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Behavioral Measures of Temporal Processing and Speech Perception in Cochlear Implant Users

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Abstract

Background: While most cochlear implant (CI) users achieve improvements in speech perception, there is still a wide variability in speech perception outcomes. There is a growing body of literature that supports the relationship between individual differences in temporal processing and speech perception performance in CI users. Previous psychophysical studies have emphasized the importance of temporal acuity for overall speech perception performance. Measurement of gap detection thresholds (GDTs) is the most common measure currently used to assess temporal resolution. However most GDT studies completed with CI participants used direct electrical stimulation not acoustic stimulation and they used psychoacoustic research paradigms that are not easy to administer clinically. Therefore it is necessary to determine if the variance in GDTs assessed with clinical measures of temporal processing such as the Randomized Gap Detection Test (RGDT) can be used to explain the variability in speech perception performance.

Purpose: The primary goal of this study was to investigate the relationship between temporal processing and speech perception performance in CI users.

Research Design: A correlational study investigating the relationship between behavioral gap detection thresholds (assessed with the Randomized Gap Detection Test [RGDT] or the Expanded Randomized Gap Detection Test [RGDT-EXP]) and commonly used speech perception measures (assessed with the Speech Recognition Test [SRT], Central Institute for the Deaf W-22 Word Recognition Test [W-22], Consonant-Nucleus-Consonant Test [CNC], Arizona Biomedical Sentence Recognition Test [AzBio], Bamford-Kowal-Bench Speech-in-Noise Test [BKB-SIN]).

Study Sample: Twelve post-lingually deafened adult CI users (24 – 83 years) and ten normal hearing (NH; 22 – 30 years) adults participated in the study.

Data Collection and Analysis: The data were collected in a sound attenuated test booth. After measuring pure-tone thresholds, gap detection thresholds and speech perception performance was measured. The difference in performance between subject groups on the aforementioned tests, as well as the correlation between GDTs and speech perception performance was examined. The

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Author Contributions

Conceived and designed the experiments: FZ, CB, RK. Performed the experiments: CB. Analyzed the data: CB, FZ. Wrote the paper: CB, FZ.

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correlations between subjects' biological factors, performance on the RGDT and speech perception measures were also explored.

Results: Although some CI participants performed as well as the NH listeners, the majority of the CI participants displayed temporal processing impairments (GDTs > 20 ms) and poorer speech perception performance than NH subjects. A statistically significant difference was found between the NH and CI test group in GDTs and some speech tests (SRT, W-22, and BKB-SIN). For the CI group, there were significant correlations between GDTs and some measures of speech perception (CNC – Phoneme, AzBio, BKB-SIN), however no significant correlations were found between biographic factors and GDTs or speech perception performance.

Conclusions: Results support the theory that the variability in temporal acuity in CI users contributes to the variability in speech performance. Results also indicate that it is reasonable to use the clinically available RGDT to identify CI users with temporal processing impairments for further appropriate rehabilitation.

Keywords

Cochlear implant; gap detection; speech perception; temporal processing

INTRODUCTION

A cochlear implant (CI) is a surgically implanted electronic device that does not restore “normal” hearing but provides access to auditory information that aids in speech understanding for individuals with severe to profound hearing loss. As of December 2012, the Food and Drug Administration estimates that approximately 324,200 individuals have received a CI worldwide, 96,000 of which reside in the United States (NIDCD, 2014). Due to technological advancements in speech processing strategies and speech processor and electrode array design, overall speech recognition abilities have steadily improved in recent years. Yet substantial variability in speech perception remains in CI users (Firszt et al, 2002; Donaldson et al, 2009; Holden et al, 2013). A better understanding of this variability is of great importance in patient counseling, guiding the maximization of CI outcomes, and providing insights into the auditory mechanisms underlying speech perception by CI users.

Several investigators state that temporal processing limitations, the ability to process temporal cues of speech, can hinder speech perception through the CI (Tyler et al, 1989; Cazals et al, 1991; Muchnik et al, 1994; Sagi et al, 2009). One aspect of temporal processing is temporal resolution, which is related to the ability to resolve and follow rapid changes in the acoustic spectrum of speech stimuli. Normal temporal resolution is very important for accurate speech understanding, especially in noisy environments (Swaminathan and Heinz, 2012; Picton, 2013). The auditory system uses temporal cues, such as the duration of speech segments and the duration of silent intervals between speech segments, to differentiate various speech sounds (Dorman et al, 1985). The American Speech - Language Hearing Association has emphasized the importance of including temporal resolution assessments in auditory processing test batteries due to its impact on overall speech understanding. For CI users, temporal processing may be of heightened importance since the degraded spectral

information provided by the CI is significantly poorer than what is heard by normal hearing (NH) listeners (Xu et al, 2005; Sagi et al, 2009).

Measurement of gap detection thresholds (GDTs) is one of the most widely used methods to assess temporal resolution in humans (Garadat and Pfingst, 2011; Lister et al, 2011a). The GDT is determined as the shortest silent interval (“gap”) between a pair of stimuli that the individual can detect (i.e., the smallest gap that the participant consistently hears as two stimuli). Since speech encoding requires listeners to accurately separate various speech elements that occur in rapid succession, normal GDTs would be critical to perceive the important speech cues that are coded by temporal gaps (Tyler et al, 1989; Muchnik et al, 1994). Previous studies have linked elevated GDTs to central auditory processing disorders, language delays, and aging-related decrements in temporal processing (Jerger et al, 2002; Smith et al, 2008; Lister et al, 2011b).

