Assessing the Quality of Low-Frequency Acoustic Hearing: Implications for Combined Electroacoustic Stimulation With Cochlear Implants

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Objectives: There are many potential advantages to combined electric and acoustic stimulation (EAS) with a cochlear implant (CI), including benefits for hearing in noise, localization, frequency selectivity, and music enjoyment. However, performance on these outcome measures is variable, and the residual acoustic hearing may not be beneficial for all patients. As such, we propose a measure of spectral resolution that might be more predictive of the usefulness of the residual hearing than the audiogram alone. In the following experiments, we measured performance on spectral resolution and speech perception tasks in individuals with normal hearing (NH) using low-pass filters to simulate steeply sloping audiograms of typical EAS candidates and compared it with performance on these tasks for individuals with sensorineural hearing loss with similar audiometric configurations. Because listeners with NH had similar levels of audibility and bandwidth to listeners with hearing loss, differences between the groups could be attributed to distortions due to hearing loss.

Design: Listeners with NH (n = 12) and those with hearing loss (n = 23) with steeply sloping audiograms participated in this study. The group with hearing loss consisted of 7 EAS users, 14 hearing aid users, and 3 who did not use amplification in the test ear. Spectral resolution was measured with the spectral-temporal modulated ripple test (SMRT), and speech perception was measured with AzBio sentences in quiet and noise. Listeners with NH listened to stimuli through low-pass filters and at two levels (40 and 60 dBA) to simulate low and high audibility. Listeners with hearing loss listened to SMRT stimuli unaided at their most comfortable listening level and speech stimuli at 60 dBA.

Results: Results suggest that performance with SMRT is significantly worse for listeners with hearing loss than for listeners with NH and is not related to audibility. Performance on the speech perception task declined with decreasing frequency information for both listeners with NH and hearing loss. Significant correlations were observed between speech perception, SMRT scores, and mid-frequency audiometric thresholds for listeners with hearing loss.

Conclusions: NH simulations describe a "best case scenario" for hearing loss where audibility is the only deficit. For listeners with hearing loss, the likely broadening of auditory filters, loss of cochlear nonlinearities, and possible cochlear dead regions may have contributed to distorted spectral resolution and thus deviations from the NH simulations. Measures of spectral resolution may capture an aspect of hearing loss not evident from the audiogram and be a useful tool for assessing the contributions of residual hearing post–cochlear implantation.

Key words: Diagnostic audiology, Electroacoustic stimulation, Hearing impairment, Psychoacoustics, Speech audiometry, Spectral resolution

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INTRODUCTION

The success of cochlear implantation for patients with severe-to-profound hearing loss has led to expanded candidacy criteria to include those with residual acoustic hearing when they do not adequately benefit from hearing aids (e.g., Verschuur et al. 2016; Holder et al. 2018). If low-frequency residual hearing can be preserved after cochlear implant (CI) surgery, it may provide benefits for sound quality (Kelsall et al. 2017), music perception (Gfeller et al. 2006; Crew et al. 2015), and complex listening situations (Turner et al. 2010). To accomplish this, extensive efforts have focused on designing electrodes and "soft" surgical techniques to preserve residual low-frequency hearing (Santa Maria et al. 2014; Causon et al. 2015). When hearing preservation is successful, patients may be encouraged to use combined electroacoustic stimulation (EAS) with the goal of providing better hearing than would be possible with either acoustic or electric stimulation alone.

Some studies using specially designed short electrodes in patients with better preoperative hearing than traditional CI candidates have shown EAS to be beneficial for hearing in background noise, music appreciation, and enhanced sound quality relative to hearing with a CI alone (Gantz et al. 2005; Turner et al. 2008; Roland et al. 2016; Kelsall et al. 2017). Other studies have found little to no benefit for EAS (Cosetti et al. 2013; Santa Maria et al. 2013; Erixon & Rask-Andersen. 2015; O'Connell et al. 2017) or even a reduction in performance while using EAS (Sheffield et al. 2015). Furthermore, some patients who qualify for EAS audiometrically reject it or perceive no benefit over electric-only stimulation (Fraysse et al. 2006; Helbig & Baumann 2010; Plant & Babic 2016). Using the audiogram alone, it is difficult to predict whether or not a patient will benefit from or prefer EAS (Kiefer et al. 2005).

The audiogram may be a poor predictor of EAS benefit or acceptance because it is a measure of pure-tone detection and not the ability to use sounds in a meaningful way (Phillips et al. 2000; Davies-Venn et al. 2015). Although useful for quantifying the degree of hearing loss, the audiogram falls short of providing the information needed to adequately counsel patients about the quality of their residual hearing. Therefore, an auditory measure that assesses more than detection is necessary.

Suprathreshold psychoacoustic tasks, such as measures of spectral or temporal resolution, have been proposed as better measures of residual hearing quality (e.g., Glasberg & Moore 1989). Specifically, deficits in frequency modulation detection, fundamental frequency (F0) temporal fine structure processing, release from masking, and cochlear nonlinearities have all been cited as potentially responsible for poor speech perception abilities in the hearing impaired (Dubno & Dirks 1989; Festen & Plomp 1990; Summers & Leek 1998; Li et al. 2015). Measures

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of spectral resolution are of particular interest because they have been shown to be highly correlated with speech perception for both CI and hearing aid users (e.g., Henry et al. 2005; Won et al. 2007; Holden et al. 2016).

The measurement of frequency selectivity using psychoacoustic tuning curves has been used as a fine-grained test of spectral resolution in humans. It is well established that frequency selectivity is poor in listeners with hearing loss due to widening of auditory filters (Florentine et al. 1980; Tyler et al. 1984; Glasberg & Moore 1989; Laroche et al. 1992) but that the equivalent rectangular bandwidth (ERB) of the filter may not depend on absolute hearing thresholds (Festen & Plomp 1983; Moore 2007). Several studies have investigated the relationship between frequency selectivity and speech perception. Horst (1987) found that ERB at 2 kHz was positively correlated with speech reception thresholds in speech-shaped noise but not speech in quiet. Other studies measuring frequency selectivity using critical bandwidth (Dreschler & Plomp 1980, 1985) and nonsimultaneous masking (Festen & Plomp 1983) have found similar results. More recently, Strelcyk and Dau (2009) measured ERBs for listeners with flat moderate sensorineural hearing loss and found no correlation with speech recognition thresholds in quiet or a (more difficult) two-talker masker. Dubno and Schaefer (1992) also measured frequency selectivity in notched noise and narrow-band maskers for listeners with hearing loss. Although performance was worse than in listeners with normal hearing (NH) in quiet or with simulated hearing impairments, there was no correlation with consonant recognition when controlling for audibility. However, others did find a positive correlation between frequency selectivity and vowel (Thibodeau & van Tasell 1987) or consonant perception (Preminger & Wiley 1985).

Measurements of frequency selectivity also have several flaws. Methodologically, differences in stimulus level and age between controls with NH and listeners with hearing loss can exaggerate the differences between the two groups (Glasberg & Moore 1986). Given the myriad of ways to measure frequency selectivity (critical bandwidth, critical ratio, notched-noise masking, nonsimultaneous masking, etc.) as well as speech perception (sentences, vowels, consonants, noise, or quiet, etc.), it is difficult to compare the results across studies. There is also evidence that psychophysical tuning curves are less accurately measured at low frequencies, where off-frequency listening is easier for listeners with NH (Glasberg & Moore 1986). Finally, they are time-consuming and require specialized laboratory equipment.

