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Evaluation of a New Algorithm to Optimize Audibility in Cochlear Implant Recipients

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Abstract

Objective: A positive relation between audibility and speech understanding has been established for cochlear implant (CI) recipients. Sound-field thresholds of 20 dB HL across the frequency range provide CI users the opportunity to understand soft and very soft speech. However, programming the sound processor to attain good audibility can be time consuming and difficult for some patients. To address these issues, Advanced Bionics (AB) developed the SoftVoice algorithm designed to remove system noise and thereby improve audibility of soft speech. The present studies aimed to evaluate the efficacy of SoftVoice in optimizing AB CI recipients' soft-speech perception.

Design: Two studies were conducted. Study 1 had two phases, 1A and 1B. Sixteen adult, AB CI recipients participated in Study 1A. Acute testing was performed in the unilateral CI condition using a Harmony processor programmed with participants' everyday-use program (Everyday) and that same program but with SoftVoice implemented. Speech recognition measures were administered at several presentation levels in quiet (35 – 60 dB SPL) and in noise (60 dB SPL). In Study 1B, ten of the participants compared Everyday and SoftVoice at home to obtain feedback regarding use of SoftVoice in various environments. During Study 2, soft-speech perception was acutely measured with Everyday and SoftVoice for ten participants using the Naida CI Q70 processor. Results with the Harmony (Study 1A) and Naida processors were compared. Additionally, Study 2 evaluated programming options for setting electrode threshold levels (T-levels or Ts) to improve the useability of SoftVoice in daily life.

Results: Study 1A showed significantly higher scores with SoftVoice than Everyday at soft presentation levels (35, 40, 45 and 50 dB SPL) and no significant differences between programs at a conversational level (60 dB SPL) in quiet or in noise. After take-home experience with SoftVoice and Everyday (Study 1B), five of ten participants reported preferring SoftVoice over Everyday; however, six reported bothersome environmental sound when listening with SoftVoice at home. Results of Study 2 indicated similar soft-speech perception between Harmony and Naida processors. Additionally, implementing SoftVoice with Ts at the manufacturer's default setting of

10% of Ms reduced reports of bothersome environmental sound during take-home experience; however, soft-speech perception was best with SoftVoice when Ts were behaviorally set above 10% of Ms.

Conclusions: Results indicate that SoftVoice may be a potential tool for optimizing AB users' audibility and in turn, soft-speech perception. To achieve optimal performance at soft levels and comfortable use in daily environments, setting Ts must be considered with SoftVoice. Future work should examine program parameters that may benefit soft-speech perception when used in combination with SoftVoice (e.g., increased input dynamic range).

Introduction

An essential component for effective communication is the ability to detect and understand speech at varying intensity levels. Very soft speech, such as a whisper, is approximately 30–35 dB SPL (Davis & Silverman 1978; Hassall & Zaveri 1979). Casual speech, spoken one meter from the listener, is approximately 56 dB SPL, normal speech approximately 60 dB SPL, and raised-to-loud speech 70 dB SPL (Pearsons et al. 1977). Real world environments introduce situational and speaker variables that can make speech difficult to hear and understand, e.g., speech originating from distances greater than one meter or speech from soft spoken individuals and children. Furthermore, speech levels naturally fluctuate within a sentence. In conversational speech, voiceless consonants such as /f/, /s/, and /th/ and final words of sentences can be as soft as 40 dB SPL (Sinks & Duddy 2002; Skinner et al. 2002; Chasin 2015). It is well established that for optimal speech understanding in daily life, detection levels for both hearing aid and cochlear implant (CI) users should approximate 20 dB HL from .25–6 kHz (Pasco 1975; Skinner 1988; Mueller & Killion 1990; Skinner 2003; Davidson et al. 2009; Holden et al. 2013a). Fundamentally, speech recognition is not possible if speech cues are inaudible.

Early CI recipients rarely achieved frequency modulated (FM) tone sound-field threshold levels of 20 dB HL across the frequency range using older sound processor technology. For example, some sound processors utilized a narrow input dynamic range (IDR), which prevented low-level acoustic signals from being mapped onto the CI user's electrical dynamic range (Zeng et al. 2002; Holden et al. 2007; Spahr et al. 2007; Davidson et al. 2009). Conversely, other sound processors used a wide IDR, which introduced potentially audible processor or microphone noise that essentially masked low-level sound and speech (Dawson et al. 2007; Holden et al. 2011). However, advances in sound processor technology (increased IDR settings, improved microphones) have led to detection levels near the normal hearing range for current CI users. In a group of 78 adult CI participants representing three CI manufacturers (Advanced Bionics, LLC, Valencia, CA; Cochlear Ltd., Sydney, Australia; MED EL, Vienna, Austria), Firszt et al. (2004) reported group mean sound-field thresholds of 29, 27, 24, 25, 25, 29 and 29 dB HL at .25, .5, .75, 1, 2, 3, and 4 kHz, respectively. Study results indicated significant negative correlations between sound-field thresholds and monosyllabic word and sentence scores at conversational (60 dB SPL) and soft (50 dB SPL) presentation levels. In 2013, Holden and colleagues reported a group mean sound-field threshold, averaged across frequencies (.25, .5, .75, 1, 1.5, 2, 3, 4 and 6 kHz), of 20.9 dB HL for 114 adult CI participants using either Cochlear Nucleus or Advanced Bionics devices.

Similar to Firszt et al. (2004), sound-field thresholds were significantly and negatively correlated with monosyllabic word scores (60 dB SPL presentation level) obtained both at two weeks and at approximately two years after initial activation of the CI. Comparable findings for children with CIs were reported by Geers et al. (2013). The authors evaluated pediatric CI users ($n = 60$) between the ages of nine and 12 who had been unilaterally implanted prior to 38 months of age. The Lexical Neighborhood Test (LNT, Kirk et al. 1995) was administered at 70 and 50 dB SPL. Group mean LNT word scores were 77% and 52% at 70 and 50 dB SPL, respectively. The difference in word scores between the two presentation levels varied among participants; however, the majority of participants had a 10 percentage point difference between scores. Notably, the authors found that the difference in word scores between the two presentation levels was negatively correlated with sound-field thresholds and sound processor technology. In other words, children with lower sound-field thresholds and newer technology showed less of a decrement in word score at 50 vs 70 dB SPL than children with older technology and higher sound-field thresholds.