In CI users, there are mixed results regarding temporal processing acuity as measured with GDTs. Among these studies, most measured GDTs using electric pulses delivered to the electrode (Shannon, 1989; Garadat and Pfingst, 2011; Bierer et al, 2015), and only a few examined GDTs using acoustic stimuli presented through the CI speech processor (Tyler et al, 1989; Muchnik et al, 1994; Wei et al, 2007). Using acoustic stimuli presented in the soundfield, Wei et al (2007) reported that the average GDT was significantly higher in CI users (ranging from 4 to 128 ms) than in NH listeners. Tyler et al (1989) also reported significantly higher GDTs in CI users than in NH listeners. Using electrode stimulation, Shannon (1989) reported a normal averaged GDT (e.g., 4 ms for loud stimuli) in CI users. Unlike the electric GDT that can only reflect restraints of temporal processing abilities in the auditory pathway, the acoustic GDT reflects both the limitation of CI processing and the limitation of temporal processing abilities of the auditory system (Tyler et al, 1989; Wei et al, 2007). Given that CI users perceive speech that is processed through their speech processor, it is reasonable to evaluate the acoustic GDT and examine how it relates to speech perception.

In addition to the differences in stimulation approach (acoustic vs. electrode), a number of stimulus parameter have also been shown to effect GDTs in CI users such as the intensity, duration, temporal envelopes, similarity of pre- and post-gap frequencies, etc. (Phillips et al, 1997; Schneider and Hamstra, 1999; Pichora-Fuller et al, 2006; Garadat and Pfingst, 2011; Horwitz et al, 2011). The discrepancies in the literature regarding GDTs in CI users may be partially caused by the variety of stimulus parameters used in those studies.

Due the aforementioned factors and the difference in speech materials used across studies, reports of the correlation between GDT and speech perception contain mixed results in post-lingually deafened adult CI users. For instance, Muchnik et al (1994) displayed the trend that CI users with open set speech recognition tend to have lower acoustic GDTs than those without. Tyler et al (1989) reported that individuals with acoustic GDTs less than 40 ms showed a wide range of performance on speech perception measures whereas patients with GDTs greater than 40 ms showed poor speech recognition. Wei et al (2007) reported that the GDT is weakly correlated with tone recognition. Nonetheless, several researchers found no correlation between electric GDTs and speech performance (Shannon, 1989).

All studies in the literature that evaluate behavioral GDTs in CI users, use a psychoacoustic measure that is not feasible to administer clinically due to time restrictions, software, and hardware requirements. Therefore, it is important to determine if a clinically available measure of temporal resolution, such as the Randomized Gap Detection Test (RGDT), provides results that are comparable to those obtained using an extensive research psychoacoustic test paradigm. The RGDT has been extensively used for the diagnosis of auditory processing disorder in previous studies (Jerger et al, 2002; Chermak and Lee, 2005; Queiroz et al, 2010; Iliadou et al, 2014) but has minimal use in the CI population (Zhang et al, 2013)

The purposes of the present study were to: 1) measure temporal resolution in CI users with the RGDT; 2) evaluate the relationship between GDTs and speech performance on commonly used speech recognition materials for CI users. The results presented below contribute to the existing literature regarding the temporal processing abilities of CI users. In addition, the results can provide important information to help improve speech processor coding strategies and post implantation rehabilitation diagnostic tools.

MATERIALS AND METHODS

Ethics

The research protocol was approved by the Institutional Review Board of the University of Cincinnati. Subjects were required to provide informed consent before testing and were paid for participation.

Participants

Twelve post-lingually deafened (four males and eight females, age range: 24–83 years, mean: 57 years) adult CI users participated in the study; five were bilaterally implanted for a total of seventeen ears tested. Post-lingually deafened was defined as the onset of severe-to-profound hearing loss in both ears occurring after three years of age. All CI participants were implanted with a Cochlear Nucleus Implant System (Cochlear Americas), had at least twelve months of experience with their device, and were recruited through the Department of Otolaryngology at the University of Cincinnati. CI participant biographic, device, and processing strategy information is shown in Table 1.

Ten NH adults (one male and nine females, age range: 22–30 years, mean: 24 years) participated in the study as controls for the CI data. NH hearing subjects had audiometric hearing thresholds ≤ 20 dB HL at octave test frequencies from 0.25 to 8 kHz, type A tympanometry, acoustic reflex thresholds (0.5, 1, 2 kHz) within normal limits. All NH and CI participants were native speakers of American English and used an oral mode of communication. No participants had any neurological/psychological disease or serious medical condition per participant report.

Procedures

The speech perception tests and the RGDT were presented in a double-walled sound attenuating booth. For CI users, stimuli were presented through a single speaker positioned

at 0 degrees azimuth, 1 meter from the participant at ear level. Stimuli were presented via ER-3A insert earphones for NH participants. Monaural stimulation was used for both CI participants and NH participants (right ear). An E-A-R disposable foam ear plug was inserted into the non-test ear for NH participants and unilaterally implanted CI participants. For bilaterally implanted CI participants, each ear was tested individually with the non-test ear speech processor removed. CI participants were tested using their typical everyday speech processor settings (program, volume, and sensitivity) and were instructed to adjust the volume as needed. The stimuli for both the NH and CI participants were presented at an intensity level of 7 on a 0–10 point scale (0: inaudible; 10: too loud) which has been demonstrated to be the most comfortable level (MCL; Hoppe et al, 2001). The MCL has been widely used in CI research to minimize the loudness effect across subjects (Danhauer et al, 1990; Donaldson et al, 2009; Bierer et al, 2015). Using the MCL in both groups can accommodate the potential difference in the audiometric thresholds between NH and CI groups. The intensity levels ranged from 60–75 dB HL in CI users and remained fixed at 60 dB HL in NH listeners.

