# Effect of consistent electric stimulation on auditory perception in cochlear implant users

By

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

For adults with moderate-to-profound sensorineural hearing loss, cochlear implants (CIs) are considered the standard-of-care treatment option; however, CI speech recognition outcomes continue to range from 0 to 100% with an average around 60-percent correct (Buchman et al., 2020; Buss et al., 2008; Gifford, Dorman, Sheffield, Teece, & Olund, 2014; Gifford, Shallop, & Peterson, 2008; Holden et al., 2013; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006) for postlingually deafened adults. Many factors contribute to this variability in auditory outcomes including, but not limited to, duration of deafness, age at implantation, etiology, surgical approach, electrode array placement, insertion depth, signal processing strategy, preoperative audiometric thresholds, preoperative suprathreshold processing, CI programming, device use/experience, neurocognitive function, aural rehabilitation, and neural health. Some of these factors, such as duration of deafness, do impact outcomes (Blamey et al., 1996; Friedland, Venick, & Niparko, 2003; Kevin M J Green, Julyan, Hastings, & Ramsden, 2005; Rubinstein, Parkinson, Tyler, & Gantz, 1999) but cannot be readily manipulated by a clinician. Many other factors such as surgical approach, electrode array placement, insertion depth, signal processing strategy, CI programming, device use, and aural rehabilitation *can* be readily altered and have in some ways been linked to better speech recognition abilities. The market penetration of CIs for adult candidates is currently estimated to be 1-7% (iData Research Inc., 2010; Kochkin, 2005; Sorkin, 2013); as we work toward gaining access to this technology for more patients, we must consider interventions designed to improve outcomes for thousands of people. The primary goal for this dissertation was to explore a method of improving CI outcomes in existing CI users in a cost-effective, accessible way that could be implemented on a large scale.

## 1.2 CI Use and Speech Recognition Outcomes in Children

CIs improve access to sound, speech production, and language skills for more than 40,000 children in the United States who otherwise could not develop spoken language. Many of these children, especially those who are implanted early in life, excel with CI technology achieving speech recognition abilities commiserate with their typically hearing peers, yet many others fall behind in auditory, speech, and language skills. Variability in outcomes has been attributed in large part to factors that cannot be altered such as age of implantation (Dettman et al., 2016; Dowell et al., 2002; Harrison, Gordon, & Mount, 2005; J. Leigh, Dettman, Dowell, & Briggs, 2013; J. R. Leigh, Dettman, & Dowell, 2016), residual hearing prior to CI (Dowell et al., 2002; Henkin, Kileny, Hildesheimer, & Kishon-Rabin, 2008; Sarant, Blamey, Dowell, Clark, & Gibson, 2001), socio-economic status (Holzinger et al., 2020; Niparko et al., 2010; Panda et al., 2019), and nonverbal intelligence (A. Geers, Brenner, & Davidson, 2003). Fortunately, there are many other factors such as auditory-oral mode of communication (Dowell et al., 2002; A. Geers et al., 2003; A. E. Geers, Mitchell, Warner-Czyz, Wang, & Eisenberg, 2017; Sarant et al., 2001), CI programming (Dowell et al., 2002; A. Geers et al., 2003; Sarant et al., 2001), and consistency of device use (Busch, Vermeulen, Langereis, Vanpoucke, & van Wieringen, 2020; Easwar, Sanfilippo, Papsin, & Gordon, 2018; Guerzoni & Cuda, 2017), which can be altered by parents and/or clinicians to potentially improve outcomes for children.

CIs provide access to spoken language only when the external processor is connected. Therefore, the effectiveness of the technology is reliant upon the compliance of the patient and the patient's caregivers. Risley and Hart (Risley & Hart, 2006) reported that children with normal hearing hear about 21,000 words per day in order to achieve a typical vocabulary. It is reasonable to hypothesize that children who inconsistently use their CI devices, do not achieve this daily exposure putting them at risk for language delay (Ambrose, VanDam, & Moeller, 2014; Kirk et al., 2002; Niparko et al., 2010; Svirsky, Teoh, & Neuburger, 2004; Vohr, Topol, Watson, St Pierre, & Tucker, 2014). Our understanding of device use and its relationship with auditory, speech, and language outcomes is in its infancy, but it is of critical importance because device use is foundational to accessing sound and language. Further, device use holds great potential for improving outcomes for children and adults due to its malleability at an individual level compared to other influential factors (Easwar et al., 2018).

Several studies have demonstrated a positive relationship between daily hearing aid (HA) or CI use and auditory-oral communication skills (Archbold, Nikolopoulos, & Lloyg-Richmond, 2009; Easwar, Sanfilippo, Papsin, & Gordon, 2016; Easwar et al., 2018; Fitzgerald, Green, Fang, & Waltzman, 2013; Guerzoni & Cuda, 2017; Haensel, Engelke, Ottenjann, & Westhofen, 2005; Holder, Dwyer, & Gifford, 2019; Marnane & Ching, 2015; Myhrum et al., 2017; Tomblin et al., 2015; Wie, Falkenberg, Tvete, & Tomblin, 2007; Wiseman & Warner-Czyz, 2018). For children with HAs (n = 290), Tomblin and colleagues (Tomblin et al., 2015) demonstrated a significant correlation between parent-reported HA use and language outcomes that persisted even when accounting for maternal education and hearing loss severity, which are known covariates (Marnane & Ching, 2015; Tomblin et al., 2015; Walker et al., 2013). Perhaps the most compelling finding from their study was that children who wear their HAs less than 10 hours per day did not show evidence of language development from 2 to 6 years of age; whereas, children wearing their HAs for more than 10 hours per day did. As a result of this finding, 10 hours per day has been used by clinicians to define "full-time", recommended device use (Wiseman & Warner-Czyz, 2018).

For children with CIs, the ability to track CI usage per day objectively and automatically within the programming software, commonly referred to as data logging, is a relatively new feature. While previous studies have investigated the relationship between subjective daily CI use and outcomes (Fitzgerald et al., 2013; Myhrum et al., 2017; Sparreboom, Beynon, Snik, & Mylanus, 2016), only three studies have investigated the relationship between daily CI use via data logging and outcomes in pediatric CI recipients. The first was a study by Guerzoni and Cuda (Guerzoni & Cuda, 2017), which investigated the correlation between processor data logging (measured from the CI software) and linguistic skills in ten children implanted prior to two years of age. They found a significant positive correlation between time spent listening to speech in quiet and lexical quotient after one year of CI use. The second was a study by Easwar and colleagues (Easwar et al., 2018), which studied the correlation between processor data logging (measured from the CI software) and speech perception scores in 65 children with CIs ranging in age from 2 to 18 years. They also found a significant, positive correlation between daily CI use and speech recognition scores. Easwar and colleagues performed a multiple regression analysis that accounted for daily CI use, age at time of testing, duration of CI experience, duration of pre-CI acoustic experience, and order of CI. Daily CI use, length of CI experience, and order of CI were significant predictors of speech recognition. Further, the model estimated that the CI user would realize a 2.6 percentage point increase in speech recognition for every additional hour of daily CI use on average. Most recently, Busch and colleagues (Busch et al., 2020) evaluated the relationship between receptive language and daily CI use in a group of 52 prelingually deafened children. They found a strong positive correlation between receptive vocabulary and daily CI use further emphasizing the importance of consistent CI use.

Based on studies utilizing subjective and objective measures of daily device use (Busch et al., 2020; Easwar et al., 2018; Fitzgerald et al., 2013; Guerzoni & Cuda, 2017; Myhrum et al., 2017), converging evidence points toward a significant, positive relationship between daily CI use and some measures of speech and language perception in children. However, the amount of daily CI use necessary to achieve optimal outcomes is not yet known (Wiseman & Warner-Czyz, 2018). Based on the HA literature (Tomblin et al., 2015; Walker et al., 2013), it would be reasonable to hypothesize that at least 10 hours of daily device use is necessary to achieve optimal outcomes given that CI users have far less access to spoken language than do children with mild to moderate hearing loss when they are not wearing their devices.

### 1.3 Relationship between CI Use and Speech Recognition Outcomes in Adults: The Present Studies

The aforementioned findings in the pediatric population motivated the current investigation into how this relationship might manifest in adult recipients. Prior to the commencement of this dissertation work, there were no prior reports of the relationship between daily CI use using data logging and speech recognition outcomes in postlingually deafened adults.

There is a known relationship between cumulative CI experience and speech recognition for adult recipients. Specifically, all CI recipients need experience and practice to learn to listen via electric stimulation for the first six to twelve months (Lenarz, Sönmez, Joseph, Büchner, & Lenarz, 2012; Massa & Ruckenstein, 2014; Mosnier et al., 2015); however, after this initial period of device use at which time adult recipients reach asymptotic performance, the relationship between daily CI use and speech recognition is largely unknown. Anecdotal reports suggest that consistency of processor use remains important after the first year of implantation. CI users who experience CI processor malfunction often experience a temporary decrease in speech recognition ability following a period of non-use. However, despite committing to surgery and attending many appointments for post-operative checks and CI programming, there is considerable variability in daily CI use in the adult population. Busch and colleagues (Busch, Vanpoucke, & van Wieringen, 2017) analyzed CI use for 1,501 CI recipients of all ages and found daily average wear time to be 10.7 hours with the 95% confidence interval ranging from 4.3 to 15.2 hours per day. This variability in daily wear time became the focus of this dissertation work for three reasons. Firstly, as a clinical audiologist, I was observing that my own patients who wore their CI processor more consistently tended to perform better on tests of speech recognition. I was interested to see if this correlation held true in a large cohort similar to correlations shown in the pediatric population. Secondly, if this correlation was in fact present, I was interested in exploring the causation between the two variables. In other words, do adults who wear their CI processor more consistently have higher speech recognition abilities? Or, alternatively, do adults who have higher speech recognition abilities tend to wear their CI processor more consistently? If in fact it is the former, CI processor use holds great potential for improving speech recognition outcomes due to its malleability and accessibility at an individual level to every recipient. Lastly, this variability in wear time suggests that the standard clinician recommendation, “wear it during all waking hours,” is not an effective way to communicate to patients. Perhaps a data-driven, numerical recommendation (i.e., 12 hours per day) would be more effective. Or, alternatively, perhaps patients experience a number of barriers to being able to wear their CI processor. I was interested in exploring why adult recipients were not wearing their CI processor consistently in order to better counsel and support recipients in their journey after a life-changing surgery as we work toward optimizing their hearing.

The primary aims of the current dissertation studies and accompanying hypotheses were as follows:

- Aim 1 (Chapter 2): Quantify the relationship between average daily processor use and measures of speech recognition in postlingually deafened adults. We hypothesized that higher daily wear time would be positively correlated with CI-only speech recognition scores.
- Aim 2 (Chapter 3): Evaluate the impact of increased CI use on speech recognition performance and assess one potential underlying mechanism driving the relationship between daily CI use and speech recognition, spectral processing. We had two accompanying hypotheses: 1) Increased CI use will result in improved speech recognition, and 2) Increased CI use would drive improved speech recognition via an improved spectral processing.
- Aim 3 (Chapter 4): Explore relationships between daily CI use, speech recognition, and other commonly studied factors thought to contribute to CI outcome variability. A secondary aim was to demonstrate the feasibility of administering the NIH Toolbox Cognitive battery to CI users, which has not been previously demonstrated in the literature. There was no associated hypothesis for Aim 3 given its exploratory nature.
- Aim 4 (Chapter 5): Design a questionnaire aimed at identifying daily CI use habits and barriers to daily CI use and collect responses to the questionnaire from

adult CI users with varying degrees of daily CI use. We hypothesized that recipients who reported a greater number of barriers to daily CI use would show lower daily CI use. Additionally, we hypothesized that this questionnaire would be a clinically useful tool for identifying specific reasons for inconsistent CI use.

# CHAPTER 2

# DURATION OF PROCESSOR USE PER DAY IS SIGNIFICANTLY CORRELATED WITH SPEECH RECOGNITION ABILITIES IN ADULTS WITH COCHLEAR IMPLANTS

## 2.1 Introduction

Cochlear implant (CI) technology is used to restore audibility and improve speech understanding for individuals with sensorineural hearing loss (SNHL). The majority of patients receive significant improvement in speech understanding with device use; however, considerable variability remains amongst adult recipients for which the range of postoperative speech recognition scores is from 0 to 100% (Buss et al., 2008; Chakravorti et al., 2019; Gifford et al., 2008; Holden et al., 2013; Litovsky et al., 2006). Understanding this variability in CI outcomes has become a hot topic of research because predicting postoperative performance for a given patient remains challenging. Over a thousand articles have been published in the last five years seeking to understand how several factors potentially affect outcomes. These factors include etiology, duration of deafness, spiral ganglion cell count, age, electrode position, manufacturer, electrode type, programming, surgical technique, etc. Many of these variables are either outside of clinician control (e.g., etiology, duration of deafness, spiral ganglion cell count, age) or completely unknown. One potentially important and malleable factor sparsely reported in the adult CI literature is the average number of hours of processor use per day, also reported as data logging.

The ability to track a CI recipient’s average usage of their CI processor per day automatically within the programming software is a relatively new feature. This feature was immediately beneficial in children for tracking consistency of wear time at home, school, and daycare. It also allows clinicians to become aware of persistent device problems when a child is unable to accurately report issues. Exposure to spoken language is vital for typical speech and language development in children (e.g., Vohr et al., 2014; Weisleder & Fernald, 2013), so it is not surprising that the current literature has focused on the correlation between CI use and auditory outcome measures in the pediatric population. Easwar and colleagues (Easwar et al., 2018) found that average CI use per day was significantly correlated with higher speech recognition scores in a group of 85 children. Guerzoni and Cuda's data (Guerzoni & Cuda, 2017) showing a positive correlation between hours of device use per day and lexical quotient corroborated this finding. Only one previous study has evaluated a similar correlation in the adult population. Schvartz-Leyzac and colleagues (Schvartz-Leyzac, Conrad, & Zwolan, 2019) found a moderate correlation between average duration of CI use per day and speech recognition measures in a sample of 177 adults. Based on these data, one could hypothesize that average duration of CI use per day may account for a significant portion of the variability in speech recognition outcomes.

It is reasonable to assume that all CI recipients need experience and practice to learn to listen via electrical stimulation. Studies showing that CI recipients require approximately six months of listening prior to reaching asymptotic performance (Lenarz et al., 2012; Massa & Ruckenstein, 2014) point to the importance of adults wearing their processor as often as possible. However, we are unable to make a data driven recommendation regarding how many hours per day a patient should use their processor for optimal performance. In 2017, Busch and colleagues (Busch et al., 2017) analyzed CI use for 1,501 CI recipients of all ages and found daily average wear time to be 10.7 hours with the 95% confidence interval ranging from 4.3 to 15.2 hours per day. This finding indicates considerable variability in average wear time for all recipients across the lifespan.

In the current study, we aimed to quantify the relationship between average daily processor use and measures of speech recognition in postlingually deafened adults. We hypothesized that higher daily wear time would be positively correlated with CI-only speech recognition scores.

## 2.2 Materials & Methods

A retrospective review of CI programming software and clinical reports was conducted for 300 postlingually deafened adult CI recipients (130 female) with an average age of 64 years (range: 18-96 years) at the time of implantation. All patients were implanted between 2012 and 2018. Recipients of three CI manufacturers were included as follows: 132 Advanced Bionics, 128 Cochlear, and 40 MED-EL. Exclusion criteria included prelingual onset of deafness and revision surgery. The following data points were recorded for each participant as available: age at implantation, gender, surgery date, hours of CI use per day, CI-only speech recognition [consonant-nucleus-consonant (CNC) word recognition, AzBio sentence recognition in quiet, and AzBio sentence recognition at +5 dB signal-to-noise ratio (SNR)], and Speech Spatial Qualities (SSQ) questionnaire.

### 2.2.1 Hours of CI Use per Day

The average number of hours of processor use per day was extracted from each individual participant's data logging information housed in the CI programming software. The data logging value closest to the one-year post-implantation time point (Mean = 12.5 months) was recorded for each recipient. Audiologic reports were also reviewed. If the patient used more than one processor per ear, data logging from each processor over identical time periods was summed. Patients using equipment that did not support data logging were not included; this group included bilaterally initialized Advanced Bionics Naida CI users, Advanced Bionics Harmony and Neptune users, MED-EL Rondo & Opus 2 users, and Cochlear Nucleus 5 users.

