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Speech Perception for Adult Cochlear Implant Recipients in a Realistic Background Noise: Effectiveness of Preprocessing Strategies and External Options for Improving Speech Recognition in Noise

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Abstract

Background—Although cochlear implant patients are achieving increasingly higher levels of performance, speech perception in noise continues to be problematic. The newest generations of implant speech processors are equipped with preprocessing and/or external accessories that are purported to improve listening in noise. Most speech perception measures in the clinical setting, however, do not provide a close approximation to real-world listening environments.

Purpose—To assess speech perception for adult cochlear implant recipients in the presence of a realistic restaurant simulation generated by an eight-loudspeaker (R-SPACE™) array in order to determine whether commercially available preprocessing strategies and/or external accessories yield improved sentence recognition in noise.

Research Design—Single-subject, repeated-measures design with two groups of participants: Advanced Bionics and Cochlear Corporation recipients.

Study Sample—Thirty-four subjects, ranging in age from 18 to 90 yr (mean 54.5 yr), participated in this prospective study. Fourteen subjects were Advanced Bionics recipients, and 20 subjects were Cochlear Corporation recipients.

Intervention—Speech reception thresholds (SRTs) in semidiffuse restaurant noise originating from an eight-loudspeaker array were assessed with the subjects' preferred listening programs as well as with the addition of either Beam™ preprocessing (Cochlear Corporation) or the T-Mic® accessory option (Advanced Bionics).

Data Collection and Analysis—In Experiment 1, adaptive SRTs with the Hearing in Noise Test sentences were obtained for all 34 subjects. For Cochlear Corporation recipients, SRTs were obtained with their preferred everyday listening program as well as with the addition of Focus preprocessing. For Advanced Bionics recipients, SRTs were obtained with the integrated behind-the-ear (BTE) mic as well as with the T-Mic. Statistical analysis using a repeated-measures

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analysis of variance (ANOVA) evaluated the effects of the preprocessing strategy or external accessory in reducing the SRT in noise. In addition, a standard *t*-test was run to evaluate effectiveness across manufacturer for improving the SRT in noise. In Experiment 2, 16 of the 20 Cochlear Corporation subjects were reassessed obtaining an SRT in noise using the manufacturer-suggested "Everyday," "Noise," and "Focus" preprocessing strategies. A repeated-measures ANOVA was employed to assess the effects of preprocessing.

Results—The primary findings were (i) both Noise and Focus preprocessing strategies (Cochlear Corporation) significantly improved the SRT in noise as compared to Everyday preprocessing, (ii) the T-Mic accessory option (Advanced Bionics) significantly improved the SRT as compared to the BTE mic, and (iii) Focus preprocessing and the T-Mic resulted in similar degrees of improvement that were not found to be significantly different from one another.

Conclusion—Options available in current cochlear implant sound processors are able to significantly improve speech understanding in a realistic, semidiffuse noise with both Cochlear Corporation and Advanced Bionics systems. For Cochlear Corporation recipients, Focus preprocessing yields the best speech-recognition performance in a complex listening environment; however, it is recommended that Noise preprocessing be used as the new default for everyday listening environments to avoid the need for switching programs throughout the day. For Advanced Bionics recipients, the T-Mic offers significantly improved performance in noise and is recommended for everyday use in all listening environments.

Keywords

Beam™; beamforming; cochlear implants; R-SPACE™; speech perception in noise; T-Mic®

INTRODUCTION

Cochlear implant technology continues to afford increasingly higher levels of speech understanding. Considering that the earliest cochlear implant recipients were never expected to achieve open-set speech understanding, the current industry standard of approximately 60% correct for monosyllabic word recognition is quite remarkable (e.g., Balkany et al, 2007; Gifford et al, 2008). Cochlear implant recipients, however, continue to exhibit considerable difficulty understanding speech in background noise. At signal-to-noise ratios (SNRs) that produce little or no decrement in performance for normal-hearing listeners, mean electric-only sentence recognition for cochlear implant users ranges between 64% for Hearing in Noise Test (HINT) sentences at +10 dB SNR (Balkany et al, 2007), 37% for HINT sentences at + 8 dB SNR (Firszt et al, 2004), and as low as 22% for AzBio sentences at +5 dB SNR (Dorman et al, 2008).

Another commonly used metric to estimate speech perception in noise is the speech reception threshold (SRT). The SRT uses an adaptive procedure to estimate the signal-to-noise ratio necessary to achieve 50% correct recognition. Recent studies using a pseudo-adaptive metric to estimate the SRT (i.e., the Bamford-Kowal-Bench Sentences-in-Noise Test [BKB-SIN; Etymōtic Research, 2005]) reported that the SNR required for unilateral and bilateral implant recipients to achieve approximately 50% correct (SNR-50) ranges from 3.5 dB to over 20 dB, with mean performance ranging from 10.5 to 11.4 dB across studies

(Litovsky et al, 2006; Gifford et al, 2008; Zeitler et al, 2008). Considering that mean SNR-50 for normal-hearing listeners is 0.75 dB for the BKB-SIN (Wilson et al, 2007), it is clear that even the best-performing cochlear implant patients demonstrate a substantial deficit for speech understanding in noise.

Cochlear implant recipients often report that improving speech understanding in noise is a top priority. There are several external accessories that can be used with cochlear implant sound processors to help improve the SNR. It is common knowledge that the use of frequency modulation (FM) systems can significantly increase the SNR delivered to listeners using hearing aids. There are also a number of reports documenting improvements in speech recognition—both in quiet and in noise—for cochlear implant recipients using FM systems (Schafer and Thibodeau, 2004, 2006; Wolfe and Schafer, 2008; Wolfe et al, 2009). In fact, Wolfe and Schafer (2008) demonstrated a highly significant 44-percentage-point improvement for HINT sentence recognition in the presence of four-talker babble at +5 dB SNR using an FM system coupled to a cochlear implant sound processor for adult recipients. In a similar study, Fitzpatrick et al (2009) report significant improvement for AzBio sentence recognition in the presence of multitalker babble for adult cochlear implant users. The degree of improvement was 20.4 and 17.5 percentage points for +10 and +5 dB SNR, respectively. Despite such dramatic improvement for performance in noise, FM systems are rarely utilized for adult cochlear implant recipients. A likely reason for this underutilization is related to the considerable out-of-pocket cost for the FM system. Of course, other nontrivial reasons are also likely factors. For example, FM systems lack practicality in group settings where multiple talkers are present, as multiple talkers would be required to wear a transmitter/microphone unit. Clinicians may not be completely comfortable explaining the use of the FM system and/or in optimizing cochlear implant processor settings for an FM system program. In addition, potential users of FM systems may consider them too cumbersome to use and/or think that they attract unwanted attention.