Speech tests included the Speech Recognition Threshold measured with the Central Institute for the Deaf W-2 adult spondee word list (SRT; Auditec), Central Institute for the Deaf W-22 Word Recognition Test (W-22; Auditec), Consonant-Nucleus-Consonant Test (CNC; Auditory Potential, LLC), Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SIN; Etymologic Research), and the Arizona Biomedical Sentence Recognition Test (AzBio; Auditory Potential, LLC). The CNC and AzBio speech perception tests were added to the original speech perception test battery (SRT, W-22, BKB-SIN) after data collection from NH subjects was complete. These measures were added because they are more appropriate test materials to assess performance of CI recipients clinically and through research studies (Nilsson et al, 1996, 2011). The presentation order of the test materials, as well as the lists used within each test, was randomized to minimize order effects.

Prior to measuring GDTs and speech performance, we measured aided soundfield thresholds for the CI participants using frequency modulated tones at 0.25, 0.5, 1, 2, 4 and 6 kHz using the Hughson-Westlake procedure (Carhart and Jerger, 1959). The purpose of measuring audiometric thresholds in the CI group was to ensure audibility rather than to use this test as a screening measure to verify normal hearing as with the NH participants. The length of time to administer all behavioral tests was approximately 45 minutes.

Randomized Gap Detection Test (RGDT):

The purpose of the RGDT is to identify and quantify temporal processing disorders in children and adults through measurement of gap detection thresholds (GDTs) at four different pure tone test frequencies (0.5, 1, 2, 4 kHz) and clicks. In this study, we only used subtests from the RGDT that contained pure tone stimuli. For each test frequency stimulus pair, the pre- and post-gap tone frequency was identical (e.g., 0.5 kHz tone – gap – 0.5 kHz tone) and had the same duration (17 ms, including a 1-ms rise-fall time). The silent gap duration ranged from 0 to 40 ms (0, 2, 5, 10, 15, 20, 25, 30, and 40 ms). Each gap duration was presented only once and the gap duration was randomized to avoid subject prediction.

The RGDT practice test was administered to familiarize the participant to the test procedure and consisted of 0.5 kHz tone pairs with silent gap durations presented in an ascending order (0, 2, 5, 10, 15, 20, 25, 30, and 40 ms). Next, GDTs were measured for each test frequency (0.5, 1, 2, 4 kHz), using variable gap durations, with the order of test frequency randomized. The task for the listener was to indicate whether one or two stimuli were heard. GDTs were recorded as the shortest gap duration at which the listener correctly indicated that two tones were heard. If the participant failed any frequency (did not indicate two tones were heard at the longest gap duration of 40 ms) contained in the RGDT, indicating a gap detection threshold greater than 40 ms, they were administered the Expanded Randomized Gap Detection Test (RGDT-EXP). The RGDT-EXP administration and scoring is identical to that of the RGDT however it contains longer gap durations ranging from 50–300 ms (50, 60, 70, 90, 100, 150, 200, 250, and 300 ms).

Speech Recognition Threshold (SRT):

The SRT is defined as the minimum hearing level (dB HL) necessary for the listener to recognize 50% of the speech material (ANSI S3.6–1969, 1970; Hirsh et al, 1952). The Central Institute for the Deaf W-2 recorded spondee words were initially presented at 40 dB sensation level. Next a bracketing procedure was implemented to determine the threshold in 5 to 10 dB steps. The threshold was defined as the lowest intensity level at which 50% of the words were repeated correctly and a minimum of three correct responses were obtained (Hirsch et al, 1952).

Central Institute for the Deaf W-22 Word Recognition Test (W-22):

The W-22 word list was administered to assess open-set word recognition in quiet (Cohen et al, 1985; Danhauer et al, 1990). The test contains 200 monosyllabic words, separated into four phonetically balanced lists, each containing 50 words that are preceded by the carrier phrase “say the word.” One list of 50 words was presented and the participant was instructed to repeat each word and to guess if they were unsure (Hirsh et al, 1952). Responses were scored based on the entire word (correct or incorrect). Individual W-22 scores were calculated by dividing the total number of correct responses by 50 and then multiplying by 100 to get the total percent correct score (Hirsh et al, 1952).

Consonant-Nucleus-Consonant Word Recognition Test (CNC):

The CNC word recognition test was administered to assess open-set monosyllabic word recognition in quiet. The CNC word recognition test is part of the Minimum Speech Test Battery for Adult Cochlear Implant Patients (MSTB) that is recommended by clinicians and researchers and is a commonly used measure of speech perception in CI users (Firszt et al, 2002; Jenkins and Uhler, 2012; Mahmoud and Ruckenstein, 2014). The test contains 500 monosyllabic words (consonant - vowel - consonant), divided into ten phonemically balanced lists of 50 words. Each word is spoken by the same male speaker and is preceded by the carrier word “Ready,” with three practice words at the beginning of each list. One CNC word list was administered to each participant. Participants were instructed to repeat each word that they heard and to guess if they were unsure. Responses were scored based on the entire word (correct or incorrect) and the number of individual phonemes repeated in the correct order. The total word percent correct score was calculated by tallying the number of

correct responses, dividing by 50, and multiplying by 100. The total phoneme percent correct score was calculated by tallying the total number of phonemes repeated correctly in each response, dividing by 150, and multiplying by 100 (Peterson and Lehiste, 1962).

Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SIN):

The BKB-SIN test, also a part of the MSTB, is commonly used to evaluate open-set sentence recognition in the presence of 4 talker babble using a modified-adaptive approach in CI users (Gifford et al, 2008; Donaldson et al, 2009; Jenkins and Uhler, 2012; Gifford et al, 2014). The test contains 18 list pairs spoken by the same male speaker that have been equated for intelligibility. Each list contains 10 sentences with one sentence presented at each of the following signal to noise ratios (SNRs) that decrease in 3-dB steps (eg., +21, +18, +15, +12, +9, +6, +3, 0, -3, -6 dB). All sentences have three key words except for the first sentence which has four key words. The carrier word “Ready” precedes each sentence. One list pair was administered and participants were instructed to repeat each sentence that they heard, ignore the background speakers, and to guess if they were unsure. The total number of key words correct repeated correctly for each list (A and B) was tallied separately. The SNR-50 for each list was calculated with the following formula; $\text{SNR-50} = 23.5 - (\# \text{ key words correct})$. The SNR-50 from list A and B were averaged to determine the average SNR-50 which is the SNR in decibels necessary for the individual to understand 50% of the key words contained in the sentence.

Arizona Biomedical Sentence Recognition Test (AzBio):

The AzBio sentences (Spahr et al, 2012) also contained in the MSTB, is another commonly used speech perception measure in CI studies (Koch et al, 2014; Mahmoud and Ruckenstein, 2014; Dorman et al, 2014). The AzBio sentences were used in this study to assess open-set sentence recognition in quiet. The sentences are spoken in a conversational speaking style by two male and two female talkers providing limited contextual cues with each list equated for intelligibility. Participants were presented with one 20sentence list, were instructed to repeat each sentence that they heard, and to guess if they were unsure (Spahr et al, 2012). The total number of words repeated correctly for each sentence was tallied, divided by the total number of words in the list, and multiplied by 100 to get the total percent correct score.

Data Analysis

A GDT was reported for each frequency tested (0.5, 1, 2, 4 kHz). The composite gap detection threshold (CGDT) was computed as the average GDT across the four test frequencies for each participant (Keith, 2000). Performance on speech perception tests were obtained according to the test manuals and is outlined above. Descriptive statistics were computed to characterize the NH and CI group mean scores and standard deviations. A mixed-model analysis of variance (MANOVA) was computed to test for differences in GDTs (0.5, 1, 2, 4 kHz) between the NH and CI group (SPSS, version 22). Next a one-way analysis of covariance (ANCOVA), with age as a covariant, was computed for each RGDT test frequency (0.5, 1, 2, 4 kHz) to determine the effect of age on differences in GDTs (SigmaPlot 13). Pearson product moment correlations were computed to determine the correlation between speech perception scores, biographic factors, and performance on the RGDT/RGDT-EXP. For all statistical measures, $p < 0.05$ was considered statistically

significant, with the exception of the Pearson product moment correlations, where the p value was adjusted for multiple correlations ($p < 0.00167$).

RESULTS

Audiometric Thresholds

CI group mean aided soundfield thresholds for each test frequency are displayed in Figure 1. Audiometric thresholds confirm a minimum of 30 dB sensation level when presenting speech perception and RGDT stimuli at individual MCL.

Gap Detection Performance

Mean GDTs for the four test frequencies (0.5, 1, 2, 4 kHz) for the NH and CI test group are displayed in Figure 2. All participants in the NH group completed the RGDT and subsequently all GDTs were within normal limits (< 20 ms) with a range of 2 to 15 ms at 0.5 – 4 kHz. The mean GDTs for the four test frequencies (0.5, 1, 2, and 4 kHz) were 5.50 ms ($SD = 4.62$), 5.10 ms ($SD = 2.92$), 5.80 ms ($SD = 4.47$), and 5.90 ms ($SD = 3.87$) respectively with a mean CGDT of 5.58 ms ($SD = 3.23$).

In the CI group, out of the twelve CI users, nine (four bilaterally implanted for a total of thirteen ears) completed the RGDT at all four test frequencies and three (one bilaterally implanted for a total of four ears) failed RGDT at a minimum of one test frequency and therefore completed the RGDT-EXP. As a group, GDTs for CI users ranged from 5 ms to 100 ms at 0.5 – 4 kHz. The mean GDTs for each test frequency (0.5, 1, 2, and 4 kHz) were 24.71 ms ($SD = 17.72$), 24.53 ms ($SD = 18.11$), 23.24 ms ($SD = 16.10$), and 27.35 ms ($SD = 22.51$) respectively with a mean CGDT of 24.96 ms ($SD = 16.21$).

A MANOVA was completed with the subject group as the between subject factor and the RGDT test frequency as the within subject factor. The main effect of group showed that there was a statistically significant difference in GDTs between the NH and CI group, $F(1, 25) = 13.752$, $p = 0.001$. The main effect of test frequency (0.5, 1, 2, 4) was not significant, $F(1.983, 49.563) = 0.281$, $p = 0.754$. There was no statistically significant interaction between subject group and test frequency on gap detection threshold, $F(1.983, 49.563) = 0.216$, $p = 0.805$.

An ANCOVA was run for each test frequency (0.5, 1, 2, 4 kHz) to evaluate the effect of age on differences in GDTs between subject groups. Results indicate that the difference in GDTs between the NH and CI group does not depend on the covariate age. There was not a significant interaction between subject group and age at 0.5 kHz ($F(1,23) = 0.201$, $p = 0.658$), 1 kHz ($F(1,23) = 0.006$, $p = 0.935$), 2 kHz ($F(1,23) = 0.296$, $p = 0.591$), 4 kHz ($F(1,23) = 0.079$, $p = 0.781$).

Speech Perception Performance

The mean speech perception scores for each test administered to the NH and CI group are shown in Table 2. For the speech perception tests that were administered to both test groups (SRT, W-22, BKB-SIN), the mean speech perception score and performance range for the NH and the CI test group respectively were SRT: 1.00 dB HL ($SD = 5.16$) and 43.21 dB HL

(SD = 8.68), W22: 98.20% (SD = 3.01) and 65.71% (SD = 24.78), and BKB-SIN: -4.15 dB SNR-50 (SD = 2.56) and 9.12 dB SNR-50 (SD = 5.52). The mean speech perception score and performance range for the speech perception tests that were only administered to the CI group (CNC-Phoneme, CNC-Word, AzBio Sentences) were 79.14% (SD = 17.19), 64.94% (SD = 23.06), and 75.47% (SD = 25.85) respectively.