### 2.2.2 Speech Recognition

Speech recognition testing was conducted as previously reported in Holder et al. (2018) (Holder, Levin, & Gifford, 2018). Speech recognition results reported herein follow the revised Minimum Speech Test Battery (MSTB) for adult CI recipients (MSTB, 2011). Speech recognition testing was completed in a sound treated booth with a presentation level of 60 dB SPL through a single loudspeaker positioned at zero degrees azimuth approximately 1 meter from the listener. Larson Davis LxT sound level meters were present in the test booths allowing for calibration prior to assessment for every patient. Participants completed CNC word recognition (50-word list) (Peterson & Lehiste, 1962) and AzBio sentence recognition (20-sentence list) (Spahr et al., 2012). Sentences were presented in quiet and +5 dB SNR multi-talker babble. Patients also completed the SSQ questionnaire, which assesses subjective hearing abilities across three listening domains: speech understanding, spatial hearing, and overall quality of speech using a visual analog scale ranging from 1 (poor) to 10 (perfect) (Gatehouse & Noble, 2004).

### 2.2.3 Statistical Analyses

The primary correlation of interest was the correlation between the average number of hours of CI use per day and CNC word recognition. Correlation analyses were completed using Spearman’s rank-order correlations, as the hours of CI use were not normally distributed.

## 2.3 Results

Average CI use was 10.2 hours per day (SD = 4.2 hours) and ranged from 0.1 to 22.7 hours per day. Males wore their processor an average of 11.1 hours per day compared to 9.0 hours per day for females; a Mann-Whitney test indicated that this 2-hour difference per day across gender was statistically significant ($U = 7604$, $p < 0.001$). There was no effect of manufacturer. Advanced Bionics users’ mean use was 10.1 hours, Cochlear users’ mean was 10.6 hours, and MED-EL users’ mean was 9.3 hours; these differences were not found to be statistically significant. A Spearman's rank-order correlation was run to determine the relationship between age at implantation and hours of CI use per day as well as age at implantation and CNC word score. There was a negative correlation between hours of CI use and age at implantation ($r_s = -0.13$, $p = 0.024$), which was statistically significant but weak (J. Cohen, 1988). There was also a negative correlation between CNC word score and age at implantation ($r_s = -0.21$, $p < 0.001$), which was also statistically significant but a small effect size (J. Cohen, 1988) (Figure 1).

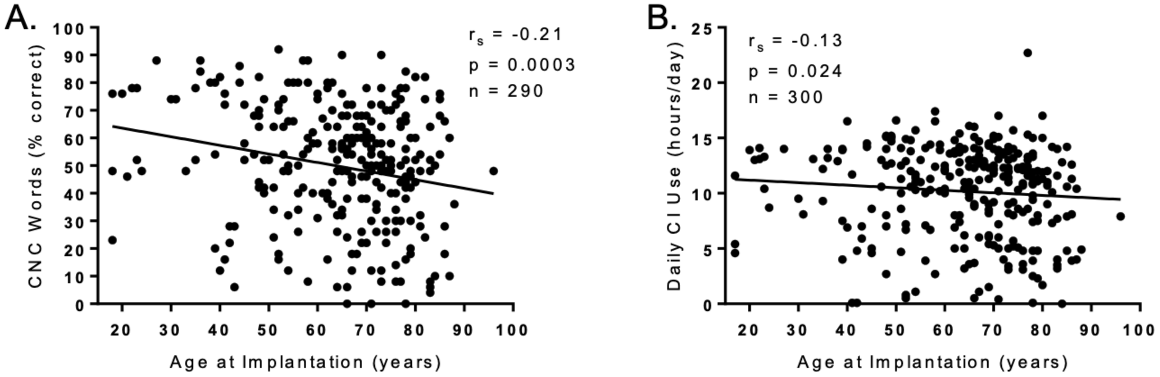


Figure 1. A) Correlation between age at implantation and average hours of cochlear implant (CI) use per day, B) Correlation between age at implantation and consonant-nucleus-consonant (CNC) word score.

Speech recognition measures were collected at an average of 12.5 months post-implantation (range: 5 to 76 months). The mean scores for CNC words, AzBio sentences in quiet, and AzBio sentences at +5 dB SNR across all CI users were 49.9%, 61.7%, and 24.3%, respectively. Spearman's rank-order correlations were completed to assess the relationship between hours of use per day and scores for CNC, AzBio, and AzBio at +5 dB SNR. The main finding of this study was the statistically significant and strong correlation between speech recognition and hours of CI use per day for CNC word recognition ($r_s = 0.61$, $p < 0.0001$, 95% Confidence Interval [0.54, 0.69]) and AzBio sentence recognition in quiet ($r_s = 0.56$, $p < 0.0001$, 95% Confidence Interval [0.46, 0.64]). We found a statistically significant and moderate positive correlation between hours of CI use per day and AzBio sentences at +5 dB SNR ($r_s = 0.41$, $p < 0.0001$, 95% Confidence Interval [0.27, 0.54]). However, there was no significant correlation with SSQ ($r_s = 0.15$, $p = 0.121$, 95% Confidence Interval [-0.04, 0.32]) (Figure 2).

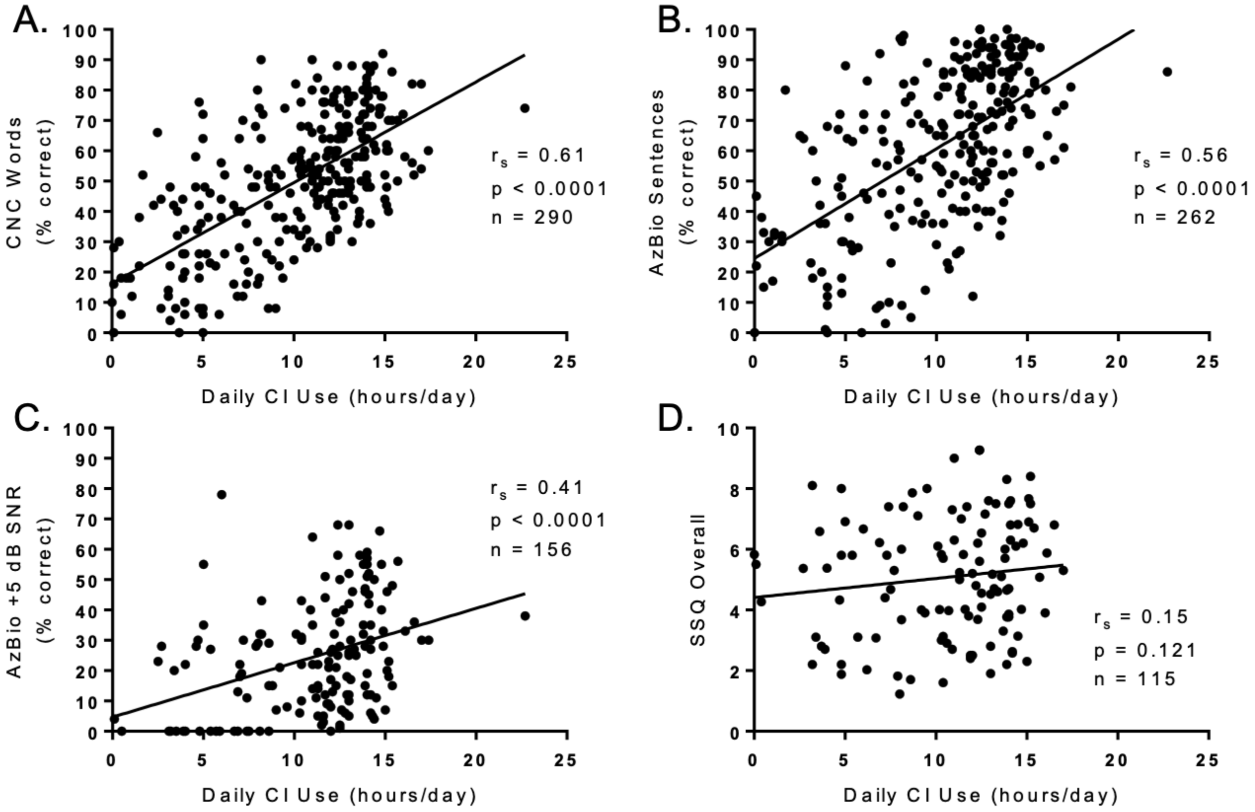


Figure 2. A) Correlation between daily cochlear implant (CI) use and consonant-nucleus-consonant (CNC) word scores, B) Correlation between average hours of CI use per day and AzBio sentence scores, C) Correlation between average hours of CI use per day use and AzBio sentence scores in +5 dB signal-to-noise ratio (SNR), D) Correlation between average hours of CI use per day and Speech Spatial Qualities (SSQ) scores.

## 2.4 Discussion

The objective of the current study was to quantify the relationship between average hours of CI use per day (data logging) and speech recognition scores. Results showed a strong positive correlation between average hours of CI use per day and both CNC word and AzBio sentence recognition. This correlation suggests that CI users who wear their processor for a greater number of hours per day demonstrate better speech recognition skills or that CI users with better speech recognition skills tend to wear their processor for more hours per day on average.

CI users in our group used their devices 10.2 hours per day, which is consistent with Busch and colleagues' report of 10.7 hours per day (Busch et al., 2017) and slightly lower than Schvartz-Leyzac and colleagues' report of 12.1 hours per day (Schvartz-Leyzac et al., 2019). Average CNC word recognition for our group was 50%, which is approximately 10-percentage points higher than a recent report by Fabie and colleagues (Fabie et al., 2018), but relatively consistent with other reports of large clinical populations (Cusumano et al., 2017; Gifford et al., 2018, 2008). We found a statistically significant and strong correlation between these measures (CI use vs. CNC: $r_s = 0.61$), which is slightly higher than a recent report by Schvartz-Leyzac and colleagues with a smaller sample size ($r = 0.43$) (Schvartz-Leyzac et al., 2019).

The results of the current study show that greater daily processor use is associated with higher, less variable speech recognition scores. The correlation between average hours of CI use per day and speech recognition was found to be 0.6, which is higher than other commonly referenced factors such as age at implantation (Blamey et al., 1996; Leung et al., 2005), duration of deafness (Blamey et al., 1996; Friedland et al., 2003; K. M.J. Green et al., 2007; Leung et al., 2005), length of CI use (Blamey et al., 1996; Chakravorti et al., 2019; Dorman, Hannley, Dankowski, Smith, & McCandless, 1989; Dowell, Mecklenburg, & Clark, 1986), or electrode position (Chakravorti et al., 2019; Holden et al., 2013; Wanna et al., 2015). This finding is promising for CI users and clinicians because it is a factor that can be readily manipulated by the CI recipient and is likely malleable, though further investigation is required to determine whether increased daily CI use will result in improved outcomes for longer term CI users. Our data suggest that 10.2 hours of processor use per day is associated with average (50%) speech recognition performance. Greater than 10 hours of daily processor use is associated with above average speech recognition and lower variability in outcomes for all measures. For example, the participants in our group wearing their processor ~10 hours per day, ranged in performance from 24 to 82% correct for CNC word recognition, whereas participants wearing their processor 15 hours per day ranged from 40 to 92% correct on the same measure. Based on these findings, audiologists may wish to be more specific in their recommendation of daily processor use. Currently, audiologists report recommending “full-time” use or “all waking hours,” but this recommendation may be ambiguous for some users. Although this study does not assess causation, it is reasonable for clinicians to use 10 hours of CI use per day as a minimum recommendation, as 10 hours was associated with average performance. Our correlational data suggest that greater than 10 hours of CI use per day is associated with higher performance, so clinicians may wish to implement higher daily use goals to improve speech recognition performance as we continue to investigate the causal link between these two measures.

These results also have implications for future CI research studies. Going forward, CI use habits should be accounted for in CI outcome studies, and some researchers may wish to consider implementing a minimum number of hours of daily use prior to enrolling participants in CI-based intervention research.

### 2.4.1 Limitations

Although we found a strong association between average hours of CI use per day and speech recognition scores, causality cannot be assumed. A reasonable, alternate interpretation could be that CI users are wearing their processor more because they are performing better. One reason we feel that this is unlikely is due to the lack of correlation between CI use and SSQ scores. Patients who wear their device more, do not self-report better performance or sound quality. Future research is needed to confirm causation as well as to further investigate whether there is a dose dependent response for auditory outcomes in long-term CI recipients. In other words, can we drive higher performance for existing CI users who are scoring below average by simply enforcing longer daily wear times?

## 2.5 Conclusion

In summary, the current study assessed the correlation between measures of speech recognition and average daily processor use in adult CI recipients. Results showed a strong, positive correlation between daily processor use and speech recognition scores (CNC and AzBio). We found that on average 10 hours of processor use per day was associated with average speech recognition (CNC = 50%). These results support current recommendation for “full-time” use of the CI processor to achieve maximal performance, but more specifically clinicians may elect to use 10 hours per day as a minimum goal and 15 hours per day as a higher recommended target to increase the likelihood of above average speech recognition performance while we continue to investigate whether or not there is a causal link between these two measures.

# CHAPTER 3

# THE EFFECT OF INCREASED DAILY COCHLEAR IMPLANT USE ON AUDITORY PERCEPTION IN ADULTS

## 3.1 Introduction

The cochlear implant (CI) is considered the most successful neural prosthetic to date, yielding significant improvement in auditory function for most recipients. Despite its success, variability in auditory outcomes remains high. Much of this variability is outside of the clinician's control (e.g., etiology, duration of deafness, age, spiral ganglion cell count) or requires extensive experimentation to investigate the potential for change (e.g., new programming strategy, place-pitch mismatch). One underreported, cost-effective variable warranting further investigation is consistency of processor use. Busch and colleagues (2017) first described the wide range of average daily CI use in a large group of CI recipients and found the average wear time to be 10.7 hours with the 95% confidence interval ranging from 4.3 to 15.2 hours per day. Based on trends in clinical performance and supporting animal studies (Fallon et al., 2009; Kral, 2002), it is logical to assume that this wide range in consistency of use is related to auditory performance.

CI recipients need some amount of experience to learn to listen via electrical stimulation. Clinically, this is evidenced by the fact that CI users rarely understand spoken language when their CI is first activated, yet six months later, adults understand 50-60% of speech, on average (Buchman et al., 2020; Buss et al., 2008; Holden et al., 2013; Litovsky et al., 2006). Even after reaching a plateau in performance 6 to 12 months following implantation, consistency of processor use remains important. Anecdotally, CI users who experience external equipment malfunction often realize a decrease in speech recognition performance following a few days to weeks without electric stimulation.

The importance of chronic stimulation is also evidenced by animal studies and the theoretical understanding of neural plasticity. Fallon and colleagues (2009) demonstrated that cats could maintain or reestablish a cochleotopically organized auditory cortex via chronic electric stimulation. Similar studies have demonstrated significantly greater cortical activation to electrical stimulation following chronic stimulation (Fallon et al., 2009, 2014; Kral, 2002). If we consider evidence from the literature regarding short-term acoustic auditory deprivation, Clarkson and colleagues (2016) demonstrated that just 10 days of monaural conductive hearing loss had long-lasting effects in the auditory brainstem. It is logical to speculate that similar processes are occurring with auditory deprivation via inconsistent processor use. This evidence points to the importance of consistent use of the external speech processor, but at this time, we cannot make a data-driven recommendation regarding how many hours of wear time per day is sufficient. Of note, Fallon's studies of chronic stimulation were designed to "reflect the temporal distribution of normal clinical usage [and thus] animals received stimulation for at least 16 hours/day, 7 days/week." While clinicians consistently recommend full-time device use, mounting evidence suggests that average use is much lower and specific recommendations regarding a prescriptive number of hours/day is rare.

Variability in average daily wear time (Busch et al., 2017; Holder et al., 2019; Schvartz-Leyzac et al., 2019) suggests that this recommendation may be ambiguous or that patients do not grasp the importance of consistent processor use. This then begs the questions: 1) How many hours of daily CI use is sufficient?, and 2) Can we drive higher performance for existing CI users who are performing below average by enforcing more consistent processor use? The answers to these questions are significant because average daily wear time can be readily altered suggesting that it may be possible to significantly improve CI outcomes for existing users in a cost-effective, highly accessible manner.

CI manufacturers have recently included the ability to track average daily CI use within the programming software making these objective data readily accessible to clinicians and researchers. Using this capability, our group investigated the relationship between hours of CI use per day and speech recognition outcomes. We found a statistically significant and strong correlation ($r = 0.6$) between hours of CI use per day and speech recognition measures suggesting that higher average daily use is associated with better performance (Holder et al., 2019). A correlation of 0.6 is stronger than correlations between speech recognition outcomes and other commonly referenced factors such as age at implantation (Blamey et al., 1996; Leung et al., 2005), duration of deafness (Blamey et al., 1996; Friedland et al., 2003; Green et al., 2007; Leung et al., 2005), or electrode position (Chakravorti et al., 2019; Holden et al., 2013; Wanna et al., 2015) and is generally equivalent to correlations between speech recognition and spectral resolution (Gifford et al., 2018; Henry et al., 2005; Won et al., 2007) and spectrotemporal resolution (Lawler et al., 2017; Tamati et al., 2019). The correlation between CI use and speech recognition has also been shown by one other group in adults (Schvartz-Leyzac et al., 2019) and two other groups in children (Easwar et al., 2018; Guerzoni and Cuda, 2017) in smaller, retrospective review studies. While these findings are promising, the current work is significant because prospective, intervention-based experimentation is warranted to evaluate whether a causal relationship exists.

