# Relating decreased acoustic contrast to decreased speech intelligibility: Perceptual consequences for children with cochlear implants

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# ABSTRACT

Children with cochlear implants (CIs) face considerable challenges throughout speech and language development, namely deprivation of early auditory input and degradation of the auditory signal. To account for the effects of this altered auditory input, it is necessary to identify sensitive tools that can help explain differences in speech intelligibility, or how well the speech of children with CIs can be identified by naïve listeners. The purpose of the study was to determine whether decreased acoustic contrast was a predictor of speech intelligibility in children with CIs within a challenging listening environment. Speakers included 10 4 to 7-year-old children with bilateral CIs and 10 4 to 7-year-old children with normal hearing (NH). Within female four-speaker babble, 80 adult listeners identified word-initial /s/ and /ʃ/ productions by children with CIs and children with NH. Results indicated that the words produced by children with CIs evidenced less acoustic contrast between /s/ and /ʃ/ compared to the words produced by children with NH, even for correct productions. This decreased acoustic contrast was associated with decreased speech intelligibility for words produced by children with CIs. This finding suggests the need for more fine-grained measures of consonant production than simply correct versus incorrect for children with CIs. Fine-grained analysis can provide information to clinicians to continue to work on speech sounds beyond just "correct," particularly for sounds that are difficult for children with CIs to perceive and produce.

# SPECIFIC AIMS

Children who use cochlear implants (CIs) have somewhat decreased speech intelligibility even after as much as seven years of CI use compared to children with normal hearing (NH) (Peng, Spencer, & Tomblin, 2004). Decreased speech intelligibility impacts children with CIs' ability to communicate and socialize, especially at a time when learning needs have to be communicated to teachers with little experience with hearing loss. This decreased speech intelligibility is further compounded by listening environments that often contain multiple speakers.

Most of the research evaluating the acquisition of phonemic contrasts has described productions as correct or incorrect. However, children gradually and continually refine speech sounds even after these sounds are judged as correct. Fine-grained acoustic analysis offers a more gradient measure of these productions to capture subtle differences that may be associated with decreased intelligibility of speech. Of particular interest for children with CIs is the production of spectral contrasts (e.g., /s/-/ʃ/) since these sounds are especially degraded in the signal provided by CIs, while temporal (e.g., /t/-/d/) and manner contrasts (e.g., /t/-/s/) are easier for children with CIs to discriminate and produce (Friesen, Shannon, Baskent, & Wang, 2001; Iverson, 2002; Munson, Donaldson, Allen, Collison, & Nelson, 2002).

To determine whether past findings of reduced acoustic and perceptual contrast at the phonemic level extend to judgments of reduced speech intelligibility at the word level and within a challenging listening environment, it is necessary to determine whether words that may be easily judged in quiet become more difficult to judge in the presence of competing speech stimuli. Understanding the implications of reduced acoustic and perceptual contrast on speech intelligibility in a listening situation characteristic of a child's everyday learning and socializing environment will better inform speech intervention targets of children with CIs. Additionally, furthered understanding of the intelligibility of children with CIs' speech will aid educators in better engineering of academic and social auditory environments.

To examine whether decreased acoustic contrast predicts decreased intelligibility at the word level, I will assess the accuracy and speed of processing of adult listeners with NH while listening to one-and two-syllable words produced by children with CIs and children with NH. These speech samples will feature words with /s/, /ʃ/, /t/, /d/, /g/, and /k/ in the initial position. All words will be placed in multi-speaker babble to determine whether there are differences in speech intelligibility that arise only during challenging listening environments.

Children with CIs face considerable challenges throughout speech and language development, namely deprivation of early auditory input and degradation of the auditory signal. Fine-grained analysis is necessary to determine whether a relationship exists between decreased acoustic contrast and decreased speech intelligibility. Additionally, utilization of an ecologically valid listening environment will aid interpretation of intelligibility differences between children with CIs and children with NH.

**CHAPTER ONE**

LITERATURE REVIEW

In the last 25 years since cochlear implants (CIs) were approved for use in children two years of age and older by the Food and Drug Administration (and then in 2000 for children 12 months of age), the language, literacy, and speech outcomes for prelingually deaf children have drastically improved compared to severe to profoundly deaf children who use hearing aids (HAs). After surgical implantation and activation, CIs offer electrical stimulation to the auditory nerve. While this signal does not contain the full acoustic information of the original presentation, over time, children with CIs learn to interpret the electric signals as sound. In addition to this increased device experience, advances in the technological design of CIs and clinical best practice improvements (e.g., early implantation and intervention) contribute to the improved language and speech outcomes of children with CIs. Tomblin, Spencer, Flock, Tyler, and Gantz (1999) report one example of improved language outcomes where children with three or more years of experience with their CIs performed significantly better than prelingually deaf children with and without HAs on measures of language comprehension and production. Additionally, children with CIs demonstrate literacy outcomes that approach performance of peers with normal hearing (NH) (Tomblin, Spencer, & Gantz, 2000; Geers, Strube, Tobey, & Moog, 2011; Spencer, Barker, & Tomblin, 2003; Connor & Zwolan, 2004; Johnson & Goswami, 2010). Improved performance in interrelated skills of language and literacy translates to improved school readiness and school success for children with CIs. In addition to language and literacy measures, exemplars of advances associated with CI use are evidenced when comparing intelligibility estimates in the speech of prelingually deaf children with HAs and children with CIs.