Since the speech perception data were not normally distributed, a Mann-Whitney rank sum test was performed to test for a group difference. A statistically significant difference was found between the NH and CI mean speech perception scores for the SRT ($T = 55.0$, $p < 0.001$), W-22 ($T = 187.5$, $p < 0.001$), and BKB-SIN ($T = 55.0$, $p < 0.001$).

Correlation Analysis

Correlational analyses were conducted to further examine the relationship between GDTs and speech perception performance in the CI group. Scatter plots for GDTs and speech perception performance are displayed in Figure 3. The linear regression line was plotted for the relations that were determined to be statistically significant. A Bonferroni correction was applied to account for the multiple (30) pairwise comparisons and therefore $p < 0.00167$ was considered statistically significant. The correlation coefficients and the corresponding levels of significance for GDTs (0.5, 1, 2, 4 kHz and CGDT) as a function of speech perception results (SRT, W-22, CNC-Phoneme, CNC-Word, AzBio, BKB-SIN) are displayed in Table 3. A significant negative relationship between the GDT and speech perception performance on the CNC-Phoneme, and AzBio test indicate that individuals with better speech perception performance (i.e., higher percentage correct scores) had better temporal resolution (lower GDTs). A significant positive relationship between the GDT and performance on the BKB-SIN speech perception test indicates that individuals with better temporal resolution (lower GDTs) were able to understand 50% of the target words in the sentences correctly at a lower signal-to-noise ratio.

It can be seen in Figure 3 and Table 3 that statistically significant correlations were found between the following speech perception measures (CNC-Phoneme, AzBio, and BKB-SIN) and GDTs (4 kHz GDT and the CGDT). No significant correlations were found between 0.5, 1, and 2 kHz GDT and any speech perception measure.

Upon closer examination of the correlation plots, some data points may appear to be outlier data however the authors feel like the data points should not be removed for the following reasons. First, these data points reflect the typical variability that is seen in CI performance. Participant Sci37, the suspected outlier, has a relatively short duration of CI use (1 year) and long duration of auditory deprivation (36 years). Moreover, compared to other participants, Sci37 has a younger age at onset of hearing loss (1 year of age). Previous CI studies examining the correlation between CI performance and demographic data showed that poor CI performance is likely the result of combined effects of several factors such as a short duration of CI use, a long duration of auditory deprivation, and an early age of deafness onset (Blamey et al, 1996; Rubinstein et al, 1999; Firszt et al, 2002; Donaldson et al, 2009; Holden et al, 2013). Secondly, Sci37's performance was consistently poor on all speech perception measures however their data points did not appear to be outliers in some scatter plots. Therefore, the authors did not feel justified to remove Sci37 data from the analysis.

However, the correlations found in this study should be confirmed in future studies with a larger sample size.

The relationships between biographic factors (age at test, length of auditory deprivation, and the length of implant use) and the RGDT/RGDT-EXP test results or speech perception scores were examined. However, none of the correlations reached statistical significance ($p > 0.05$).

DISCUSSION

The present study examined whether a clinically available behavioral measure of temporal processing, the RGDT, is correlated with speech perception performance in CI users. Significant correlations were displayed between some GDTs (4 kHz GDT and the CGDT) and several clinically utilized measures of speech perception (CNC-Phoneme, AzBio, BKB-SIN).

GDT Data

Our data showed that in the NH group, the mean GDTs ranged from 5.10 – 5.90 ms (SD = 2.9 to 4.6 ms) at the four test frequencies, when stimuli were presented monaurally. The suggested norms for GDTs assessed with RGDT range from 6.0 – 7.8 ms (SD = 2.5 to 5.3 ms) with binaural presentation (Chermak and Lee, 2005). Although there are no norms for monaural presentation, Roberts and Lister (2004) reported that GDTs do not seem to differ when the stimuli are monaurally vs. binaurally presented but GDTs may be affected by gender. Queiroz et al (2010) reported statistically poorer performance on the RGDT in females compared to males in group of elderly individuals (60–80 years of age). Yet others have reported no statistical difference in GDTs based on gender in a group of children (8–10 years of age; Marculino et al, 2011; Amaral et al, 2013) and adults (17–55 years of age; Prem et al, 2012). Therefore, based on the age range of the NH participants, the differences in the GDTs obtained in the current study compared to the aforementioned norms are unlikely to be attributed to gender.

GDTs in CI users are most commonly measured using single-electrode stimulation (Shannon, 1989; Cazals et al, 1991; Busby and Clark, 1999; Garadat and Pfingst, 2011) with only a few studies using acoustic stimulation processed by their speech processors (Tyler et al, 1989; Muchnik et al, 1994; Wei et al, 2007). Our group was the first to examine the relationship between GDTs and neural temporal properties in CI recipients using the clinically available RGDT and acoustic stimulation processed by the CI speech processor (Zhang et al, 2013). Acoustically measured GDTs reflect limitations imposed by both electrical stimulation and the speech processing strategy, which is a better reflection of the how well CI users are able to process temporal information in everyday life. Our results indicated that using the clinically available RGDT, CI users had an average composite gap detection threshold of 24.96 ms with a range of 7.5 to 67.5 ms which is consistent with the acoustic GDTs reported in the literature for post-lingually deafened CI users. For instance, Wei et al (2007) reported that the average GDT was significantly higher in CI users (ranging from 4 to 128 ms) than in NH listeners. Tyler et al (1989) also reported a significantly higher GDTs (> 40 ms) in CI users than in NH listeners. GDTs measured using electrical

stimulation are much lower and do not show as much variability. For example, Shannon (1989) reported a normal averaged GDT of 4 ms for loud stimuli and Garadat and Pfingst (2011) reported GDTs that ranged from 0.5 to 9.6 ms when measured at 90% of the CI recipient's electrical dynamic range.