Over one thousand peer-reviewed studies related to understanding and improving CI outcomes have been published in the past five years. The majority of the findings are limited by cost of implementation or are only applicable to a subset of patients such as patients who have not yet received a CI, patients with specific hearing loss configurations (EAS or Bimodal), or patients with access to research-based interventions at large academic medical centers. Several interventions currently under investigation for implant recipients include the use of different types of imaging. While many of these studies show promising results, they are not clinically feasible for large populations under the current care model. The market penetration of CIs for adult candidates is currently estimated to be 1-7% (iData Research Inc., 2010; Kochkin, 2005; Sorkin, 2013); as we work toward gaining access to this technology for more patients, we must consider interventions designed to improve outcomes for thousands of people.

The goal of the current project was to investigate the relationship between speech recognition and daily CI processor use by implementing increased average daily CI use in long-term CI recipients. A secondary goal was to investigate one mechanism that may be responsible for this relationship. The chosen mechanism for investigation in this study was spectral processing because of the known relationship between spectral processing and speech perception (Baer, Moore, & Gatehouse, 1993; Gifford et al., 2018; Henry, Turner, & Behrens, 2005; Horn et al., 2017; Nittrouer, Tarr, Wucinich, Moberly, & Lowenstein, 2015). While there is no prior work suggesting that spectral resolution is trainable, per se, one study has demonstrated improvements in spectral resolution over the first year of device use (Drennan et al., 2016). Additionally, Berg and colleagues (2019) demonstrated considerable SMD improvement from CI activation to 1 month of CI use with more stable SMD performance from 1 to 12 months for 531 adult CI users. While Berg and colleagues did not record daily CI use information, their data suggest that some criterion amount of CI experience is necessary to achieve stable performance on tasks of spectral processing. CI users who use their device inconsistently may need a longer span of time to achieve stable performance. If spectral processing is also correlated with daily CI use, we can begin to develop a hypothesis regarding a mechanistic pathway responsible for an improvement in speech recognition.

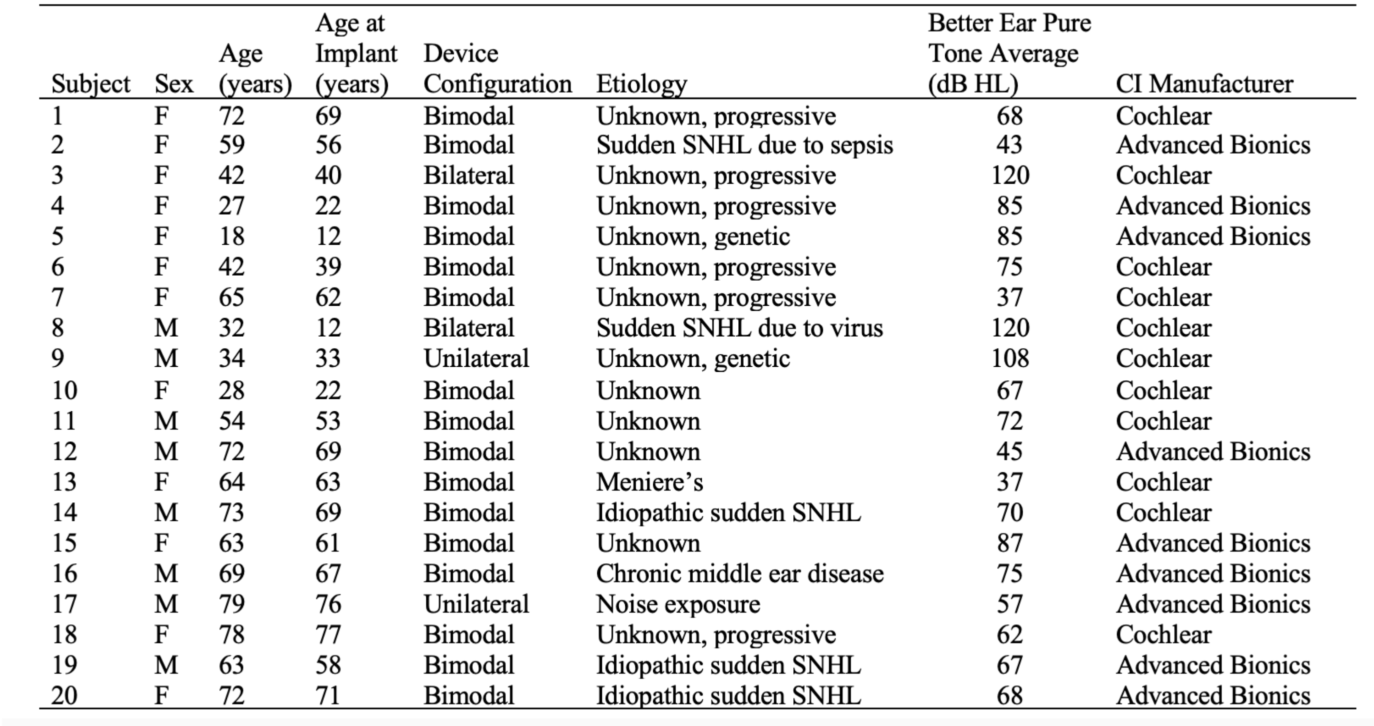
The aims of the current project were as follows, 1) to evaluate the impact of increased CI use on speech recognition performance, and 2) assess one potential underlying mechanism driving the relationship between daily CI use and speech recognition, spectral processing. We had two accompanying hypotheses: 1) Increased CI use will result in improved speech recognition, and 2) Increased CI use would drive improved speech recognition via improved spectral processing.

## 3.2 Materials & Methods

### 3.2.1 Participants

The design and methods of this study were approved by the institutional review board (IRB# 192159). Participants were recruited from the Vanderbilt Bill Wilkerson Center CI patient pool. Exclusionary criteria included participants who were unable to demonstrate understanding of the tasks, participants who did not speak English, participants with CI processors that did not support accurate data logging, participants with less than twelve months of experience with their CI, and participants who wore their CI processor more than ~10 hours per day. At least twelve months of experience with their CI was selected to reduce the impact of acclimatization following activation as much as possible (e.g., Lenarz et al., 2012; Massa and Ruckenstein, 2014). Less than 10 hours per day was selected based on our previous study (Holder et al., 2019), in which 10 hours per day was found to be the average hours of use per day in 300 patients and also so that participants would feasibly be able to increase their average daily use. Participants were strategically recruited based on their pre-study average daily CI use such that the full range (0-10 hours) was represented. Participants were 25 postlingually deafened adult CI recipients (average age = 55, range = 18-79) with bilateral sensorineural hearing loss.  Two participants were excluded due to internal device failure secondary to Advanced Bionics' Ultra version 1 recall. One participant was excluded due to >10 hours of initial data logging (12.6 hours). One participant was excluded due to recent traumatic brain injury and inability to complete the study tasks. One participant was excluded due to perilingual deafness and poor speech intelligibility. Following these five exclusions, 20 participants completed both study visits. Participant characteristics are shown in Table 1.

Table 1. Participant characteristics; SNHL = sensorineural hearing loss, CI = cochlear implant, pure tone average = average of 500, 1000, and 2000 Hz



| Subject | Sex | Age (years) | Age at Implant (years) | Device Configuration | Etiology | Better Ear Pure Tone Average (dB HL) | CI Manufacturer |
|---|---|---|---|---|---|---|---|
| 1 | F | 72 | 69 | Bimodal | Unknown, progressive | 68 | Cochlear |
| 2 | F | 59 | 56 | Bimodal | Sudden SNHL due to sepsis | 43 | Advanced Bionics |
| 3 | F | 42 | 40 | Bilateral | Unknown, progressive | 120 | Cochlear |
| 4 | F | 27 | 22 | Bimodal | Unknown, progressive | 85 | Advanced Bionics |
| 5 | F | 18 | 12 | Bimodal | Unknown, genetic | 85 | Advanced Bionics |
| 6 | F | 42 | 39 | Bimodal | Unknown, progressive | 75 | Cochlear |
| 7 | F | 65 | 62 | Bimodal | Unknown, progressive | 37 | Cochlear |
| 8 | M | 32 | 12 | Bilateral | Sudden SNHL due to virus | 120 | Cochlear |
| 9 | M | 34 | 33 | Unilateral | Unknown, genetic | 108 | Cochlear |
| 10 | F | 28 | 22 | Bimodal | Unknown | 67 | Cochlear |
| 11 | M | 54 | 53 | Bimodal | Unknown | 72 | Cochlear |
| 12 | M | 72 | 69 | Bimodal | Unknown | 45 | Advanced Bionics |
| 13 | F | 64 | 63 | Bimodal | Meniere's | 37 | Cochlear |
| 14 | M | 73 | 69 | Bimodal | Idiopathic sudden SNHL | 70 | Cochlear |
| 15 | F | 63 | 61 | Bimodal | Unknown | 87 | Advanced Bionics |
| 16 | M | 69 | 67 | Bimodal | Chronic middle ear disease | 75 | Advanced Bionics |
| 17 | M | 79 | 76 | Unilateral | Noise exposure | 57 | Advanced Bionics |
| 18 | F | 78 | 77 | Bimodal | Unknown, progressive | 62 | Cochlear |
| 19 | M | 63 | 58 | Bimodal | Idiopathic sudden SNHL | 67 | Advanced Bionics |
| 20 | F | 72 | 71 | Bimodal | Idiopathic sudden SNHL | 68 | Advanced Bionics |

### 3.2.2 Study Design

The current study was designed to assess a causal relationship between average daily CI use and speech recognition by assessing the feasibility of improving speech recognition via an increase in average daily CI use. The study design included two visits: baseline and post-increased CI use. The baseline visit consisted of auditory perception testing, questionnaire administration, and recording of daily CI use from the CI software. Additionally, participants watched an educational video (https://www.youtube.com/watch?v=Ch-NpY98-30), and they were informed of the compensation schedule, which compensated participants for every additional hour per day that they wore their processor, on average. Participants were then asked to increase their daily CI use as much as possible over a four-week period during everyday life. At the post-increase visit, all baseline measures were reassessed.

### 3.2.3 Study Measures – Average Daily CI Use, Spectral Processing, Speech Recognition, & Questionnaires

*Average Daily CI Use.* Daily CI use was the independent variable. The average number of hours of processor use per day was extracted from each participant's data logging information housed in the CI programming software. When a processor is connected to the software, this value effectively resets allowing for collection of data logging information over a specific period of time.

*Speech Recognition.* Speech recognition was the main dependent variable. The recommended materials from the Minimum Speech Test Battery (MSTB) (MSTB, 2011) were used to mimic clinical testing procedures. Words and sentences were presented at 60 dB SPL in quiet and 65 dB SPL in the presence of noise from a single loudspeaker inside a sound booth using recorded stimuli, which were calibrated using a sound level meter prior to every session. Specifically, we used Consonant-Nucleus-Consonant (CNC) (Peterson & Lehiste, 1962) monosyllabic word recognition in quiet and AzBio sentence recognition (Spahr et al., 2012) in quiet and in +10 dB signal-to-noise ratio (SNR) noise. A +10 dB SNR was chosen because the participants recruited for testing were expected to be lower performers based upon our correlational study (Holder et al., 2019), and we wanted to avoid potential floor effects with this measure. All speech recognition testing was audio recorded and scored by a blinded researcher to ensure validity of scoring, guard against subjective biases, and to serve as a quality control standard.

*Spectral Processing*. Spectral processing was assessed via spectral modulation detection (SMD) for which the participant was asked to discriminate between noises with a flat spectrum and those with spectral modulation. We used a broadband stimulus (125-8000 Hz) incorporating a spectral modulation rate of 0.5 and 1.0 cycles per octave (Litvak, Spahr, Saoji, & Fridman, 2007; Saoji & Eddins, 2007; Saoji, Litvak, Spahr, & Eddins, 2009). We used a two-down, one-up tracking procedure to track 70.7% correct on the psychometric function using stimuli at 65 dB SPL presented to the CI ear alone in the sound field. The contralateral ear was plugged when necessary. We used a three-interval, two-alternative forced choice paradigm. Participants responded via touchscreen monitor to avoid investigator bias.

*Questionnaires.* The Speech Spatial Qualities (SSQ) (Gatehouse & Noble, 2004) and the Cochlear Implant Quality of Life Profile (CIQOL-35 Profile) (McRackan, Hand, Consortium Cochlear Implant Quality of Life, & Dubno, 2019) were administered at both study visits. The SSQ is a self-reported questionnaire assessing speech understanding, spatial awareness, and quality of sound. The CIQOL is an instrument specifically designed for use with adult CI recipients, which includes 35 items that measure quality of life in six unidimensional domains (communication, emotional, entertainment, environment, listening effort, and social). We also collected data from our participants about their daily CI use habits and the barriers to using their processor. These data were collected in the form of a questionnaire called the Cochlear Implant Use Questionnaire (CIUQ). The CIUQ was created specifically for this study, and it is described in detail in Chapter 5. The CIUQ probes employment status, living situation, wearing habits, and their surgeon/audiologist's recommendation for how often they should wear their CI processor. The quantitative questions probe specific barriers to daily CI use such as equipment, motivation to hear, sound quality, and pain using a five point scale. Total scores range from 0 to 100 such that a higher total corresponded to a greater number of reported barriers to CI use.

### 3.2.4 Statistical Analysis

Statistical software (SPSS and GraphPad Prism) was used to conduct statistical analyses. Descriptive statistical and graphical methods were used to summarize data. Tests of statistical significance maintained Type I error rates of less than 0.05; 95% confidence intervals and effect sizes were reported where applicable. All variables were normally distributed except for the 'Change in AzBio sentences in quiet' variable. To address this, we transformed this variable by adding three and taking the square root.

To prospectively evaluate the effect of CI use and spectral resolution on speech recognition, we used generalized linear models to assess the following two main effects: 1) change in CI use on change in speech recognition performance, and 2) change in spectral resolution on speech recognition, while controlling for baseline measures. Our sample size was not adequate to appropriately evaluate the effect of change in CI use and change in spectral resolution on speech recognition; however, we made inferences about this effect based on the main effects.

## 3.3 Results

### 3.3.1 Data logging

Data logging revealed mean CI device use was 5.9 hours per day (range = 0 – 10.3 hours) at visit one and 8.9 hours per day (range = 1.1 – 12.9 hours) at visit two. On average, participants increased their daily CI use by 3.0 hours per day (range = 0 – 8.8 hours) over a 33-day period (range = 27 – 53 days) (Figure 3). Three out of 20 participants did not increase their daily CI use. These three participants were included in the generalized linear model analyses, but they were removed from group comparison tests.

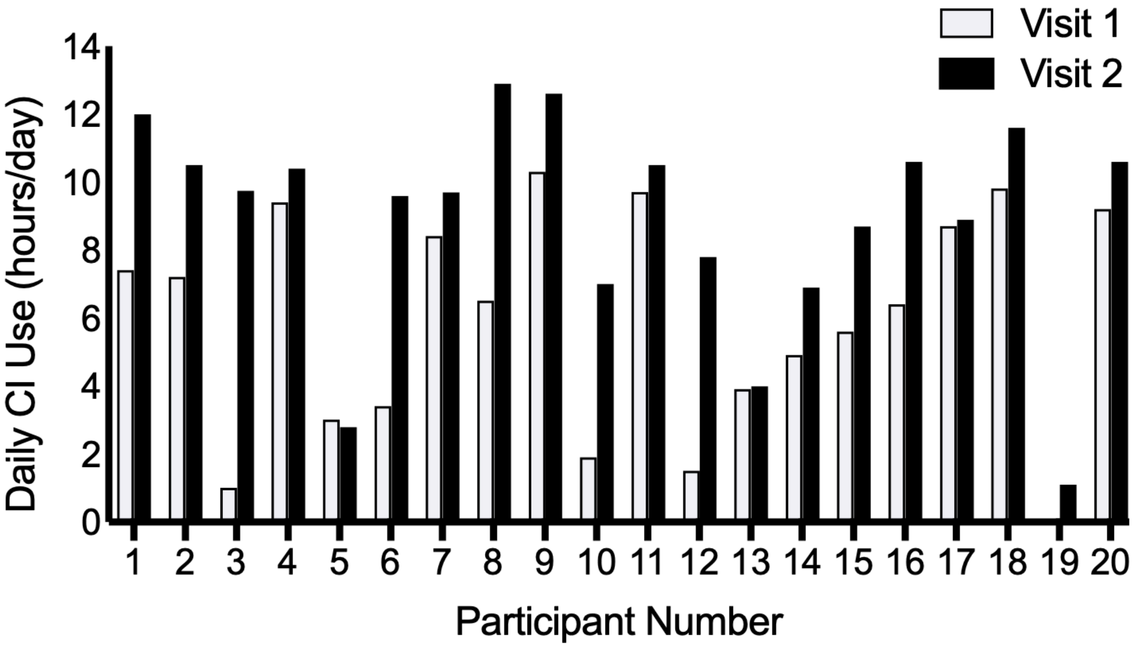


Figure 3. Objective daily CI use information (average hours/day) collected from the CI software (data logging) at visit 1 and visit 2 is shown for each participant.