When examining speech intelligibility outcomes in children with hearing loss, researchers and clinicians define the construct in terms of both speech production (i.e., the amount of speech a listener can identify from a child with CIs) and speech perception (i.e., how much speech a child with CIs is able to decode from a signal). The current review and study will refer to speech intelligibility in terms of speech production. In addition to defining speech intelligibility as a construct, it is important to recognize that the measure does not equal understandability. Fontan, Tardieu, and Gaillard (2015) found a weak relationship between intelligibility and comprehension of sentence level information when presented in a challenging listening environment (i.e., multi-talker babble). Lastly, speech intelligibility estimates are listener, context, and content dependent, which necessitate a critical definition of how the measure was calculated. For example, speech intelligibility can be evaluated at the sound and word level, as well as in connected speech. Additionally, researchers and clinicians can select varying criteria for an identified signal. For example, Hustad (2006) examined total word phonemic matches, informational word phonemic matches, and informational word semantic matches. Hustad (2006) illustrated the need for consistency in analysis procedures when describing speech intelligibility, as well as cautious interpretation of the generalizability of a speech intelligibility estimate.

While a variety of designs are utilized in the studies referenced below, intelligibility is defined generally as the amount of speech from a speaker identified by listeners. In Baudonck, Van Lierde, D'haeseleer, and Dhooge (2011), 7-year-old children with CIs were judged as 92% intelligible in daily situations and 8-year-old children with HAs as 40% intelligible in daily situations by two speech-language pathologists (one with experience with the speech of children who are deaf and one without the same exposure). Raters watched a video-recorded speech sample of picture naming, sentence repetition, and short story repetition. Intelligibility judgments were made using a five-point scale (i.e., 1 = "totally unintelligible speech," 2 = "nearly unintelligible speech, some single words are intelligible while lip-reading and using a known context," 3 = "an intelligible speech if the listener is concentrated and reads the child's lips," 4 = "an intelligible speech for listeners with little experience with deaf speech," and 5 = "an intelligible speech for all listeners in daily situations.") Lejeune and Demanez (2006) also found significantly higher speech intelligibility in native French 7-year-old children with CIs compared to native French 9-year-old children with HAs. The authors used a five-point rating scale to evaluate connected speech intelligibility. A general trend of increased speech intelligibility is also demonstrated as CI experience increases (Miyamoto, Iler Kirk, Robbins, Todd, & Riley, 1996; Mondain, Sillon, Vieu, Lanvin, Reuillard-Artieres, Tobey, & Uziel, 1997; Allen, Nikolopoulos, & O'Donoghue, 1998; Vieu, Mondain, Blanchard, Sillon, Reuillard-Artieres, Tobey, Uziel, & Piron, 1998; Chin, Tsai, & Gao, 2003; Calmels, Saliba, Wanna, Cochard, Fillaux, Deguine, & Fraysse, 2004; Flipsen & Colvard, 2005; Huttunen, 2008; Phillips, Hassanzadeh, Kosaner, Martin, & Deibl, 2009; Khwaileh & Flipsen, 2010). While caution must be taken when comparing estimates across studies because intelligibility is task dependent (i.e., estimates vary according to the context, listener, and content of the sample), the body of speech intelligibility research as a whole illustrates an improvement in speech intelligibility with CI use compared to HA use and as CI experience increases.

Despite improvement in speech and language performance compared to prelingually deaf children with and without HAs, children with CIs generally perform at a lower level than their peers with NH in areas important for school success (e.g., production of speech and perception of contrasts). This relationship also holds true for speech intelligibility across studies with variable methods of estimating intelligibility (Chin, Tsai, & Gao, 2003; Chin, Bergeson, & Phan, 2012; Chuang, Yang, Chi, Weismer, & Wang, 2012). Chin, Tsai, and Gao (2003) evaluated speech intelligibility in English-speaking children using the Beginners' Intelligibility Test (BIT; Osberger, Robbins, Todd, & Riley, 1994). Children with CIs (chronological ages 2-10 years) were judged to be 34.5% correct on average at the level of connected speech (*SD* = 35.0%, range = 0-98% correct) compared to children with NH (chronological ages 2-6 years) who were judged to be 86.7% correct on average (*SD* = 19.5%, range = 13.5-100%). In 2012, Chin, Bergeson, and Phan also found intelligibility scores to be higher for English-speaking children with NH compared to children with CIs at the level of connected speech as measured by the BIT (i.e., listeners judging samples from children with NH were near ceiling and were ~80% correct for samples from children with CIs). Lastly, Chuang et al. (2012) examined the speech intelligibility of 7-year-old Mandarin-speaking children. At the sentence-level, children with CIs were rated as significantly less intelligible overall (using a rating scale) and percent correct for vowels, consonants, tone, and words (Chuang et al., 2012). Some studies, such as Baudonck et al. (2011) describe lower intelligibility for children with CIs compared to children with NH that does not reach significance. However, lowered speech intelligibility can impact children with CIs' abilities to communicate and socialize, especially at a time when learning needs must be communicated to teachers with little experience with hearing loss. Listening environments that often contain multiple speakers further compound this decreased speech intelligibility.

In addition to decreasing frustration associated with communication breakdown, a better understanding of the factors affecting speech intelligibility will assist interventionists and parents during speech therapy. Tomblin, Peng, Spencer and Lu (2008) describe that the development of speech sound production in prelingually deaf children stabilizes after six years of CI experience and, on average, approaches a plateau by eight years of device use. Further understanding of the factors that account for the variability in speech intelligibility in children with CIs will allow interventionists and parents to maximize the impact of therapy during these identified time windows.