Signal Processing for Enhancing the SNR

Considerable attention has been paid to the development of methods that would improve the SNR for cochlear implant users. With the commercial release of the Freedom sound processor in 2005, Cochlear Corporation incorporated a two-microphone adaptive beam-former referred to as Beam™. As explained by Spriet et al (2007), Beam combines both a front directional and a rear omnidirectional microphone on the processor. The directional microphone system contains two ports separated by 0.7 cm. The rear omnidirectional microphone is separated from the front port of the directional microphone by 1.9 cm. For additional detail regarding the Beam system, see Spriet et al (2007). Spriet et al (2007) obtained SRTs for five adult cochlear implant users using a standard directional microphone system as compared to Beam preprocessing. They used two different noise source conditions: (1) 90 degrees and (2) 90, 180, and 270 degrees. For a single noise location of 90 degrees, Spriet et al (2007) found that the mean improvement of the SRT in noise for Beam was 13.4 dB and 15.9 dB for steady-state noise and multitalker babble, respectively. For noise originating from 90, 180, and 270 degrees, the mean improvement of the SRT in noise for Beam was 6.5 dB and 11.6 dB for steady-state noise and multitalker babble, respectively.

For both noise source conditions, the improvement in the SNR was found to be statistically significant.

The improvement demonstrated by Beam, while substantial, was established using discrete noise source locations that are not typically encountered in the real world. In fact, one could argue that the experimental conditions chosen were those that would have the greatest possibility of showing benefit. Generally, a more diffuse noise is encountered in everyday life in restaurants, shopping centers, social gatherings, sporting events, etc. For patient counseling purposes, it is important to assess the effectiveness of Beam in improving speech recognition in noise for more realistic listening environments.

Microphone Location Designed to Enhance the SNR

Another advancement of the cochlear implant processor design that was intended to aid with speech recognition in noise is the T-Mic® by Advanced Bionics. The T-Mic uses the same omnidirectional transducer as the one integrated in the behind-the-ear (BTE) micro-phone, with the exception that the microphone location is proximal to the pinna at the opening of the external auditory canal. The placement of the T-Mic is intended to allow the listener to take advantage of the natural amplification and frequency response characteristics offered by the pinna as well as a "natural directivity," as its placement allows for acoustic enhancement of high-frequency sounds arriving from in front of the listener while attenuating high-frequency sounds arriving from the rear (e.g., Shaw, 1974). Secondary intended uses of the T-Mic include a more natural use of telephone receivers and headphones or earbuds. Frohne-Büchner et al (2004) examined the effectiveness of the T-Mic for eight adult cochlear implant recipients for subjective comfort and sound quality as well as for usefulness of talking on the telephone. In addition, for a single subject, Frohne-Büchner et al (2004) examined localization for a 12-loudspeaker array for the T-Mic as compared to the standard BTE microphone. The subjective ratings of comfort and sound quality were overwhelmingly positive for seven of the eight subjects. For the single-subject localization experiment, less localization error was found for the T-Mic. While these reports are positive, the researchers failed to report on the potential benefit of the natural directivity of the T-Mic for speech understanding in noise, which continues to be one of the greatest complaints for cochlear implant recipients.

The Present Study

Given that Beam is recommended to Cochlear Corporation implant recipients for *focused* listening in noise, one must question the impact that Beam may have on listening in the type of noise that most cochlear implant recipients would report as being most bothersome—such as the high-level, multitalker, semidiffuse noise typically encountered in a restaurant or at a social gathering. Furthermore, for Advanced Bionics cochlear implant recipients, the claimed natural directivity offered by the T-Mic has yet to be shown to improve speech recognition in such a realistic noise environment. Thus the purpose of the current study was to examine the effectiveness of Beam (Cochlear Corporation) and the T-Mic (Advanced Bionics) for improving speech recognition in high-level, semidiffuse noise as might be encountered in an everyday noisy listening environment.

EXPERIMENTAL DESIGN

Subjects

Speech recognition performance both in quiet and in noise was assessed for 34 adult cochlear implant recipients (12 male, 22 female). The mean age of the subjects at the time of testing was 54.5 yr, with a range of 18 to 90 yr (median 58.5 yr). The mean duration of cochlear implant use at the time of evaluation was 45.9 mo, with a range of 8 to 200 mo (median 65.0 mo). Of the 34 subjects, 20 were recipients of Cochlear Corporation implants and 14 were Advanced Bionics recipients. Tables 1 and 2 provide details regarding subject age, months of experience with electric stimulation, etiology, device type, and preferred program or mic location.

All 34 subjects were recruited from the clinical database of adult cochlear implant recipients at the Mayo Clinic in Rochester, Minnesota. Recruitment letters were mailed to all postlingually deafened, adult cochlear implant recipients wearing Nucleus Freedom, Advanced Bionics Auria, or Advanced Bionics Harmony sound processors. The recruitment letter stated that testing could be completed at the time of their next scheduled programming appointment or at a separately scheduled appointment. Subject remuneration was provided.

Stimuli and Methods

Experiments were conducted using the Revitronix R-SPACE™ environment simulation system (Revit et al, 2002, 2007). This system consists of an eight-loudspeaker array that is placed in a circular pattern around the subject. Each loudspeaker is placed at ear level and at a distance of 24 in (60 cm) from the subject's head. The loudspeakers are each separated by 45 degrees. A schematic of the loudspeaker array is shown in Figure 1. In validation studies, the restaurant environment simulated by this system has been shown to yield speech-intelligibility-in-noise results that are very similar to those for real-world conditions, for normal-hearing listeners (Compton-Conley et al, 2004) and hearing-impaired listeners (Revit et al, 2007).

The proprietary restaurant environment recordings were recorded in a real restaurant using eight highly directional microphones set in a circular pattern similar to that of the loudspeakers diagramed in Figure 1. The eight tracks that were captured in the restaurant were fed to the eight loudspeakers at respective positions in the R-SPACE playback system. The restaurant noise and target speech stimuli were delivered to the loudspeakers via a computer-controlled, multichannel, digital audio system. During experiments, all target speech stimuli originated from the loudspeaker at 0 degrees azimuth, and the noise tracks originated from all eight loudspeakers—re-creating acoustic conditions that typically occur at a large social gathering or noisy restaurant.