The ability to detect and understand soft to casual speech may also benefit children's vocabulary development through incidental or passive learning (Akhtar et al. 2001). Davidson et al. (2014) evaluated receptive vocabulary and novel word learning ability in a group of 101 children with CIs. The mean age at diagnosis of hearing loss for the group was eight months, the mean age at implant was 24 months, and the mean age at study was nine years. The authors found that CI participants fell into two groups, those with good audibility (FM tone, sound-field threshold levels at .5, 1, and 2 kHz ≤ 20 dB HL, $n = 46$) and those with poor audibility (FM tone, sound-field thresholds at .5, 1, and 2 kHz > 20 dB HL, $n = 55$). Children with good audibility with the CI had significantly better receptive vocabulary and novel word learning than those with poor audibility.

In addition to speech perception and language acquisition, audibility for soft input levels may affect non-auditory aspects of communication for CI users, specifically listening effort and fatigue. Several studies (Dwyer et al. 2014; Alhanbali et al. 2017; Perreau et al. 2017) compared subjective reports of listening effort between adult normal hearing (NH) and CI participants and found that CI participants had significantly greater perceived listening effort than those with NH. Less than ideal listening conditions, like soft speech and background noise, are encountered by CI users throughout the day and require effortful listening, which may lead to fatigue. Study results from Alhanbali et al. (2017) revealed that CI recipients ($n = 50$) had significantly higher perception of fatigue than those with NH ($n = 50$); additionally, the authors found a significant correlation between self-reported fatigue and self-reported listening effort for CI participants. Hornsby et al. (2014) examined self-perceived fatigue in children with hearing loss ($n=10$) and age matched NH children ($n=10$). Results indicated that the children with hearing loss reported significantly more fatigue than those with NH. The ability to detect and understand soft speech may have the potential to improve many aspects of communication that can negatively impact CI users.

The importance of audibility for speech perception in both pediatric and adult CI users has been recognized; however, programming sound processors to obtain optimal audibility for individual CI recipients is time consuming, as it often requires obtaining detection levels on each active electrode. Moreover, the task can be difficult for certain patients, e.g., young

children or patients with tinnitus. To address these issues, Advanced Bionics developed the SoftVoice algorithm. The algorithm is intended to optimize CI recipients' audibility and speech understanding at soft listening levels with little additional programming time or patient effort. The algorithm is designed to remove microphone and other system noise and thereby improve audibility of soft sounds. A cochlear implant sound processor contains one or more microphones. Each microphone is an electronic component that transforms sound pressure level into voltage, which is then captured by the processor. Due to its relatively small size, the sound processor microphone is prone to noise. This noise may introduce a static or sizzle-like sound, which could be audible to the listener in a quiet environment and potentially mask soft environmental or speech sounds. SoftVoice is designed to combat microphone and system noise. Specifically, SoftVoice is implemented after frequency analysis. Frequency analysis separates incoming sounds into narrow frequency bands, and the SoftVoice algorithm is applied independently to each band. The algorithm computes the energy within a band, smooths the energy signal across time (time constant of approximately 30 ms), and compares that value to a band-specific threshold, which is pre-set based on a known average measurement of the noise (both system and microphone noise) in each band. Input sounds that exceed the narrow frequency-band noise threshold will be present, while sounds on adjacent bands falling below their thresholds will be removed. Consequently, any input signals above the band-specific threshold should theoretically be more easily detectable by the CI recipient. Figure 1 shows the activation pattern for each electrode for the recorded speech token /aSa/ presented at 33 dB SPL. The left image displays /aSa/ without SoftVoice applied and the right image with SoftVoice applied.

To evaluate the efficacy of the SoftVoice algorithm in optimizing audibility and soft- speech perception in both the lab and in daily life, two studies were conducted over a two-year period at Washington University School of Medicine in St. Louis (WUSM). Study 1 included an acute phase (1A) and a chronic-use phase (1B). The objective of Study 1A was to evaluate acute performance with the SoftVoice algorithm (hereafter referred to as SoftVoice) using speech recognition measures presented in quiet (at conversational, soft, and very soft levels) and in noise and to compare SoftVoice performance with the recipient's everyday-use program (hereafter referred to as Everyday). It was hypothesized that implementation of SoftVoice, on a Harmony processor, would yield improved speech understanding at soft levels compared to Everyday and would not impair understanding at conversational levels or in noise. In Study 1B, participants used Everyday and SoftVoice at home for a two-week period, which allowed participants to assess qualitative differences between programs in a variety of listening environments. In Study 2, participants utilized the most current sound processor, the Naida CI Q70. Since differences between the Harmony and Naida processors, e.g., microphone technology, could affect benefit obtained from SoftVoice, Study 2's primary objective was to compare the efficacy of SoftVoice between processors. A second objective was to examine programming options, specifically the setting of electrode threshold levels, that could improve the the useability of SoftVoice in daily life.

Material and Methods – Study 1A

Participants

The study was approved by the Human Research Protection Office (ID #: 201403100) at WUSM. Sixteen postlingual, adult CI recipients (ages 44–77 years; mean 62.8 years; 9 females, 7 males) participated. Cochlear implant experience ranged from eight months to 12 years (mean 7.1 years). Participants were bilateral, bimodal (CI + hearing aid in contralateral ear), and unilateral CI users. Demographic and device information is provided in Table 1. Each participant's Consonant-Vowel-Consonant (CNC) Word Test (Peterson & Lehiste 1962) score for the test ear is also listed in Table 1. This word score was obtained at participants' most recent clinical evaluation, prior to the study. When programming a CI device at WUSM, sound processor program, electrode threshold levels (T-levels or Ts) and most comfortable levels (M-levels or Ms) are set for optimal audibility and comfortable loudness, respectively. Four study participants used Everyday programs with Ts set at the manufacturer's default setting of 10% of Ms; whereby, each electrode's T-level is automatically set by the clinical software to 10% of the corresponding M-level. The other twelve participants used Everyday programs with Ts behaviorally set above 10% of Ms to assist in obtaining FM tone sound-field threshold levels of 20 dB HL from .25–6 kHz with the CI alone (Holden et al. 2011; Baudhuin et al. 2012). In our clinic, setting Ts behaviorally requires the Advanced Bionics CI user to report when the stimulus is first heard on each electrode. T-levels are then verified and, if necessary, adjusted for each patient to optimize audibility and ensure that microphone and/or processor noise is inaudible.