When assessing speech sound development, it is important to utilize fine-grained acoustic analysis to avoid the limitations of binary coding of speech sounds (e.g., "correct" vs. "incorrect,") and to capture the subtle refinements of speech demonstrated by children that can impact intelligibility. The current study focuses on two of the seven approaches that Nickerson and Stevens (1980) suggest to examine the relationship between physical properties of speech and intelligibility. One example of a physical property of speech that has already been successfully related to intelligibility of speech is voice onset time (Metz, Samar, Schiavetti, Sitler, & Whitehead, 1985). The authors observed that reversals of typical temporal contrasts predict lower speech intelligibility for children with hearing loss.

While numerous acoustic measures have been used to describe speech sound contrast, two significant measures for /s/ and /ʃ/ in the English language include spectral peak and mean during the frication noise.  Spectral mean provides a measure of the first spectral moment (i.e., the frequencies of the spectrum weighted by the respective normalized amplitudes).  Spectral peak represents the frequency with the most energy relative to the spectrum.  Less acoustic contrast is defined by a decreased difference between the spectral peaks, as well as the spectral means of /s/ and /ʃ/.  A number of studies of adult speech have shown that the single parameter of spectral peak or spectral mean during the fricative noise can differentiate /s/ and /ʃ/ productions with high accuracy levels (Forrest, Weismer, Milenkovic, &

Dougall, 1988; Nittrouer, 1995; Jongman, Wayland, & Wong, 2000; Nissen & Fox, 2005). Utilizing the measures of spectral mean and/or spectral peak offers a fine-grained and non-categorical description of the speech sounds.

In the current study, the acoustic analysis of interest is peak ERB, a psychoacoustic analogue to spectral peak, when distinguishing the /s/-/ʃ/ contrast. The spectrums of /s/ and /ʃ/, voiceless sibilant fricatives, feature aperiodic energy from the turbulent airflow resulting from the airstream meeting the teeth. The characteristic spectral peaks are higher in /s/ than /ʃ/, and the concentration of spectral energy is higher for /s/ than /ʃ/ due to the more anterior constriction of the tongue for /s/ and lack of lip rounding. The /s/-/ʃ/ contrast is intriguing to examine because the speech sounds are acquired over an extended period of time in children with NH (Nittrouer, Studdert-Kennedy, & McGowan, 1989; Nittrouer, 1995; Nissen & Fox, 2005). For example, Li, Edwards, and Beckman (2009) found that some children evidenced use of covert contrasts (i.e., productions of two speech sounds that significantly differ acoustically but are not reliably perceived by listeners) between [s] and [ʃ] for /ʃ/ substitutions. The extended period of refinement and existence of covert contrasts suggests the need for auditory-feedback loop experience and self-monitoring of the sounds. A reliance on the auditory-verbal feedback loop frames the /s/ and /ʃ/ contrast as interesting to explore in children with CIs, a population that has delayed access to auditory input and a consistently degraded auditory signal. Altered speech perception is intrinsically linked to altered speech production and represents a continued need to understand the speech of children with CIs.

Like children with NH, children with CIs undergo a protracted period of acquisition of /s/ and /ʃ/, and researchers have described the accompanying acoustic properties of the /s/-/ʃ/ contrast in children with CIs. Using correct and incorrect productions of /s/ and /ʃ/ (Uchanski & Geers, 2003; Mildner & Liker, 2008; Liker, Mildner, & Sindija, 2007), researchers found less acoustic contrast in productions of /s/ and /ʃ/ for children with CIs than for children with NH. The finding of decreased contrast remained while using only correct productions to avoid bias in the analysis from substitutions of other fricatives for the target phonemes (Todd, Edwards, & Litovsky, 2011). Children with CIs produce /s/ with a lower spectral peak than children with NH while /ʃ/ productions from the two groups have comparable spectral peaks. Thus, children with CIs evidence decreased contrast within the /s/-/ʃ/ contrast.

Furthermore, adult listeners with NH perceptually rate the productions of /s/ and /ʃ/ for children with CIs as less distinct than productions of the speech sounds by children with NH (Bernstein, Todd, & Edwards, 2013). The authors also found that listeners respond more slowly to /s/ productions with lower spectral peaks; however, listeners did not have slower performance overall for the productions of /s/ from children with CIs (Bernstein, Todd, & Edwards, 2013). The current study builds upon these findings of reduced acoustic and perceptual contrast for children with CIs to determine whether there are perceptual consequences at the word level and within multi-talker babble for the decreased contrast for /s/ and /ʃ/ production in children with CIs. To identify potential perceptual consequences, the ecologically valid measure of a single-word intelligibility task was selected. Additionally, in response to longer reaction times for participants identifying /s/ vs. /ʃ/ in quiet from talkers with between-category overlap (Newman, Clouse, & Burnham, 2001), the present investigation sought to determine whether this finding was replicated in the population of children with CIs in a challenging listening environment (i.e., multi-talker babble). To determine whether differences in speech intelligibility occur at the single-word level in the speech of children with CIs, the following questions were proposed:

1. Is there a difference in peak ERB for /s/ and /ʃ/ in the speech of children with CIs compared to children with NH?

(1a) Is the hypothesized group difference attributed more to lower peak ERB for /s/ or higher peak ERB for /ʃ/?

2. Is a lower peak ERB for /s/ associated with decreased speech intelligibility at the single-word level (as measured by accuracy and reaction time) in a challenging listening environment for children with CIs?

3. Does peak ERB predict accuracy and reaction time by sound (/s/ vs. /ʃ/)?

(3a) Is there an effect of hearing group (CI vs. NH)?