We assessed HINT sentence recognition in the background of restaurant noise originating from the eight-loudspeaker array. The adaptive HINT procedure (Nilsson et al, 1994) was used to determine the SNR required to achieve 50% correct recognition using a one-down, one-up stepping rule (e.g., Levitt, 1971). The noise level was fixed at 72 dB SPL to simulate the average level of the noise observed during the recordings. For each trial, two 10-sentence lists were concatenated and run in sequence. The last six presentation levels for sentences 15 through 20 were averaged to provide an SRT. Two runs of 20-sentence lists were presented for each listening condition, and the mean of the two SRT estimates was taken to represent a single SRT, in dB SNR, for any given condition. The reliability of this scoring procedure was demonstrated by Gifford et al (2007). Prior to data collection, all the subjects were presented with a practice run of 20 sentences to familiarize them with the task. The sentence lists and the condition for each run were randomly selected to counterbalance for order effects. Though this information was not intentionally withheld from the subjects, they were not directly told which of the listening programs was being used for a given listening condition as the experimenter manually switched the processor programs.

In addition to the adaptive HINT sentence-recognition-in-noise procedure with the R-SPACE system, all subjects were also assessed on speech-perception performance in quiet. HINT sentence recognition in quiet was assessed for all participants to ensure that at least 50% correct performance could be achieved in quiet prior to the administration of the adaptive SRT procedure. Consonant–nucleus–consonant (CNC [Peterson and Lehiste, 1962]) monosyllabic word recognition was also assessed using a single 50-item list for all participants. For both the HINT sentences in quiet and the CNC words, speech stimuli were presented at a calibrated presentation level of 60 dBA using a single loudspeaker placed at 0 degrees azimuth at a distance of 1 m from the listener. Speech-perception scores in quiet are presented in Tables 1 and 2 for all participants. For all 34 subjects, the mean speech-perception scores in quiet for CNC words and HINT sentences were 76.3% and 96.0%, respectively. Stratifying subjects on the basis of manufacturer, Cochlear Corporation and Advanced Bionics recipients performed quite similarly in quiet, with mean performance at 76.5% and 76.0% correct, respectively, for CNC words and 95.6% and 96.2% correct, respectively, for HINT sentences. On average, these subjects were performing above the current industry standards for cochlear implant recipients for the CNC and HINT sentence stimuli (e.g., Firszt et al, 2004; Balkany et al, 2007; Gifford et al, 2008).

The total time spent in the study for each subject averaged 2 hr, which included consenting, equipment checks of sound processors, and all speech-perception testing. Frequent breaks were offered at 15 to 20 min intervals, though the majority of subjects took just a single 15 min break during the 2 hr session.

Cochlear Corporation Recipients

All 20 recipients of a Cochlear Corporation implant used Freedom sound processors. Each of the 20 subjects was tested using his or her own everyday listening program and preferred preprocessing strategy (autosensitivity [ASC], adaptive dynamic range optimization [ADRO], or ASC + ADRO as shown in Table 1) as well as with the manufacturer-suggested "Focus" program, which includes Beam plus ASC plus ADRO. As explained by Dawson et al (2004), ADRO is a preprocessing strategy that adjusts gain across multiple channels to place the output signal *optimally* within the recipient's dynamic range (i.e., the range between the thresholds and maximum comfort levels in each channel). The ultimate goal of ADRO is to provide improved speech perception for low and medium input levels and improved sound quality and loudness comfort for high input levels (James et al, 2002; Blamey et al, 2004). Based upon the work of Dawson and colleagues (2004) Cochlear

Corporation had implemented ADRO as the default preprocessing strategy used for listeners' "Everyday" listening programs (Custom Sound 3.0, Cochlear Corporation).

ASC is also a preprocessing strategy that works across all channels, but in this case to adjust the sensitivity of the microphone based on the noise floor of the incoming signal (Custom Sound 3.0 manual, 2009). When ASC is enabled, if the ambient noise level is ≥57 dB SPL, the speech-processor microphone sensitivity is reduced to ensure that speech peaks exceed the long-term average noise spectrum by at least 15 dB before infinite compression sets in. Conversely, if ASC is not active, once the incoming acoustic signal reaches or exceeds 65 dB SPL—which is the default C-SPL setting—the signal is infinitely compressed.

Of the 20 Cochlear Corporation patients, five were bilateral implant recipients (see Table 1). Given that two of the five bilateral recipients used an older-generation processor on the N22 implanted side (subjects 1 and 12), those two patients were assessed unilaterally with the Freedom processor only, for informational purposes.

Advanced Bionics Recipients

Of the 14 recipients of an Advanced Bionics implant system, two used the Auria processor and 12 used the Harmony processor. All 14, however, had a T-Mic auxiliary (AUX) microphone for use in the current experiment. All subjects were tested using the behind-the-ear integrated processor mic as well as the AUX-only or T-Mic setting. Table 2 notes the individual subject preference for listening in terms of mic location. Five of the 14 subjects used the BTE mic for everyday preferred listening, while the remaining nine subjects preferred a T-Mic. Of the 14 Advanced Bionics patients, three were bilateral implant recipients (see Table 2). All bilateral recipients were tested in their bilaterally implanted condition for the experiment.

Results

Figure 2 displays individual and mean SRT data for the 20 Cochlear Corporation recipients. The dark bars represent the SRT using the subjects' preferred programs, and the shaded bars represent the SRT using the Focus program incorporating Beam plus ASC plus ADRO. For all subjects, the Focus program yielded equivalent or better performance in noise. The degree of improvement in the SNR ranged from 0 to 7.33 dB. Mean SRT performance for the preferred program and Focus was 11.2 and 7.3 dB SNR, respectively. Thus the mean degree of improvement in the SRT demonstrated for all 20 subjects was 3.9 dB. Statistical analysis using a one-way repeated-measures analysis of variance (ANOVA) revealed that the Focus program (i.e., Beam + ASC + ADRO) resulted in significantly better performance in noise over the subjects' own preferred listening programs ($F_{1, 19} = 50.87$, $p < .001$).

Figure 3 displays individual and mean SRT data for the 14 Advanced Bionics recipients. The dark bars represent the SRT using the BTE mic, and the shaded bars represent the SRT using the T-Mic. For all 14 subjects, the T-Mic yielded equivalent or better performance in noise. The degree of improvement in the SRT with the use of the T-Mic ranged from 1.3 to 8.3 dB. Considering mean SRT performance for all 14 Advanced Bionics subjects, mean SRTs for the BTE mic and the T-Mic were 14.6 and 10.2 dB SNR, respectively. Thus the mean degree of improvement in the SNR demonstrated for all 14 subjects with the use of the T-Mic was 4.4 dB. Statistical analysis using a one-way repeated-measures ANOVA revealed that the T-Mic yielded significantly better performance in noise over the processor-integrated BTE mic ($F_{1, 13} = 87.3$, $p < .001$).