Procedures

During Study 1A, participants completed two test sessions, one week apart, using a research Harmony processor and T-Mic. Research software (BEPS+, Version 1.8.16.26267) was used to program the Harmony processor for each participant with either Everyday or that same program with SoftVoice implemented (identical program parameters between Everyday and SoftVoice, see Table 1). At each test session, half of the participants were tested with Everyday and the other half with SoftVoice; participants tested with Everyday during session one were tested with SoftVoice during session two. Each participant's volume control was set identically for testing Everyday and SoftVoice. All testing with SoftVoice was acute, i.e., no take-home experience was given prior to testing. Speech recognition measures were administered in a double-walled sound attenuating booth (IAC). Measures were stored as audio files on a PC and presented through a 24-bit studio sound card (Lynx Studio Technology L22) and power amplifier (Crown D-150A) to a loudspeaker (JBL LSR32) in the sound-field at 0 degrees azimuth and 1.5 meters from the center of a participant's head. Testing was completed with all participants using a unilateral CI. Bimodal users turned off their contralateral hearing aid prior to testing. Participants 8 and 9 competed testing with the non-implant ear plugged (Howard Leight MAX foam earplugs) as both had a pure-tone average (PTA) in the non-implant ear of 50 dB HL. The remaining bimodal participants had PTAs in the non-implant ear > 70 dB HL. Bilateral CI users chose their test ear if performance for the most recent CNC word test was equal between ears, i.e., < 10% difference. If performance was not equivalent between ears, the ear with the lower score was chosen for testing during the study to provide a wider range in CNC performance among

participants. This was the case for participants 2, 6, and 10. A wide range in performance outcomes better represents the postlingual, adult CI population (Firszt et al. 2004; Gifford et al. 2008; Holden et al. 2013). However, even with the use of the poorer performing ear, these study participants had considerable CNC word recognition with the test ear (mean word score = 68%; see Table 1 for individual word scores). Prior to testing, the audiologist spoke with each participant for approximately ten minutes to provide some practice listening with the research Harmony processor in the unilateral CI condition. Participants reported similar sound quality between their own processor (Harmony or Naida, see Table 1) and the research Harmony processor.

Test Measures

At each test session, FM tone sound-field threshold levels were obtained in 2 dB steps at .25, .5, .75, 1, 1.5, 2, 3, 4 and 6 kHz. A step-size of 2 dB, instead of 5 dB, was used to examine fine differences in audibility between programs. Speech recognition measures included words and sentences in quiet and sentences in noise. Presentation levels varied from very soft to conversational. Test measures and corresponding presentation levels are provided in Table 2. Two test lists were administered at each presentation level for CNC words (50 words per list) and AzBio sentences in quiet and noise (20 sentences per list; Spahr et al. 2012). Sentence level presentation order in quiet was pseudo-randomized for each participant to ensure variety in level presentation order across participants and between test sessions for an individual participant. An adaptive speech reception threshold (SRT) test was administered in which participants used a touchscreen to identify the spondaic word heard from a closed-set of four words listed on the screen. The spondees were randomly presented in one of four conditions: quiet, male talker competing noise, female talker competing noise, and multi-talker babble. Presentation level for each condition was tracked independently beginning at 60 dB SPL and varied adaptively based on participant responses. For each condition, testing ended after four reversals, and the last three reversals were averaged for the final SRT score. The SRT measure is fully described in Firszt et al. 2017.

Results – Study 1A

Data were analyzed for normality and outliers. Due to non-normal distributions, nonparametric statistics were used to analyze sound-field threshold levels and speech recognition results. Kruskal-Wallis tests ruled out significant outcome differences based on stimulation modality experience (bilateral CI, unilateral CI, or bimodal), $p_s > 0.05$. Group mean sound-field thresholds across frequencies were 19.3 dB HL (SD = 5.6 dB) and 14.5 dB HL (SD = 4.8 dB) for Everyday and SoftVoice, respectively. Sound-field thresholds were significantly lower with SoftVoice than Everyday for each frequency, Wilcoxon Zs ranged from -2.6 to -3.5 , $p_s = 0.01$. Figure 2 shows Everyday and Softvoice group mean scores for AzBio sentences in quiet, AzBio sentences in noise, and CNC words. Wilcoxon Signed Ranks tests indicated that participants obtained significantly higher sentence scores in quiet with SoftVoice compared to Everyday at 35, 40, 45 and 50 dB SPL (Wilcoxon Zs ranged from -3.36 to -2.77 , $p_s = 0.01$); there was no significant difference in scores for sentences in quiet at 60 dB SPL (Wilcoxon $Z = -1.03$, $p > 0.05$). As expected, there was a significant level effect for both Everyday and SoftVoice (Everyday Kendall's $W = 0.97$, $p = .001$;

SoftVoice Kendall's $W = 0.99$, $p = .001$). Post-hoc Bonferroni adjusted pair-wise comparisons indicated all levels were significantly different from each other, Wilcoxon Z s ranged from -3.52 to -3.41 , $ps = 0.01$. Wilcoxon Signed Ranks tests did not identify significant program differences for CNC words (60 dB SPL, Wilcoxon $Z = -.75$, $p > 0.05$) or AzBio Sentences in noise (60 dB SPL, +8 dB SNR, Wilcoxon $Z = -1.86$, $p > 0.05$). Wilcoxon Signed Ranks test of the adaptive SRT in quiet indicated no significant difference in scores between SoftVoice and Everyday (Wilcoxon $Z = -.68$, $p > 0.05$). In noise, there was no significant noise type effect (Male talker, Female talker and Multi-talker babble), Kendall $W = .07$, $p > 0.05$; therefore, scores were averaged across noise type. The averaged SRT noise scores did not differ significantly between Everyday and SoftVoice (Wilcoxon $Z = -.74$, $p > 0.05$).