# CHAPTER TWO

## METHOD

### *Participants*

Speakers. The speech stimuli were produced by 10 children with NH and 10 children with CIs. Children in both groups were 4 to 7 years of age. Table 1 provides descriptive information for the two groups of children. The children with NH were recruited from schools and day care centers in Columbus, Ohio. The children with CIs traveled from various areas in the United States for a larger study on binaural hearing. Other than hearing loss in the children with CIs, all children providing speech samples were typically developing. All children were native English speakers. Additionally, all children with CIs were implanted before 30 months of age. Hearing age was calculated by subtracting the first CI activation date by the child's date of birth. Background information for the 10 speakers with CIs is summarized in Appendix A. Children with NH and children with CIs were matched by sex and chronological age (CA) within four months. Appendix B identifies the CA matches. Receptive vocabulary standard scores are also included in Table 1. It can be noted that the two groups do not differ significantly in their receptive vocabulary standard scores.

Table 1. Demographic characteristics of the two groups of children.

| Group | Number of speakers | Mean Chronological Age in years;months (SD, range) | Mean Hearing Age (SD, range) | Number of Male:Female Speakers | Average receptive vocabulary standard score (SD, range)[1] |
|---|---|---|---|---|---|
| CI | 10 | 5;3 (1;1, 4;1-7;8) | 4;0 (1;0, 2;9-6;5) | 4:6 | 105.5 (15.30, 82-123) |
| NH | 10 | 5;3 (1;0, 4;3-7;9) | - | 4:6 | 109.8 (15.63, 85-145) |

[1]As assessed by the *Peabody Picture Vocabulary Test* (PPVT-4, Dunn & Dunn, 2007) for the children with CIs and by the *Receptive One Word Picture Vocabulary Test* (ROWPVT-2, Brownell, 2000) for the children with NH.

Listeners. Listeners included 80 adults (40 males and 40 females) with an average age of 21 years (*SD* = 3.68 years, *range* = 18-35 years). The participants were self-reported native English speakers with NH, had no training in phonetic transcription, and did not have significant experience listening to the speech of children with CIs (as evidenced by a short questionnaire prior to participation). Listeners were recruited from Madison, WI via posting on a student job site and class announcements. Each listener signed consent forms approved by the IRB and received payment or course credit. Listeners were randomly assigned to one speaker to avoid learning effects for the single-word intelligibility task.

### ***Materials***

Speech stimuli. The speech stimuli were single words elicited in a picture-prompted auditory word repetition task (see Todd, Edwards, & Litovsky, 2011 for a comprehensive task description). There were nine /s/-initial words and nine /ʃ/-initial words in the sample. In addition, filler words beginning with /t/, /k/, /d/, or /g/ were also included. Only words that were transcribed as completely correct by a trained phonetician were used as stimuli. Furthermore, correct productions that included distortion due to signal clipping were excluded. Therefore, not all speakers had the same number of tokens. Appendix C provides information on the number of /s/-initial, /ʃ/-initial, and filler words for each child. Table 2 shows the target words along with word frequency information from the *Corpus of Contemporary American English* (Davies, 2008). The target words were segmented from a larger recording using Praat and were root-mean-square (RMS) amplitude normalized.

Table 2. List of words and word frequency of speech stimuli used in intelligibility study.

| /s/-Initial Words | Word Frequency (Davies, 2008) | /ʃ/-Initial Words | Word Frequency (Davies, 2008) |
|---|---|---|---|
| Sauce | 15903 | Ship | 28578 |
| Sun | 32646 | Shoot | 17363 |
| Seal | 6660 | Shoe | 26945 |
| Seashore | 680 | Sugar | 28052 |
| Suitcase | 3586 | Shield | 5719 |
| Soup | 10571 | Shark | 6164 |
| Soccer | 10635 | Shop | 28589 |
| Sister | 41450 | Sheep | 6320 |
| Super | 15303 | | |
| **Mean** | 15270.44 | **Mean** | 18466.25 |
| **Standard Deviation** | 13485.17 | **Standard Deviation** | 10896.13 |
| **Range** | 680 | **Range** | 5719 |

*Multi-speaker babble*. The female four-talker babble was generated from recordings of four female adults reading sentences. The babble consisted of four female speakers producing sentences from various copra (i.e., one speaker producing sentences from the IEEE corpus [IEEE, 1969], one speaker producing sentences from the BKB corpus [Bench & Bamford, 1979], and two speakers producing sentences from the AzBio corpus [Spahr, Dorman, Litvak, Van Wie, Gifford, Loizou, Loiselle, Oakes, & Cook, 2012]). The use of four-speaker babble helps to avoid amplitude modulation where the signal may be presented in a randomly low amplitude portion of the babble, which would confound listener performance. Four-speaker babble also minimizes informational masking, which occurs when a listener can decode individual words from within the babble. While each speaker's recording was RMS amplitude normalized to avoid one speaker standing out from the rest of the babble, the multi-talker babble was not standardized. Including a higher amount of speakers in the babble would have further decreased the likelihood of informational masking; however, four-speaker babble offered a better ecologically valid fit with the specific aims of the current study. Following pilot testing to identify a challenging signal-to-noise ratio (SNR), 0 dB SNR was selected where listeners correctly identified ~60% of single words produced by children with NH. Random selections of the babble were added offline to the individual speech samples using MATLAB.

***Procedures***

While speech intelligibility can be operationally defined in many ways, within the scope of this study, speech intelligibility referred to the number of words spoken by a child with or without CIs that were identified by an unfamiliar adult listener with NH. Speech intelligibility was also measured indirectly by analyzing the time required for the listener to process the word spoken by the child. Thus, dependent variables included accuracy (percent correct) and reaction time (ms). Independent variables included hearing status (CIs vs. NH), target sound (/s/ vs. /ʃ/), and peak ERB. To avoid familiarity effects due to word repetition, the current study utilized a between-subjects design so that words from a single speaker were randomly presented to the listener. Therefore, each listener only heard a single production of each target word. Each child's responses were presented to four listeners.