As shown in Figures 2 and 3 and in the above described statistical analyses, both Beam and the T-Mic yielded significant improvements in the SRT. In fact, the mean degree of improvement in the SRT was quite similar for Beam and the T-Mic at 3.9 and 4.4 dB, respectively. A statistical analysis using a two-tailed *t*-test revealed no significant difference in the degree of SRT improvement for Beam and the T-Mic ($t = -0.657$, $p = .526$). Thus these results would suggest that (i) Cochlear Corporation and Advanced Bionics have mechanisms by which their recipients can significantly improve speech recognition in noisy environments and (ii) the two approaches result in essentially equivalent improvements in the SRT for high-level, multitalker semidiffuse noise as may be encountered in social gatherings and/or restaurant environments.

During the course of completing experiment 1, the first author polled the 34 subjects to question what they do differently in noise with their listening programs. Of the 20 Cochlear Corporation patients, only two of them (subjects 4 and 12) responded that they routinely switched from their preferred listening program to their Focus program with Beam in noisy environments. The remaining 18 subjects responded that they hardly ever change programs, if at all, as they either were most comfortable with their preferred listening program or didn't like switching programs.

For the 14 Advanced Bionics recipients, the responses were quite similar. The question, however, was posed differently for these subjects. The first author inquired whether those five subjects who preferred using their BTE mic—which yielded poorer outcomes in noise —would be willing to switch to a T-Mic for the majority of their listening environments. Two of the five subjects (2 and 5) were more than willing to switch and even requested that T-Mic programs be loaded to their processors. The remaining three of five subjects preferring the BTE mic (subjects 6, 11, and 12) were unwilling to switch from a BTE mic to a T-Mic. Of interest is that these three subjects were the youngest subjects in the experiments at ages 18, 26, and 27. Subjects 11 and 12 cited cosmetic concerns, whereas subject 6 preferred the overall feel of the smaller ear-hook used with the BTE mic over the T-Mic accessory. Thus, 11 of the 14 Advanced Bionics subjects (79% of the population) either already used their T-Mic for all listening or were convinced to switch to a T-Mic following completion of the experiment.

EXPERIMENT 2

Following the subject poll regarding preferred strategies and/or accessories for everyday listening and noisy listening, a supplemental experiment was designed. Given that 18 of the 20 Cochlear Corporation subjects admittedly did not switch programs in noise to take advantage of their Focus program, one must question whether ADRO—which is the default for the Everyday program in the Cochlear software—is the best preprocessing strategy to allow for high levels of speech perception in noise. Theoretically speaking, the addition of the ASC preprocessing would intuitively yield higher levels of performance in noisy environments over ADRO alone. ASC automatically adjusts mic sensitivity depending upon the background noise level and signal-to-noise ratio at the processor microphone. The default ASC breakpoint is set to 57 dB SPL. Once the level of background noise reaches 57 dB SPL, the sensitivity of the processor mic is reduced such that the peaks of speech are designed to exceed the long-term average noise spectrum by at least 15 dB before infinite compression sets in (Custom Sound 3.0 manual, 2009). Thus it is more likely that an individual already using ASC in his or her preferred program is less likely to notice a large change in speech understanding with the addition of Beam over an individual who is using ADRO alone in his or her everyday program.

Thus a secondary experiment was conducted with 16 of the original 20 Cochlear Corporation subjects. The other four subjects (2, 3, 16, and 20) were unavailable to participate in the second experiment. For the 16 subjects, an SRT was obtained using ADRO (default Everyday strategy), ASC plus ADRO (default Noise strategy), and Beam plus ASC plus ADRO (default Focus strategy). The purpose of this experiment was to determine (i) whether patients might achieve a lower, that is, better, SRT in noise using ASC plus ADRO as compared to ADRO alone; (ii) whether Beam plus ASC plus ADRO yields lower SRTs than both ADRO and ASC plus ADRO; and (iii) whether ASC plus ADRO may be considered a better alternative for an Everyday program in order to aid speech understanding when entering noisy environments, particularly given that many subjects do not regularly switch programs.

As with experiment 1, prior to data collection, all the participants were presented with a trial run of 20 sentences to familiarize them with the task. The sentence lists as well as condition order were randomly selected to counterbalance for order effects. The subjects were not told which program was being used for any of the conditions.

Results

Figure 4 displays individual and mean SRT data for the 16 Cochlear Corporation recipients. The dark bars represent the SRT for Everyday (ADRO), the hatched bars represent the SRT for Noise (ASC + ADRO), and the shaded bars represent the SRT for Focus (Beam + ASC + ADRO). Mean SRT performance for all 16 subjects for Everyday, Noise, and Focus was 12.7, 10.2, and 6.6 dB SNR, respectively. A statistical analysis using a one-way repeated-measures ANOVA revealed a significant effect of preprocessing strategy ($F_{2,35} = 35.5, p < .001$). A post hoc all-pairwise multiple-comparison procedure using a Tukey test revealed a statistically significant difference across all three preprocessing strategies. Comparing Everyday with Noise, the difference between the means was 2.5 dB ($p = .006$). The difference between the means for Everyday and Focus was 6.1 dB ($p < .001$). The difference between Noise and Focus was 3.6 dB ($p < .001$).

The results of experiment 2 provide two main findings. First, given that Noise preprocessing resulted in a lower, that is, better, SRT than Everyday, clinicians should consider using Noise (ASC + ADRO) as the default Everyday program for adult Cochlear Corporation recipients—particularly those who may not be willing or able to change programs in different environments. Second, Focus resulted in the lowest, or best, SRT as compared to either of the two other preprocessing strategies. Thus, clinicians would be advised to educate their patients on the demonstrated effectiveness of Focus in increasing the preprocessing SNR in environments with high levels of diffuse noise even though Focus may not have been designed to work most effectively in such a situation.

DISCUSSION

Improving speech perception in noise for cochlear implant recipients continues to be a high priority for a number of researchers as well as the cochlear implant manufacturers. Even the best-performing patients complain of poor speech understanding in noise, particularly when the background noise reaches high levels and is semidiffuse such as in crowded restaurants and social gatherings. The current study examined commercially available preprocessing strategies or accessories that were designed to increase the SNR of the input signal, thereby leading to improved speech recognition in noise as measured by an SRT metric. For Cochlear Corporation patients, the use of Focus (Beam + ASC + ADRO) was shown to significantly reduce, that is, improve, the SRT over the listeners' preferred listening programs, with a mean improvement of 3.9 dB (individual improvement ranging from 0 to 7.33 dB). For Advanced Bionics patients, the use of the T-Mic, which places the mic close to the pinna at the opening of the ear canal, also significantly reduced the SRT, with a mean improvement of 4.4 dB (individual improvement ranging from 1.3 to 8.3 dB). It is presumed that the primary mechanism for the reduced SRTs is an increase in the effective SNR. One might question the perceived benefit of effectively improving the SNR by 3.9 to 4.4 dB. Previous research has shown that every 1 dB improvement in the SNR can translate to an 8- to 15-percentage-point improvement in speech-recognition performance (e.g., Plomp and Mimpen, 1979; Nilsson et al, 1994; Wouters et al, 1994). Based on estimates from previous studies, for the subjects in the current study using either Focus (Beam + ASC + ADRO) or the T-Mic, we might expect an improvement ranging anywhere from 32 to 66 percentage points for speech understanding in background noise. Clearly, this degree of improvement is substantial.