In recent years, tests of broadband spectral processing have been developed to address some of these issues. Spectral modulation *detection*, also known as spectral ripple depth detection, requires the listener to detect a stimulus with spectral peaks and valleys from stimuli without modulation (e.g., Supin et al. 1999; Litvak et al. 2007; Saoji et al. 2009; Gifford et al. 2014a). Similarly, spectral ripple phase *discrimination* (e.g., Supin et al. 1994, 1998; Henry et al. 2005; Drennan et al. 2014) evaluates the highest spectral ripple density (measured in ripples per octave; RPO) for which a listener can discriminate a spectral ripple with one phase from another 180 degrees out-of-phase. Because these tests are nonlinguistic, unrelated to auditory thresholds (Bernstein et al. 2013), and can be measured quickly (Drennan et al. 2014; Gifford et al. 2014a; Landsberger et al. 2019a), spectral ripple tasks may be a practical choice to evaluate the quality of residual hearing in clinical settings. Like more fine-grained tests of spectral resolution, there is good evidence of correlation between broadband spectral ripple detection/discrimination ability and speech perception in noise for listeners with hearing loss (e.g., Henry et al. 2005; Bernstein et al. 2013; Sheft et al. 2012; Davies-Venn et al. 2015). Henry et al. (2005) measured spectral peak discrimination for listeners with hearing loss and found weak but significant correlations between performance and consonant and vowel perception. Bernstein et al. (2013) used a spectro-temporal modulation detection task at several modulation rates (4, 12, or 32 Hz) and densities (0.5, 1, 2, or 4 cycles/octave) for listeners with hearing loss. The study found that performance for the 4 Hz modulation rate, 2 cycles/octave density was significantly correlated with frequency selectivity at 4 Hz as well as speech perception for sentences in steady state noise. Furthermore, the authors found that the variance in speech perception was better explained by the combination of spectral resolution, temporal resolution, and audibility than by the audiogram alone. Similarly, Sheft et al. (2012) found a significant correlation between the ability to detect a phase shift in a spectral-ripple stimulus of 1.5 RPO and performance on a clinical measure of speech-in-noise (QuickSIN; Killion et al. 2004). In general, these studies show potential for measuring the spectral resolution of acoustic hearing as it relates to speech perception in a format practical for clinical use.

One major limitation of studies using either broadband (e.g., spectral ripple) or narrow (e.g., frequency selectivity) measures of spectral resolution is the lack of validation on patients with steeply sloping hearing loss. This is likely due to a desire to minimize the confounding factor of audibility and because very little speech perception information is conveyed at low frequencies (Henry et al. 1998). In general, frequency selectivity appears to be normal or near-normal for subjects with low-frequency hearing losses less than 30 dB HL (Hopkins & Moore 2011; Summers et al. 2013). It remains unknown how patients with "ski-slope" hearing losses perform on broadband measures of spectral resolution.

Overall, there is significant evidence that hearing impairment results in loss of more than just audibility and bandwidth. Spectral resolution, whether measured narrowly (as with psychoacoustic tuning curves) or broadly (using spectral ripple detection) may relate to deficits in speech perception. To date, research in this topic has focused on patients with milder degrees or flatter configurations of hearing loss or used tests that are impractical for clinical use (e.g., Dubno & Schaefer 1992; Strelcyk & Dau 2009).

In the present study, we conducted two experiments designed to investigate the relationship between a clinically feasible measure of spectral resolution (spectral-temporal modulated ripple test [SMRT]; Aronoff & Landsberger 2013) and speech perception (AzBio Sentences; Spahr et al. 2012) for patients with steeply sloping hearing losses presenting as candidates for or users of EAS CIs. The SMRT was chosen as it is free to download, can be self-administered by the patient, and typically takes less than 3 minutes (Landsberger et al. 2019b). Furthermore, it has been demonstrated many times to correlate with speech perception for listeners with hearing aids and CIs (e.g., Holden et al. 2016; Kirby et al. 2015). However, although the SMRT is a practical choice for evaluating spectral resolution, it would be expected that other spectral tests would provide similar information, such as the Quick Spectral Modulation Detection test (Gifford et al. 2014b; Landsberger et al. 2019a), Spectro-Temporal Ripple

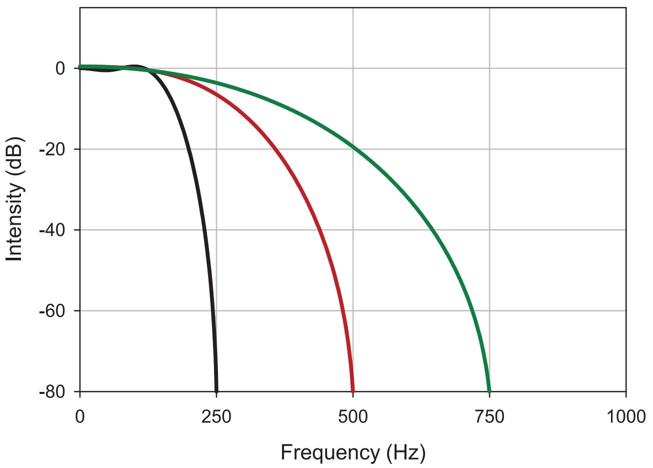

FIG. 1. Filters used for Experiment 1 (NH simulations) are shown in black (250 Hz stopband), red (500 Hz stopband), and green (750 Hz stopband). NH, normal hearing.

for Investigating Processor EffectivenesS (Archer-Boyd et al. 2018), Spectral-temporally modulated ripple test Lite for computeRless Measurement (Landsberger et al. 2019b), ripple-phase discrimination tests (e.g., Supin et al. 1994; Sheft et al. 2012; Golub et al. 2012; Drennan et al. 2014), or other spectral temporal ripple tests (e.g. Bernstein et al. 2013; Smith et al. 2013).

In Experiment 1, we sought to examine a best-case scenario of the utility of good low-frequency hearing using filtered stimuli in subjects with NH using different frequency cutoffs to simulate patients with sloping hearing loss commonly seen presenting as candidates for EAS CIs. In Experiment 2, the results were compared with SMRT and AzBio scores for a large group of subjects with steeply sloping hearing loss to probe the usefulness of low-frequency hearing for spectral resolution and speech understanding in a clinically relevant population: EAS CI users. Everyday listening conditions for these subjects included no amplification, hearing aids, or EAS in the test ear. We hypothesized that if audibility or bandwidth were solely responsible for poor speech perception, we would see equivalent performance for NH simulations and listeners with hearing loss. Therefore, any deviations from NH performance may help to quantify the quality of residual hearing in patients with steeply sloping hearing loss beyond audibility issues. Furthermore, these experiments may provide insight into the relative contributions of audibility, bandwidth, and spectral resolution for speech perception. Results from these experiments may assist in counseling patients with residual hearing undergoing CI on the potential for benefit with EAS.

METHODS

Experiment 1: Normal Hearing Listeners

In Experiment 1, spectral resolution and speech understanding were tested in adult listeners with normal hearing using low-pass filtered stimuli to determine how performance is affected by limiting audibility (such as with a "ski-slope" audiogram) but leaving the auditory system otherwise intact. Data collected in this experiment should serve as a theoretical "best-case scenario" reference for evaluation of listeners with true sensorineural hearing loss and residual low-frequency acoustic hearing.

Participants • Twelve listeners with NH (4 males and 8 females; age range, 22 to 40 years; mean, 28.2 years) participated in Experiment 1. Hearing thresholds were screened at 20 dB HL for pure-tone octave frequencies between 125 and 8000 Hz. All participants denied a history of ear disease or prior hearing loss. Written informed consent was obtained from all participants, and all procedures were approved by our Institutional Review Board (s14-00435).