Listening task. Participants were tested in a quiet room using a laptop, Sennheiser HD 280 Pro headphones, a Serial Response Box with voice key, and microphone. The experiment was presented in E-Prime. The listeners completed two phases: the practice and testing phase. To help avoid a learning effect confound, listeners judged four unanalyzed words from a novel speaker. After this exposure to the novel listening task, the participants judged words from the target speaker. Listeners were instructed that they would first hear overlapping speech from several adult speakers. Within this babble, the listener would hear a single word spoken by a child, and the listener's job was to repeat this word as quickly as possible once all the speakers had stopped talking. Listeners were asked to avoid starting a response with a filler, such as "umm, pizza." Some listeners also needed prompting to speak loudly enough for the voice-activated switch to measure the reaction time.

Scoring. Listeners' oral responses were scored online using an informational word semantic match (Hustad, 2006). Responses were scored as correct if the semantic intent of the word was preserved (i.e., morphological modifications were accepted). If the voice-activated switch did not accurately reflect reaction time (i.e., response started with a filler or was too quiet to activate the response box), the scorer marked the correctness of the response and discarded the reaction time. Reaction time was calculated through E-Prime as the onset of the listener's voicing subtracted by the offset of the babble.

*Peak ERB calculation*. Peak ERBs were taken from the Reidy (2015) analysis of a larger data set that included the 20 speakers of this study. Briefly, peak ERB (Equivalent Rectangular Bandwidth) is a psychoacoustic analogue of centroid frequency (of the fricative noise). Multi-taper analysis was used to calculate centroid frequency, and the peak ERB for each fricative was the center frequency on the ERB scale that had the greatest excitation (Reidy, 2015, p. 54). For more details on the analysis, see Reidy (2015). Peak ERB, a psychoacoustic measure, was used instead of spectral peaks, an acoustic measure, because the ERB scale is more closely related to human hearing (Moore & Glasberg, 1983).

# CHAPTER THREE

## RESULTS

*Peak ERB:* The first question was whether there was a difference in peak ERB for /s/ and /ʃ/ in the speech of children with CIs compared to children with NH in this smaller data set, as in Reidy (2015). The dependent variable was peak ERB, which was modeled using a general linear model in the R software environment (R core development team, 2013). The independent variables were hearing status (CI vs. NH), target sound (/s/ vs. /ʃ/), and the interaction between hearing status and target sound. The reference conditions were the normal hearing group and the target sound /s/. There was a significant main effect for hearing group ($\beta = -1.60$, $S.E. = 0.27$, $t = -5.84$, $p = <.001$). As in Reidy (2015) and Todd, Edwards, and Litovsky (2011), peak ERB was lower for /s/ word-initial productions by children with CIs compared to children with NH. There was a main effect of target sound ($\beta = -5.88$, $S.E. = 0.27$, $t = -22.05$, $p = <.001$). As predicted, /ʃ/ word-initial productions from children with NH had significantly lower peak ERBs than /s/ word-initial productions from children with NH. Lastly, there was a significant interaction between hearing group and target sound ($\beta = 2.69$, $S.E. = 0.39$, $t = 6.88$, $p = <.001$). Children with CIs also had significantly higher peak ERBs for /ʃ/ word-initial productions. This interaction highlights the decreased acoustic contrast between /s/ and /ʃ/ word-initial productions for children with CIs. Thus, the hypothesized group difference in the robustness of the /s/-/ʃ/ contrast was due to both lower peak ERBs for /s/ and higher peak ERBs for /ʃ/. See Table 3 for descriptive information and Figure 1 for a comparison of peak ERB by hearing group and target sound.

Table 3. Peak ERB mean, standard deviation, and standard error by target sound and speaker group.

| Hearing Status | Target Sound | Mean Peak ERB | Peak ERB Standard Deviation | Peak ERB Standard Error |
|---|---|---|---|---|
| CI | /s/ | 32.12 | 1.66 | 0.52 |
| TD | /s/ | 33.60 | 2.62 | 0.83 |
| CI | /ʃ/ | 28.83 | 1.66 | 0.52 |
| TD | /ʃ/ | 27.73 | 3.02 | 0.95 |

