical Dynamic Range (EDR)

APPENDIX B

All Participants: Values for Map Characteristics and Aided PTA at Elementary Assessment

Participant ID	***Speech Processor***	***Speech Coding Strategy***	***T level***	***C level***	***EDR***	***Proportion of Active Electrodes***	***Aided PTA***	***Bilateral***
EISFU02	Freedom SP	ACE	3.40	11.94	8.54	1.00	20	Yes
EISFU03	Freedom SP	ACE	7.08	14.81	7.74	1.00	20	Yes
EISFU04	PSP	CIS	8.09	32.13	24.04	1.00	23.33	No
EISFU06							20	No
EISFU08	Clarion Platinum	SAS				1.00	25	No
EISFU09	Sprint JG	ACE	10.65	31.29	20.65	0.86	28.33	Yes
EISFU10	Freedom SP	ACE	4.41	11.43	7.02	1.00	20	No
EISFU11	Platinum Series	SAS				1.00	36.67	No
EISFU12	Platinum Series	CIS	5.69	17.54	11.85	1.00	36.67	No
EISFU13	Clarion S-Series	CIS	10.00	28.33	18.33	1.00	28.33	No
EISFU14	Freedom	ACE	7.07	24.26	17.19	0.86	21.67	Yes
EISFU18	Freedom SP	ACE	5.58	10.67	5.09	0.91	15	No
EISFU19	BTE	MPS	2.59	11.74	9.15	1.00	28.33	No
EISFU20							16.67	No
EISFU21	Platinum Series	SAS				1.00	31.67	No
EISFU22	Freedom SP	ACE	6.62	21.52	14.90	1.00	16.67	Yes
EISFU23	Auria	HiRes-P	1.93	19.10	17.17	0.94	28.33	Yes

EISFU24	Freedom SP	ACE	9.17	31.05	21.88	1.00	23.33	No
EISFU25	Freedom SP	ACE	4.94	11.88	6.93	0.91	26.67	Yes
EISFU28	ESPrit 3G	ACE	7.56	25.76	18.21	0.91	20	No
EISFU29	Auria	HiRes-P	1.75	17.83	16.08	0.38	28.33	Yes
EISFU31	Freedom SP	ACE	11.57	22.89	11.33	0.91	21.67	Yes
EISFU32	Freedom SP	ACE	9.01	21.65	12.64	1.00	20	Yes
EISFU33							21.67	No
EISFU34							25	No
EISFU35	Freedom SP	ACE	15.14	42.44	27.30	1.00	13.33	No
EISFU36							48.33	No
EISFU38	Freedom SP	ACE	6.42	19.43	13.01	0.95	21.67	No
EISFU39	Platinum Series	SAS				1.00	13.33	Yes
EISFU40	Freedom SP	ACE	7.86	16.18	8.32	1.00	16.67	Yes
EISFU42	Freedom SP	ACE	16.54	52.35	35.81	1.00	16.67	No
EISFU44	SPrint	ACE	3.63	15.62	11.98	0.91	33.33	No
EISFU45	Harmony	HiRes-S with Fidelity 120	4.25	20.48	16.24	0.69	20	Yes
EISFU49	Freedom SP	ACE	14.97	33.70	18.74	1.00	25	Yes
EISFU52	Freedom	ACE	26.64	44.85	18.21	0.91	15	No
EISFU53	Harmony	HiRes-P with Fidelity 120	1.64	16.29	14.65	1.00	30	No
EISFU54	BTE	MPS	15.54	38.84	23.30	1.00	21.67	Yes
EISFU55							18.33	No
EISFU57	Platinum Series	HiRes-P with Fidelity 120	1.65	16.59	14.94	1.00	18.33	No
EISFU59	Freedom SP	ACE	2.84	9.57	6.73	1.00	10	Yes
EISFU60	Freedom SP	ACE	8.08	16.67	8.58	1.00	23.33	Yes

EISFU61	Freedom SP	ACE	4.76	12.73	7.97	1.00	15	No
EISFU62	Freedom SP	ACE	4.82	19.18	14.35	1.00	16.67	Yes
EISFU63	Platinum Series	HiRes-P with Fidelity 120	1.15	11.70	10.55	0.88	30	No
EISFU64	Harmony	HiRes-S with Fidelity 120	1.18	11.92	10.74	1.00	25	No
EISFU65	Harmony	HiRes-S with Fidelity 120	1.59	15.80	14.21	1.00	18.33	Yes
EISFU66	Freedom SP	ACE	11.30	28.28	16.98	0.91	16.67	Yes
EISFU67	Freedom SP	ACE	12.46	23.10	10.64	1.00	10	Yes
EISFU68	Freedom SP	ACE	1.69	7.27	5.58	0.95	20	Yes
EISFU69	SPrint	ACE	5.71	12.14	6.42	0.82	10	Yes
EISFU70							18.33	No
EISFU71	ESPrit 3G	ACE	10.50	27.04	16.54	0.91	18.33	No
EISFU72	Platinum BTE	SAS				1.00	28.33	No
EISFU74	SPrint	ACE	8.08	21.94	13.86	1.00	8.33	No
EISFU75	Freedom SP	ACE	2.30	6.95	4.64	1.00	18.33	Yes
EISFU76	Freedom SP	ACE	9.65	26.73	17.08	1.00	10	Yes
EISFU77	Auria	HiRes-P	3.80	12.21	8.41	1.00	18.33	No
EISFU79	Freedom SP	ACE	4.79	17.86	13.06	1.00	16.67	No
EISFU80	Freedom SP	ACE	5.78	17.84	12.06	1.00	21.67	Yes
EISFU81	Harmony	HiRes-S with Fidelity 120	1.89	18.95	17.06	0.94	20	Yes