Stimuli and Procedure • Three minimum order low-pass equiripple finite impulse response filters were created using custom Matlab (v2018b, Mathworks) scripts (Fig. 1). All filters had a passband frequency of 125 Hz, passband ripple of 1 dB, stopband attenuation of 80 dB, and a sampling rate of 20 kHz. The filters differed in stopband frequency (250, 500, or 750 Hz) to simulate steeply sloping hearing losses of increasing severity. These stopbands were chosen based on common audiograms of CI users with residual hearing.

Participants were tested using AzBio sentences (Spahr et al. 2012) and SMRT (Aronoff & Landsberger 2013). For AzBio sentences, lists 1 to 20 were used. Each list contains 20 sentences, with 10 sentences spoken by two male talkers and 10 sentences spoken by two female talkers. Sentences ranged in length from 4 to 12 words and were scored as the percentage of words repeated correctly out of the total number of words from each list. Sentences were presented in quiet and in continuous multitalker babble at a signal to noise ratio (SNR) of +10 dB. Two presentation levels were used: 60 and 40 dBA (noise presented at 50 and 30 dBA, respectively) to simulate low and high levels of audibility. Variants of each list (in quiet and in noise) were created with each of the three low-pass filters shown in Figure 1. Each participant was tested on 16 AzBio lists (2 levels [60 and 40 dBA] × 4 filters [250, 500, and 750 Hz and unfiltered] × 2 conditions [quiet and +10 dB SNR]). Participants were not familiarized with the speech material prior to testing. Testing was completed in a sound-proof booth using monaural (right) insert earphones (Etymotic Inc EAR-3A, Elk Grove, IL) to isolate the test ear.

SMRT is a three-alternative forced choice test consisting of spectral-temporally modulated ripple stimuli with a 5 Hz phase drift. The reference stimulus is modulated at 20 RPO, and the target is initially modulated at 0.5 RPO and adaptively modified using a 1-up/1-down procedure in 0.2 RPO step sizes. Threshold is calculated as the average of the last 6 of 10 reversals. Higher modulation thresholds are indicative of better performance. The standard SMRT stimuli (as described in Aronoff & Landsberger 2013) were low-pass filtered by the three previously described filters and presented at either 60 or 40 dBA, yielding six conditions (3 filters × 2 presentation levels). These two levels were chosen to simulate the variations in sensation levels for listeners with hearing loss based on their degree of hearing loss. The standard stimuli range from 100 to 6400 Hz. Stimuli were presented using an eight-inch tablet computer running Windows 10 routed to an external soundcard (Tascam US-322, Santa Fe Springs, CA) and a modified version of the SMRT software package (Landsberger et al. 2018), which allowed randomization of the order of the six SMRT conditions tested. Each participant was tested with the SMRT 16 times (2 levels × 4 filters [including unfiltered] × 2 runs). Performance on the 2 runs for a given stimulus condition was averaged. Prior to testing, participants were familiarized with the task through several presentations of target stimuli with low RPO and the reference stimulus. Testing was completed in a sound-proof booth using monaural (right) insert earphones.

Experiment 2: Hearing Impaired Listeners

Participants • Twenty-four listeners with hearing impairment (age range, 27 to 83, mean age, 63.1; 18 females and 6 males) were recruited for Experiment 2. Seven were EAS CI users, 14 were hearing aid users, and 3 were unaided in the test ear. Because the purpose of the study was to investigate the usefulness of residual hearing post-CI, listeners were required to have thresholds of 75 dB HL or better for at least 125 and 250 Hz, a typical cutoff for considering the use of EAS (e.g., MED-EL Sonnet EAS fitting guide, Cochlear N7 Hybrid Fitting Guide). These criteria are similar to those used in other studies of EAS systems with standard-length electrodes (e.g., Pillsbury et al. 2018; Battmer et al. 2019). Audiograms for the group can be found in Figure 2. Duration of deafness was calculated as the number of years since the listener first noticed hearing loss up until either the point of implantation for EAS CI users or until the point of testing. Because the significance of an additional year of hearing loss is greater for short durations than for long durations of hearing loss (e.g., the difference between 1 and 2 years is greater than the difference between 20 and 21 years), duration of deafness was converted to a log scale. This transform has been used for age in other hearing literature (e.g., Buss et al. 2014, 2016). Further information regarding the everyday listening conditions can be found in Table 1. Written informed consent was obtained from all participants, and all procedures were approved by our Institutional Review Board (s14-00435).

Stimuli and Procedure • Participants were evaluated on the same AzBio sentences in quiet and in +10 dB noise described in Experiment 1. Participants were also evaluated on consonant-nucleus-consonant (CNC) words, a test of monosyllabic word recognition (Peterson & Lehiste 1962). The score was calculated as the percentage of words repeated correctly from the 50-word list. Stimuli were unfiltered and presented in a soundproof booth through a speaker calibrated to 60 dBA. For nonimplanted patients, their personal hearing aid or a clinic stock BTE hearing aid was used in the test ear. Hearing aids were verified to meet NAL-NL2 adult targets prior to testing. CI users were tested with the acoustic-only portion of their speech processor, which was also verified to meet NAL-NL2 targets as closely as possible. For most participants, the test ear was the better ear. In cases where the contralateral ear may have contributed, it was plugged and muffed. Together, the plug and muff resulted in 34 dB of noise reduction. All participants were familiar with these speech materials from prior evaluations but were not given practice stimuli for the experiment.

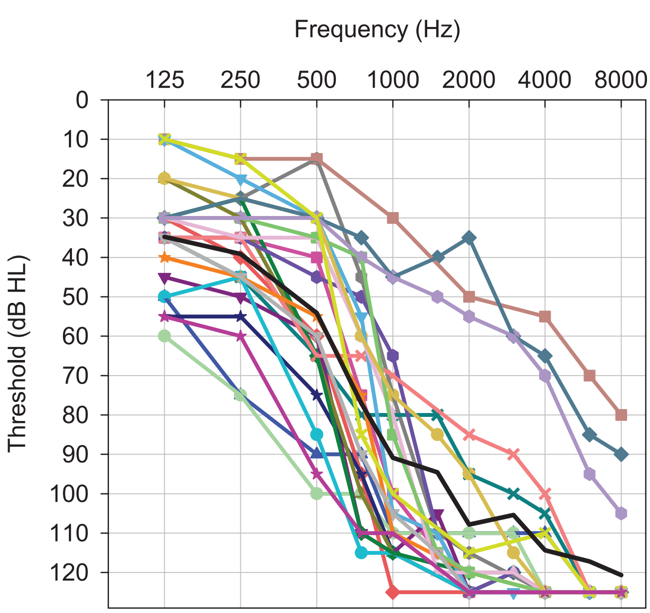

FIG. 2. Individual (colors) and mean (black) audiograms for Experiment 2 subjects (listeners with hearing loss). “No Response” for a particular frequency is plotted as 125 dB HL.

Participants were tested on SMRT as described in Experiment 1, with the exception that input from the sound card was routed through an audiometer (GSI Audiostar Pro, Eden Prairie, MN) for amplification purposes. Prior to the experiment, the SMRT software was calibrated in the sound field to determine the difference between the audiometer dial setting and the output of the speaker. Stimuli were unfiltered and presented through insert earphones (i.e., unaided) at the participant’s most comfortable listening level via overall gain. For most participants, this was 75 to 85 dB HL. This level was confirmed through the talk-over feature of the audiometer. This new level was confirmed to be comfortable and sufficiently audible for the test stimuli before testing began. The maximum presentation level was 105 dB HL. At least a 30 dB SL re: 250 Hz was achieved for all participants. In many cases, a 30 dB SL was achieved at 500 and 750 Hz. In cases where the contralateral ear may have contributed, it was plugged and muffed. Participants were familiarized with the task by listening to several practice stimuli prior to experimental testing.

Due to time constraints, participants were evaluated on two AzBio lists (one in quiet, one in noise, chosen randomly from the corpus), one CNC list (50 words, also chosen randomly), and one run of SMRT.