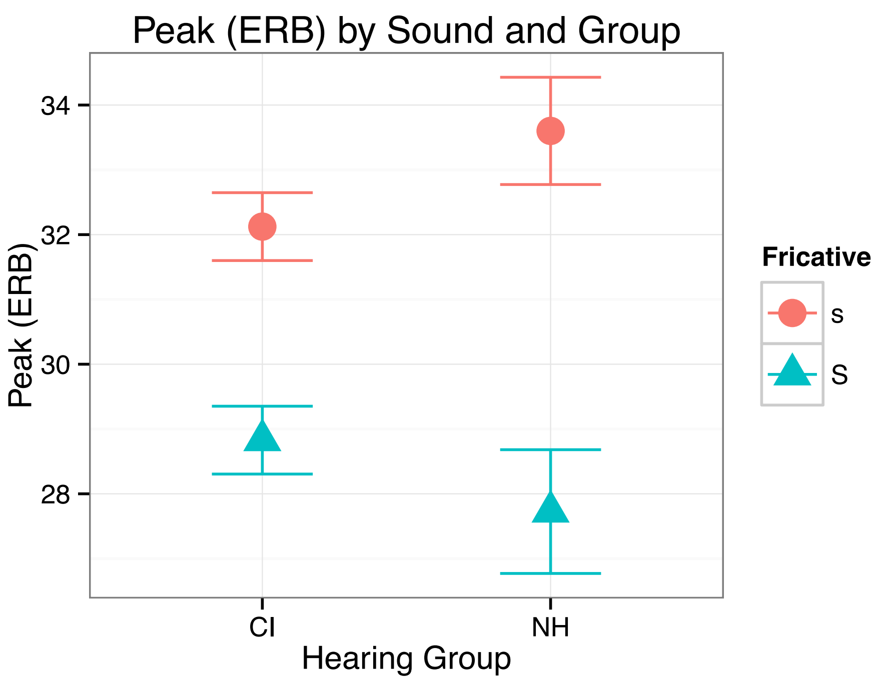


Figure 1. Peak ERB by Fricative (/s/ vs. /ʃ/) and Hearing Group (CI vs. NH). The plot shows means and standard errors.

*Accuracy*. The second question was whether the peak ERB differences for /s/ and /ʃ/ that were observed for the children with CIs were associated with decreased speech intelligibility, as measured by response accuracy. All responses were used in the accuracy analysis regardless of whether the associated reaction times were useable. Figure 2 shows accuracy of response separately by target sound and hearing group, and Table 4 provides descriptive information. Accuracy of response was modeled using logistic regression with the glm routine (Bates et al., 2013). The initial model included three independent variables: peak ERB, hearing status (NH or CI), target sound (/s/ vs. /ʃ/), as well as all possible interactions among these variables. Peak ERB was not a significant predictor of response accuracy, nor were any of the interactions involving peak ERB. Therefore, these predictor variables were removed from the model. The final model included only hearing status, target sound, and the interaction between hearing status and target sound. The reference conditions were the NH group and the target sound /s/. Hearing status was a significant predictor *($\beta = -0.42$, S.E. $= 0.18$, $z = -2.35$, $p = .02$)*. Accuracy was lower for words produced by children with CIs compared to words produced by children with NH. There was also a significant interaction between hearing status and target sound *($\beta = 0.94$, S.E. $= 0.27$, $t = 3.49$, $p = <.001$)*. This shows that for children with CIs, productions with word-initial /s/ were perceived less accurately than productions with word-initial /ʃ/.

Table 4. Accuracy mean, standard deviation, and standard error by target sound and speaker group.

| Hearing Status | Target Sound | Mean Accuracy (1 = correct, 0 = incorrect) | Accuracy Standard Deviation | Accuracy Standard Error |
|---|---|---|---|---|
| CI | /s/ | 0.52 | 0.20 | 0.06 |
| TD | /s/ | 0.62 | 0.12 | 0.04 |
| CI | /ʃ/ | 0.74 | 0.10 | 0.03 |
| TD | /ʃ/ | 0.62 | 0.17 | 0.06 |

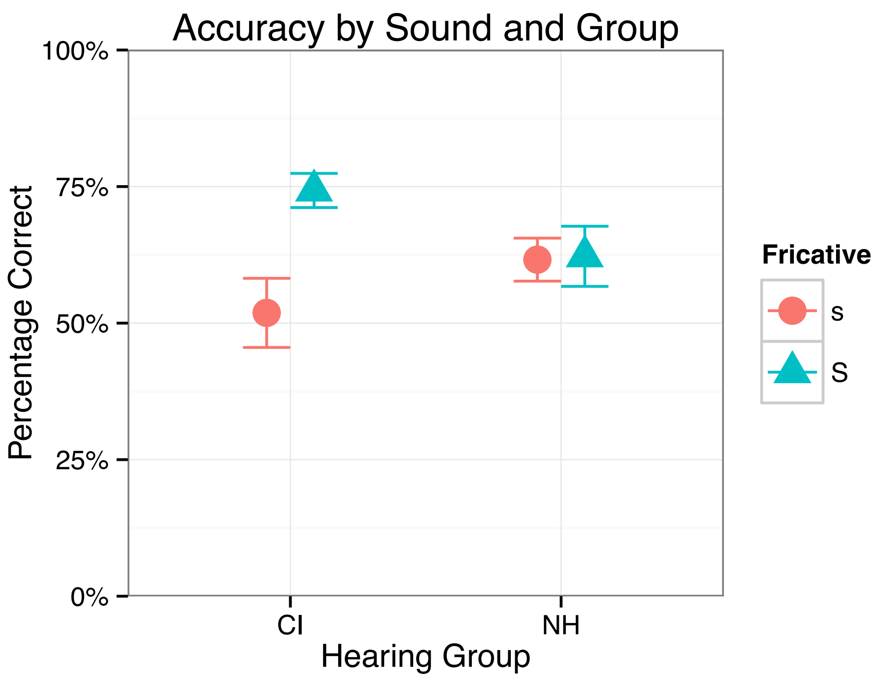


Figure 2. Accuracy (Percent Correct) by Fricative (/s/ vs. /ʃ/) and Hearing Group (CI vs. NH). The plot shows means and standard errors.