*Advanced Combination Encoder (ACE); Continuous Interleaved Sampling (CIS); High Resolution Paired (HiRes-P); High Resolution Paired with Fidelity 120 (HiRes-P with Fidelity 120); High Resolution Simultaneous with Fidelity 120 (HiRes-S with Fidelity 120); Multiple Pulsatile Sampler (MPS); Simultaneous Analog Stimulation (SAS); Threshold Level (T level); Comfort/Maximum Level (C/M level); Electrical Dynamic Range (EDR); Aided Pure Tone Average (Aided PTA).

APPENDIX C

All Participants: Scores on Spoken Language and Speech Perception Measures.

	Preschool		**Elementary**					
Participant ID	***PPVT-III***	***PLS***	***PPVT-III***	***CELF-4***	***LNT-50***	***LNT-70***	***BKB-SIN***	***Language Group***
EISFU02	94	74	97	93	76	80	8	2
EISFU03	98	80	81	76	62	84	7	3
EISFU04	96	81	87	106	84	90	9	2
EISFU06	70	57	100	87	60	72	9	2
EISFU08	75	57	62	66	48	86	12	3
EISFU09	100	96	135	124	16	84	6	1
EISFU10	81	68	93	94	62	86	7	2
EISFU11	42	50	53	50	12	62	22	3
EISFU12	90	82	81	76	0	72	15	3
EISFU13	85	62	109	109	20	54	17	2
EISFU14	87	113	100	96	54	84	6	1
EISFU18	84	56	115	85	62	78	9.5	2
EISFU19	71	67	76	58	8	30	21.5	3
EISFU20	102	97	118	112	62	92	8.5	1
EISFU21	40	50	44	46	12	30	18.5	3
EISFU22	105	95	125	112	94	90	5.5	1
EISFU23	49	53	74	50	12	38	18	3
EISFU24	88	69	94	91	68	82	12	2
EISFU25	79	63	109	88	62	84	7.5	2
EISFU28	89	78	97	82	76	88	11.5	3
EISFU29	91	87	112	87	36	74	14.5	1
EISFU31	90	55	112	91	80	88	7.5	2

EISFU32	101	117	102	106	88	94	5.5	1
EISFU33	108	101	90	100	70	86	5	1
EISFU34	64	50	73	66	4	34	16.5	3
EISFU35	105	98	108	104	72	88	8.5	1
EISFU36	40	50	79	67	0	0	22.5	3
EISFU38	67	60	100	85	40	84	8.5	2
EISFU39	81	63	88	84	18	70	11.5	3
EISFU40	103	102	142	104	44	88	9	1
EISFU42	57	74	72	99	48	64	9.5	2
EISFU44	59	58	58	50	18	70	11.5	3
EISFU45	85	63	121	90	38	66	12	2
EISFU49	89	73	80	93	58	92	8	2
EISFU52	87	66	98	102	60	68	7	2
EISFU53	68	71	87	81	14	74	10	3
EISFU54	80	78	91	91	70	86	7.5	2
EISFU55	86	85	97	104	50	58	10	1
EISFU57	89	77	140	109	30	64	16.5	2
EISFU59	93	96	113	108	80	92	6.5	1
EISFU60	69	53	85	84	86	82	10.5	3
EISFU61	110	99	106	88	84	90	5.5	1
EISFU62	103	110	124	115	64	94	5.5	1
EISFU63	53	54	56	42	16	62	14.5	3
EISFU64	107	126	123	115	62	78	6	1
EISFU65	55	50	62	48	54	66	14	3
EISFU66	104	98	125	114	72	92	5	1
EISFU67	111	117	112	118	94	88	3.5	1
EISFU68	52	50	69	84	70	92	6.5	3

EISFU69	75	72	89	85	78	86	9.5	2
EISFU70	81	55	75	75	48	84	8	3
EISFU71	112	107	129	132	76	90	9.5	1
EISFU72	94	67	81	88	34	76	9.5	2
EISFU74	107	101	121	108	74	92	6.5	1
EISFU75	72	57	89	76	46	86	10.5	3
EISFU76	97	73	95	93	82	84	3.5	2
EISFU77	88	74	89	87	56	94	4	2
EISFU79	86	71	98	90	52	80	7.5	2
EISFU80	86	63	100	94	58	96	5.5	2
EISFU81	94	105	96	93	50	82	5.5	1

* Peabody Picture Vocabulary Test - III (PPVT – III); Preschool Language Scale, Third Edition (PLS – 3); Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF – 4); Lexical Neighborhood Test at 50 dB SPL (LNT – 50); Lexical Neighborhood Test at 70 dB SPL (LNT – 70); Bamford – Kowal – Bench Sentence in Noise (BKB-SIN)
**Language Emergence Groups (Language Group): 1 = Normal Language Emergence (NLE); 2 = Late Language Emergence (LLE); 3 = Persistent Language Delay (PLD)