Table 2. Main study variables; means and ranges are shown for all variables.

| Measure | Visit 1 | Visit 2 | Change |
|---|---|---|---|
| Daily CI use (hours/day) | 5.9<br>(0-10.3) | 8.9<br>(1.1-12.9) | 3.0<br>(-0.2-8.8) |
| CNC words (%) | 55.6<br>(24.0-88.0) | 64.6<br>(32.0-88.0) | 9.0<br>(-4.0-36.0) |
| AzBio sentences in quiet (%) | 69.9<br>(38.0-93.0) | 77.2<br>(48.0-98.0) | 7.3<br>(-2.0-31.0) |
| AzBio sentences in +10 dB SNR (%) | 44.7<br>(0.0-79.0) | 65.8<br>(0.0-93.0) | 21.1<br>(-8.0-57.0) |
| Composite score | 170.2<br>(100.0-249.0) | 207.5<br>(106.0-276.0) | 37.3<br>(-8.0-95.0) |
| Spectral ripple 0.5 (dB) | 16.5<br>(8.8-28.8) | 14.7<br>(4.9-24.5) | -1.8<br>(-8.6-3.8) |
| Spectral ripple 1.0 (dB) | 18.9<br>(5.8-28.2) | 16.1<br>(5.2-27.7) | -2.8<br>(-14.1-3.2) |

### 3.3.2 Speech Recognition

Mean speech recognition for CNC monosyllabic words, AzBio sentences in quiet, and AzBio sentences in +10 dB SNR at visit 1 were 55.6%, 69.9%, and 44.7%, respectively. At visit 2, on average scores increased to 64.6%, 77.2%, and 65.8% (Figure 4). A composite score, the sum of CNC, AzBio, and AzBio +10 scores, was also calculated for all participants. Mean composite scores were 170.2 at visit 1 and 207.5 at visit 2.

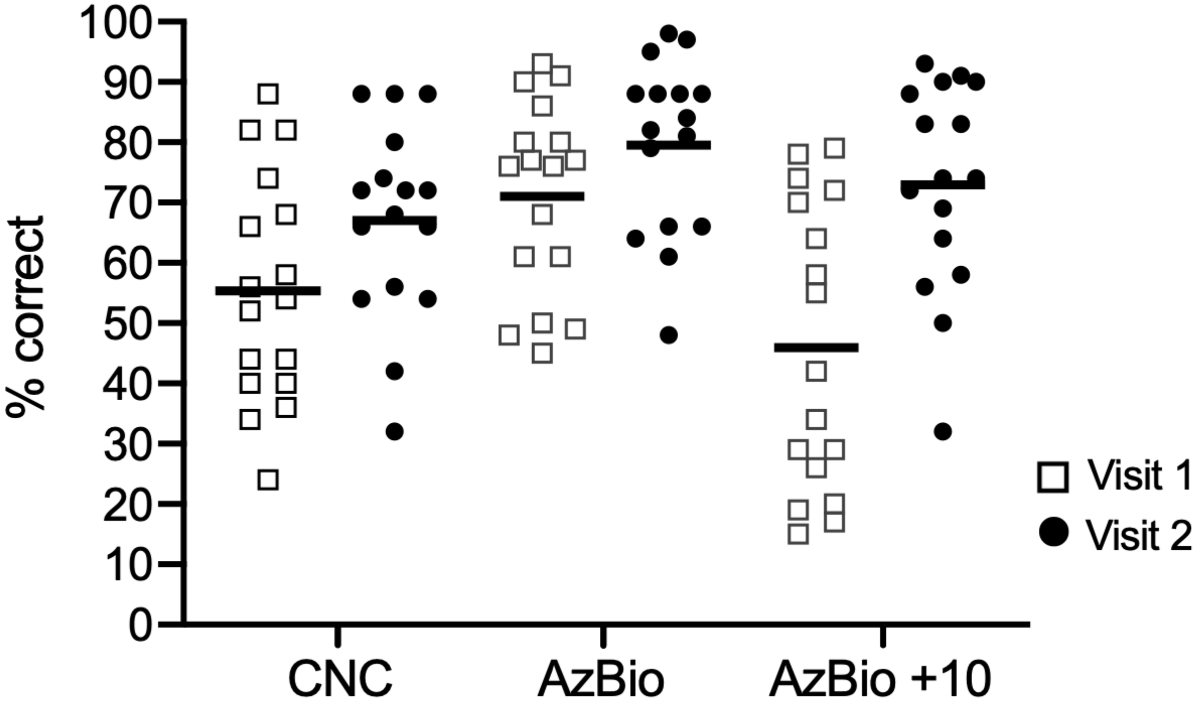


Figure 4. Individual and mean speech recognition scores are shown for visit 1 (squares) and visit 2 (circles) for the 17 participants who increased their daily CI use. All three measures were significantly higher at visit 2.

To test our first hypothesis, we used a generalized linear model to assess the effect of change in CI use on change in speech recognition performance (Table 3). Initial data logging information and speech recognition were included in all models. Results of the generalized linear model for CNC word recognition indicated that change in CI use was a significant predictor of change in CNC word recognition and change in AzBio sentence recognition in noise, but it was not a significant predictor of the change in AzBio sentence recognition in quiet. Increase in CI use also explained a significant proportion of variance in CNC word scores, $R^2 = 0.234$, $F(1,19) = 5.485$, $p = 0.031$, and AzBio sentence in noise scores, $R^2 = 0.217$, $F(1,19) = 4.994$, $p = 0.038$, but not in AzBio sentences in quiet, $R^2 = 0.075$, $F(1,19) = 0.102$, $p = 0.753$. On average, participants' speech recognition improved by 3.0-, 2.4-, and 7.0-percentage points per hour of increased use for CNC, AzBio, and AzBio in noise, respectively (Figure 5).

Table 3. Generalized linear model coefficients for the effect of increased cochlear implant use on speech recognition

| | Unstandardized coefficients | | Standardized coefficients | | |
|---|---|---|---|---|---|
| Measure | B | SE | Beta | t | p |
| CNC Words | 2.301 | 0.867 | 0.512 | 2.653 | 0.017 |
| AzBio Sentences in Noise | 4.219 | 1.146 | 0.131 | 2.819 | 0.020 |
| AzBio Sentences in Quiet | 0.124 | 0.121 | 0.282 | 1.019 | 0.323 |
| Composite Score | 7.264 | 2.509 | 0.631 | 2.895 | 0.011 |

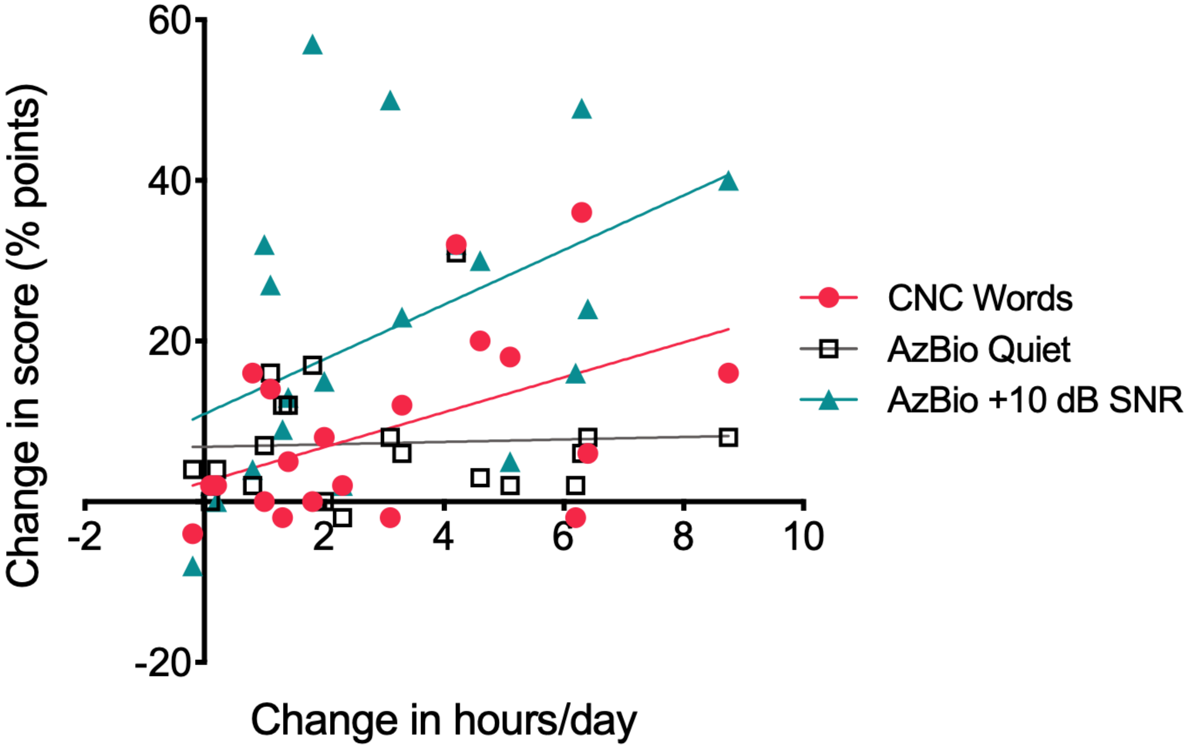


Figure 5. The relationship between change in hours per day and change in speech recognition score is shown for all participants.

Interscorer reliability was assessed for speech recognition tasks. All speech recognition measures were scored by a trained researcher in person and then again by a second scorer via audio recording. Scores were considered reliable if they were within 5-percentage points of each other. Interscorer reliability was greater than 90% (range: 93.5%-100.0%) for all speech recognition measures. Interscorer reliability is also commonly reported using correlations. Spearman's correlations between in person and audio recording scoring for CNC, AzBio, and AzBio + 10 dB SNR were 0.99, 0.98, and 1.0, respectively for visit 1 and 0.97, 0.98, and 0.98, respectively, for visit 2. Given excellent interscorer reliability, scores from the initial scorer were used for analyses.

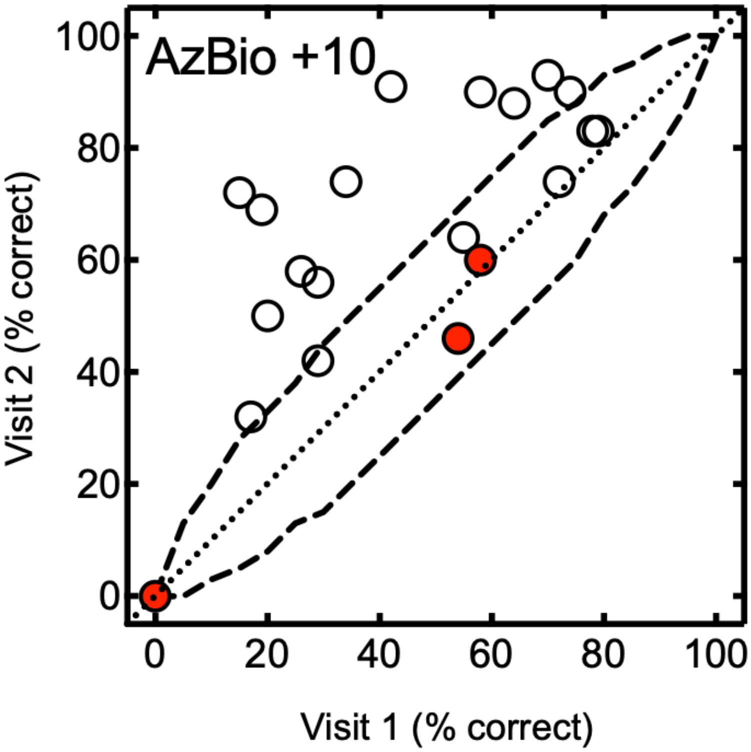


Figure 6. Individual data for AzBio sentences in noise at +10 dB SNR are shown for visits 1 and 2. The dashed line represents the 95% confidence interval. The red circles indicate participants who did not increase their daily CI wear time.

### 3.3.3 Spectral Processing

Mean SMD thresholds for modulation rates of 0.5 and 1.0 cycles per octave were 16.5 dB and 18.9 dB, respectively. At visit 2, on average scores decreased (improved) to 14.7 dB and 16.1 dB, respectively.

To test our second hypothesis, we used a generalized linear model to assess the effect of change in SMD on change in speech recognition performance. Initial SMD and speech recognition were controlled in both models. Results of the generalized linear model for 0.5 cycles per octave indicated that change in spectral processing was a significant predictor for change in CNC word recognition; it did not significantly predict change in AzBio sentence recognition in quiet or change in AzBio sentence recognition in noise. Results of the generalized linear model for 1.0 cycles per octave indicated that change in spectral processing did not significantly predict changes in any of the speech recognition tasks (Table 4).

Table 4. Generalized linear model for the effect of change in spectral processing on change in speech recognition

| | | Unstandardized coefficients | | Standardized coefficients | | |
|---|---|---|---|---|---|---|
| Cycles/ Octave | Measure | B | SE | Beta | t | p |
| 0.5 | CNC Words | -1.624 | 0.689 | -0.455 | -2.357 | 0.031 |
| | AzBio Sentences in Noise | -0.917 | 1.365 | -0.158 | -0.672 | 0.511 |
| | AzBio Sentences in Quiet | 0.033 | 0.092 | 0.095 | 0.359 | 0.725 |
| | Composite Score | -1.835 | 2.306 | -0.201 | -0.796 | 0.438 |
| 1.0 | CNC Words | -0.892 | 0.581 | -0.348 | -1.535 | 0.144 |
| | AzBio Sentences in Noise | -2.016 | 0.957 | -0.485 | -2.107 | 0.051 |
| | AzBio Sentences in Quiet | -0.032 | 0.068 | -0.128 | -0.471 | 0.644 |
| | Composite Score | -2.816 | 1.673 | -0.429 | -1.683 | 0.112 |

3.3.4 Questionnaires

Mean SSQ, CIQOL, and CIUQ scores at visit 1 and visit 2 are shown in Table 5. No significant differences in questionnaire scores were observed between visits. Anecdotally, four participants reported that they felt that listening required less effort and concentration and that they were able to passively listen to conversation rather than intensely focus.

Table 5. Mean questionnaire scores and statistics.

| Questionnaire | Visit 1 | Visit 2 | Z-value | Significance | Effect Size (r) |
|---|---|---|---|---|---|
| SSQ12 | 4.4 | 4.5 | -0.24 | 0.810 | -0.05 |
| CIQOL | 31.8 | 31.6 | -0.07 | 0.944 | -0.02 |
| CIUQ | 29 | 27.7 | -0.89 | 0.373 | -0.19 |

## 3.4 Discussion

The primary aim of this study was to evaluate whether an increase in daily CI use could improve speech recognition scores over a four-week period. All participants who increased their daily CI use by more than one hour of use per day except for participant 9 showed a clinically significant improvement (>10 percentage points) on at least one measure of speech recognition with the largest average improvement on the AzBio sentences in noise measure. Participant 9 did not show an improvement in speech recognition scores despite a 2.3-hour increase in daily CI use; lack of improvement may be attributed to severe-to-profound hearing loss for 29 years prior to CI. The four participants with ≤ 1 hour of increased use per day, did not show a significant increase in speech recognition scores.

To assess our first hypothesis, we implemented a generalized linear model to evaluate the effect of change in daily CI use on the change in speech recognition scores. The models for CNC word recognition and AzBio sentence recognition in noise indicated that increase in daily CI use was a significant predictor of improved performance on these measures. Further, the increase in CI use accounted for a significant portion of the variance in the change in speech recognition variable. For AzBio sentences in quiet, participants only demonstrated a 7.3-percentage point improvement, on average. This can likely be explained by the fact that sentences, especially in quiet, are less sensitive to peripheral processing differences due to the availability of context clues (e.g., Moberly & Reed, 2019). The improvement in CNC words per additional hour of use was in line with our expected results and results from Easwar and colleagues (2018). Our previously defined equation, % words = 3.3*(hours) + 16.5, predicted a 3.3-percentage point improvement per additional hour of use (Holder et al., 2019), and in the current study we observed a 3.0-percentage point improvement in word recognition per additional hour of use.