The significantly larger GDTs in CI users compared to NH controls could be attributed to several main factors. The first factor is regarding the limitation of CI technology. The CI bypasses the damaged cochlea and stimulates the surviving auditory nerve fibers with electric pulses delivered to a maximum of 22 electrodes. The limited acoustic information from the output of the speech processing strategy can result in elevated GDTs. Several studies provide evidence that the limited information provided by the speech processing strategy can affect temporal acuity (Zhang et al, 2015, Wei et al, 2007). Wei et al (2007) reported elevated acoustic GDTs measured through the speech processor compared to electric GDTs in a previous study. Zhang et al (2015) reported elevated vocoded GDTs in NH individuals compared to GDTs obtained with the original stimuli (non-vocoded). In addition, vocoded GDTs were elevated when the number of spectral channels was 4 or 20 but at 32 channels GDTs were comparable to GDTs with original stimuli. Results suggest that the CI processing can affect temporal processing however additional studies need to be conducted to tease out the limiting factors (limited spectral information, spectral smearing, channel interaction, and limited fine structure information).

Secondly, deficits in the auditory pathway associated with sound deprivation in the pre-implantation stage are likely to affect both bottom-up sensory processing and top-down cognitive modulation of sounds, which can result in elevated GDTs in CI users (Kral and Eggermont, 2007). Previous studies showed that hearing loss can lead to degraded neural encoding of temporal cues, psychoacoustic temporal processing abilities, and decreased speech perception performance in hearing impaired individuals (George et al, 2006; Anderson et al, 2013).

Although, an ANCOVA indicated that differences in GDTs seen between the NH and CI group in our study does not depend on age, it is well established in the literature that advancing age can result in decreased neural efficiency for encoding timing cues. It has been reported that temporal processing ability declines after the fourth decade of life and deterioration accelerates after 70 years of age (Snell, 1997; Pichora-Fuller et al, 2006; Humes et al, 2010; Kumar and Sangamanatha, 2011;), even after peripheral hearing loss has been factored in (Grose et al, 2001; Roberts and Lister, 2004; Queiroz et al, 2010). In this study, the mean age was 57 years for the CI group and 24 years for NH group. Future studies are needed to investigate the role of age on temporal processing abilities in CI users.

Speech Perception Data

The CI group had significantly poorer performance on all speech tests compared to the NH group. In the CI group, the mean scores in this study are similar to those reported in previous studies with post-lingually deafened CI users. For instance, Donaldson et al (2009) reported a BKB-SIN SNR-50 value of 11.9 dB SNR in a CI group in which most subjects were post-lingually deafened. Gifford et al (2008) reported mean speech perception values for a large group of subjects (n = 156) that included CNC word recognition (55.7% for unilateral CI

users, 65.3% for bilateral CI users), AzBio sentence recognition (72.1% for unilateral CI users, 81.2% for bilateral CI users) and the BKB-SIN (11.4 dB SNR-50 for unilateral CI users, 9.8 dB SNR-50 for bilateral CI users). The current study tested CI users monaurally, the results for the CNC and AzBio were 64.94% (SD = 23.06) and 75.47 % (SD = 25.85), which are very similar to the unilateral results reported by Gifford et al (2008). Our result for the BKB-SIN was 9.12 dB SNR-50 (SD = 5.52), which is slightly better than that reported by both Gifford et al (2008) and Donaldson et al (2009). One possible reason for this discrepancy is that there are a greater proportion of CI users wearing bilateral CIs in our group (five of twelve CI subjects) and the benefit of bilateral CI use in their daily life plays an important role in speech perception in noise, even when the stimuli are monaurally presented.

Correlation Between GDTs and Speech Perception Performance

Several significant correlations were found between CI users' speech perception scores (CNC-Phoneme, AzBio, and BKB-SIN) and GDTs (4 kHz GDT and the CGDT). At 4 kHz significant correlations were seen with CNC-Phoneme, AzBio and BKB-SIN and CNC-Phoneme was significantly correlated with the CGDT ($p < 0.00167$). However, no correlations were found between these speech performance and GDTs at any other frequency.

Results indicate that the CNC, AzBio, and BKB-SIN speech perception measures, all of which are contained in the MSTB, are more likely to be predicted by GDTs than the W-22 and SRT. Most CI users with a GDT of less than 40 ms can obtain moderate to good speech performance (e.g., 60% correct for CNC-Phoneme, CNC-Word, AzBio, and 10–15 dB SNR-50 on the BKB-SIN). The deficit in gap detection (GDT > 40 ms) may have an adverse effect on CI users' speech performance. This finding is consistent with the observation that CI performers who have GDTs greater than 40 ms showed poor word recognition skills (Tyler, 1989; Wei et al, 2007). A GDT of less than 40 ms is critical for accurate speech performance because this value is close to the common duration found for voice onset times and form the temporal boundary for categorical perception of some fricative/plosive contrasts (Eggermont, 1995).