To examine individual variability in soft-speech perception, composite AzBio soft-speech scores for Everyday and SoftVoice were obtained by calculating the average of scores across the presentation levels found to be significantly different between Everyday and SoftVoice (35, 40, 45 and 50 dB SPL). Figure 3 shows composite soft-speech scores for both programs and each participant. Participants are ordered by Everyday scores, which ranged from 11% to 80% (mean = 35%; SD = 16%). SoftVoice scores ranged from 13% to 82% (mean = 45%; SD = 17%). The difference in soft-speech scores between Everyday and SoftVoice (SoftVoice soft-speech score minus Everyday soft-speech score) ranged from -4 to 22 percentage points (mean = 10 percentage points). Ten participants had at least a 10-percentage-point improvement in their soft-speech score with SoftVoice compared to Everyday.

To determine if age, length of CI experience, T-level settings (Ts at 10% of Ms, $n=4$; Ts behaviorally set above 10% of Ms, $n=12$), or audibility (sound-field thresholds averaged across frequencies .25–6 kHz, SF-AAF) were related to performance at soft presentation levels, correlation analysis was completed between these factors and composite soft-speech scores (see Table 3). The false discovery rate controlling procedures of Benjamini and Hochberg (1995) were applied to these multiple correlation results, which confirmed the use of $p = 0.05$ as appropriate. No correlation was found between composite soft-speech score and age or electrode T-level settings for either program. There was a significant positive correlation between length of CI experience and the composite soft-speech score for Everyday but not SoftVoice. Figure 4 shows a significant negative correlation between SF-AAFs and soft-speech scores for both Everyday and SoftVoice; that is, lower SF-AAFs were associated with better soft-speech perception regardless of program. Length of CI experience and SF-AAFs were not correlated with each other. The fact that the relationship between SF-AAFs and soft-speech scores was similar between programs was not unexpected as significant correlations were found between SF-AAFs with each program and soft-speech scores with each program.

Materials and Methods - Study 1B

Participants and Procedures

Approximately eight months after Study 1A, ten of the 16 participants (1, 2, 4, 5, 7, 9, 12, 13, 15, 16) participated in Study 1B; the objective was to compare Everyday and SoftVoice

programs at home for two weeks to extend listening environments beyond the laboratory. The research Harmony processors held only two programs, Everyday and SoftVoice; as in Study 1A, program parameters were identical between programs. Bilateral recipients used research processors programmed with Everyday and SoftVoice on each ear ($n = 3$). Prior to home use, participants listened with both programs in the office, and all were able to identify SoftVoice; therefore, participants were not blinded to the location of each program on the research processor. During the take-home comparison, participants were asked to spend equal time listening with each program; however, data logging was not available to track time spent using each program. To help facilitate use of both programs, participants were asked to complete a questionnaire at home rating their ability to hear and understand speech with each program in a variety of listening situations. Ratings were based on a five-point scale; participants circled the number corresponding to their rating for each program (1 = poor, 5 = excellent). Participants were also asked how well they heard environmental sounds and to rate their overall speech understanding with each program. Participants were encouraged to note any benefits or problems experienced when listening with each program. Table 4 lists each item on the questionnaire.

Results – Study 1B

Generally, participant ratings for each listening environment were either the same for each program or differed by only one point, e.g., 3 vs. 4. Figure 5 (Panel A) indicates the group mean ratings for Everyday and SoftVoice for questionnaire items 1 – 21 (Table 4). Wilcoxon signed rank tests indicated no significant differences between programs for any listening situation (Wilcoxon Z s ranged from -1.73 to $-.18$, p s > 0.05), environmental sound detection (Wilcoxon $Z = -1.90$, $p > 0.05$), or overall speech understanding (Wilcoxon $Z = -.91$, $p > 0.05$). However, there was a significant difference between programs for the presence of irritating environmental sounds (Wilcoxon $Z = -2.45$, $p = 0.05$). Six of ten participants reported that environmental sounds (e.g., heating system, printers, traffic noise) were bothersome with SoftVoice, whereas none of the participants reported irritating sounds with Everyday. Of note, nine of the ten Study 1B participants had T s set above 10% of M s (T s and M s were identical for Everyday and SoftVoice). The combination of raised T s and SoftVoice was thought to increase some participants' audibility such that environmental sound became bothersome. Consequently, it was hypothesized that decreasing T s to 10% of M s with SoftVoice may reduce bothersome environmental sound and still provide soft-speech perception comparable to Everyday (T s above 10% of M s).

Material and Methods - Study 2

Study 2 was initiated approximately 15 months after Study 1B, when many Advanced Bionics CI recipients were using the most current sound processor, the Naida CI Q70. The Naida processor utilizes improved microphone technology and has enhanced resolution in the analog-digital converter compared to the Harmony processor. Both improvements affect (i.e., lower) the system noise floor of the Naida processor. The lower noise floor could impact Naida users' perception of soft sound and thus benefit derived from SoftVoice. Therefore, the primary objective of Study 2 was to determine if SoftVoice on the Naida processor provided similar benefits to soft-speech perception as SoftVoice on the Harmony

processor. A second objective was to determine whether decreasing Ts to 10% of Ms with SoftVoice reduces bothersome sound yet maintains soft-speech perception comparable to Everyday (Ts above 10% of Ms).

Participants

Ten participants from Study 1A (1, 2, 4, 5, 7, 8, 9, 12, 13, 15) were invited to participate in Study 2. Nine of the ten participants had a 10 percentage-point improvement in composite soft-speech scores with SoftVoice compared to Everyday in Study 1A; participant 2 had similar soft-speech scores between programs (Figure 3). All participants were using an Everyday program that had Ts behaviorally set above 10% of Ms to optimize audibility. Table 5 shows participants' sound processor and program information. The last column of Table 5 indicates T-level settings for each participant's preferred, daily-use program. T-levels are given as a percentage of M-levels; both Ts and Ms were averaged across active electrodes.