*Reaction Time*. The final question was whether the peak ERB differences for /s/ and /ʃ/ that were observed for the children with CIs were associated with decreased speech intelligibility, as measured by reaction time. Only reaction times for correct responses were used in the analysis. False starts and equipment failures were also excluded. Reaction times were logarithmically transformed and trimmed to exclude those < 200ms or > 2000 ms. Figure 3 shows reaction time for correct responses by target sound and hearing group, and Table 5 provides descriptive information. Reaction time was modeled using a general linear model in R. The dependent variable in the general linear model was reaction time (for correct responses only). The independent variables were hearing group (CI vs. NH), target sound (/s/ vs. /ʃ/), as well as all possible interactions among these variables. The reference conditions were the NH group and the target sound /s/. Hearing status was a significant predictor ($\beta = 0.03$, $S.E. = 0.01$, $t = 2.37$, $p = .02$). Reaction time was longer for word-initial /s/ words produced by children with CIs compared to word-initial /s/ targets produced by children with NH. Peak ERB was also a significant predictor ($\beta =$

*-0.01, S.E. = 0.003, t = -2.04, p = .04*). Reaction times were shorter across both groups of speakers for word-initial /s/ targets as peak ERB increased.

Table 5. Reaction Time (log ms) for correct responses by Hearing Group and Fricative (/s/ vs. /ʃ/).

| Hearing Status | Target Sound | Mean Reaction Time (log ms) | Reaction Time Standard Deviation | Reaction Time Standard Error |
|---|---|---|---|---|
| CI | /s/ | 2.56 | 0.27 | 0.02 |
| TD | /s/ | 2.54 | 0.31 | 0.02 |
| CI | /ʃ/ | 2.62 | 0.17 | 0.01 |
| TD | /ʃ/ | 2.59 | 0.18 | 0.01 |

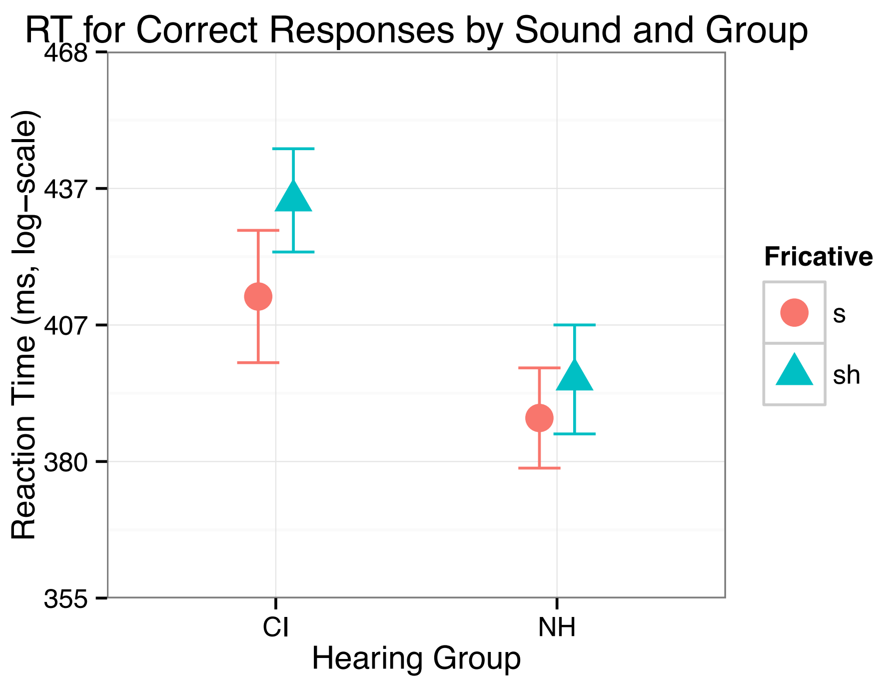


Figure 3. Reaction Time for Correct Responses by Fricative (/s/ vs. /ʃ/) and Hearing Group (CI vs. NH). The y-axis is scaled in log ms and labeled in ms. The plot shows means and standard errors.

# CHAPTER FOUR

## DISCUSSION

Overall, correct productions of /s/ and /ʃ/-initial words by children with CIs were less intelligible in a challenging listening environment compared to words produced by children with NH. This relationship was observed despite the selection of only correct productions from within the high performing sample of children with CIs (i.e., a group of children with early implantation, bilateral CIs, and receptive vocabulary scores within normal limits).

Additionally, the pattern of reduced intelligibility mirrored the psychoacoustic results. Peak ERB was lower for /s/ word-initial productions by children with CIs compared to children with NH, and intelligibility was particularly reduced for these /s/-initial words produced by children with CIs as measured by accuracy. Peak ERB also predicted reaction time for /s/ word-initial productions across hearing groups. Furthermore, the current study's different method of calculating acoustic contrast extends previous findings of reduced contrast for children with CIs (Todd, Edwards, & Litovsky, 2011). This finding suggests that the decreased acoustic contrast in /s/ and /ʃ/ for children with CIs is a robust result.

Lastly, the intelligibility patterns observed in the current study are consistent with the findings of Bernstein, Todd, and Edwards (2013) who asked listeners to rate the goodness of /s/ or /ʃ/ in initial CV's using a VAS scale. The authors found that listeners rated /s/ productions by children with CIs as less /s/-like and that listeners responded more quickly to /s/ productions with higher spectral peaks for both groups (Berstein, Todd, & Edwards, 2013). These findings align with the current study's finding of lower accuracy for word-initial /s/ targets compared to word-initial /ʃ/ targets for children with CIs. Furthermore, the present study's finding of longer reaction times for word-initial /s/ productions by children with CIs (relative to children with normal hearing) and shorter reaction times across groups for word-initial /s/ productions with higher peak ERBs offers additional overlap of results. Findings of decreased intelligibility at the word level extends Bernstein, Todd, and Edwards' (2013) finding of less perceptual distinction at the sound level for /s/ and /ʃ/ productions by children with CIs.