Correlation Between Biographic Factors and GDTs or Speech Perception

This study did not find significant correlations between biological factors and GDTs or speech perception performance. Bierer et al (2015) reported a significant correlation between the mean GDTs across electrodes and the duration of deafness. The lack of correlation between GDTs and duration of deafness in our study may be because the effects of CI signal processing on acoustic GDTs negates the correlation of electric GDT and duration of deafness. Although duration of auditory deprivation and age at implantation have been reported to be correlated to speech perception performance in multiple studies (Blamey et al, 1996; Rubinstein et al, 1999; Holden et al, 2013), the current study did not find this correlation. Holden et al (2013) suggested that CI outcomes are limited by different categories of factors. Factors related to electrode insertion, the interface between the electrode and neural elements, programming parameters, the neural status of the auditory system, and neural cognitive factors can all affect CI outcomes. Biological factors are more

related to the neural conditions of the subjects. Therefore, the lack of relationships between biological factors and GDTs or speech perception performance provides the evidence that the CI outcome is the result of complicated interaction of multiple known and unknown factors. The variability of the aforementioned factors in subjects recruited for previous studies may attribute to the contradictions in the literature regarding the correlation between biological factors and CI speech performance (Blamey, 1997; Blamey et al, 2013).

Future Studies and Clinical Implications

As a clinically used test, the RGDT is a fast and easy test to administer, as long as the examiner has a proper understanding of the task required (Amaral et al, 2013). Administration of the RGDT (including patient instruction and practice) takes less than 10 minutes which is the quickest clinical measure of temporal resolution available (Chermak and Lee, 2005). Compared to previous studies measuring acoustic GDTs, the RGDT includes tones with a much shorter duration (17 ms). It is known that GDTs are affected by stimulus parameters such as stimulus duration (short vs. long) and type (tone vs. noise). Shorter stimulus durations (decades of ms), which are similar to temporal speech features (eg., the voice onset time), are more challenging than longer stimulus durations and thus can better separate subjects with and without temporal processing deficits (Schneider and Hamstra, 1999). Gap detection tests with a sinusoidal stimulus appears to be more challenging than those using noise stimuli. Moore and Glasberg (1988) examined GDTs using sinusoidal and noise stimuli. The GDTs for sinusoids were significantly smaller than those for noise bands. The pattern of their results is consistent with the concept that the inherent fluctuations in the noise envelope can be confused with the gap to be detected, which in turn increases gap thresholds. The RGDT has several advantages including a reasonable stimulus duration, the ability to evaluate GDTs for both tonal and click stimuli, test stimuli covering the frequency range most important for speech perception, ease of administration, GDT results similar to those measured using psychoacoustic tests, and results that support a significant correlation to the clinical speech tests for CI users. Moreover, since the RGDT evaluates GDTs up to 40 ms, it can separate CI subjects with moderate-to-good performance from subjects with poor performance with no need to do RGDT-EXP if the goal is to simply identify poor performers. Therefore, the RGDT has good potential to be used as a clinical tool to evaluate the temporal processing deficits and predict speech perception performance in CI users.

Limitations

One limitation of the RGDT as a tool for temporal resolution, is that performance may be affected by auditory fusion. Since the listener's task is to indicate whether one or two distinct tones are heard, the former indicates the perception of a fused image or silent interval in a stimulus that a listener is not able to detect (Iliadou et al, 2014). Moreover, the advantage of being a fast test by using only one trial for one gap duration may be at the expense of test repeatability. Future investigations may benefit from repeating the RGDT to determine test re-test reliability of the measure.

With the advancement in CI technology that results in improved speech outcomes and the development of theories of speech perception, more test tools that will potentially be

standard clinical tools for CI users have been proposed in recently years. For instance, the TIMIT (Texas Instruments/Massachusetts Institute of Technology) sentence corpus, has been designed to reflect realistic listening conditions incorporating common speaker variations such as gender, rate of speech, and regional dialects (King et al, 2012). PRESTO (Perceptually Robust English Sentence Test Open set) is a newly designed, high-variability sentence recognition test, that was created using sentences from the TIMIT speech corpus. The PRESTO sentence recognition test is balanced for number of keywords, frequency, and familiarity and was developed to include talker and dialect variability (Gilbert et al, 2013). If these test materials eventually become clinically standard materials in CI users, it is necessary to re-evaluate the correlation between GDTs and the performance of the aforementioned tests.

Due to the large variability in CI performance on both the speech perception and GDTs, future studies should include a larger sample size. CI recipients should have a range of etiologies, durations of deafness, age at onset of hearing loss, length of CI use ect, which would enable us to better capture the variability seen in CI outcomes. In addition, to better control for effects of age on temporal processing, age and gender matched NH controls should be recruited.

CONCLUSIONS

This current study re-evaluated the relationship between temporal processing abilities, speech recognition performance, and biographic factors using a clinically available measure of temporal processing, the RGDT. CI users' GDTs, as measured in the soundfield, were consistent with the acoustic GDTs reported in the literature for post-lingually deafened CI users. Correlation analysis displayed the most significant correlations between 4 kHz GDT and several speech perception measures contained in the adult CI MSTB. No significant correlations were found between GDTs and biographic factors or between speech perception measures and biographic factors. Results suggest that speech perception performance on tests contained in the MSTB, are more likely to be predicted by GDTs that can be easily assessed with the clinically available RGDT, than the W-22 and SRT. However, the correlations found in this study should be confirmed in future studies with a larger sample size.

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Abbreviations:

AzBio	Arizona Biomedical Sentence Recognition Test
BKB-SIN	Bamford-Kowal-Bench Speech-in-Noise Test

CI	Cochlear Implant
CNC	Consonant-NucleusConsonant Test
GDT	Gap Detection Threshold
MCL	Most Comfortable Loudness
MSTB	Minimum Speech Test Battery
NH	Normal Hearing
RGDT	Randomized Gap Detection Test
RGDT-EXP	Expanded Randomized Gap Detection Test
SNR	Signal to Noise Ratio
SRT	Speech Recognition Test
W-22	Central Institute for the Deaf W-22 Word Recognition Test

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Figure 1. Mean audiometric thresholds of the test ear for 12 cochlear implant subjects (5 bilaterally implanted for a total of 17 ears). Error bars indicate ± 1 standard deviation. ANSI = American National Standards Institute; kHz = kilohertz.