Procedures

In Study 2, research Naida CI Q70 sound processors programmed with BEPS+ research software (Version 2.6.26.22610) were used for testing at two sessions. During the first test session, acute testing was completed with the participant's preferred Everyday program and with that same program with SoftVoice implemented. Program test order was counterbalanced; half the participants were tested with Everyday first and half with SoftVoice first. The bilateral participants in Study 2 had successfully used Everyday and SoftVoice on their right and left ear processors at home for two weeks during Study 1B; therefore, in Study 2, bilateral participants (n=4) were tested using a research Naida processor on each ear programmed with Everyday and SoftVoice. Bimodal participants (n=3) again turned their hearing aid off prior to testing, and participants 8 and 9 had their non-implant ear plugged during testing. Participants were blinded to the program order used for testing. Volume control settings remained the same for testing with both programs. Test measures included FM tone sound-field thresholds, AzBio sentences in quiet, and AzBio sentences in noise as shown in Table 2 except that AzBio sentences in quiet were only given at 40, 45, and 50 dB SPL.

At the end of the first test session, Ts were lowered to 10% of Ms for each participant's SoftVoice program. T-levels were unchanged in the Everyday program (Ts above 10% of Ms). All other program parameters were identical. Both Everyday and SoftVoice were placed on research Naida processors. Participants were blinded to program locations; they were unable to differentiate the programs when listening to each for a short time in the lab. Participants were instructed to use both programs in as many listening situations as possible over a two week period, to compare sound quality and speech understanding between programs, and to choose their overall preferred program. In addition, participants were asked to complete the same questionnaire as completed in Study 1B. After two weeks of take-home experience, participants returned for the second test session. As in session one, participants were tested with both Everyday and SoftVoice; program test order was the reverse of that used in session one. The same tests (different lists) administered in the first

test session were administered in the second test session. After testing, the questionnaire and participant experiences with each program were discussed.

Results – Study 2

To determine if SoftVoice on the Naida processor provided similar benefits to soft-speech perception as SoftVoice on the Harmony processor, acute test results from Study 2 (Naida) were compared with acute test results from Study 1A (Harmony). As a reminder, the ten participants who were in Study 1A and Study 2 (first test session) had Ts above 10% of Ms for Everyday and SoftVoice. Like Study 1A, nonparametric statistics were used to analyze the data. Table 6 shows group mean AzBio sentence scores at 40, 45 and 50 dB SPL presentation level in quiet and at 60 dB SPL in noise (SNR +8) for each processor (Harmony and Naida) and program (Everyday and SoftVoice). Wilcoxon Signed Ranks tests, Bonferroni corrected for multiple comparisons, indicated no significant processor effect for either program in quiet (Wilcoxon Zs for Everyday ranged from -0.26 to -2.19 , $ps > 0.05$; and for SoftVoice ranged from -2.09 to -0.56 , $ps > 0.05$) or in noise (Wilcoxon Zs = -2.24 for Everyday and -1.07 for SoftVoice, $ps > 0.05$). Similar to Study 1A, a significant level effect was present (Kendall's Ws = 1.0, $ps < .001$). Post-hoc Bonferroni adjusted pair-wise comparisons indicated all levels were significantly different from each other, Wilcoxon Zs = -2.80 , $ps < 0.05$ for Everyday and SoftVoice. A Wilcoxon Signed Ranks test indicated SoftVoice scores were significantly higher than Everyday scores at each of the presentation levels (Wilcoxon Zs ranged from -2.40 to -2.70 , $ps < 0.05$) for scores averaged across processors.

To assess whether SoftVoice with Ts at 10% of Ms provided comparable soft-speech perception to Everyday with Ts above 10% of Ms, Wilcoxon Signed Ranks Tests were performed for sentences in quiet at each presentation level and for sentences in noise. Group mean FM tone sound-field thresholds across frequencies were 18.9 dB HL (SD = 4.8 dB) and 19.2 dB HL (SD = 4.7 dB) for Everyday and SoftVoice, respectively. Group mean sound-field thresholds were not significantly different between programs (Wilcoxon Z = -0.54 , $p > 0.05$). Figure 6 shows group mean sentence scores in quiet and in noise for Everyday and SoftVoice at each presentation level. No significant difference in scores were seen between programs for sentences in quiet presented at 50 dB SPL (Wilcoxon Z = -1.48 , $p > 0.05$) or in noise at 60 dB SPL (Wilcoxon Z = -0.26 , $p > 0.05$); however, sentence scores in quiet at the two softest presentation levels were significantly higher with Everyday than SoftVoice (40 dB SPL Wilcoxon Z = -3.0 ; 45 dB SPL Wilcoxon Z = -2.50 , $ps < 0.05$).

Like Study 1B, questionnaire ratings for each listening environment were similar between Everyday and SoftVoice. Figure 5 (Panel B) indicates the group mean ratings for Everyday and SoftVoice for questionnaire items 1 – 21 (Table 4). Wilcoxon signed rank tests indicated no significant differences between programs for any of the questionnaire items (Wilcoxon Zs for questions 1–20 ranged from 0 to 2.00, $ps > 0.05$; Wilcoxon Z for overall speech understanding = -0.38 , $p > 0.05$; Wilcoxon Z for irritating sounds = -1.00 , $p > 0.05$). When comparing participant questionnaires ($n = 9$) from Study 1B (SoftVoice, Ts above 10% of Ms) and Study 2 (SoftVoice, Ts at 10% of Ms), fewer participants reported bothersome environmental sound during Study 2. Specifically, only two of five participants who reported

bothersome environmental sound with SoftVoice during Study 1B continued to report it during Study 2. None of the remaining eight participants in Study 2 reported bothersome environmental sound with SoftVoice. Even with the decrease in bothersome sound, a number of Study 2 participants claimed to prefer their “original” SoftVoice program, namely SoftVoice with Ts above 10% of Ms as used in Study 1A, 1B, and during the first test session of Study 2. To examine differences in sentence scores between SoftVoice programs differing in T-level settings, a Wilcoxon Signed Ranks Test compared sentence scores at 40, 45 and 50 dB SPL from both test sessions of Study 2 (session one: SoftVoice [Ts above 10% of Ms]; session two: SoftVoice [Ts at 10% of Ms]). Figure 7 indicates group mean sentence scores were significantly higher at each presentation level when using SoftVoice with Ts above 10% of Ms compared to SoftVoice with Ts at 10% of Ms (Wilcoxon Zs = -2.70, ps 0.05).