Cochlear Corporation

Experiment 2 provided some additional findings relating to preprocessing strategies used with Cochlear Corporation patients. Ninety percent of the Cochlear Corporation subjects in the current study admitted to rarely if ever manipulating their processor settings away from their preferred listening program. Given that the default Everyday listening preprocessing strategy is ADRO alone, experiment 2 examined whether the addition of ASC to ADRO might prove a more useful Everyday listening program—particularly for those patients who are known to not change programs. ASC plus ADRO—which is the default Noise setting in the Cochlear Corporation Custom Sound 3.0 software—was shown to yield significantly better SRTs than ADRO alone, with a mean improvement of 2.5 dB. Thus these findings would suggest that clinicians consider using Noise, or ASC plus ADRO, as the default Everyday listening program for cochlear implant patients. A frequent complaint for those patients who have tried ASC and decided against its regular use is that they do not like the perception of sounds getting quieter and louder with changes in their environment.

Wolfe et al (2009) demonstrated similar findings for the addition of ASC to the sound processor settings for 12 adult Cochlear Corporation implant recipients. They demonstrated that the addition of ASC did not affect subjects' HINT sentence recognition in quiet or at a + 10 dB SNR with a "classroom noise" background (Schafer and Thibodeau, 2006). This is an important point, as the addition of ASC would not affect a listener's speech perception in quiet or at a high SNR. For higher-level speech and noise with speech at 70 and 74 dBA and noise at 63 and 70 dBA, respectively, the addition of ASC resulted in significantly higher levels of HINT sentence recognition. In fact, the mean improvement with ASC was 30 percentage points. Wolfe et al (2009) attribute ASC-related improvement to the fact that when ASC is not active, input stimuli exceeding 65 dB SPL are infinitely compressed with the Freedom sound processor. Since individuals tend to increase the level of their voice in the presence of background noise (e.g., Pearsons et al, 1977), when high levels of noise are present, it is likely that the incoming speech signal would be infinitely compressed, resulting in poor speech understanding. In the current study with background noise at 72 dB SPL, ADRO *without* ASC would expectedly infinitely compress both the speech and noise stimuli. Thus, although a positive SNR may be presented acoustically, any fluctuations in the dynamic range of the *processed* speech signal would effectively be reduced or completed eliminated.

Should a clinician prefer not to incorporate ASC, given that the default C-SPL setting is 65 dB SPL— the level at which incoming stimuli are infinitely compressed—another possibility for preserving the dynamics of the *processed* speech at high incoming acoustic levels is to increase the patient's C-SPL setting. The maximum allowable C-SPL setting using the Custom Sound 3.0 software is 84 dB SPL; however, research is needed in order to determine whether manipulating the C-SPL setting(s) might improve speech perception in noise for patients using ADRO without ASC. Thus manipulation of this parameter is *not* recommended until further research is completed.

Despite the fact that ASC plus ADRO was shown to yield significantly lower, that is, better, SRTs than ADRO alone, the addition of Beam provided a further, significant reduction in the SRT for the Cochlear Corporation patients. Thus, regardless of which program patients may prefer for quieter listening environments, the use of the default Focus program (Beam + ASC + ADRO) will yield the best speech perception in semidiffuse noise. Beam was designed to reduce microphone sensitivity in the directions of the noise to the side and behind the listener while allowing for maximum sensitivity for sounds originating from the front. The polar plot pattern for adaptive Beam places a null in the direction of the highest noise location. Beam works best with discrete noise source locations such as those typically designed in the laboratory, with noise at either 90 or 270 or 90, 180, and 270 degrees (e.g., Spriet et al, 2007). Thus, for the current experiment, designed with more realistic semidiffuse noise with loudspeakers placed in a circumferential pattern about the listener's head, it was not known whether the addition of Beam to ASC plus ADRO would truly yield an improvement in speech perception. The fact that such a highly significant improvement in the SRT was observed in this complex listening environment speaks to the need for cochlear implant recipients to be educated and encouraged to use Beam or the Focus program for listening in noise.

Advanced Bionics

The natural directivity offered by the T-Mic over the BTE processor mic can be active in all programs, including the patient's preferred daily listening program. The default microphone setting in the SoundWave software is 50/50, which allows for equal inputs from both the T-Mic and the BTE mic. For the purposes of the current study, 50/50 mixing was not assessed, given that all participating subjects preferred either the T-Mic (AUX only) or the BTE mic. The results of the current study suggest that clinicians should consider setting the default microphone to AUX only for the T-Mic to be active for the recipients' everyday listening programs. This way, the patient is not required to manually switch programs when entering a noisy listening environment but, rather, can take advantage of the natural directivity offered by the T-Mic for all environments.

One potential flaw with the T-Mic-only setting is that, should the T-Mic port become occluded or the T-Mic accessory malfunction, it is not always readily apparent to the listener. Nearly all clinicians have encountered a patient making an appointment for reprogramming or a patient thinking that a processor was defective when, in fact, all that was needed was a T-Mic replacement. It is for this reason that it is essential to provide thorough education for patients using T-Mic-only programs so that they know how to troubleshoot their equipment. Another option would be to provide patients with a backup BTE mic or 50/50 program as a means of diagnosing potential T-Mic problems.

CONCLUSIONS

For speech understanding in environments of high-level, semidiffuse noise, both Beam (Cochlear Corporation) and the T-Mic (Advanced Bionics) yielded significant improvements in the SRT for adult cochlear implant recipients. The degree of improvement in the SRT was essentially equivalent for Beam and the T-Mic accessory. The use of Noise preprocessing (ASC + ADRO) was found to yield lower SRTs than Everyday (ADRO) for Cochlear Corporation patients and is thus suggested for use as the default Everyday preprocessing strategy for adult Cochlear Corporation patients. For listening in noisy environments, however, the use of Focus (Beam + ASC + ADRO) is recommended, as it provided a significantly lower SRT than either ADRO alone or ASC plus ADRO. For Advanced Bionics recipients, the T-Mic, or AUX-only setting, is recommended for both everyday and noisy listening, as it provides natural directivity without the need for switching programs.