Clinically, the present results suggest that there are limitations associated with the use of transcription for children with CIs in speech therapy. Categorical transcription of correct or incorrect can lack the sensitivity to capture subtle differences in speech sounds. These missed differences can contribute to decreased speech intelligibility. Thus, there is a need for a finer-grained measure of speech production. Clinicians may need to consider, particularly for sounds that are difficult for children with CIs to perceive and produce, continuing to work on speech sounds beyond just "correct."

Several limitations of this research should be noted. First, the findings are based on a relatively small sample – only 10 children with CIs and 10 children with NH. Furthermore, a small number of words were used, and word frequency, which is known to affect intelligibility, was not controlled. However, the fact that differences emerged between groups in spite of these limitations suggests that these results are likely to be replicated in a larger study with more words and speakers. Additionally, it is important to remember that intelligibility estimates are listener, context, and content dependent, and further research is needed to determine the generalization of the current study's findings.

# CHAPTER FIVE

## CONCLUSIONS

Within a challenging listening environment, significant differences in accuracy and reaction time were observed between hearing groups and target sounds despite the inclusion of only correct productions. Additionally, a conservative measure of judging accuracy of listener responses was consistently applied during online scoring (i.e., accepting errors if the semantic intent of the word was preserved). The finding of decreased intelligibility at the single-word level suggests that targeting accuracy of /s/ and /ʃ/ productions in the speech of children with CIs is not enough to assist in closing the speech intelligibility gap between children with CIs and same-age peers. Additionally, clinicians can consider the use of a more continuous measure of intelligibility like acoustic analysis or perceptual goodness ratings to help capture perceptual differences that emerge when judging productions as correct or incorrect.

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Appendix A

Background information for children with CIs

| Child | Sex | CA (months) | Hearing Age (months) | Etiology of Hearing Loss (HL) | Age of HL Identification (months) | Age at 1st CI Implantation (months) | Age at 2nd CI Implantation (months) | 1st Device Type (Ear, Strategy) | 2nd Device Type (Ear, Strategy) |
|---|---|---|---|---|---|---|---|---|---|
| CIBV1 | M | 60 | 43 | Connexin | Birth | 17 | 23 | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, R | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, L |
| CIEF1 | F | 70 | 54 | Unknown | 9 | 15 | 58 | N24, ACE, R | Freedom, ACE, L |
| CIBW1 | F | 59 | 47 | Connexin | Birth | 12 | 45 | N24, ACE, R | Freedom, ACE, L |
| CICN1 | F | 49 | 33 | Connexin | Birth | 15 | 32 | Freedom, ACE(RE), R | Freedom, ACE, L |
| CICB1 | F | 50 | 40 | Connexin | Birth | 10 | 24 | N24, ACE, R | Freedom, ACE(RE), L |
| CICM1 | M | 52 | 39 | Connexin | Birth | 12 | 38 | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, R | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, L |
| CIDT1 | F | 76 | 57 | Usher Syndrome | 3-6 | 18 | 37 | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, R | HiRes 90K/HiFocus, HiRes-P w/Fidelity 120, L |
| CIAW1 | M | 92 | 77 | CMV | 3 | 14 | 65 | N24, ACE, R | Freedom, ACE, L |
| CIDF1 | F | 71 | 57 | Unknown | Birth | 13 | 65 | N24, ACE, R | Freedom, ACE, L |
| CICL1 | M | 58 | 41 | Connexin | 12 | 16 | 32 | Freedom, ACE(RE), R | Freedom, ACE, L |

Appendix B

Chronological age matches for children with CIs

| Speaker with CIs | CA (months) | Sex | Speaker with NH | CA (months) | Sex |
|---|---|---|---|---|---|
| CIBV1 | 60 | M | e5at07 | 62 | M |
| CIEF1 | 70 | F | e5bt15 | 66 | F |
| CIBW1 | 59 | F | e4bt20 | 58 | F |
| CICN1 | 49 | F | e4at10 | 53 | F |
| CICB1 | 50 | F | e4at05 | 51 | F |
| CICM1 | 52 | M | e4at09 | 52 | M |
| CIDT1 | 76 | F | e5bt25 | 71 | F |
| CIAW1 | 92 | M | e7bCKB | 93 | M |
| CIDF1 | 71 | F | e5bt17 | 67 | F |
| CICL1 | 58 | M | e5at11 | 63 | M |

Appendix C

Stimuli summary by child

| Speaker with CIs | Total /s/-initial tokens | Total /ʃ/-initial tokens | Total filler tokens | Speaker with NH | Total /s/-initial tokens | Total /ʃ/-initial tokens | Total filler tokens |
|---|---|---|---|---|---|---|---|
| CIBV1 | 4 | 4 | 18 | e5at07 | 5 | 3 | 29 |
| CIEF1 | 5 | 5 | 22 | e5bt15 | 7 | 6 | 16 |
| CIBW1 | 5 | 5 | 21 | e4bt20 | 6 | 3 | 26 |
| CICN1 | 4 | 6 | 12 | e4at10 | 6 | 8 | 24 |
| CICB1 | 7 | 4 | 12 | e4at05 | 7 | 7 | 23 |
| CICM1 | 4 | 8 | 20 | e4at09 | 4 | 5 | 12 |
| CIDT1 | 7 | 5 | 17 | e5bt25 | 7 | 8 | 20 |
| CIAW1 | 8 | 7 | 12 | e7bCKB | 9 | 7 | 30 |
| CIDF1 | 6 | 7 | 24 | e5bt17 | 7 | 6 | 29 |
| CICL1 | 9 | 6 | 26 | e5at11 | 9 | 7 | 26 |