Discussion

Study results indicate that understanding soft and even very soft speech is a realistic expectation following cochlear implantation. This performance outcome is relatively recent, within the last 10–15 years. Advances in sound processor technology, e.g., increased IDR, decreased microphone noise, and pre-processing strategies, have provided the ability to capture and deliver soft and very soft input. In addition, fundamental work by Skinner and colleagues (1997, 1999, 2003) as well as others (James et al. 2002, 2003; Firszt et al. 2004; Holden et al. 2007, 2011, 2013a; Davidson et al. 2009, 2014; Geers et al. 2013) definitively established the positive relationship between audibility and CI performance. The results of the current study compared to previous studies illustrate the improvement in soft-speech understanding over time. Skinner et al. (1997) evaluated a group of ten Nucleus 22 CI users at 70, 60 and 50 dB SPL using City University of New York sentences (CUNY, Boothroyd et al. 1988). Firszt et al. (2004) evaluated a group of 78 CI recipients (Advanced Bionics, Cochlear, and MED EL) at the same three presentation levels using Hearing in Noise Test (HINT) sentences (Nilsson et al. 1994). In 1997, the group mean CUNY sentence score was 29% at 50 dB SPL. In 2004, the mean HINT sentence score was 57% at 50 dB SPL. Current study results revealed mean AzBio sentence scores at 50 dB SPL for Everyday and SoftVoice of 69% and 77%, respectively. Even with the use of more difficult sentence material, there has been a continuous increase in speech understanding at 50 dB SPL over the past 20 years.

The current study included presentation levels softer than 50 dB SPL since speech occurs at soft and very soft levels in daily communication. As noted in the Introduction, obtaining optimal audibility for individual CI users can be time consuming and is difficult for some patients. The overall goal of the SoftVoice algorithm is to provide Advanced Bionics CI recipients audibility for soft-speech perception using a clinically feasible method that requires little additional programming time or patient effort and is applicable to all patient populations. Furthermore, the increased audibility for soft speech provided by SoftVoice should not result in performance or sound quality decrements at conversational levels or in noise. Study 1A confirmed the effectiveness of SoftVoice at improving participants’ audibility and soft-speech perception. First, FM tone sound-field thresholds were significantly lower with SoftVoice than Everyday. As reported in previous studies (Firszt et al. 2004;

Geers et al. 2013; Holden et al. 2013a), there was a relationship between sound-field threshold levels and soft-speech perception. Specifically, lower SF-AAFs were significantly correlated with better soft-speech scores, regardless of program (Figure 4). On the other hand, length of CI experience was positively correlated with soft-speech scores for Everyday but not for SoftVoice, suggesting that SoftVoice might be equally beneficial to newly implanted as well as experienced CI users. Second, group mean sentence scores in quiet at all soft presentation levels (35, 40, 45, and 50 dB SPL) were significantly higher with SoftVoice than Everyday. Interestingly, there were no significant differences, in either quiet or noise, between Everyday and SoftVoice for the SRT test. Given participants' good audibility and considerable word recognition with both programs, it is possible that the closed-set task used in the SRT test may not have been sensitive to the differences in audibility between programs. Lastly, no significant differences in speech understanding were found between Everyday and SoftVoice at conversational levels in quiet or noise. In other words, results from Study 1A suggest that implementing SoftVoice would not be detrimental to speech understanding in most listening situations encountered in daily life.

To this point, Study 1B participants compared Everyday and SoftVoice at home for two weeks. Questionnaire results revealed no significant differences in ratings between programs for any listening situation, indicating that SoftVoice was not detrimental to speech understanding in daily life, or conversely, no significant benefit was obtained with SoftVoice. The lack of a significant difference in ratings between programs could be attributed to the listening situations on the questionnaire. The majority of listening situations were those in which the participant listened to conversational speech in quiet or in noise. Study results showed no significant differences between programs for those conditions. Perhaps questionnaire items specifically addressing soft-speech understanding are needed to parse out differences between programs. The question regarding the presence of irritating environmental sound did, however, reveal a significant difference between programs with six of ten participants reporting bothersome sound with SoftVoice. Those six participants all had Ts above 10% of Ms. The combination of raised Ts and SoftVoice likely led to an increase in audibility and consequently, an increase in unwanted environmental sound. During the study, data logging was not available; therefore, the total time that participants wore each program was unknown. It is possible that participants, especially those reporting bothersome environmental sound, mainly used their familiar, Everyday program during the take-home comparison. Perhaps with an extended period of SoftVoice use or implementation of SoftVoice at or soon after the initial CI activation, individuals could acclimatize to the increase in environmental sound with SoftVoice.

Study 2 investigated the hypothesis that decreasing Ts to the default setting of 10% of Ms with SoftVoice may reduce bothersome sound and still provide soft-speech perception comparable to Everyday (Ts above 10% of Ms). After two-weeks use of SoftVoice (Ts at 10% of Ms) and Everyday (Ts above 10% of Ms) on the Naida processor, speech recognition results were not significantly different between programs for FM tone sound-field thresholds, sentence scores in quiet at 50 dB SPL or sentence scores in noise (60 dB SPL, + 8 SNR); however, sentence scores at the two softest presentation levels (40 and 45 dB SPL) were significantly higher with Everyday (Ts above 10% of Ms) than SoftVoice (Ts at 10% of Ms) (Figure 6). Even though results indicated that soft-speech perception was not

comparable between SoftVoice (Ts at 10% of Ms) and Everyday (Ts above 10% of Ms), reports of bothersome environmental sound with SoftVoice were reduced in Study 2 compared to Study 1B. The reduction in bothersome sound can likely be attributed to both the decrease in Ts with SoftVoice and the use of the Naida processor with its lower noise floor compared to the Harmony processor (used in Study 1B).