To assess our second hypothesis, we implemented a generalized linear model to evaluate the effect of change in spectral processing on change in speech recognition. Participants showed a small improvement in spectral processing, but change in spectral processing was only a significant predictor of change in CNC word recognition for one of the spectral modulation rates, 0.5 cycles per octave. This finding is consistent with previous results from Saoji et al. (2009) which showed a correlation between SMD thresholds at 0.5 cycles/octave and phoneme, vowel, and consonant recognition. Litvak et al. (2007) also showed a similar relationship using an average of SMD thresholds at 0.25 and 0.5 cycles/octave. The purpose of this aim in our study was to evaluate one possible underlying mechanism that could be driving the improvement in speech recognition following an increase in daily CI use. Our sample size did not allow for evaluation of change in CI use on change in spectral resolution while controlling for the main effects. Based on the two main effects, we can speculate that improvement in spectral processing did account for a portion of the increase in speech recognition following an increase in daily CI use, but it is likely not the only underlying mechanism. This finding may be explained by the fact that spectral resolution requires less auditory experience than speech recognition to reach asymptotic performance (Berg, Roberts, Burchesky, & Gifford, 2019; Drennan, Won, Timme, & Rubinstein, 2016). Even though study participants did not use their CI processor consistently, perhaps their cumulative auditory experience was sufficient to develop spectral processing abilities at or near their asymptotic performance level. Further work is needed to investigate other potential driving mechanisms for the relationship between daily CI use and speech recognition that may contribute in addition to spectral processing.

Future directions for this line of work may gain insight from previous studies related to the effects of auditory deprivation. Inconsistent CI use is not unlike auditory deprivation, which has been shown to affect presynaptic and postsynaptic structures of the auditory nerve in the cochlear nucleus in mice in as little as 10 days (Clarkson et al., 2016). Sparreboom and colleagues' (2016) study supports these findings in children with bilateral CIs. They studied electrically evoked auditory brainstem responses (eABR) in children with bilateral CIs with differing wear times across ears as assessed by a Likert scale. They concluded that the less the device is used, the larger the difference in interaural eABR wave V latencies, which translated to larger differences in speech recognition between implants. Although their study relied on subjective report of device use, it provides two important pieces of evidence. It supports our findings that device use and speech recognition are related, and it suggests that changes at the level of the auditory brainstem as measured by eABR may be responsible for this relation. Gordon and colleagues (2015) showed a similar pattern of results for sequentially implanted children with longer delays between first and second ear implantation. A logical next step in this line of work would be to include eABR in conjunction with objective daily CI use information (data logging) to further explore the mechanism underlying the relationship between CI device use and speech understanding in the adult population.

Results from the three questionnaires showed no significant differences between visits 1 and 2. This was an unexpected finding given the improvement in speech recognition scores. Many of the questions on the SSQ and CIQOL are related to listening outside of the home and in social situations. Given that all data were collected during the COVID-19 pandemic, participants may not have been able to experience the situations probed in these questionnaires. Although the CIUQ did not show a significant change in score, the qualitative portion yielded some interesting findings. One participant's magnet was too strong, which caused them to remove their processor due to head pain. Another participant's batteries were only lasting 3 hours, so when their batteries died, they just took the processor off. Because of the CIUQ, we were made aware of these issues, and we were able to correct them to support more consistent use. We were also able to use the questionnaire to help participants create a plan for how they were going to use their processor more often during the study period. For example, one participant reported that they did not put their processor on until they leave the house, but for the purposes of this study, they put it on immediately upon waking. The CIUQ may be used in a similar manner in the clinic to identify and overcome barriers to support more consistent CI use.

### 3.4.1 Clinical and Research Application

As stated in the introduction, the current market penetration for CIs is estimated to be 1-7% (iData Research Inc., 2010; Kochkin, 2005; Sorkin, 2013). As we expand access to more individuals with hearing loss, there is a need for interventions to be cost-effective and accessible for all CI recipients. The intervention described in this project is promising because it is immediately available to all CI users, and there is no cost associated with implementation. Clinicians can use data logging information already available in the CI software for most recipients to counsel patients regarding their device use consistency and recommend increasing their CI use to further optimize their speech recognition scores.

An exact recommendation for the number of hours per day a recipient should wear their CI processor cannot be made based on the current data; however, three participants in the current study started with daily CI use > 9 hours per day and still realized clinically significant improvements in speech recognition scores following an increase in CI use. This suggests that CI users should be using their CI processor for at least 10 hours per day to achieve their maximum possible speech recognition performance. This finding coupled with our previous correlational study (Holder et al., 2019) suggest that greater that 10 hours of use per day will likely yield additional gains in speech recognition performance, but this has not yet been studied explicitly.

The current findings suggest that an increase in daily CI use over a period of four weeks impacts speech recognition outcomes. Future research studies should control for daily CI use using data logging to avoid contaminating results. Participants enrolled in a research study, especially one with a new intervention (i.e., new programming strategy, new processor, or new accessory) may be prone to using their CI processor more consistently. Increased daily CI use during the study period may lead researchers to wrongly conclude that the intervention was favorable if daily CI use is not controlled.

### 3.4.2 Limitations

There are some limitations that should be noted. The current study lacks a proper control group, which is an important next step in this line of research. A control group was not included due to stipulation of the intended funding mechanism and feasibility of study completion under the scope of a dissertation project. Another limitation of the study was the sample size. Originally a sample size of 30 participants was proposed; however, due to the coronavirus pandemic, the sample size was reduced to 20 participants. Finally, the findings in this study may be underestimated due to the initial speech recognition of this particular cohort. Given an initial wear time of 5.9 hours, we expected much lower initial speech recognition scores (word scores = ~36%) than the mean scores observed here (55.6% and 44.7% for CNC and AzBio in noise scores, respectively) . If the cohort had been more typical, we may have seen more robust results.

## 3.5 Conclusion

Current work suggests that improved consistency of processor use over a four-week period yields clinically significant improvements in speech recognition scores. Spectral processing does not appear to be the only underlying driver of this improvement. Future work should include a proper control group and further investigation of other potential underlying mechanisms for improvement in speech recognition scores.

# CHAPTER 4

# EXPLORATORY STUDY MEASURES

## 4.1 Introduction

Many factors contribute to the variability in auditory outcomes for cochlear implant (CI) recipients including, but not limited to, duration of deafness, age at implantation, etiology, surgical approach, electrode array placement, insertion depth, signal processing strategy, preoperative audiometric thresholds, preoperative suprathreshold processing, CI programming, device use/experience, neurocognitive function, aural rehabilitation, and neural health. Further, these variables have never been previously studied in conjunction with daily CI use or data logging measures. During data collection described in the previous chapter, we also collected data on a few of these factors for exploratory analyses. Specifically, we collected data related to CI programming, neurocognitive function, and CI electrode placement.

### 4.1.1 Cochlear Implant Programming

*Lower stimulation levels*. The goal of setting lower stimulation levels is to ensure that lower level sounds are perceived as soft, yet still audible. This is verified by completing aided audiometric detection testing in the sound field using frequency modulated (FM) tones. The CI user should be able to detect FM tones across the frequency range (250-6000 Hz) in the 20-30 dB HL range to ensure that low-level speech stimuli can be detected (Busby & Arora, 2016). Detection lower than 15 dB HL is undesirable as it can result in perception of circuit noise and unnecessary compression of the electric dynamic range (Davidson, Geers, & Brenner, 2010). If the aided detection thresholds are too low or too high, lower stimulation levels (i.e., T-levels or Threshold Levels) should be adjusted accordingly.

Incorrectly programmed lower stimulation levels resulting in poor aided detection can have detrimental effects on speech recognition. Davidson and colleagues (Davidson et al., 2010) and Holden and colleagues (Holden et al., 2013) found a correlation between aided detection and speech recognition such that individuals with poor aided detection showed poorer speech recognition especially at lower presentation levels (i.e., 50 dB SPL). Audibility of lower level sounds which are generally perceived as “soft” is foundational to all other components of speech recognition, particularly given the relatively low level of high-frequency consonants which are known to significantly influence speech perception. High-frequency audibility is especially important for children acquiring auditory-based language who have normal hearing (Pittman, 2008) as well as for children with hearing loss (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Therefore without audibility of low-level speech—particularly in the high-frequency region—the CI user cannot expect to reach optimal performance.

*Upper stimulation levels*. The accuracy with which upper stimulation levels are programmed also significantly affects speech recognition outcomes for CI users (Baudhuin, Cadieux, Firszt, Reeder, & Maxson, 2012; A. Geers et al., 2003; Hodges et al., 1997; Holden et al., 2013; Wolfe & Kasulis, 2008). Upper stimulation levels are most commonly set using behavioral loudness scaling, which requires the CI user to rate the loudness of a sound played on each electrode. This method is prone to error because loudness is highly variable in individuals with hearing loss (A. Geers et al., 2003; Marozeau & Florentine, 2007; Polak, Hodges, King, Payne, & Balkany, 2006; Zwolan, O’Sullivan, Fink, Niparko, & CDACI Investigative Team, 2008). A less common, but potentially more accurate approach to programming upper stimulation levels involves the use of electrically-evoked stapedial reflex thresholds (eSRTs), which provide an objective correlate to a stimulation level shown to be perceived as “loud but comfortable” on average (Allum, Greisiger, & Probst, 2002; Brickley, Boyd, Wyllie, O’Driscoll, & Nopp, 2005; Gordon, Papsin, & Harrison, 2004; Hodges et al., 1997; Lorens, Walkowiak, Piotrowska, Skarzynski, & Anderson, 2004; Shallop & Ash, 1995; Spivak, Chute, Popp, & Parisier, 1994; Stephan & Welzl-Müller, 2000; Walkowiak et al., 2011). CI programming using eSRTs to set upper stimulation levels have shown equal (Hodges et al., 1997; Spivak et al., 1994) or better (Bresnihan, Norman, Scott, & Viani, 2001; Wolfe & Kasulis, 2008) speech recognition results compared to behavioral-based (loudness scaling) maps. Further, eSRT-based maps have been shown to result in equal loudness across the electrode array, and patients tend to prefer eSRT-based maps over behavioral maps (Polak et al., 2006).

### 4.1.2 Neurocognitive Function

Neurocognitive functioning abilities are often referred to as the “top-down” processing abilities. These abilities allow CI recipients to use the spectrally and temporally degraded speech signal provided by the CI to interpret speech. The underlying linguistic and cognitive processes include working memory, inhibitory control, nonverbal reasoning, general cognition, perceptual closure, and information processing speed. Existing evidence suggests that nonverbal reasoning, working memory, and inhibitory control contribute to the overall variability in speech recognition outcomes in individuals with hearing loss, while more general cognitive tests do not (Collison, Munson, & Carney, 2004; Heydebrand, Hale, Potts, Gotter, & Skinner, 2007; Jerger, Jerger, & Pirozzolo, 1991; Knutson et al., 1991). Nonverbal reasoning refers to one’s ability to solve novel reasoning tasks without access to explicit prior knowledge. Nonverbal reasoning is used in the process of piecing together degraded auditory sentences to form compete sentences in speech recognition (Holden et al., 2013; Knutson et al., 1991; Mattingly, Castellanos, & Moberly, 2018). Working memory is a capacity-limited, temporary storage mechanism tasked with holding important information for further processing. This mechanism is important for temporarily holding linguistic information during the process of speech recognition (Heydebrand et al., 2007; Kaandorp, Smits, Merkus, Festen, & Goverts, 2017; Moberly, Castellanos, & Mattingly, 2018). Inhibitory control refers to the ability of an individual to suppress competing information in favor of the target information. This ability is implicated in speech in noise performance as well as resolving semantic confusions. Individuals who are able to suppress incorrect lexical competitors may be better able to capitalize on semantic context to fill in a misheard word (Moberly, Houston, & Castellanos, 2016; Moberly & Reed, 2019; Sommers & Danielson, 1999). Current literature suggests that the most effective tools to measure these abilities in adults with CIs are the following: Stroop test to assess inhibitory control (Moberly et al., 2016; Stroop, 1935), Raven's Progressive Matrices to assess nonverbal reasoning (Mattingly et al., 2018; Moberly et al., 2018; Raven, Raven, & Court, 1998), and Digit Span Test (Wechsler, 2004) or Reading-Span Test (Akeroyd, 2008; Daneman & Carpenter, 1980; Moberly et al., 2018) to assess working memory.

### 4.1.3 CI Electrode Placement

*Scalar location*. Postoperative imaging techniques have allowed us to localize the position of the CI electrode array within the cochlea including scalar location and distance from the electrode array to the modiolus. Converging evidence from several groups suggests that electrode arrays placed fully within scala tympani (ST) yield better outcomes compared to arrays placed partially or fully within scala vestibuli (SV) (Aschendorff, Kromeier, Klenzner, & Laszig, 2007; Chakravorti et al., 2019; Finley et al., 2008; Holden et al., 2013; O'Connell et al., 2016; Skinner et al., 2007; Wanna et al., 2014). On average, electrode arrays that translocate result in a 10-15 percentage point decrement in consonant-nucleus-consonant (CNC) word scores (Chakravorti et al., 2019; O'Connell et al., 2016) with a greater effect for precurved arrays on average (Chakravorti et al., 2019; Holden et al., 2013; Morrel, Holder, Dawant, Noble, & Labadie, 2020). Better performance with full ST insertion is attributed to two main reasons. First, when an electrode array crosses from ST to SV, trauma may be inflicted to the osseous spiral lamina, basilar membrane, spiral ligament, and/or Reisner's membrane (Skinner et al., 2007); this trauma likely results in an inflammatory response which may result in the formation of scar tissue (fibrosis), bony growth (neo-osteogenesis), as well as ultimately spiral ganglion cell death (e.g., Kamakura & Nadol, 2016). Secondly, electrodes delivering stimulation from the SV are more likely to stimulate spiral ganglion cells in the subsequent, more-apical turn of the cochlear. Finley and colleagues (Finley et al., 2008) refer to this as cross-turn stimulation, which they attribute to pitch confusion and poor speech recognition outcomes.

*Electrode-to-modiolus distance*. In addition to scalar translocation, electrode-to-modiolus distance, quantified using postoperative computerized tomography (CT), has emerged as a significant predictor of speech recognition outcomes (Chakravorti et al., 2019; Holden et al., 2013) such that electrode arrays positioned closer to the modiolus result in better speech recognition scores. This factor likely underlies the difference in performance observed between precurved and straight arrays, but it is also a contributing factor within the precurved subset of arrays. Chakravorti and colleagues (Chakravorti et al., 2019) used a general linear model to predict speech recognition scores, which included the following factors: scalar location, mean modiolar distance, base insertion depth, tip insertion depth, age at implantation, gender, length of CI use, and pre/postlingual deafness. Their model estimated that CNC word scores decrease at a rate of 4.3-percentage points per 0.1mm for precurved electrode arrays in a sample of 92 adult recipients. The correlation between electrode-to-modiolus distance and speech recognition outcomes is thought to be driven by increased spatial selectivity when the electrode contacts are in closer proximity to the site of neural stimulation (L. T. Cohen, 2009; Davis et al., 2016; Gordin, Papsin, James, & Gordon, 2009; Litvak, Spahr, & Emadi, 2007; Saunders et al., 2002). Smaller electrode-to-modiolus distances are thought to be associated with reduced charge required for upper stimulation levels resulting in less channel interaction and hence improved channel independence, which results in better spectral resolution (Chatterjee & Shannon, 1998; L. T. Cohen, Saunders, Knight, & Cowan, 2006; Davis et al., 2016; Kang et al., 2015; Saunders et al., 2002; Shepherd, Hatsushika, & Clark, 1993).

*Insertion depth.* Lastly, insertion depth has garnered attention in the literature as a factor potentially contributing to outcomes especially with straight electrode arrays. Some studies show a positive correlation (Helbig et al., 2018; O'Connell et al., 2017; Rivas et al., 2017; Skinner et al., 2002; Yukawa & Blamey, 2004), some show a negative correlation (Holden et al., 2013), and some show no correlation (Whiting, Holden, Brunsden, Finley, & Skinner, 2008) between insertion depth and speech recognition outcomes. Insertion depth is measured in different ways for different electrode array types, such as angular insertion from apex or base or trajectory length; as a result, across-study comparisons and interpretations regarding the effects of insertion depth can be quite difficult. Based on recent data from our center (Chakravorti et al., 2019; Morrel et al., 2020; O'Connell et al., 2017; Rivas et al., 2017) and interpretation provided by Holden and colleagues (Holden et al., 2013), insertion depth is dependent upon the intended design of the electrode array and the length of the individual's cochlea. For precurved arrays, base insertion depth is negatively correlated with outcomes because higher base insertion depth is associated over insertion resulting in the mid-portion of the electrode approaching the lateral wall of the cochlea. For straight arrays, base insertion depth is positively correlated with outcomes up to a certain point. For example, greater insertion depth is associated with increased cochlear coverage and better place-pitch matching until the apical tip of the array begins to interfere with the basilar membrane or the array is so over-inserted that the basal portion of the cochlea lacks stimulation (Finley et al., 2008; Holden et al., 2013; Morrel et al., 2020).