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Abbreviations

ADRO	adaptive dynamic range optimization
ASC	autosensitivity

BKB-SIN	Bamford-Kowal-Bench Sentences-in-Noise Test
BTE	behind-the-ear
FM	frequency modulation
HINT	Hearing in Noise Test
SNR	signal-to-noise ratio
SRT	speech reception threshold

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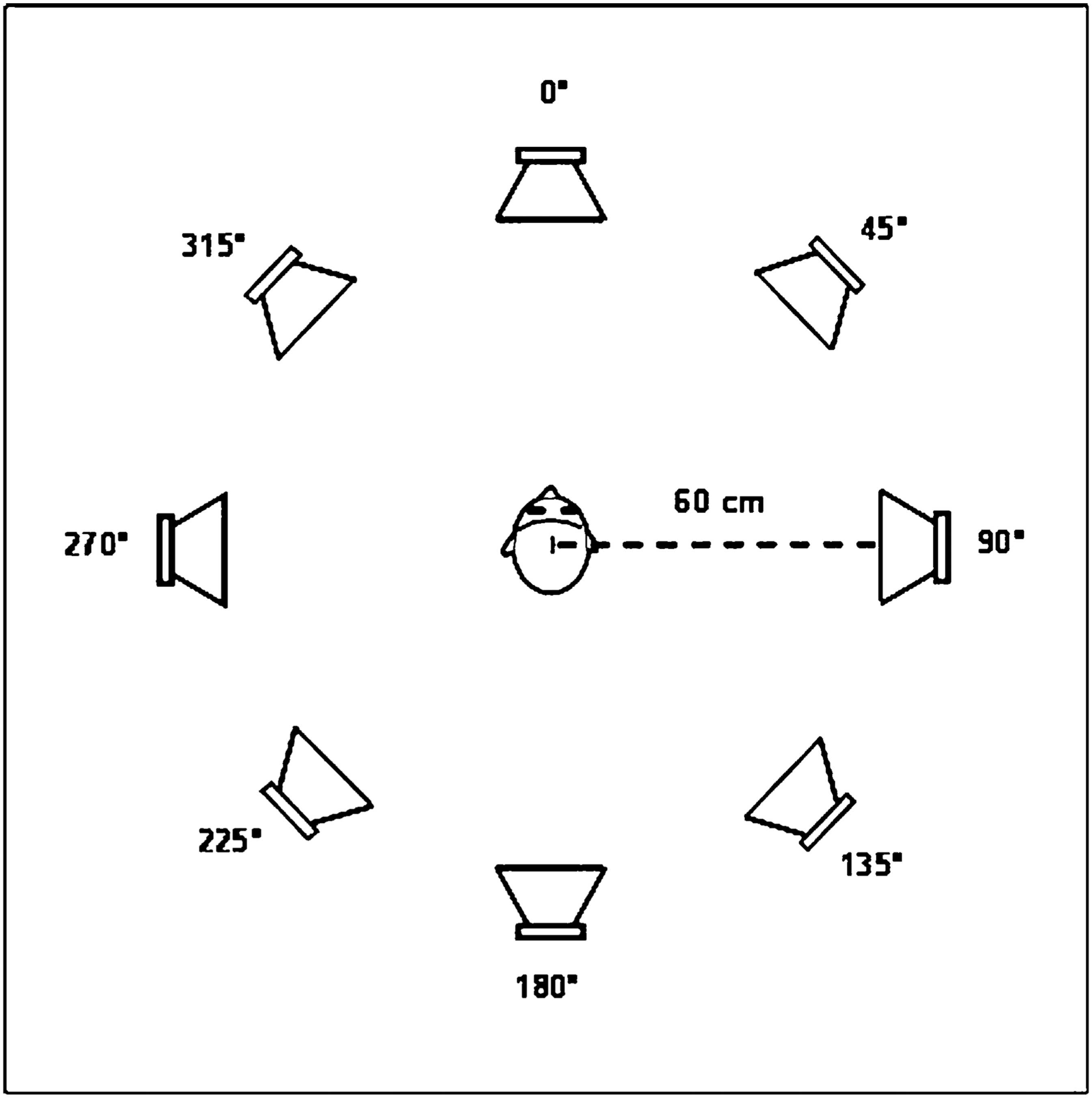

Figure 1.
R-SPACE eight-loudspeaker system.