RESULTS

Experiment 1: Normal Hearing Listeners

Scores on the SMRT were averaged across subjects with NH for each presentation level and filter and plotted in Figure 3. Performance for the two presentation levels was similar, with a maximum difference of 0.8 RPO, suggesting that at least for these two presentation levels, audibility did not strongly influence performance. As spectral information was reduced with decreasing filter stopband frequency, average performance decreased. Collapsing across presentation level, SMRT scores decreased from 8.3 RPO with no filtering to 7.9, 7.3, and 5.5 RPO with 750, 500, and 250 Hz filters, respectively. The score of 8.3 RPO with unfiltered stimuli (range, 5.7 to 10.1 RPO; SD, 1.2 RPO) is similar to previously published normal hearing data from Aronoff and Landsberger (2013) and Landsberger et al. (2018). The clinical relevance of a reduction in SMRT from the acoustic filtering of stimuli remains unknown because no data have been published describing the relationship between SMRT and speech understanding for acoustic hearing listeners. For CI listeners, a decrease in SMRT of 0.5 RPO is approximately equivalent to a decrease of seven percentage points in performance on AzBio in +8 dB SNR babble (Holden et al. 2016; Lawler et al. 2017). However, the generalizability of this finding to acoustic hearing listeners remains unknown and unreported.

A two-way repeated measures analysis of variance was conducted using within-subject factors of presentation level (40 or 60 dBA) and filter (250, 500, and 750 Hz or no filter). A main

TABLE 1. Additional Experiment 2 participant details

Participant Code	Symbol	Ear Tested	Everyday Listening Condition: Test Ear	Acoustic/Electric Cutoff Frequencies: Test Ear	Everyday Listening Condition: Contralateral Ear	PTA (0.5, 1, and 2 kHz): Contralateral Ear
N110	▲	L	Cochlear/CI532	438 Hz/313 Hz	Cochlear/CI532	105 dB HL
N110	●	R	Cochlear/CI532	438 Hz/313 Hz	Cochlear/CI532	103.30 dB HL
N108	■	R	HA	—	Cochlear/Freedom CA	No response
T104	◆	R	HA	—	HA	81.67 dB HL
N109	⬢	L	HA	—	Cochlear/CI532	108.33 dB HL
C128	✖	R	HA	—	Advanced Bionics/HR90K Mid-Scala	No response
M111	▼	L	HA	—	MED-EL/Flex24	101.67 dB HL
N100	★	R	Cochlear/Hybrid L24	1313 Hz/1188 Hz	Cochlear/CI532	No response
N111	▲	R	HA	—	Cochlear/CI532	111.67 dB HL
N111	●	L	Cochlear/CI532	563 Hz/438 Hz	HA	98.33 dB HL
N112	■	L	HA	—	Cochlear/CI532	No response
M108	◆	L	Unaided	—	MED-EL/standard	No response
N113	⬢	L	HA	—	Cochlear/CI532	No response
C130	✖	L	HA	—	Advanced Bionics/HR90k Mid-Scala	No response
C131	▼	L	HA	—	Advanced Bionics/HR90k Mid-Scala	No response
N114	★	L	Unaided	—	Cochlear/CI532	No response
N116	▲	R	HA	—	Cochlear/CI512	No response
N117	■	L	Cochlear/CI422	1313 Hz/1188 Hz	HA	66.67 dB HL
N117	●	R	HA	—	Cochlear/CI422	78.33 dB HL
T105	◆	L	HA	—	HA	43.33 dB HL
T105	⬢	R	HA	—	HA	36.67 dB HL
N118	✖	R	Unaided	—	Cochlear/Hybrid L24	No response
N119	▼	L	Cochlear/CI532	688 Hz/563 Hz	Cochlear/CI532	115 dB HL
N119	★	R	Cochlear/CI532	438 Hz/313 Hz	Cochlear/CI532	103.33 dB HL

Colors and symbols correspond to the colors and symbols of data points in Figures 2, 6 and 7. Acoustic/electric cutoff frequency: For patients using EAS, acoustic stimulation is provided from 100 Hz to the first (higher) frequency. Electric stimulation is provided from the second (lower) frequency through 7938 Hz, resulting in an overlap of 125Hz. All subjects were tested without assistive devices for the study.
EAS, electroacoustic stimulation; HA, hearing aid.

effect of filter was detected ($F(3,33) = 85.67$, $p < 0.001$) but not of presentation level ($F(1,11) = 2.53$, $p = 0.14$). No interaction was detected between the factors ($F(3,33) = 2.71$, $p = 0.06$). Post hoc paired *t* tests were conducted to compare scores for different filters by collapsing across level. Performance was significantly worse for the 500 Hz ($t(33) = 5.58$, $p < 0.001$) and 250 Hz filtered stimuli ($t(33) = 14.91$, $p < 0.001$) relative to the no filter condition even after Type I error correction using Rom's method (Rom 1990). However, no difference was detected between the 750 Hz and unfiltered stimuli ($t(33) = 2.36$, $p = 0.15$).

Scores for AzBio sentences were averaged across subjects for each presentation level, filter, and condition (noise or quiet) and plotted in Figure 4. Performance without filtering was near 100% correct for both levels and conditions. As filter bandwidth decreased, average performance declined for both levels and conditions. As expected, performance was worse for the softer level and in noise. For the 60 dBA presentation level, average performance was relatively similar for 750 Hz filters (97.9% in quiet and 92.6% in noise) and 500 Hz filters (90.7% in quiet and 80.7% in noise) but decreased significantly for the 250 Hz filter (54.4% in quiet and 37.12% in noise). For the 40 dBA presentation level, average performance systematically declined for the 750 Hz (84.6% in quiet and 79.7% in noise) and 500 Hz filters (72.5% in quiet and 64.8% in noise) while also sharply dropping for the 250 Hz filter (34.8% in quiet and 24.5% in noise). In general, performance declined more sharply in noise, especially with the 250 Hz filter. Performance also declined quicker and more

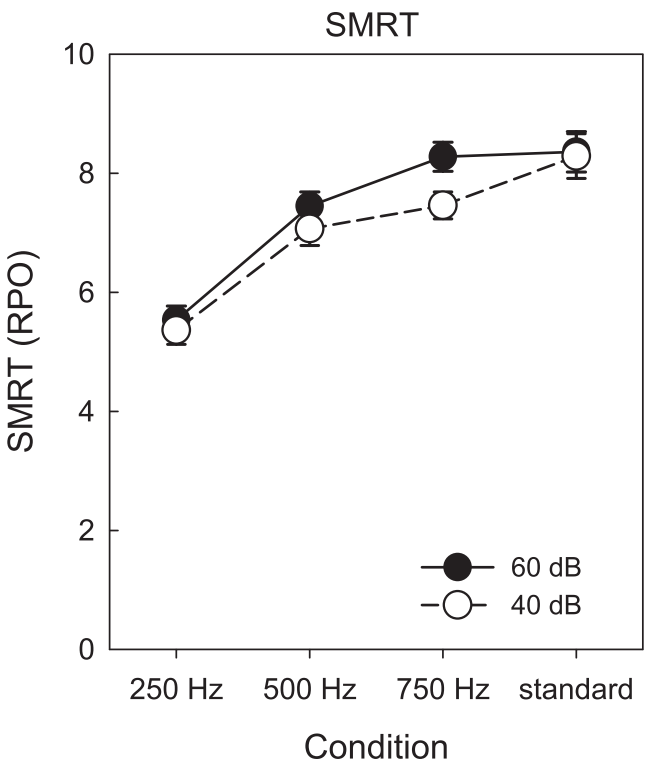

FIG. 3. Spectral-temporal modulated ripple test (SMRT) scores for Experiment 1 as a function of filter (x-axis) and presentation level (filled circles/solid line, 60 dBA; open circles/dotted lines, 40 dBA). Error bars indicate ±1 SEM. RPO, ripples per octave