Figure 2. Mean gap detection thresholds identified by RGDT/RGDT-EXP Test (0.5 – 4 kHz and computed CGDT) in the normal hearing and cochlear implant test group.

Figure 3. Scatterplots displaying the relations between GDTs and measures of speech perception in the cochlear implant test group. The regression lines are plotted for the relations that are statistically significant ($p < 0.00167$).

Table 1.

Biographic and cochlear implant device information

Participant	Gender	Ear	Etiology	Age at Test (yrs)	Length of Implant Use (yrs)	Length of Auditory Deprivation (yrs)	Internal Device	Speech Processor	Strategy (Maxima)	Rate (pps/ch)
Sci01	F	R	Menieres	75	5	40	N24CA	Nucleus 5	ACE (10)	900
Sci16	F	L	Genetic	61	5	16	N24CA	Freedom	ACE (8)	900
Sci16	F	R	Genetic	61	7	14	N24CA	Freedom	ACE (8)	900
Sci19	F	L	Fistulas	24	3	17	N24CA	Nucleus 5	ACE (8)	720
Sci19	F	R	Fistulas	24	9	11	N24M	Nucleus 5	ACE (10)	900
Sci21	M	L	Unknown	83	4	3	Freedom CA	Freedom	ACE (8)	900
Sci21	M	R	Unknown	83	4	49	Freedom CA	Freedom	ACE (8)	1200
Sci30	M	L	Noise	65	3	18	N24CA	Nucleus 5	ACE (8)	900
Sci31	F	L	MMR	44	1	39	CI512	Nucleus 5	ACE (8)	900
Sci31	F	R	MMR	44	1	39	N24CA	Nucleus 5	ACE (8)	900
Sci32	F	L	Maternal Rubella	47	5	43	N24CA	Freedom	ACE (8)	900
Sci33	F	R	Unknown	75	1	64	CI512	Nucleus 5	ACE (8)	900
Sci34	M	L	Alports Syndrome	58	13	25	N24CS	Freedom	SPEAK (8)	250
Sci35	F	L	Unknown	59	1	55	CI512	Nucleus 5	ACE (8)	900
Sci36	M	L	Unknown	67	1	51	CI512	Nucleus 5	ACE (8)	900
Sci36	M	R	Unknown	68	1	51	CI512	Nucleus 5	ACE (8)	900
Sci37	F	R	Unknown	37	1	36	Freedom CA	Nucleus 5	ACE (8)	900

Note: L = Left, R = Right, M = Male, F = Female, MMR = Measles Mumps and Rubella, yrs = years, N24CA = Nucleus 24 Contour Advance N24M = Nucleus 24, CA = ContourAdvance, CI512 = Nucleus 5, N24CS = Nucleus24, ACE = Advanced Combination Encoder SPEAK = Spectral Peak, pps/ch = pulses per second/channel

Table 2.

Speech recognition performance in NH participants and CI users

Speech Perception Tests	Normal Hearing Group				Cochlear Implant Group				<i>P</i> *
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	
SRT (dB HL)	1.00	5.16	-5.00	10.00	43.21	8.68	35.00	65.00	<.001
W-22 (% correct)	98.20	3.01	92.00	100.00	65.71	24.78	0.00	100.00	<.001
CNC Phoneme (% correct)	DNT	DNT	DNT	DNT	79.14	17.19	32.00	95.30	CNT
CNC Word (% correct)	DNT	DNT	DNT	DNT	64.94	23.06	8.00	96.00	CNT
AzBio Sentences (% correct)	DNT	DNT	DNT	DNT	75.47	25.85	6.16	99.35	CNT
BKB-SIN SNR-50 (dB HL)	-4.15	2.56	-1.00	-7.50	9.12	5.52	1.50	23.00	<.001

Note: *p* * value shows the results of Mann - Whitney Rank Sum Test, DNT= Did not test, CNT = Could not test.

Table 3.

Correlation between GDTs and speech perception performance in CI users

Speech Perception Tests	Gap Detection Thresholds											
	0.5 kHz		1 kHz		2 kHz		4 kHz		CGDT			
	<i>r</i>	<i>p</i> *	<i>r</i>	<i>p</i> *	<i>r</i>	<i>p</i> *	<i>r</i>	<i>p</i> *	<i>r</i>	<i>p</i> *	<i>r</i>	<i>p</i> *
SRT	0.316	0.2710	0.302	0.2950	0.461	0.0975	0.689	0.0064	0.519	0.0573		
W-22	-0.364	0.2010	-0.279	0.3340	-0.431	0.1240	-0.650	0.0112	-0.507	0.6450		
CNC-Phoneme	-0.526	0.0301	-0.410	0.1020	-0.655	0.0043	-0.792	0.0002*	-0.696	0.0016*		
CNC-Word	-0.524	0.0308	-0.398	0.1130	-0.563	0.0187	-0.690	0.0022	-0.634	0.0063		
AzBio	-0.571	0.0166	-0.357	0.1590	-0.640	0.0056	-0.799	0.0001*	-0.692	0.0021		
BKB-SIN	0.648	0.0049	0.392	0.1200	0.566	0.0180	0.736	0.0007*	0.682	0.0025		

Note: *p** value shows the results of Pearson Product Moment Correlation, kHz = Kilohertz, CGDT = Composite Gap Detection Threshold* = significant at $p < 0.00167$ (Bonferroni correction applied to *p*-value).