For this group of participants, SoftVoice with Ts behaviorally set above 10% of Ms provided the best soft-speech perception. However, Everyday (Ts above 10% of Ms) provided better soft-speech perception than SoftVoice (Ts at 10% of Ms). Overall, study results indicate that even with SoftVoice implemented, setting Ts ensures the audibility necessary to understand soft and very soft speech; consequently, additional programming time and patient effort may still be required to obtain optimum benefit from SoftVoice. The results, however, may have been impacted by the small number of participants, and the fact that the majority of participants had substantial experience using programs with Ts above 10% of Ms. Participants' long-term use of raised T-level programs contraindicated an at-home comparison of Everyday and SoftVoice with Ts at 10% of Ms and may have biased preferences towards programs providing increased audibility. Additionally, even though an effort was made to include a wide range of performance outcomes, the majority of participants in this study were above average performers and may not be representative of the postlingual, adult CI population whose CNC scores typically span a wider range. Therefore, definitive conclusions can not be drawn from this study regarding SoftVoice benefit for individuals experienced using Ts at the default setting of 10% of Ms or for below average performers. Results from the current study do provide some evidence that SoftVoice may benefit these individuals. As shown in Figure 3, several participants with the lowest composite soft-speech scores obtained 10 percentage point improvement with SoftVoice compared to Everyday. Additionally, when participants' T-levels were identical between Everyday and SoftVoice, group mean sentence scores (at soft presentation levels) were better with SoftVoice compared to Everyday (Figure 2 and Table 6), indicating that if Ts are set to default with both programs, best soft-speech perception would be provided by SoftVoice. Nonetheless, optimal soft-speech perception is likely to occur with SoftVoice when Ts are behaviorally set above 10% of Ms. Besides setting Ts, other programming parameters potentially could improve soft-speech perception when used in combination with SoftVoice. Participants in Study 2 used the manufacturer's default IDR setting of 60 dB when comparing Everyday (Ts above 10% of Ms) and SoftVoice (Ts at 10% of Ms). Previous research has shown that increasing IDR can improve soft-speech perception (Zeng et al. 2002; Spahr et al. 2007; Davidson et al. 2009; Holden et al. 2011). Subsequently, using SoftVoice in conjunction with a wider IDR (e.g., 70 vs. 60) may provide better soft-speech understanding than seen in this study, especially when Ts are set at 10% of Ms. Likewise, the noise suppression algorithm, ClearVoice High, may be more effective at alleviating bothersome environmental sound when used in combination with SoftVoice than ClearVoice Medium (used by most participants in this study, see Table 1). Stationary or steady-state noise is attenuated by up to -18 dB when ClearVoice High is activated in the sound processor program compared to -12 dB with ClearVoice Medium (Buechner et al. 2010; Holden et al. 2013b). Overall, study findings indicate that SoftVoice has the potential to be a

useful tool in optimizing audibility and in turn, soft-speech perception, especially when behaviorally setting Ts is not a viable option.

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Figure 1.

The activation pattern for each electrode for the recorded speech token /aSa/ without SoftVoice applied (left panel) and with SoftVoice applied (right panel).

Figure 2.

Group mean scores with Everyday and SoftVoice for AzBio sentences in quiet (35, 40, 45, 50 and 60 dB SPL presentation levels), AzBio sentences in noise (60 dB SPL, +8 dB SNR), and CNC words in quiet (60 dB SPL). Error bars represent ± 1 standard error of the mean. Asterisks denote significant differences, *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. dB = decibels, SNR = signal-to-noise ratio, SPL = sound pressure level.

Figure 3.

Composite soft-speech scores (AzBio sentence scores averaged across 35, 40, 45 and 50 dB SPL presentation levels) with Everyday and SoftVoice for each participant. Participants are ordered by Everyday scores. Error bars represent ± 1 standard error of the mean.

Figure 4.

Each participant's frequency modulated tone sound-field threshold levels, averaged across frequencies (250–6000 Hz) with Everyday (A) and SoftVoice (B) plotted in relation to each participant's composite soft-speech score with Everyday and SoftVoice. dB = decibel, HL = hearing level, SF-AAF = sound-field thresholds averaged across frequencies.

Panel A: Harmony Processor Study 1B

Panel B: Naida Processor Study 2

Figure 5.

Group mean ratings for Everyday and SoftVoice for questionnaire items 1 – 21. Panels A and B represent Study 1B and Study 2 results, respectively. Error bars represent ± 1 standard error of the mean.

Figure 6.

Group mean AzBio sentence scores in quiet (40, 45, 50 dB SPL presentation level) and in noise (60 dB SPL, +8 dB SNR) for Everyday (Ts above 10% of Ms) and SoftVoice (Ts at 10% of Ms) with the Naida processor. Error bars represent ± 1 standard error of the mean.

Asterisk denotes a significant difference, * $p < 0.05$. dB = decibels, SNR = signal-to-noise ratio, SPL = sound pressure level.

Figure 7.

Group mean AzBio sentence scores in quiet at 40, 45 and 50 dB SPL for two SoftVoice programs (Naida processor) differing in T-level settings, i.e., SoftVoice (Ts above 10% of Ms) and SoftVoice (Ts at 10% of Ms). Error bars represent ± 1 standard error of the mean. Asterisk denotes a significant difference, $*p < 0.05$. SPL = sound pressure level.

Table 1.

Participant demographic, device, and sound processor program information

Part ID	Age	Listening Mode	CI Device	CI Use (Years)	Study TE	LOD TE	Processor	Strategy	ClearVoice Setting	T-Level Setting	Clinical CNC score TE	Part in Study IB
1	59	Bilateral	R - CII/IJ	R - 11	L	11	Naida	HiRes Opt P	Med	>10% of Ms	84%	Y
			L - 90K/Helix	L - 7								
2	64	Bilateral	R - CII/IJ	R - 11	R	11	Harmony	HiRes 120 S	Med	>10% of Ms	88%	Y
			L - 90K/IJ	L - 7								
3	59	Bilateral	R - CII/IJ	R - 11	R	8	Harmony	HiRes Opt S	Med	> 10% of Ms	77%	N
			L - 90K/IJ	L - 5								
4	54	Bilateral	R - 90K/IJ	R - 1.5	L	10	Harmony	HiRes 120 S	Med	> 10% of Ms	65%	Y
			L - 90K/IJ	L - 2.5								
5	63	Bimodal	L - 90K/IJ	L - 6	L	4	Naida	HiRes Opt S	Off	> 10% of Ms	76%	Y
6	57	Bilateral	R - 90K/IJ	R - 7	R	5	Naida	HiRes Opt S	Med	= 10% of Ms	70%	N
			L - 90K/IJ	L - 5								
7	63	Bimodal	R - 90K/IJ	R - 6	R	8	Naida	HiRes Opt S	Med	> 10% of Ms	84%	Y
8	64	Bimodal	L - 90K/IJ	L - 1.5	L	1.5	Harmony	HiRes Opt S	Off	> 10% of Ms	57%	N
9	62	Bimodal	L - 90K/MS	L - .66	L	9	Naida	HiRes Opt S	Med	> 10% of Ms	58%	Y
10	63	Bilateral	R - 90K/IJ	R - 8.5	L	30	Naida	HiRes Opt S	Med	> 10% of Ms	54%	N
			L - 90K/IJ	L - 6.5								
11	44	Bilateral	R - CII/IJ	R - 12	L	16	Harmony	HiRes 120 S	Off	= 10% of Ms	74%	N
			L - 90K/IJ	L - 3.5								
12	77	Bimodal	L - 90K/IJ	L - 5.5	L	25	Naida	HiRes Opt S	Med	> 10% of Ms	57%	Y
13	69	Unilateral	L - CII/IJ	L - 11	L	30	Naida	HiRes Opt S	Med	> 10% of Ms	61%	Y
14	74	Unilateral	R - 90K/IJ	R - 6.5	R	2	Naida	HiRes Opt S	Med	= 10% of Ms	62%	N
15	61	Unilateral	R - 90K/IJ	R - 5	R	3	Harmony	HiRes 120 S	Med	> 10% of Ms	63%	Y
16	73	Bimodal	R - 90K/Helix	R - 9	R	5	Harmony	HiRes 120 S	Low	= 10% of Ms	65%	Y