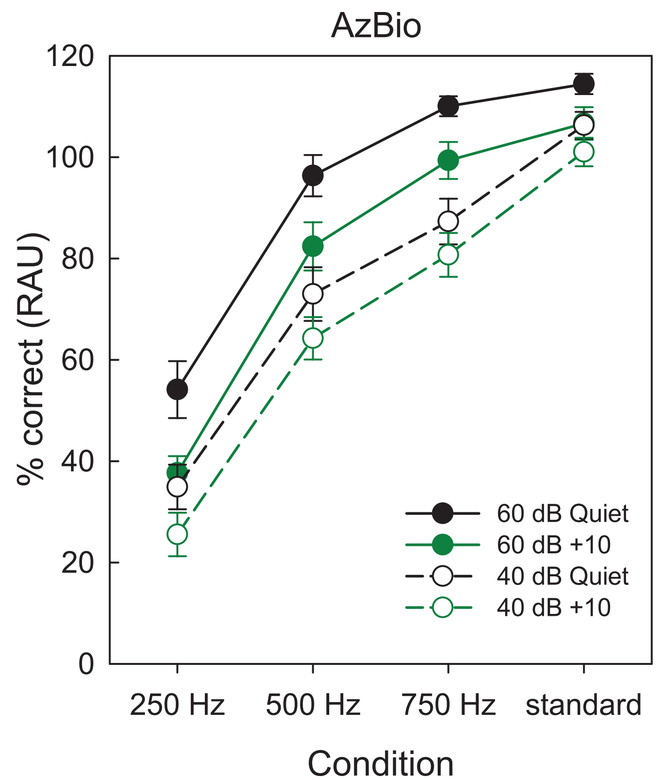

FIG. 4. AzBio scores (RAU) for Experiment 1 as a function of filter (x-axis), and presentation level (filled circles/solid lines, 60 dBA; open circles/dotted lines, 40 dBA). Sentences in quiet are shown in black; noise are shown in green. Error bars indicate ± 1 SEM. RAU, rationalized arcsine units.

steeply for the softer presentation level. These results suggest that speech understanding with reduced frequency information is influenced by both presentation level and the presence of background noise.

A three-way repeated measures analysis of variance was conducted using within-subject factors of presentation level (40 or 60 dBA), filter (25, 500, and 750 Hz or no filter), and condition (quiet or noise). To mitigate floor and ceiling effects, speech scores were converted to rationalized arcsine units (RAU; Studebaker 1985). Main effects were detected for all three factors (level, $F(1,11) = 90.96$, $p < 0.001$; filter, $F(3,33) = 487.8$, $p < 0.001$; condition, $F(1,11) = 60.92$, $p < 0.001$). There were significant interactions between level and condition ($F(1,11) = 6.66$, $p = 0.03$) and between filter and condition ($F(3,33) = 6.62$, $p = 0.001$). Significant interactions were not detected between level and filter ($F(3,33) = 1.47$, $p = 0.24$) or for all three factors ($F(3,33) = 0.22$, $p = 0.88$). Post hoc paired *t* tests showed significant differences between the two conditions for all four filters and between the two levels and two conditions (see Supplemental Digital Content 1, http://links.lww.com/EANDH/A714).

Pearson product correlations between SMRT scores and AzBio scores (both levels in quiet and in noise) were examined for each filter (250, 500, and 750 Hz and unfiltered). Because we did not detect a significant effect of level on SMRT scores, scores were collapsed across level. After Type I error correction using Rom's method, no significant correlations were detected.

Experiment 2: Hearing Impaired Listeners

One participant (N118) could not complete the SMRT task and was thus excluded from further analyses. SMRT scores ranged from 0.4 RPO to 3.4 RPO (mean, 1.6 RPO; SD, 0.7 RPO), considerably lower than the normal-hearing low-pass filtered results from Experiment 1 (see Fig. 5). Even when compared to the lowest SMRT score from Experiment 1 (5.4 RPO at 250 Hz filter, 40 dBA presentation level), Cohen's effect size (d = 4.78) suggests an extremely large effect. AzBio scores were missing for some participants (quiet, n = 3; noise, n = 10). Thus, these participants were excluded from correlational analyses between speech perception and SMRT.

Figure 6 depicts correlations between speech perception and SMRT. Performance on speech perception tests spanned almost the entire percentage range, though floor effects were seen for all three tests. The group mean CNC score was 29.9% (range, 0% to 92%; SD, 31.8%); the group mean AzBio Quiet score was 34.0% (range, 0% to 97%; SD, 33.9%); the group mean AzBio +10 score was 34.7% (range, 0% to 95%; SD, 31.0%). Scores were converted to RAU for data analyses. Pearson product correlations between several demographic measures and SMRT performance were examined with Type 1 error correction using Rom's method. Performance on speech perception tests (converted to RAU) were correlated with SMRT scores. Significant, positive correlations were detected between SMRT and CNC ($r(23) = 0.59$, $p = 0.003$), AzBio Quiet ($r(20) = 0.55$, $p = 0.01$), and AzBio +10 scores ($r(14) = 0.59$, $p = 0.03$).

No significant correlation was detected between SMRT and age at test ($r(23) = 0.11$, $p = 0.63$), but longer durations of hearing loss (log scale) were significantly correlated with worse SMRT scores ($r(22) = -0.53$, $p = 0.01$), as shown in Figure 7. Interestingly, if the duration of deafness is 0 years (i.e., normal hearing), the SMRT score predicted by the regression line shown in Figure 7 is 8.72 RPO, which is not statistically significantly different from the mean SMRT of subjects with NH in Experiment 1 (mean = 8.36 RPO; 95% confidence interval, 7.62 to 9.11 RPO). A longer duration of deafness was also correlated with worse performance on AzBio +10 ($r(13) = -0.76$; $p = 0.002$), but no significant correlations were detected between duration of deafness and performance on CNC words ($r(23) = -0.29$; $p = 0.18$) or AzBio in quiet ($r(20) = -0.42$; $p = 0.07$). However, this correlation should be taken with caution as not all participants were tested on AzBio sentences in noise. There were no statistically significant correlations detected between age at test and any speech test (CNC words, $r(23) = 0.03$, $p = 0.89$; AzBio in quiet, $r(20) = -0.18$, $p = 0.43$; AzBio in noise, $r(13) = -0.18$, $p = 0.54$).

Finally, mean thresholds at each pure-tone frequency were correlated with SMRT and speech perception scores (Table 2). After Type I error correction using Rom's method, significant negative correlations were detected between the speech measures (CNC words, AzBio sentences in quiet) and mid-frequency audiometric thresholds, with the strongest correlation seen for 1000 Hz (CNC, $r(23) = -0.66$, $p < 0.001$; AzBio quiet, $r(21) = -0.64$, $p = 0.002$). A significant correlation was also seen between SMRT score and the 1000 Hz threshold ($r(23) = -0.61$, $p < 0.001$). There were no significant correlations detected between AzBio sentences in noise and any audiometric threshold, though not all subjects completed testing in noise (n = 14/24). No significant correlations were detected between low/high-frequency audiometric thresholds and either SMRT or any speech perception measure. There were also no significant correlations detected between duration of deafness and any pure-tone threshold. All comparisons are detailed in Table 2.

DISCUSSION

Spectral Resolution

In the preceding experiments, we measured spectral resolution (using SMRT) and speech perception (using CNC words and AzBio sentences) for listeners with hearing loss with ski-slope audiograms and compared their performance to subjects with normal hearing listening to low-pass filtered stimuli. Because we expected audibility to be sufficient for both groups, at least for SMRT, any differences in scores could be attributed to sequelae of hearing impairment beyond the loss of audibility.