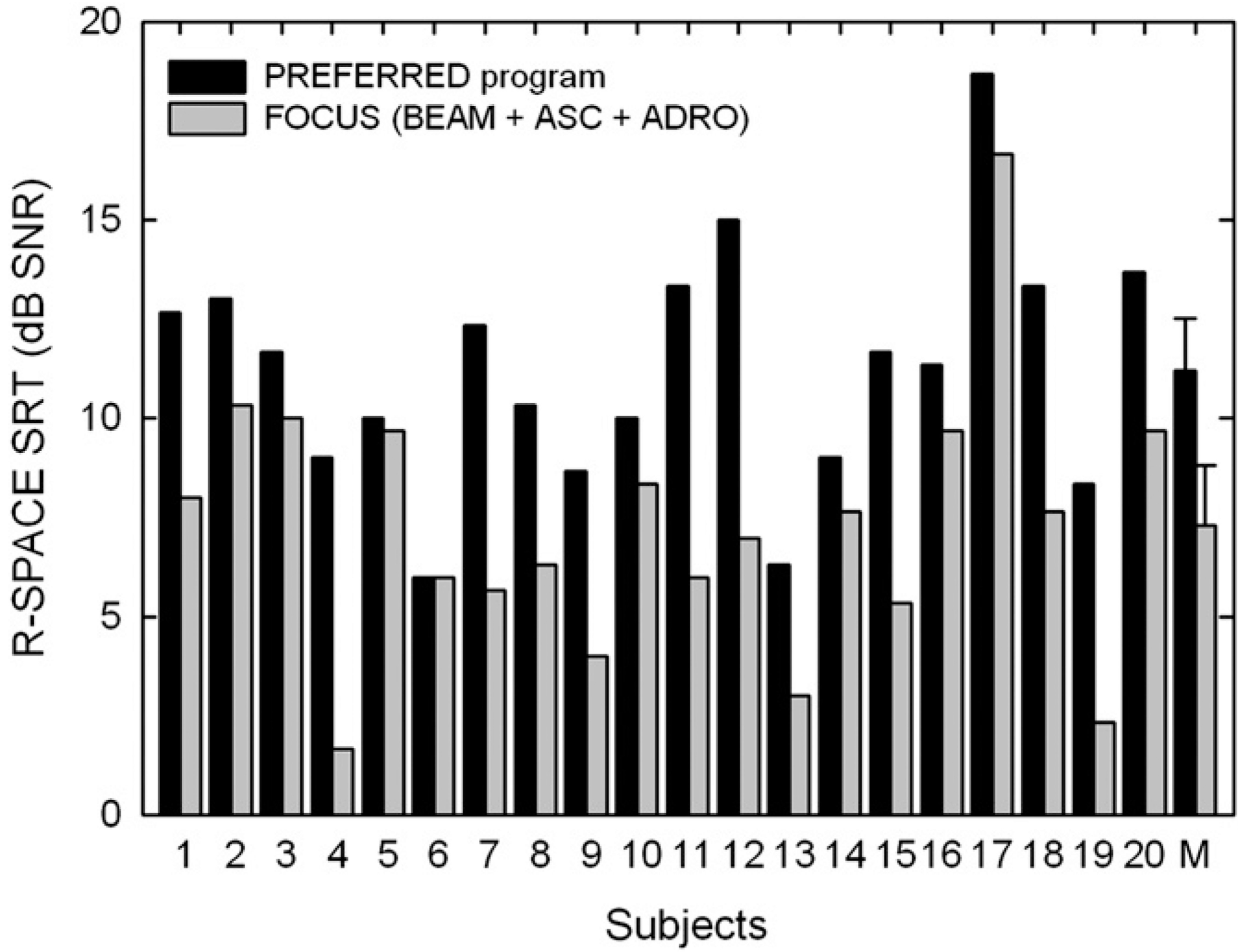

Figure 2.

Individual and mean R-SPACE speech reception thresholds (SRTs) for the 20 Cochlear Corporation recipients. The black and gray bars represent the SRTs obtained with the subjects' preferred preprocessing strategy and Focus (Beam+ autosensitivity + adaptive dynamic range optimization), respectively. Subjects' preferred listening strategies are listed in Table 1. Error bars represent ±2 SE measurements.

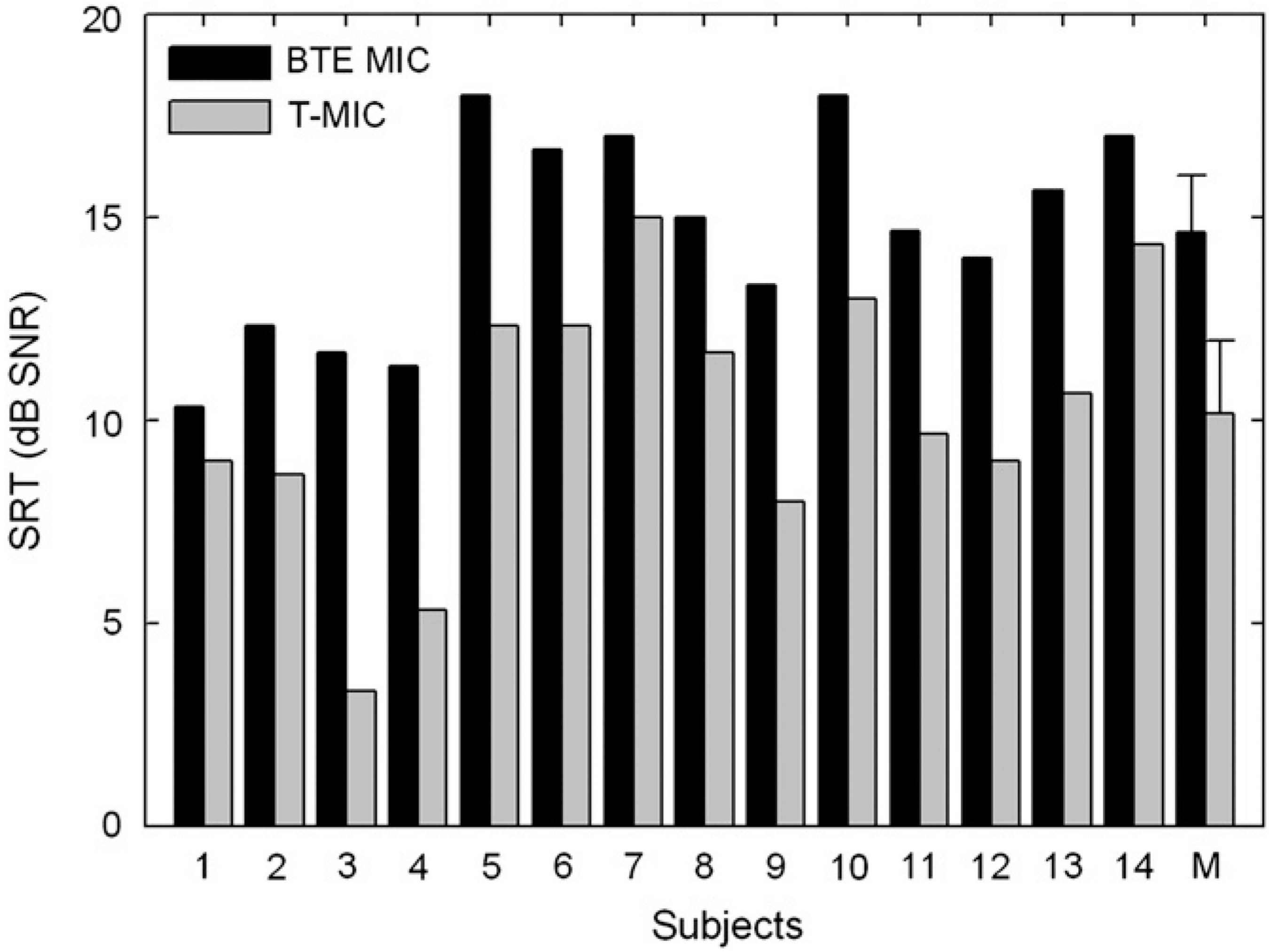

Figure 3.

Individual and mean R-SPACE speech reception thresholds (SRTs) for the 14 Advanced Bionics recipients. The black and gray bars represent the SRTs obtained with the behind-the-ear mic and T-Mic, respectively. Error bars represent ±2 SE measurements.