CI=Cochlear Implant, CNC=Consonant-Vowel-Consonant, HiRes Opt P=HiRes Optima-Paired, HiRes Opt S=HiRes Optima-Sequential, HiRes 120 S=HiRes 120-Sequential, L=Left ear, LOD=Length of Deafness, Ms=electrode most comfortable levels, Med=Medium, N=no, Part=Participant, R=Right ear, TE=Test Ear, Y=yes, CI Devices: CII/IJ=CII with HiFocus IJ electrode, 90K/Helix=HR90K with Helix electrode, 90K/IJ=HR90K with HiFocus IJ electrode, 90K/MS=HR90K Advantage with Midscale electrode

Table 2.

Test Measures

Test Measures	Presentation Level
CNC Monosyllabic Words	60 dB SPL
AzBio Sentences in quiet	35, 40, 45, 50, and 60 dB SPL
AzBio Sentences in noise (SNR = +8 in 4-talker babble)	60 dB SPL
SRT test (quiet, single-talker competing noise, multi-talker babble)	Adaptive

CNC=Consonant-Vowel-Consonant, dB=decibel, SNR=signal-to-noise ratio, SPL=sound pressure level

Table 3.

Correlation results

Comparison	Correlation
Age	
vs Everyday soft speech	−0.10
vs SoftVoice soft speech	−0.20
T-level settings	
vs Everyday soft speech	0.19
vs SoftVoice soft speech	0.31
Length of CI Experience	
vs Everyday soft speech	0.57 *
vs SoftVoice soft speech	0.43
vs Everyday Audibility (SF-AAF)	−0.27
vs SoftVoice Audibility (SF-AAF)	−0.10
Audibility (SF-AAF)	
vs Everyday soft speech	−0.76 ***
vs SoftVoice soft speech	−0.65 **
Everyday Audibility (SF-AAF)	
vs SoftVoice Audibility (SF-AAF)	0.83 ***
Everyday soft speech	
vs SoftVoice soft speech	0.89 ***

Note:

* p 0.05,
** p 0.01,
*** p 0.001,

SF-AAF = sound-field thresholds averaged across frequencies

Table 4.

Items listed on the questionnaire

Rate how well you hear and understand speech with program 1 and 2 in the following situations.	
1	Conversation in a quiet room with one person
2	Conversation in a quiet room with several people
3	Conversation with several friends around dinner table
4	Conversation on the telephone or cell phone
5	Message on an answering machine or voice mail
6	News on TV
7	Movies/dramas/sitcoms on TV
8	Radio in the car
9	Radio/computer at home in a quiet room
10	Lyrics to music
11	Conversation in a car
12	Conversation with friends at a social gathering
13	Conversation at a restaurant
14	Conversation with a cashier at the grocery store
15	Conversation with a child
16	Conversation outside
17	Someone speaking from a distance
18	Church service
19	Meeting in a large room
20	Rate how well you hear environmental sounds (especially soft sounds) with each program.
21	Rate your overall speech understanding with each program.
22	a) Were any environmental sounds irritating with program 1?
	b) Were any environmental sounds irritating with program 2?

Table 5.

Study 2 participants' test ear, daily-use sound processor, and program information

Participants	Test Ear	Sound Processor(s)	Strategy	T-levels as a percentage of M-levels
1	Bilateral	Naida	HiRes Opt P	R: 19%, L: 33%
2	Bilateral	Harmony	HiRes Opt S	R: 29%, L: 27%
4	Bilateral	Harmony	HiRes Opt S	R: 48%, L: 30%
5*	Bilateral	Naida	HiRes Opt S	R: 62%, L: 39%
7	R	Naida	HiRes Opt S	40%
8	L	Harmony	HiRes Opt S	23%
9	L	Naida	HiRes Opt S	34%
12	L	Naida	HiRes Opt S	18%
13	L	Naida	HiRes Opt S	29%
15	R	Naida	HiRes Opt S	34%

* Participant 5 was bilaterally implanted prior to Study 2 (Right CI: HR90K Advantage with Midscale electrode). Avg= Average, HiRes Opt P=HiRes Optima-Paired, HiRes Opt S=HiRes Optima-Sequential, L=Left, R=Right

Group mean AzBio sentence scores with Everyday and Softvoice for each presentation level and sound processor.

Table 6.

Harmony (N=10)	Everyday Mean Score	SoftVoice Mean Score	Naida (N=10) Everyday Mean Score	SoftVoice Mean Score
Presentation Level				
40 dB SPL	28%	41%	30%	39%
45 dB SPL	45%	61%	51%	61%
50 dB SPL	58%	73%	69%	77%
60 dB SPL, +8 SNR	38%	42%	47%	48%

dB=Decibel, N=Number, SNR=Signal-to-Noise Ratio, SPL=Sound Pressure Level