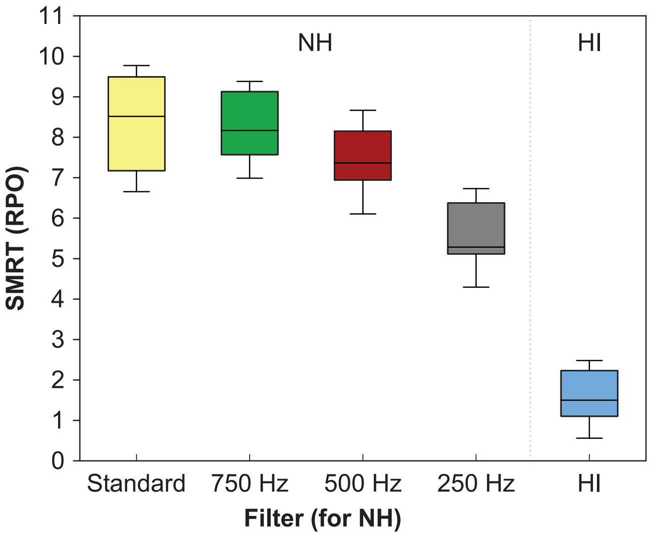

FIG. 5. Boxplots of spectral-temporal modulated ripple test (SMRT) scores for participants with normal hearing (NH; Experiment 1; left four boxplots) and with hearing loss (Experiment 2; right boxplot). RPO, ripples per octave

In Experiment 1, we measured spectral resolution and speech perception with control subjects with NH. Stimuli were low-pass filtered and presented at two presentation levels to simulate steeply sloping hearing loss. As expected, SMRT scores decreased as the filter became more restrictive, though they remained fairly high. Given that the spectral information provided by the SMRT is redundant across the frequency range, performance may not be directly dependent on the bandwidth of the stimulus but instead on the best "local" frequency representation as previously argued by Anderson et al. (2011) and Narne et al. (2018). That is, as the bandwidth of the SMRT stimulus is reduced, the likelihood of providing information at the best local frequency range is reduced. For the most restrictive filter (250 Hz), there is approximately one octave of bandwidth in the signal (due to the sharpness of the filter), limiting the number of spectral peaks in the stimuli available to resolve the spectral ripples. This finding suggests differences in audibility across the frequency range may slightly decrease performance on the SMRT, especially when information above 250 Hz is inaudible. Furthermore, these results suggest that the lower frequency ranges do not provide optimal spectral representation. No significant difference was detected in the score between the two presentation levels (60 and 40 dBA). This suggests that the results of an SMRT test may not be highly dependent on stimulation level, which is important for evaluating subjects with hearing loss where controlling for audibility can be difficult.

In contrast to the results for listeners with NH in Experiment 1, listeners with hearing loss (Experiment 2) scored much worse on SMRT. There was no overlap in the distributions of the two groups' scores, resulting in not only a significant difference but also a very large effect size (Cohen's $d = 4.78$). As demonstrated by the NH results, a small frequency range is sufficient to achieve a high score. Given that the stimuli were sufficiently audible for the listeners with hearing loss (at least a 30 dB SL re: 250 Hz was achieved in all cases, in many cases 500 and 750 Hz were also sufficiently audible), the results suggest that factors other than audibility across a sufficiently wide frequency bandwidth caused scores to be poor. Perhaps due to widened auditory filters and the distorted nature of their residual hearing, listeners with hearing loss required several octaves to perform well on the task.

Listeners with hearing loss in the present study also performed worse on SMRT using only acoustic hearing than listeners with CI, based on previously published data. These studies showed mean scores of 2.03 to 4.30 RPO (Holden et al. 2016; Vickers et al. 2016; Zhou 2017; Goehring et al. 2019) for adult listeners with CI, at least 1 RPO better than the mean performance in our study. Although a direct comparison is difficult given the difference in inputs (acoustic versus electric), it was unexpected that CI listeners scored higher, given that CIs are known to have poor spectral resolution (Fu et al. 1998; Won et al. 2007). However, the broad frequency range provided by the CI will increase the chances of representation at the highest performing frequency band. As performance on the spectral ripple tests are dependent on the highest performing frequency band, this may provide an additional advantage for listeners with CI. This is especially true given that the current data (and Narne et

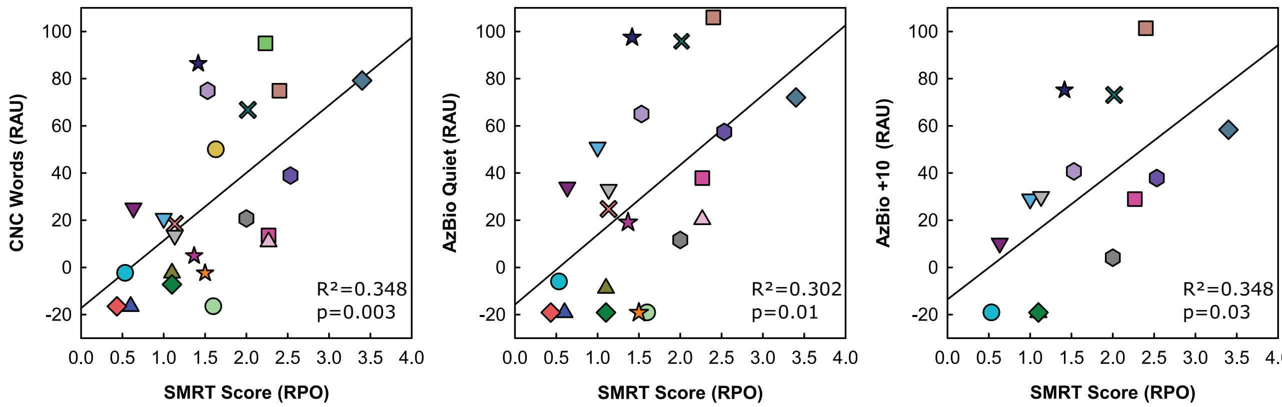

FIG. 6. Scatterplots representing speech perception scores (converted to RAU, y-axis) and spectral-temporal modulated ripple test (SMRT) scores (x-axis) for listeners with hearing loss (HI). The three panels represent CNC words (left), AzBio sentences in quiet (middle), and AzBio sentences in noise (right). Lines represent the best fitting lines. Colors and symbols of individual points correspond to the colors and symbols of individual audiograms in Figure 2 and of demographic data in Table 1. CNC, consonant-nucleus-consonant; RAU, rationalized arcsine units; RPO, ripples per octave.

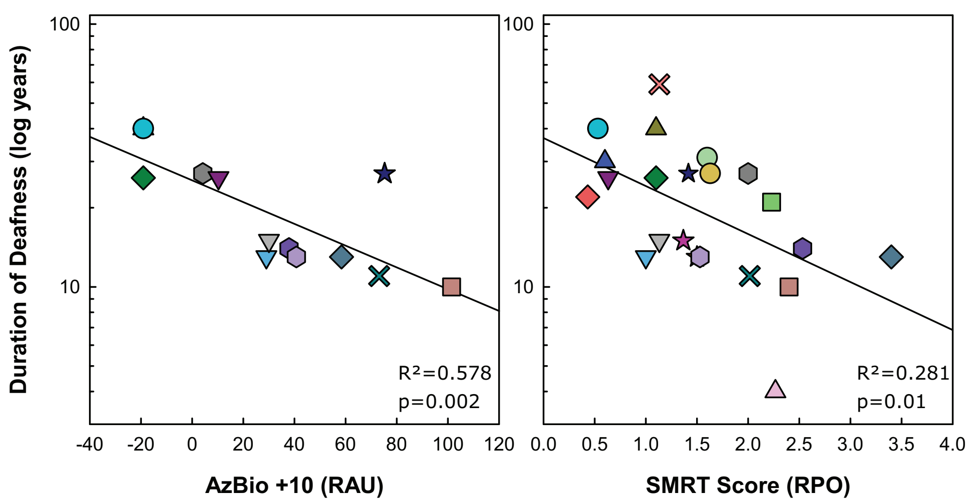

FIG. 7. Scatterplots representing the relationship between duration of deafness (log scale, y-axis) and AzBio sentences in noise (converted to RAU, left panel) and spectral-temporal modulated ripple test (SMRT) score (right panel) for listeners with hearing loss. Lines represent the best fitting lines. Colors and symbols of individual points correspond to the colors and symbols of individual audiograms in Figure 2 and to demographic data in Table 1. RAU, rationalized arcsine units; RPO, ripples per octave.