The primary aim of this chapter was to explore relationships between daily CI use, speech recognition, and other commonly studied factors thought to contribute to CI outcome variability. A secondary aim was to demonstrate the feasibility of administering the NIH Toolbox Cognitive battery to CI users, which has not been previously demonstrated in the literature. There was no associated hypothesis given the exploratory nature of these aims.

## 4.2 Methods

### 4.2.1 CI Programming

In order to assess how CI programming may be affecting the outcomes of patients in our study, we measured electrically evoked stapedial reflex thresholds (ESRTs) to assess programming of upper stimulation levels, and we completed aided detection testing to assess audibility of low-level stimuli (Busby & Arora, 2016; Holden, Reeder, Firszt, & Finley, 2011). Tympanometry was completed prior to ESRT measurement to ensure normal middle ear function. ESRTs were measured in the ear contralateral to the CI. If the participant was bilateral, we measured ESRTs from the ear with the most favorable tympanogram. A 678 Hz probe tone was used initially for all participants. A 226 Hz probe tone yielded responses for three participants that were otherwise absent using a 678 Hz probe tone. ESRTs were determined to be absent or unavailable if the participant reported pain associated with stimulation or the compliance limits of the device were reached. Aided detection testing was completed using warble tones presented from a loudspeaker placed 1 meter in front of the participant. For ESRTs and aided detection, participants were assigned a pass or fail rating. For upper stimulation levels, they were assigned a pass rating if their upper stimulation levels were set at ESRT or shifted globally from their ESRT levels. For example, if only high frequency electrodes deviated from ESRT measurement, a fail rating would be assigned, but if all electrodes were increased or decreased from ESRT by the same amount (e.g., upper stimulation levels set at 80% of ESRT levels), a pass rating would be assigned. For aided detection testing, they were assigned a pass rating if no more than one threshold was greater than 25 dB HL.

### 4.2.2 Neurocognitive Measures

We administered the Stroop test to assess inhibitory control (Moberly et al., 2016; Stroop, 1935), Raven's Progressive Matrices to assess nonverbal reasoning (Mattingly et al., 2018; Moberly et al., 2018; Raven et al., 1998), and Visual Digit Span Test (Wechsler, 2004) to assess working memory. For the Stroop test, we used an iPad application found here: https://www.encephalapp.com, which was first developed to assess patients with encephalopathy (Bajaj et al., 2015). For Raven's Progressive Matrices, we used Raven's Progressive Matrices 2, Clinical Edition found here: https://www.pearsonassessments.com/store/usassessments/en/Store/Professional-Assessments/Cognition-%26-Neuro/Non-Verbal-Ability/Raven%27s-Progressive-Matrices-

%7C-Clinical-Edition/p/100001960.html (Raven, Rust, Chan, & Zhou, 2018). Raven's Progressive Matrices was administered on the iPad via the Pearson online assessment portal. For the Visual Digit Span task we used an iPad application found here: https://apps.apple.com/us/app/sequencetrainer/id976855592 (Origami Tesseract, 2016). In addition to these short, publicly available neurocognitive measures, we also administered the NIH Toolbox Cognition battery, which measures executive function, episodic memory, language, processing speed, working memory, and attention (Heaton et al., 2014). All sections of the NIH Toolbox Cognition battery provided written instructions for each task.

### 4.2.3 Electrode Placement

To assess electrode placement, we analyzed the patient's post-operative computerized tomography (CT) scan to determine electrode array location using methods proposed by Noble and colleagues (e.g., Noble et al., 2013). From this scan, we were able to determine scalar location, electrode-to-modiolus distance, and angular insertion depth.

### 4.2.4 Statistical Analyses

Results were described using descriptive statistics. The effect of these exploratory factors on baseline measures and change in CI use were explored in post-hoc analyses using non-parametric correlations and t-tests; however, the current study is not adequately powered to draw firm conclusions from the exploratory factors.

## 4.3 Results

### 4.3.1 CI Programming

Aided detection was assessed in all 20 participants. Detection thresholds ranged from 10 to 40 dB HL. 50% of participants had no more than one threshold outside of the desirable range (15-25 dB HL). CNC word recognition scores at baseline were not significantly different between the group of participants who had appropriate aided detection and those who did not (U = 43.5, p = 0.653, r = 0.01).

ESRTs were attempted in all 20 participants. ERSTs were obtained in 14 out of 20 (70%) participants. Of those 14 participants, 9 participants' upper stimulation levels were assigned a pass rating for programming of upper stimulation levels based on ESRTs as described above. CNC word recognition scores at baseline were not significantly different between the group of participants who had appropriate upper stimulation levels and those who did not (U = 28.5, p = 0.142, r = 0.33).

### 4.3.2 Electrode Placement

A CT scan was obtained for 13 out of 20 (70%) participants. Four participants declined the scan, and the scanner was unavailable during three of the participants' study visits. Three patients had 2 extracochlear electrodes which were appropriately deactivated. Three electrode arrays translocated from ST to SV. The mean distance to modiolus was 0.72 (Range = 0.2 – 1.31). The mean angular depth of insertion was 374.8 degrees (Range = 231.8 – 477.6). We did not observe a significant correlation between CNC scores and mean distance to modiolus or mean angular depth of insertion (CNC vs. distance to modiolus: $r_s = 0.01$, p = .967; CNC vs. angular depth of insertion: $r_s = 0.16$, p = .654).

### 4.3.3 Neurocognitive Measures

Table 6. Neurocognitive measures individual and average scores

| Participant | Stroop On Time (ms) | Visual Digit Span (Points) | Raven's Progressive Matrices (Standard Score) |
|---|---|---|---|
| 1 | 129.1 | 260 | 92 |
| 2 | 81.6 | 452 | 100 |
| 3 | 76.0 | 197 | 66 |
| 4 | 57.0 | 175 | 104 |
| 5 | 70.3 | 190 | 80 |
| 6 | 60.1 | 233 | 90 |
| 7 | 67.3 | 344 | 92 |
| 8 | 67.9 | 465 | 111 |
| 9 | 75.5 | 360 | 104 |
| 10 | 72.5 | 476 | 92 |
| 11 | 77.5 | 165 | 97 |
| 12 | 112.9 | 140 | 108 |
| 13 | 101.2 | 381 | 122 |
| 14 | 100.4 | 276 | 75 |
| 15 | 80.7 | 365 | 89 |
| 16 | 98.2 | 163 | 91 |
| 17 | 127.3 | 55 | 111 |
| 18 | 102.3 | 358 | 94 |
| 19 | 104.0 | 338 | 92 |
| 20 | 92.0 | 190 | 93 |
| Average | 87.7 | 279 | 95 |

All twenty participants completed the Stoop test, Visual Digit Span, Raven's Progressive Matrices, and the NIH Toolbox Cognition Battery. Individual data are shown in Table 6 and 7. Spearman's correlation analyses were used to explore relationships between neurocognitive measures and measures of speech recognition, change in speech recognition, spectral processing, change in spectral processing, daily CI use, and change in daily CI use. The only significant finding was correlations between the Stroop score and all measures of speech recognition (CNC: $r_s = -0.61$, $p = 0.005$; AzBio: $r_s = -0.50$, $p = 0.026$; AzBio in Noise: $r_s = -0.65$, $p = 0.002$).

Table 7. NIH Toolbox Cognitive Battery individual and average age-corrected standard scores

| Participant | Picture Vocabulary Test | Flanker Inhibitory Control & Attention Test | List Sorting Working Memory Test | Dimensional Change Card Sort Test Age | Pattern Comparison Processing Speed Test | Picture Sequence Memory Test | Oral Reading Recognition | Cognition Fluid Composite | Cognition Crystalized Composite | Cognition Total Composite Score | Cognition Early Childhood Composite |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 111 | 75 | 88 | 81 | 61 | 88 | 99 | 68 | 105 | 84 | 84 |
| 2 | 112 | 88 | 81 | 88 | 88 | 94 | 123 | 81 | 119 | 100 | 93 |
| 3 | 74 | 79 | 91 | 90 | 96 | 92 | 90 | 84 | 80 | 79 | 76 |
| 4 | 70 | 72 | 76 | 93 | 128 | 74 | 84 | 83 | 75 | 76 | 68 |
| 5 | 81 | 74 | 80 | 54 | 89 | 82 | 89 | 64 | 84 | 70 | 61 |
| 6 | 110 | 79 | 107 | 102 | 72 | 125 | 121 | 96 | 117 | 107 | 106 |
| 7 | 112 | 96 | 124 | 123 | 104 | 103 | 113 | 115 | 113 | 116 | 112 |
| 8 | 118 | 193 | 115 | 198 | 68 | 109 | 117 | 100 | 119 | 111 | 113 |
| 9 | 91 | 81 | 88 | 79 | 98 | 99 | 84 | 80 | 86 | 80 | 78 |
| 10 | 73 | 66 | 72 | 87 | 99 | 68 | 94 | 92 | 88 | 93 | 82 |
| 11 | 103 | 103 | 95 | 103 | 103 | 97 | 110 | 100 | 107 | 104 | 102 |
| 12 | 111 | 75 | 93 | 88 | 81 | 100 | 104 | 81 | 108 | 94 | 91 |
| 13 | 116 | 108 | 146 | 142 | 146 | 133 | 137 | 146 | 129 | 146 | 135 |
| 14 | 102 | 86 | 115 | 106 | 93 | 92 | 108 | 98 | 106 | 102 | 95 |
| 15 | 79 | 95 | 94 | 122 | 89 | 90 | 118 | 97 | 98 | 97 | 95 |
| 16 | 102 | 86 | 115 | 106 | 93 | 92 | 108 | 98 | 106 | 102 | 95 |
| 17 | 102 | 82 | 82 | 82 | 96 | 76 | 86 | 75 | 93 | 82 | 79 |
| 18 | 93 | 97 | 115 | 113 | 119 | 104 | 112 | 114 | 102 | 109 | 102 |
| 19 | 106 | 94 | 117 | 109 | 75 | 95 | 113 | 97 | 110 | 104 | 101 |
| 20 | 106 | 101 | 105 | 116 | 146 | 88 | 104 | 122 | 105 | 116 | 104 |
| Average | 99 | 92 | 100 | 104 | 97 | 95 | 106 | 95 | 103 | 99 | 94 |

## 4.4 Discussion

The primary aim of this chapter was to explore relationships amongst commonly studied variables thought to affect CI outcomes (CI programming, neurocognitive measures, and electrode placement) and the data described in the previous chapter (daily CI use, speech recognition, and spectral processing). Given the small sample size, firm conclusions cannot be drawn from the analyses in this chapter; rather, these descriptive data are intended to spawn future, adequately powered studies.

Exploratory analyses showed only one significant and consistent finding. The Stroop score was found to be significantly correlated with CNC word recognition, AzBio sentence recognition, and AzBio sentence in noise recognition with a large effect size for all three measures. Although multiple comparisons were used in our exploratory analyses, it is reasonable to speculate that the relationship between the Stroop score and speech recognition measures is accurate given that it is present and robust for all three measures. This finding is also corroborated by Moberly and Reed (2019) who found the Stroop test to be the only significant predictor of meaningful sentences; Visual Digit Span and Raven's Progressive Matrices were not significant predictors. The Stoop test evaluates inhibitory control, or the ability of an individual to suppress information in favor of different information. One explanation for the relationship between the Stroop test and speech recognition is related to semantic context. Participants who are better able to suppress incorrect lexical competitors may be better at resolving semantic confusions by capitalizing on semantic context (Moberly & Reed, 2019).

Working memory as measured via the visual digit span test was not found to be significantly correlated with any other measures in our data exploration. This finding is supported by previous studies in CI users (Moberly, Harris, Boyce, & Nittrouer, 2017; Moberly et al., 2016; Moberly & Reed, 2019) and inconsistent with others (Akeroyd, 2008; Rönnberg et al., 2013). Some consider forward digit span to be an assessment of short-term memory instead of working memory because the processing required for a forward digit span test is minimal (Moberly & Reed, 2019); however, we also did not observe a correlation with the working memory subtest of the NIH toolbox cognition battery either, which requires more mental manipulation than the forward digit span test. The relationship between working memory and speech recognition remains unclear.

To our knowledge, this is the first report of NIH Toolbox Cognition Battery results in CI recipients. All 20 participants were able to complete the battery demonstrating feasibility of use in this population. The first sub-test of the battery, Picture Vocabulary Test, requires participants to choose a picture most closely associated with a vocabulary word. The word is not presented visually, so there was some concern that participants may not be able to complete the task if they were unable to hear the word accurately. Participants are able to repeat the word as many times as necessary within the task screen. For the purposes of our study, we invited participants to ask for clarification of the pronunciation of the word if needed; however, no participants required clarification. Average, age-corrected standard scores shown in Table 7 are within one standard deviation of 100 suggesting that our cohort performed similarly to typical hearing peers. These findings suggest that the NIH Toolbox Cognition Battery may be an efficient measure of executive function, episodic memory, language, processing speed, working memory, and attention for CI users that will work toward NIH's goal of standardizing neurocognitive assessments across labs.

Given the small sample size available for exploratory analyses, it is challenging to draw conclusions regarding CI programming and electrode array placement. We did not observe any differences for participants programmed with appropriate aided detection levels and upper stimulation levels compared to those who were not. Prior literature is relatively conclusive that these factors are important for CI outcomes (Davidson et al., 2010; Holden et al., 2013), so this null finding can likely be attributed to sampling. We also did not observe any correlations amongst our data and electrode location information. Given that only 13 subjects obtained CT scans, and participants used different electrode arrays, this null finding is not surprising.

### 4.4.1 Application & Future Directions

The NIH Toolbox Cognition battery was easy to administer, score, and interpret, and our results demonstrate that it is feasible to administer in individuals with hearing loss. In an effort to standardize neurocognitive measurements across labs, it would be reasonable to use the NIH Toolbox Cognition Battery in place of the Montreal Cognitive Assessment (MOCA) or the

Hearing Impaired MOCA to evaluate executive function, episodic memory, language, processing speed, working memory, and attention.

The Stroop test was also easy to administer, score, and interpret using a recently created iPad application. It provides only written instructions, and it does not require any additional instruction on the part of the researcher or clinician. Given that the Stroop test was the cognitive measure most closely associated with outcomes based on our data and others, it may provide additional insight to administer this clinically with CI patients to help guide expectations for speech recognition outcomes. Patient scores and demographics can be entered in the application to compare against age-normative data.

The findings discussed in the previous chapter suggest that daily CI use directly affects speech recognition outcomes. Given the variability in wear time observed amongst adult CI users, we must consider how daily wear time interacts with other factors thought to influence speech recognition outcomes in an adequately powered, systematic way. Especially in intervention studies, such as studying a new programming strategy for example, daily CI use should be controlled.

# CHAPTER 5

# THE COCHLEAR IMPLANT USE QUESTIONNAIRE: ASSESSING HABITS AND BARRIERS TO USE

## 5.1 Introduction

Cochlear implant (CI) devices have successfully improved speech recognition and communication abilities for many years, yet recipients continue to demonstrate high variability in outcomes. Understanding this variability continues to be of interest clinically and in the CI literature as a clearer understanding of this variability can support interventions to optimize outcomes for CI users. Historically, major factors of consideration have included duration of deafness, etiology, age, spiral ganglion cell count, electrode position, programming, electrode type and manufacturer, surgical technique, aural rehabilitation, etc. More recently, daily CI use, or the average number of hours a recipient uses their external CI processor per day, has been added to the list of factors thought to contribute to variability in speech recognition outcomes (Busch et al., 2017, 2020; Easwar et al., 2018; Glaubitz, Liebscher, & Hoppe, 2020; Holder et al., 2019; Schvartz-Leyzac et al., 2019; Sparreboom et al., 2016; Wiseman & Warner-Czyz, 2018).