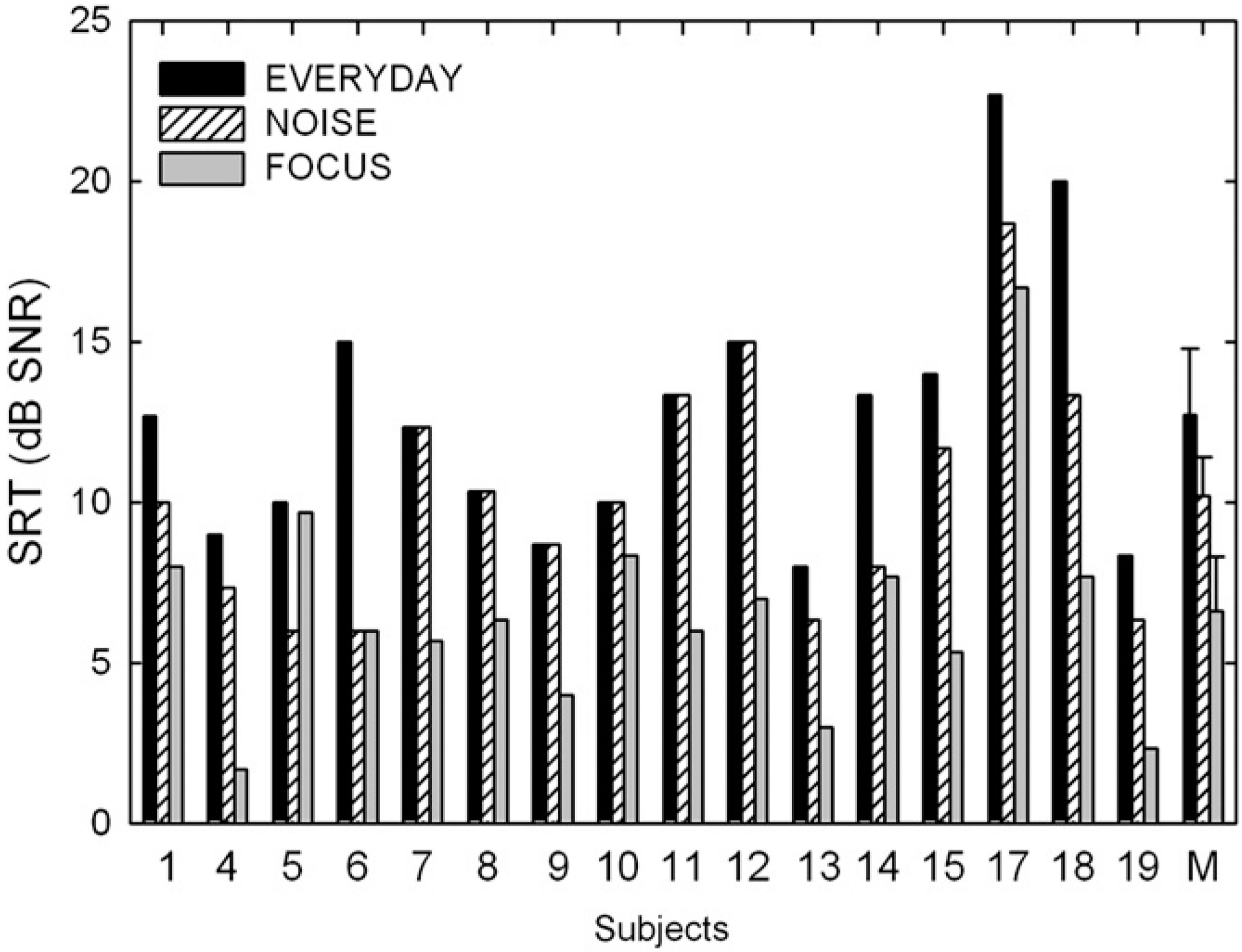

Figure 4.

Individual and mean R-SPACE speech reception thresholds (SRTs) for the 16 Cochlear Corporation recipients who participated in Experiment 2. The black, hatched, and gray bars represent the SRTs obtained with Everyday (adaptive dynamic range optimization [ADRO]), Noise (autosensitivity [ASC] + ADRO), and Focus (Beam + ASC + ADRO), respectively. Error bars represent ±2 SE measurements.

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Table 1

Cochlear Corporation Recipients' Data

Subject	Age at Testing	Months of Experience with Cochlear Implant	Etiology of Hearing Loss	Implant Type	Consonant–Nucleus–Consonant Word-Recognition Score in Quiet (% Correct)	Hearing in Noise Test Sentence-Recognition Score in Quiet (% Correct)	Preferred Everyday Preprocessing Program
1	58	200, 68	Mondini	N22, 24RCS	52	87	autosensitivity (ASC)
2	50	24, 15	autoimmune	24RE, 24RE	76	96	adaptive dynamic range optimization (ADRO)
3	53	12	Enlarged vestibular aqueduct	24RE	72	98	ADRO
4	20	11, 11	Susac syndrome, sudden	24RE, 24RE	88	100	ADRO
5	58	47	autoimmune	24RCS	70	99	ADRO
6	59	49	unknown	24RCA	58	88	ASC + ADRO
7	49	22	otosclerosis	24RCA	80	99	ASC
8	68	31	sudden idiopathic	24RE	80	100	ADRO
9	19	76, 13	congenital, unknown	24M, 24RE	78	98	ADRO
10	69	8	unknown	24RE	54	87	ADRO
11	71	37	sudden idiopathic	24RCA	74	99	ADRO
12	69	131, 72	otosclerosis	N22, 24M	84	99	ADRO
13	68	24	noise exposure/familial	24RE	94	100	ASC + ADRO
14	69	19	familial	24RE	74	93	ASC
15	65	13	unknown	24RE	80	100	ASC + ADRO
16	74	51	radiation	24RE	88	97	ASC + ADRO
17	76	12	mumps	24RE	60	86	ASC + ADRO
18	90	13	noise exposure/presbycusis	24RE	84	98	ASC + ADRO
19	18	9	congenital, unknown	24RE	94	100	ASC
20	67	18	unknown	24RE	90	100	ADRO
MEAN	58.5	40.4	N/A	N/A	76.5	96.2	N/A
SD	19.5	47.6	N/A	N/A	12.6	5.0	N/A

Table 2

Advanced Bionics Recipients' Data

Subject	Age at Testing	Months Experience with Cochlear Implant	Etiology of Hearing Loss	Implant Type	Consonant-Nucleus-Consonant Word-Recognition Score in Quiet (% Correct)	Hearing in Noise Test Sentence-Recognition Score in Quiet (% Correct)	Preferred Mic Location
1	59	71, 48	familial	HR90K, HR90K	82	99	T-Mic
2	63	15	unknown	HR90K	88	100	behind-the-ear (BTE) mic
3	57	60	familial	HR90K	76	96	T-Mic
4	52	80, 12	unknown	CII, HR90K	92	100	T-Mic
5	47	59	rubella (prenatal)	CM	88	99	BTE mic
6	18	25	Usher's syndrome	HR90K	76	94	BTE mic
7	47	70	rubella (postnatal)	CM	68	91	T-Mic
8	36	15	familial	HR90K	62	96	T-Mic
9	66	12	unknown	HR90K	74	95	T-Mic
10	65	19	familial	HR90K	76	98	T-Mic
11	26	82	meningitis (2 yr)	CM	82	96	BTE mic
12	27	85	meningitis (1 yr)	CM	72	98	BTE mic
13	43	84,36	congenital/unknown	CII, HR90K	48	80	T-Mic
14	77	78	familial	HR90K	80	97	T-Mic
MEAN	48.8	53.9	N/A	N/A	76.0	95.6	N/A
SD	17.3	29.6	N/A	N/A	11.4	5.1	N/A