TABLE 2. R^2 values, n, and *p* values based on linear regressions between audiometric thresholds, SMRT scores, speech perception scores (converted to RAU), and duration of deafness (log scale)

Threshold Frequency	SMRT Score (R^2, n, *p*)	CNC Words (R^2, n, *p*)	AzBio Quiet (R^2, n, *p*)	AzBio + 10 (R^2, n, *p*)	Duration of Deafness (R^2, n, *p*)
125 Hz	0.07, 23, 0.19	0.04, 24, 0.33	0.08, 21, 0.21	0.02, 14, 0.65	0.04, 23, 0.33
250 Hz	0.16, 23, 0.07	0.12, 24, 0.10	0.12, 21, 0.12	0.00, 14, 0.91	0.03, 23, 0.43
500 Hz	0.31, 23, 0.008	0.23, 24, 0.02	0.21, 21, 0.04	0.13, 14, 0.20	0.16, 23, 0.06
750 Hz	**0.38, 22, 0.005***	**0.38, 23, 0.002***	0.24, 20, 0.03	0.18, 13, 0.14	0.13, 22, 0.10
1000 Hz	**0.42, 23, 0.002***	**0.44, 24, <0.001***	**0.41, 21, 0.002***	0.36, 14, 0.02	0.14, 23, 0.08
1500 Hz	0.14, 11, 0.27	0.39, 11, 0.04	0.45, 9, 0.05	0.38, 8, 0.10	0.00,11, 0.97
2000 Hz	0.25, 23, 0.01	0.30, 24, 0.006	0.26, 21, 0.02	0.33, 14, 0.03	0.04, 23, 0.34
3000 Hz	0.20, 13, 0.13	0.48, 13, 0.009	0.27, 12, 0.08	0.34, 8, 0.13	0.01, 13, 0.75
4000 Hz	0.19, 23, 0.04	0.27, 24, 0.01	0.32, 21, 0.008	0.39, 14, 0.02	0.06, 23, 0.26
6000 Hz	0.34, 16, 0.02	0.39, 17, 0.007	0.30, 16, 0.03	0.34, 14, 0.06	0.14, 17, 0.13
8000 Hz	0.27, 23, 0.01	0.27, 24, 0.01	0.29, 21, 0.01	0.35, 14, 0.03	0.12, 23, 0.11

**Statistically significant after Type I error correction (indicated in bold).*
CNC, consonant-nucleus-consonant; RAU, rationalized arcsine units; SMRT, spectral-temporal modulated ripple test.

al. 2018) suggest that the highest performing frequency band is typically inaudible to listeners with hearing loss in this study.

Speech Perception

For both listeners with NH and with hearing loss, scores for AzBio sentences were affected by sensation level and frequency bandwidth. This finding suggests that even with appropriate audibility for low frequencies, good speech perception is highly dependent on access to high-frequency speech phonemes such as fricatives and plosives (Thornton et al. 1980; Stelmachowicz et al. 2001; Warren et al. 2005). Mean performance on AzBio sentences in noise was similar to performance in quiet for listeners with hearing loss, suggesting that a +10 dB SNR may have been too easy for listeners with these audiometric configurations.

Correlations Between SMRT and Speech Perception

We did not find a correlation between speech perception and SMRT scores for listeners with NH, further indicating that SMRT performance is unrelated to audibility at specific frequencies, given a nondistorted auditory system. We presume that if the stimulus was presented at a higher frequency but similarly limited in bandwidth, performance would be similar, at least for listeners with NH (Saoji & Eddins 2007). It is also likely that ceiling effects were present for both measures, hindering our ability to detect correlations. In contrast, we saw statistically significant but weak ($R^2 = 0.3$ to 0.35) correlations between performance on SMRT and speech perception scores for listeners with hearing loss, suggesting that ability to resolve spectral information is important for understanding speech in a degraded auditory system. This is consistent with previous work showing that providing listeners with hearing loss with access to more spectral channels results in better speech perception (Shannon et al. 2004). Although the participants and stimuli were slightly different, other studies have found similar correlations between spectral ripple discrimination and speech perception (Henry et al. 2005; Bernstein et al. 2013; Davies-Venn et al. 2015). Presumably, the loss of audibility due to underlying pathophysiology (rather than filtering) results in broader auditory filters and thus poorer spectral resolution. However, the weak correlation suggests that although these two outcomes are related, there are likely other factors influencing performance. It is also worth noting that the correlation extends over a small region of SMRT scores. It is unknown if this correlation would hold if a greater range of hearing losses (with a presumably greater range of SMRT scores) were tested. It is possible that the ceiling effect seen for listeners with NH also exists for listeners with hearing loss, which may limit the correlation above a certain SMRT score.

Correlations With Audiometric Thresholds

Although we focused on low-frequency audibility for the NH simulations to mimic the clinical population with sloping losses, performance on SMRT was better predicted by mid-frequency audiometric thresholds for subjects with hearing loss. While speech perception is certainly reliant on mid-frequency information more than on other frequencies (Başkent & Shannon 2007; Bosen & Chatterjee 2016), it was surprising that SMRT performance increased with better mid-frequency thresholds. To determine that a stimulus contains a spectral ripple, only a small amount of bandwidth is required, regardless of where in the frequency spectrum that band is located (e.g., Anderson et al. 2011; Narne et al. 2018). However, a wider available bandwidth may result in better performance. Listeners with NH are able to do the task using approximately an octave (i.e., with the 250 Hz filter) without a serious detriment in performance. Nevertheless, having good access to frequency information up to 500 Hz was not predictive of a good SMRT score for listeners with hearing loss. It is possible that due to widened auditory filters and the degraded quality of their hearing, listeners with hearing loss required more than an octave of information to perform well on the task. Although redundant spectral information is not necessary for listeners with NH, the listener with hearing loss may be able to take advantage of it to fill in parts of the signal that are otherwise missed or distorted (Hood & Poole 1971; Smoorenburg 1992). It is also likely that even if thresholds are obtained at high dB levels, they may reflect off-frequency listening or be adjacent to a cochlear dead zone (Moore 2001; Vinay & Moore 2007). Therefore, good audiometric thresholds at mid-frequencies may simply be reflective of a healthier overall auditory system. Few of our subjects had measurable hearing beyond 2000 Hz: only 7 of 24 had a measurable threshold and only 3 of 24 had a threshold better than 100 dB HL. The lack of correlation between higher frequency thresholds and SMRT performance may be caused by floor effects. If we had a wider range of thresholds at higher frequencies, the relationship between performance and high-frequency audiometric thresholds may have been stronger. It is worth noting that of the five highest CNC scores, three of them (T105_L, T105_R, and N112) were ears with better thresholds at 2000 Hz (See Figs. 2 and 6). Two of these subjects (T105_L and N112) also had high SMRT scores. It is also difficult to disentangle spectral distortions that occur due to hearing loss and distortions that occur due to the high stimulus levels needed for the participant to complete the task, such as changes in cochlear mechanics. However, using amplification (such as hearing aids) to reduce stimulus levels might introduce additional distortions, such as dynamic range compression or frequency lowering.