Data logging has been a feature in hearing aids for over a decade, but it is a newer feature to CIs (first released with the Cochlear Nucleus 6 in 2013). Data logging in the CI software allows for objective calculation of the number of hours per day that the CI processor is on and connected to the internal device. Unlike hearing aids, removal of the CI processor leads to loss of access to spoken communication for most. Despite this, there is significant variability in average daily CI use in the adult population, ranging from 0 to 24 hours per day with an average of about

10 hours per day (Busch et al., 2017; Holder et al., 2019; Schvartz-Leyzac et al., 2019). Clinical recommendations are to use the CI processor "all day" or "during all waking hours," but these data suggest that adult recipients are wearing their devices much less. In addition to these findings, it is also of significance to audiologists, surgeons, healthcare payers, and perhaps the general public that CI recipients are making use of and receiving benefit from an expensive, surgically implanted device. Without use of the external processor, the surgically implanted device is rendered useless.

Several groups have already studied average daily CI use with data logging in pediatric CI recipients and have concluded that consistent use of the external CI processor optimizes speech and language outcomes (Busch et al., 2020; Easwar et al., 2016, 2018; Gagnon, Eskridge, & Brown, 2020; Glaubitz et al., 2020; Guerzoni & Cuda, 2017). Two studies have shown a similar trend in adult CI recipients. Schvartz-Leyzac and colleagues (2019) and Holder and colleagues (2019) demonstrated a moderate to strong correlation ($r_s = 0.43 – 0.61$) between average daily CI use and speech recognition outcomes in adult recipients. This correlational data suggest that daily CI use may account for a significant portion of the variability in speech recognition outcomes in adult CI recipients.

Given the variability in daily CI use and the emerging literature suggesting this variability is related to speech recognition outcomes, daily CI use is of important clinical interest. Identifying reasons people use or do not use their CI and barriers to using it more is critical to understanding and addressing this variability. To our knowledge, a questionnaire aimed at assessing habits and barriers to daily CI use does not yet exist. Therefore, we created a questionnaire to probe daily routines and barriers to daily CI use in a quantitative and qualitative manner. Formulation of the questionnaire was based on the Information-Motivation-Behavioral skills (IMB) model of adherence (Fisher, Fisher, Amico, & Harman, 2006).

The IMB is a theory-based model for identifying factors that contribute to successful medication adherence (K. R. Amico, Toro-Alfonso, & Fisher, 2005; Mayberry & Osborn, 2014), which we applied to understand CI device use adherence (Figure 7). The IMB model of adherence asserts that adherence behavior is a function of the extent to which the patient is informed about the recommendation, motivated to adhere, and has the requisite skills and self-efficacy to adhere to the recommendation (K. R. Amico et al., 2005; K. Rivet Amico et al., 2009; Mayberry & Osborn, 2014; Starace, Massa, Amico, & Fisher, 2006). Adherence information includes accurate knowledge about wearing the CI processor (i.e., how and when to put the processor on and take it off), potential side effects of wearing the processor (i.e., headaches, fatigue, loudness, ear pain), and accurate theories that support consistent adherence (as opposed to inaccurate heuristics such as “I only have to wear my processor when I want to hear.”) (K. R. Amico et al., 2005; K. Rivet Amico et al., 2009; Mayberry & Osborn, 2014; Starace et al., 2006). Adherence motivation refers to the patient’s personal and social motivation to adhere. Personal motivation to adhere is consistent with a patient’s attitudes about adherence and is rooted in one’s beliefs that wearing the CI processor is helpful and not wearing the CI processor would produce undesirable outcomes. Social motivation to adhere reflects one’s experience of social norms regarding adherence and their social support for adherence. Lastly, adherence behavioral skills include one’s objective and perceived abilities to manage functional CI equipment in different situations despite difficulties (Fisher et al., 2006). Applications of IMB models have resulted in successful, data-driven interventions for improving medication adherence for patients with HIV and diabetes (K. Rivet Amico et al., 2009; Mannheimer et al., 2006; Nelson et al., 2020).

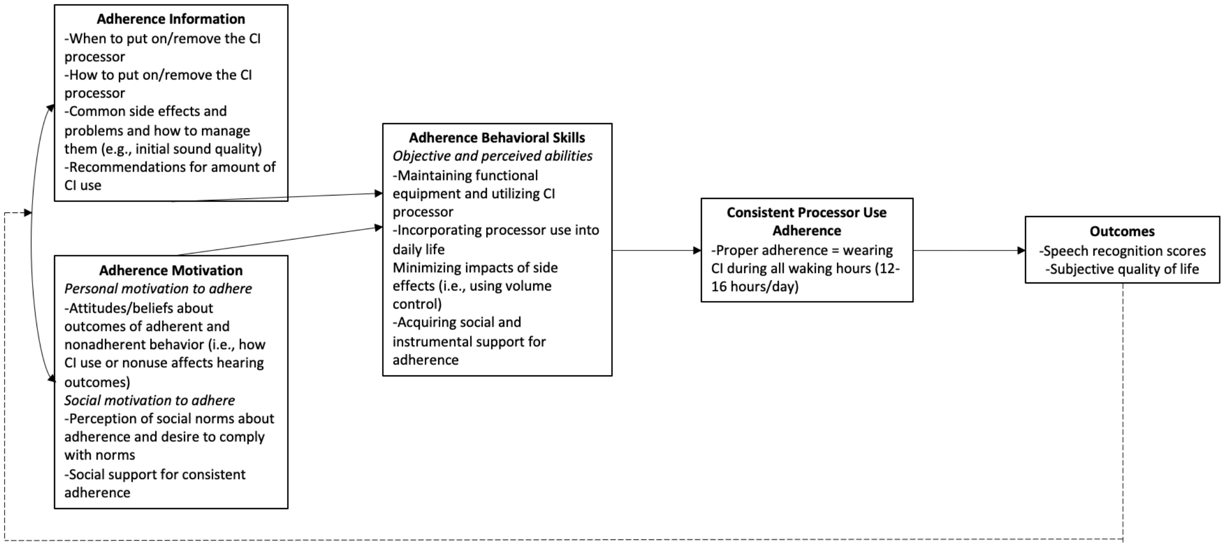


Figure 7. An IMB model of cochlear implant processor use adherence, adapted from Fisher et al. (Fisher et al., 2006), Amico et al. (K. R. Amico et al., 2005), and Mayberry & Osborn (Mayberry & Osborn, 2014). Solid lines indicate effects between IMB components and desired adherence, and the dashed line shows a feedback loop in which the outcomes affect future adherence information and motivation.

The purpose of the current study was to: 1) design a questionnaire aimed at identifying daily CI use habits and barriers to daily CI use using the IMB model; and 2) administer this questionnaire to adult CI users with varying degrees of daily CI use to determine construct validity. We hypothesized that recipients who reported a greater number of barriers to daily CI use would show lower daily CI use.

## 5.2 Research Design and Methods

The design and methods of this study were approved by the Vanderbilt Institutional Review Board (IRB# 200807). Participants were recruited from the Vanderbilt University Medical Center CI patient pool. Participants were invited via email to complete online informed consent for the study team to access their CI programming software and electronic medical record and finish the questionnaire online via REDCap. Responses were obtained May 2020 through October 2020. We collected data from consenting participants' medical record or CI programming software retrospectively. In total, 100 adult CI recipients provided responses to the questionnaire. The mean age of the sample was 61.6 years (SD = 15.9) and ranged from 18 to 87 years. Exclusion criteria included less than 18 years of age, prelingual onset of deafness, and incomplete questionnaire response.

Table 8. Participant characteristics; CI = cochlear implant.

| Participants | N = 100 |
|---|---|
| Sex | Male = 55, Female = 45 |
| Age (years) | Mean = 61.6, SD = 15.9, Range = 18-87 |
| CI Manufacturer | Advanced Bionics = 29, Cochlear = 39, Med-El = 12 |
| Hearing Device Configuration | Bilateral CI = 27, Bimodal = 58, Unilateral CI = 15 |
| Living Situation | Alone = 15, With Someone = 85 |
| Employment | Retired = 58, Full-time = 31, Part-time = 11 |
| Average data logging from software (hours/day) | Mean = 10.4, SD = 3.7, Range = 0.5-15.2 |
| Average participant reported CI use (hours/day) | Mean = 13.0, SD = 3.3, Range = 2.5-24 |

### 5.2.1 Questionnaire Design

First, clinical audiologists were asked to provide a list of most commonly reported barriers to CI use. Responses were compiled from six clinical audiologists. Items were then created based off of these responses and mapped onto the IMB model. Additional items that aligned with the IMB model constructs were also added following consultation with IMB model expert (author LSM). The questionnaire was piloted with ten CI recipients. Pilot participants were asked to provide feedback on the questions to ensure that the questions were clear, and they were also asked to suggest additional barriers to CI use that we had not previously considered. Following this pilot, the wording of two questions was amended, but no questions were added or deleted. This process established the face validity and content validity for the measure. The finalized items were compiled to form the Cochlear Implant Use Questionnaire (CIUQ). The CIUQ and accompanying instructions had a Flesch readability score of 68.7 (standard/average) and a Flesch-Kincaid grade level of 5.9.

The CIUQ consists of two sections. The first section probes the following: employment status, living situation, time of day they put the CI on, time of day they take the CI off, activities for which they remove their CI, number of hours per day they think they wear their CI, their surgeon/audiologist's recommendation for how often they should wear their CI processor, and any additional information they would like to share about their daily CI use habits. The second section contains quantitative questions that probe specific barriers to daily CI use using a five point scale in which the choices consist of: never, rarely, sometimes, often, or always. The participants were instructed to, "think about your daily life with your cochlear implant(s) and answer how often each statement applies to your feelings and experiences." The questions covered the following categories: equipment management, motivation to hear, social support, social norms, listening fatigue, hearing benefit, sound quality, hearing configuration, ear/head pain, and alternate forms of communication. See Table 9 and Appendix for specific questions. The quantitative question responses were assigned a value from 0-4 and reverse scored when necessary. Responses were added together for a total between 0 and 100 such that a higher total corresponded to a greater number of reported barriers to CI use.

Construct validity refers to the extent to which a test or tool actually measures what it intends to measure (Messick, 1995). We evaluated the construct validity of the quantitative portion of the CIUQ using a correlation analysis between total questionnaire score and CI use assessed with data logging. A significant negative correlation between these two measures would provide evidence of construct validity. If the CIUQ is valid, patients who report a low number of barriers to CI use should, in theory, wear their CI processor more consistently (higher data logging), and patients who report a high number of barriers to CI use should, in theory, wear their CI processor less consistently (lower data logging).

### 5.2.2 Demographic and data logging data collection

We collected participants' age, sex, hours of CI use per day, and listening configuration (i.e., unilateral, bilateral, bimodal). Data logging data were extracted from the CI programming software. The data logging value closest to the time of questionnaire completion was recorded for each participant. Audiology reports were also reviewed to ensure data logging accuracy for patients utilizing more than one processor. Specifically, if patients used more than one processor, the data logging from each processor was added together. Data logging information could not be included for patients utilizing equipment that did not support data logging such as bilaterally initialized Advanced Bionics Naida CI users, Advanced Bionics Harmony and Neptune users, Cochlear Nucleus 5 users, and MED-EL Rondo and Opus 2 users. 78 of the 100 participants had data logging information available.

## 5.3 Results

### 5.3.1 Cochlear Implant Use Questionnaire Items

The average total score for the quantitative section of the CIUQ was 23.3 (SD = 11.3), and total scores ranged from 3 to 54 (possible range 0 to 100). Table 9 shows the percentage of respondents who provided a response other than “never” for the barriers (or “always” if the item was reverse scored) for each item and the mean and standard deviation for responses to each question.

Table 9. Cochlear Implant Use Questionnaire items (N = 100). Percentage refers to the percent of participants who provided a response other than “never” (or “always” if the item was reverse scored) to each item. Asterisk indicates that the item was reverse scored such that a higher number is consistent with greater barrier to cochlear implant use.

| Questionnaire Item | IMB Model Distinction | Participants reporting as a barrier (%) | Average score, 0 = “never” to 4 = “always” (Mean ± SD) |
|---|---|---|---|
| 1. When my cochlear implant processor battery dies, I have a backup battery with me.* | Behavioral Skills | 36% | 0.7 ± 1.1 |
| 2. It is important that I hear my best at all times.* | Motivation | 32% | 0.4 ± 0.6 |
| 3. When I take my cochlear implant processor off, I enjoy the silence. | Motivation | 93% | 2.2 ± 1.1 |
| 4. I take my cochlear implant processor off when I am home alone. | Information | 75% | 1.5 ± 1.2 |
| 5. I get so exhausted from listening that I want to take my cochlear implant processor off. | Motivation | 68% | 1.3 ± 1.1 |
| 6. When sounds are annoying, I take my cochlear implant processor off. | Behavioral Skills | 76% | 1.5 ± 1.0 |
| 7. If I am sick or do not feel well, I do not like to wear my cochlear implant processor. | Motivation | 78% | 1.6 ± 1.2 |
| 8. I do not see the purpose of wearing my cochlear implant processor because it does not benefit my hearing ability. | Motivation | 14% | 0.2 ± 0.6 |
| 9. My cochlear implant processor or processor parts are broken. | Behavioral Skills | 72% | 0.7 ± 0.9 |
| 10. I remove my cochlear implant processor because it is too loud to wear comfortably. | Information | 37% | 0.5 ± 0.7 |
| 11. The sound quality of my cochlear implant discourages me from wearing it. | Motivation | 59% | 0.6 ± 1.0 |
| 12. I can hear and communicate effectively without my cochlear implant processor. | Motivation | 43% | 0.8 ± 1.1 |

| | | | |
|---|---|---|---|
| 13. I tend to remove my cochlear implant processor when I am not communicating. | Information | 37% | 0.7 ± 1.0 |
| 14. It is hard for me to put my cochlear implant processor on. | Behavioral Skills | 18% | 0.2 ± 0.6 |
| 15. I forget to put my cochlear implant processor on. | Behavioral Skills | 37% | 0.5 ± 0.7 |
| 16. It is important that I maximize my results with my cochlear implant.* | Motivation | 21% | 0.4 ± 0.8 |
| 17. I take breaks from wearing my cochlear implant processor because my ear hurts. | Behavioral Skills | 48% | 0.8 ± 0.9 |
| 18. My cochlear implant processor falls off of my ear. | Behavioral Skills | 79% | 1.4 ± 1.0 |
| 19. I look forward to putting my cochlear implant processor on in the morning.* | Motivation | 56% | 1.0 ± 1.1 |
| 20. If I forget to wear my cochlear implant processor, my friends or family members will ask me why I'm not wearing it.* | Motivation | 78% | 2.5 ± 1.6 |
| 21. I take off my cochlear implant processor to avoid getting it wet while exercising or working outside during the summer. | Behavioral Skills | 87% | 2.1 ± 1.3 |
| 22. I don't wear my cochlear implant processor because I'm afraid of what people might think or say about it. | Motivation | 8% | 0.1 ± 0.5 |
| 23. I use alternate forms of communication (Ex. ASL, writing). | Motivation | 47% | 0.8 ± 0.9 |
| 24. My friends and family members think it is important that I wear my cochlear implant processor.* | Motivation | 10% | 0.3 ± 0.8 |
| 25. Wearing my cochlear implant processor gives me a headache. | Information | 23% | 0.7 ± 0.8 |

### 5.3.2 Device Use Habits Questions

Recipients were asked about their employment status. Responses were as follows: 31 respondents worked full-time, 11 respondents worked part-time, and 58 respondents were retired. A Kruskal-Wallis test showed no difference total questionnaire score for employment status (H(3) = 0.155, p = 0.925, r = 0.138). 15 respondents reported that they lived alone, while 85 reported that they lived with someone. Mann Whitney test showed no difference in total questionnaire score between living situation ($U = 389$, $p = 0.168$, $r = 0.248$).

Respondents were asked to recall their surgeon or audiologist's recommendation for how often they should wear their CI processor. Free responses were categorized into three categories: 1) don't remember or no recommendation was made, 2) response was inconsistent with current recommendations (i.e., "5 hours per day," "as much as I want to"), or 3) all waking hours or all day. 43 respondents (43%) reported that they did not remember or no recommendation was made. 14 respondents (14%) provided a response inconsistent with current recommendations. 43 respondents (43%) reported being told to wear it all day or all waking hours.

When asked if they remove their processor for certain activities, 67 respondents (67%) reported that they did. Commonly reported activities for which respondents removed their processor included: sleep/nap, showering, exercise, working outside (heat/sweat), to enjoy silence, and noisy environments (mowing lawn, woodworking).

### 5.3.3 Construct Validity

To assess construct validity, Spearman's rho correlation between the total questionnaire score and the data logging data from the CI software was computed. A significant negative correlation would indicate presence of construct validity. Spearman's correlation between these two measures yielded a large, significant effect size ($r_s = -0.561$, $p < 0.0001$, 95% confidence interval [-0.694, -0.391] (J. Cohen, 1988) suggesting that the questionnaire is valid for its intended purpose (Figure 8).

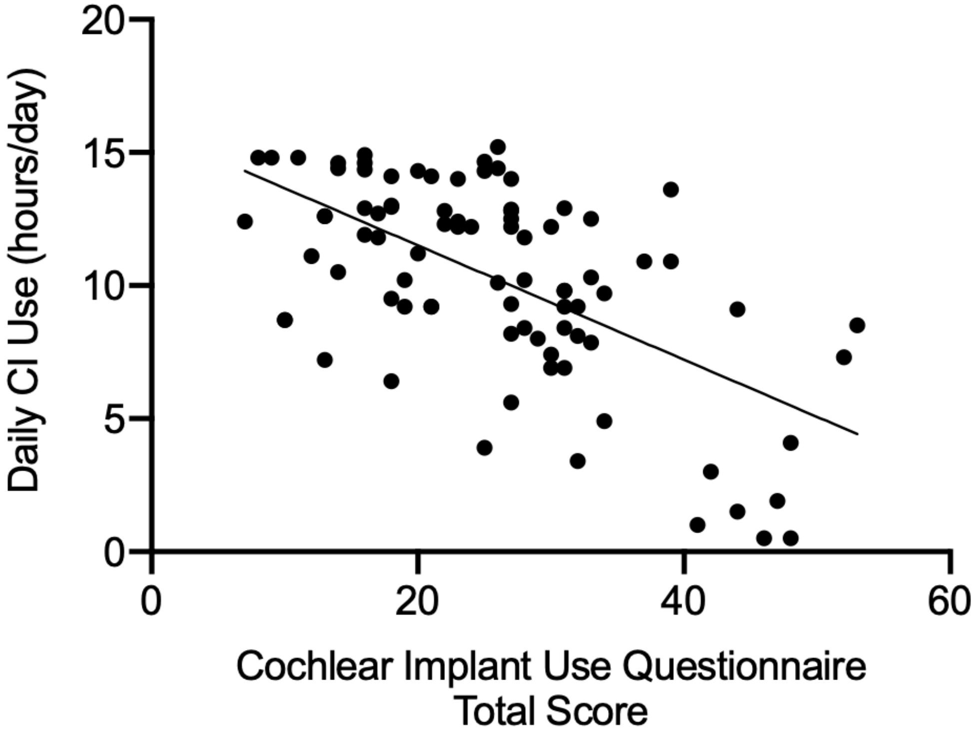


Figure 8. The correlation ($r_s = -0.561$, $p<.0001$) between the total score from the questionnaire and the participants' daily CI use (data logging values mined from the CI software) is shown. This figure demonstrates construct validity of the Cochlear Implant Use Questionnaire (CIUQ).

### 5.3.4 Subjective vs. Objective Data logging

Respondents were asked to report how many hours per day they wear their CI processor. On average, they reported 13.0 hours per day (n = 100, SD = 3.3, range = 2.5 – 24). Objective data logging collected from the software indicated a mean of 10.4 hours per day (n = 78, SD = 3.7, range = 0.5 – 15.2). This difference of 2.6 hours was significant (W = 2387, p < 0.0001, r = 0.857) (Figure 9).

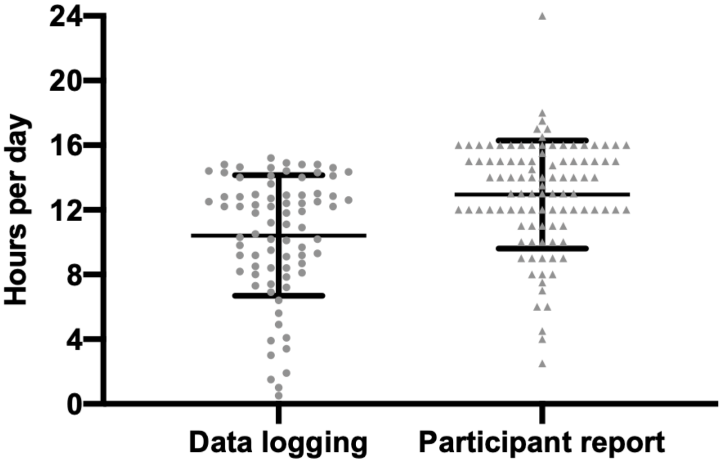


Figure 9. Figure compares subjective and objective daily cochlear implant (CI) use. Individual data are shown for average daily CI use collected from the CI software (data logging) and from a question (participant report) on the Cochlear Implant Use Questionnaire (CIUQ).

## 5.4 Discussion

The purpose of this study was to design a questionnaire aimed at identifying daily CI use habits and barriers to daily CI use and to administer the questionnaire to adult CI users to determine the construct validity of the questionnaire. We developed items based on the IMB model and found them to be items acceptable to CI users. The resulting scale, the CIUQ, had an average overall score of 23.3 and a range of 3 to 54 indicating that responses were quite variable, and CI recipients experience different barriers to using their CI processor. The five statements yielding the highest average response were as follows: “I take off my cochlear implant processor to avoid getting it wet such as while exercising or working outside during the summer;” “If I forget to wear my cochlear implant processor, my friends or family members will ask me why I’m not wearing it;” “When I take my cochlear implant processor(s) off, I enjoy the silence;” “If I am sick or do not feel well, I do not like to wear my cochlear implant processor(s);” “I take my cochlear implant processor off when I am home alone.” The CIUQ showed evidence of construct validity via a significant, large correlation between total score and the recipients’ daily CI use mined from the CI software suggesting that the questionnaire is a valid tool to use for understanding the underlying drivers of daily CI use.

Recipients were asked about their employment and living status (alone or with someone). No significant difference in total questionnaire score was found for these responses; however, two of the most frequently reported questions were related to living/social status ("If I forget to wear my cochlear implant processor, my friends or family members will ask me why I'm not wearing it" and "I take my cochlear implant processor off when I am home alone."). These findings suggest that CI recipients may need additional counseling and/or support from family members or friends to ensure that they are wearing their CI during all waking hours. Previous studies of adherence to medical recommendations such as diabetes have also shown that social support contributed to adherence (e.g., Mayberry, Berg, Greevy, & Wallston, 2019; Sherbourne, Hays, Ordway, DiMatteo, & Kravitz, 1992).

Respondents were asked to recall their surgeon or audiologist's recommendation for how many hours per day they should be wearing their CI processor. Nearly half of the respondents (43%) reported that they were never provided a recommendation, or they could not recall a recommendation. While we do not yet have a data-driven recommendation for exactly how long recipients should wear their CI processor daily, our clinicians recommend wearing their CI processor all the time except when showering or sleeping. This finding coupled with an average data logging value of 10.4 suggests that the importance of use during all waking hours (~15 hours per day) is not being communicated effectively. Clinicians may wish to provide this recommendation in writing and/or reiterate this recommendation at follow-up visits to improve patient retention of this recommendation.

67% of respondents reported removing their CI processor for certain activities such as exercising, working outside, napping, enjoying silence, or when environmental noise is too loud. Removing the processor for these activities contributes to lower daily average CI use. CI recipients may be unaware of  potential solutions that could be implemented to keep them on the air during these activities. The CIUQ may allow clinicians to identify and address these activities via accessories such as a waterproof case to use while exercising if the patient is concerned about sweat harming the processor or a remote control to reduce the volume when environmental noise is too loud. During the collection of these data, anecdotally, we noticed that patients had forgotten about some of the solutions available to them because they had not been reviewed since their initial order form was submitted. They had coped with some of the challenges they experience by just removing their processor rather than potentially utilizing an available accessory. We found that the questions directly posed in the CIUQ helped bring these challenges to light, when otherwise they may have not been shared.

Respondents reported that they wore their CI processor 13 hours per day on average compared to 10.4 hours per day measured by data logging in the CI software. 10.4 hours per day is in line with previous average data logging reports in adult CI users (Busch et al., 2017; Holder et al., 2019; Schvartz-Leyzac et al., 2019). This finding suggests that CI recipients overestimate how consistently they wear their CI processor, which is in agreement with previous reports in hearing aid users (Laplante-Lévesque, Nielsen, Jensen, & Naylor, 2014; Muñoz et al., 2015; Walker et al., 2013). Subjective versus objective daily CI use has not been previously compared in the literature to our knowledge. Given this finding, audiologists may wish to review data logging with their patients at follow-up visits to allow patients to accurately monitor their daily use. CI manufacturers have begun to implement data logging in patient-accessible phone applications. Currently only “time in speech” is reported in such applications, but perhaps future iterations could give patients access to average CI use per day to allow them to monitor their own usage similar to a fitness tracker.

During data collection, we anecdotally noted several ways the CIUQ was able to identify fixable barriers to more consistent CI use for patients. One respondent, when asked about headaches in item number 25, reported that she removed her processor due to pain between the external and internal magnet. This challenge was easily resolved by reducing the external magnet strength. Another patient reported that her only rechargeable battery lasted 4 hours per charge, so if it dies at work, she didn’t have a replacement. She had not asked about a replacement battery because she could not afford it, but the questionnaire prompted us to identify the challenge and seek new batteries for her through her insurance. Yet another respondent reported that she often removes her processor because she is afraid it will fall off and get damaged. Item 18 allowed us to address this challenge by ordering her an accessory to support retention of the external processor. In these three examples, the respondents had been implanted for over a year, and they had completed at least five CI appointments with their audiologist; however, only when they completed this questionnaire were these concerns brought to light. Clinicians may consider administering the CIUQ to recipients with low data logging to explore potential barriers to CI use that may be driving inconsistent processor use. In our experience, we were able to uncover otherwise unknown barriers, which were easily addressed, to support patients’ consistent processor use.

## 5.5 Conclusion

The CIUQ is a newly developed tool to measure CI use habits and barriers to daily CI use. It is quick and easy to administer, and it shows evidence of construct validity via a significant correlation with daily CI use. Increasing evidence suggests that daily CI use is correlated with speech recognition outcomes. In order to optimize outcomes, clinicians should consider implementing this questionnaire to identify and overcome barriers to consistent, full-time CI processor use.

## 5.6 Appendix

*Cochlear Implant Use Questionnaire (CIUQ)*

1. Do you work? Full-time Part-time Retired
2. Do you live alone or with someone? _________
3. When do you put your cochlear implant processor on for the day? Time: ________
Further explanation (please explain if it varies day to day): _____________________
4. When do you take your cochlear implant processor off for the day? Time: ________
Further explanation (please explain if it varies day to day): _____________________
5. Do you routinely take off your processor for certain activities (ex. nap, exercise)? Yes / No
Further explanation (please explain if it varies day to day): _____________________
6. How many hours per day do you wear your cochlear implant processor? Hours per day: ________. Further explanation (please explain if it varies day to day): _____________________
7. What was your surgeon/audiologist’s recommendation for how often you should wear your cochlear implant processor? _____________________
8. Is there anything else you would like us to know about your cochlear implant processor use habits? _____________________

Instructions: Think about your daily life with your cochlear implant. Answer how often each of the following statements applies to your feelings and experiences.

| | Never (0) | Rarely (1) | Sometimes (2) | Often (3) | Always (4) |
|---|---|---|---|---|---|
| 1. When my cochlear implant processor battery dies, I have a backup battery with me.* | | | | | |
| 2. It is important that I hear my best at all times.* | | | | | |
| 3. When I take my cochlear implant processor off, I enjoy the silence. | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| 4. I take my cochlear implant processor off when I am home alone. | | | | | |
| 5. I get so exhausted from listening that I want to take my cochlear implant processor off. | | | | | |
| 6. When sounds are annoying, I take my cochlear implant processor off. | | | | | |
| 7. If I am sick or do not feel well, I do not like to wear my cochlear implant processor. | | | | | |
| 8. I do not see the purpose of wearing my cochlear implant processor because it does not benefit my hearing ability. | | | | | |
| 9. My cochlear implant processor or processor parts are broken. | | | | | |
| 10. I remove my cochlear implant processor because it is too loud to wear comfortably. | | | | | |
| 11. The sound quality of my cochlear implant discourages me from wearing it. | | | | | |
| 12. I can hear and communicate effectively without my cochlear implant processor. | | | | | |
| 13. I tend to remove my cochlear implant processor when I am not communicating. | | | | | |
| 14. It is hard for me to put my cochlear implant processor on. | | | | | |
| 15. I forget to put my cochlear implant processor on. | | | | | |
| 16. It is important that I maximize my results with my cochlear implant.* | | | | | |
| 17. I take breaks from wearing my cochlear implant processor because my ear hurts. | | | | | |
| 18. My cochlear implant processor falls off of my ear. | | | | | |
| 19. I look forward to putting my cochlear implant processor on in the morning.* | | | | | |
| 20. If I forget to wear my cochlear implant processor, my friends or family members will ask me why I’m not wearing it.* | | | | | |
| 21. I take off my cochlear implant processor to avoid getting it wet while exercising or working outside during the summer. | | | | | |
| 22. I don’t wear my cochlear implant processor because I’m afraid of what people might think or say about it. | | | | | |
| 23. I use alternate forms of communication (Ex. ASL, writing). | | | | | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 24. My friends and family members think it is important that I wear my cochlear implant processor.* |  |  |  |  |  |
| 25. Wearing my cochlear implant processor gives me a headache. |  |  |  |  |  |

** Questions with an asterisk (1, 2, 16, 19, 20, & 24) should be reverse scored (i.e., 4 = 0, 3 = 1, 1=3, 0=4)*

# CHAPTER 6

# DISSERTATION CLOSING REMARKS

The primary goal of this project was to investigate the relationship between daily CI use and speech recognition outcomes in postlingually deafened, adult CI recipients. This goal was addressed using four related experiments. The investigation started with experiment 1 (Chapter 2)-- a correlational analyses of daily CI use measured via data logging in the CI software and speech recognition outcomes. The primary finding of this experiment was a strong, significant correlation between daily CI use and CNC word recognition ($r_s = 0.61$, $p < 0.0001$, 95% Confidence Interval [0.54, 0.69]) in a sample of 300 patients. This finding motivated our second experiment (Chapter 3), which aimed to evaluate the causal link between daily CI use and speech recognition measures. Specifically, we aimed to evaluate the impact of increased CI use on speech recognition performance and assess one potential underlying mechanism. The results of the second experiment showed that speech recognition can be improved with more consistent daily CI use. On average, participants' ($n = 20$) speech recognition improved by 3.0-, 2.4-, and 7.0-percentage points per hour of increased use for CNC, AzBio, and AzBio in noise, respectively. The one potential underlying mechanism that we assessed, spectral resolution, accounted for a small amount of variance for one speech recognition measure, CNC words. In experiment 3 (Chapter 4), we explored a number commonly studied factors thought to contribute to CI outcome variability but have not yet been studied in combination with daily CI use: electrode location, neurocognitive measures, and CI programming. This experiment was not adequately powered to draw firm conclusions, but we did see a correlation between a measure of inhibitory control (Stroop test) and all measures of speech recognition. Lastly, in experiment 4 (Chapter 5), we aimed to design a questionnaire to identify daily CI use habits and barriers to daily CI use. The Cochlear Implant Use Questionnaire (CIUQ) was developed and administered to 100 CI recipients. It was immediately useful for identifying and overcoming barriers to CI use with our study participants, and it showed evidence of construct validity via a significant correlation with daily CI use. In summary, this dissertation project discovered a novel correlation between daily CI use and speech recognition in adults, provided evidence that more consistent daily CI use causes improved speech recognition, and created a tool to help patients identify and overcome barriers to more consistent CI use.

The findings from these experiments can be immediately applied in the CI clinic and research lab. The correlation described in Chapter 2 can be used to identify patients with poor data logging and determine if their daily CI use may be restricting their potential speech recognition performance. Especially for patients wearing their CI less than 10 hours per day, the CIUQ described in Chapter 5 may be administered to identify daily CI use habits and potential barriers preventing CI users from wearing their CI processor more consistently. The CIUQ may be used as a counseling tool for audiologists to reduce barriers and create constructive daily CI use habits to support more consistent use. Finally, if barriers to use are reduced and daily CI use is increased, the patient should realize an improvement in speech recognition scores (Chapter 3). In the research realm, daily CI use as measured via data logging should be controlled in all future studies to reduce the impact of wear time on results especially for intervention studies.

Overall, this set of experiments delineated the importance of consistent CI use in the adult population, and it demonstrated that daily CI use is a malleable factor that directly affects speech recognition outcomes in a relatively short amount of time (four weeks). Clinicians can use this evidence combined with the CIUQ to motivate and support patients to achieve their full speech recognition potential. Improved CI use consistency is a cost-effective, accessible intervention that holds great potential for improving outcomes for *all* CI users.

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