We also found significant, but weaker, correlations between speech perception scores in quiet (AzBio sentences and CNC words) and mid-frequency audiometric thresholds. However, no correlations were detected between speech perception in noise and thresholds at any frequency. Given the purported importance of low-frequency hearing for distinguishing F0 differences leading to improved speech perception in noise (e.g., Shpak et al. 2014), it was surprising that no relationship was found. It is possible that the lower number of data points ($n = 13$ versus $n = 24$ for speech in quiet) made it difficult to detect any correlations, or that too many scores were at floor, despite using the RAU transform.

Although there were no significant correlations between either SMRT performance or speech perception and any demographic variables (i.e., age at test), we did find a significant relationship between duration of deafness and SMRT score. Additionally, there was a strong correlation ($R^2 = 0.58$) between duration of deafness and speech perception in noise but no relationship between duration of deafness and speech perception in quiet. Although there is a lack of literature on this topic for hearing aid users, longer durations of deafness have been associated with poorer CI outcomes (e.g., Blamey et al. 1996), presumably because the longer the auditory system has been impaired, the more degraded it becomes, regardless of the degree of loss. It is reasonable to assume that greater degrees of hearing loss are likely to be associated with poorer quality hearing. SMRT and speech perception in noise are relatively difficult tasks that require the ability to distinguish two signals based at least in part on spectral information. Better hearing quality, which is likely associated with shorter durations of deafness, may lead to better performance on these tasks. For easier tasks (such as speech perception in quiet), audibility alone may be sufficient for good performance.

There are several limitations to this study. The simulations in Experiment 1 were intended to mimic only the audibility issues associated with hearing loss. True sensorineural hearing loss is known to cause a variety of other perceptual issues, such as recruitment and loss of spectral resolution, the degrees of which are individually variable and difficult to measure. Therefore, our simulations are limited to a "best case" scenario; any deviations seen in patients with hearing loss represent distortions beyond audibility. However, it is unknown to what degree each type of distortion contributes to the decrement in performance. Our results are limited to saying that some deficit in spectral resolution beyond audibility must exist for patients with hearing loss. Furthermore, subjects varied in their everyday listening situations. Although all subjects were tested unaided, those listening to an acutely different signal (i.e., hearing aid or CI-EAS users) may have had a disadvantage compared to those who were listening unaided every day (Vermeire et al. 2010). SMRT stimuli were amplified with a flat gain through the audiometer, which may have resulted in less audibility at frequencies above 500 Hz. It is unknown how increased audibility would affect SMRT scores for listeners with hearing loss. As clinical adoption of a test requires administration to be as quick as possible, only one run of the SMRT was conducted. This is typical of implementation of spectral ripple tasks in the clinic (e.g., Gifford et al. 2014b). If more runs of the test were conducted, a more precise estimate of SMRT thresholds may have been obtained and reduced some of the noise in the data. Previous studies are mixed as to the short-term test–retest reliability and practice effects for SMRT, with some showing no effect (e.g., de Jong et al. 2018) and others showing a slight effect (e.g., Goehring et al. 2019). Finally, both the mean and standard deviation of age was larger for the group with hearing loss than for the group with NH. It is unknown how differences in age may have affected the results.

In the present study, data collected using NH simulations of hearing loss suggested that higher sensation levels were important for a speech perception task but not for a spectral resolution task. Data from subjects with sensorineural hearing loss were generally similar for speech perception when compared with the 250 Hz filtered speech presented to listeners with NH, but starkly different for spectral abilities. These findings suggest that SMRT may be capturing an attribute of spectral resolution not dependent solely on audibility or bandwidth. The lack of correlation with speech and low-frequency thresholds was surprising, given the weight usually placed on these thresholds for determining whether or not a patient has usable residual hearing. SMRT may be a useful tool for gauging the quality of residual hearing and determining whether or not to use EAS. However, more research is needed to determine the relationship between spectral abilities and EAS benefit and acceptance. These data suggest it may be more prudent to ascribe greater weight to mid-frequency (i.e., 1000 Hz thresholds) as a marker of residual hearing quality, for both CI candidates and EAS users.

A test such as SMRT could have clinical implications. If a patient is known to have higher-quality residual hearing, a surgeon might prescribe steroids (despite some inherent risks) and/or opt for an electrode they believe more likely to preserve that hearing. Similarly, an audiologist may be more likely to encourage that patient to use EAS if they know that they are more likely to benefit from it. A patient with higher quality residual hearing may be programmed with a higher cut-off frequency to take additional advantage of the acoustic input. On a more basic level, these results help clarify how hearing loss degrades spectral processing abilities, as well help explain individual performance variability. Future studies may investigate how tests such as SMRT add to the predictive power of the audiogram for speech perception.

CONCLUSIONS

Auditory thresholds are currently used to assess the utility of residual hearing for combined electroacoustic hearing. Suprathreshold testing including spectral abilities demonstrate that in a population with sloping hearing losses, broadening of auditory filters, loss of cochlear nonlinearities, and possible cochlear dead regions may have contributed to poor spectral resolution. This contrasts significantly with NH simulations, a "best case scenario" for hearing loss where high-frequency audibility is the only deficit. Measures of spectral resolution may capture an aspect of hearing loss not evident from the audiogram and be a useful tool for assessing residual hearing function post-cochlear implantation.

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REFERENCES

Anderson, E. S., Nelson, D. A., Kreft, H., Nelson, P. B., Oxenham, A. J. (2011). Comparing spatial tuning curves, spectral ripple resolution, and speech perception in cochlear implant users. *J Acoust Soc Am, 130*, 364–375.

Archer-Boyd, A. W., Southwell, R. V., Deeks, J. M., Turner, R. E., Carlyon, R. P. (2018). Development and validation of a spectro-temporal processing test for cochlear-implant listeners. *J Acoust Soc Am, 144*, 2983.

Aronoff, J. M., & Landsberger, D. M. (2013). The development of a modified spectral ripple test. *J Acoust Soc Am, 134*, EL217–EL222.

Başkent, D., & Shannon, R. V. (2007). Combined effects of frequency compression-expansion and shift on speech recognition. *Ear Hear, 28*, 277–289.

Battmer, R.-D., Scholz, S., Geissler, G., et al. (2019). Electric acoustic stimulation (EAS) with the Naída CI Q90 sound processor in experienced cochlear implant users. *Cochlear Implants Int, 20*, 331–340.

Bernstein, J. G., Mehraei, G., Shamma, S., Gallun, F. J., Theodoroff, S. M., Leek, M. R. (2013). Spectrotemporal modulation sensitivity as a predictor of speech intelligibility for hearing-impaired listeners. *J Am Acad Audiol, 24*, 293–306.
Blamey, P., Arndt, P., Bergeron, F., Bredberg, G., Brimacombe, J., Facer, G., Larky, J., Lindström, B., Nedzelski, J., Peterson, A., Shipp, D., Staller, S., Whitford, L. (1996). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiol Neurootol, 1*, 293–306.
Bosen, A. K., & Chatterjee, M. (2016). Band importance functions of listeners with cochlear implants. *J Acoust Soc Am*, *139*, 2045–2045.
Buss, E., Hall, J. W. III, Porter, H., Grose, J. H. (2014). Gap detection in school-age children and adults: Effects of inherent envelope modulation and the availability of cues across frequency. *J Speech Lang Hear Res, 57*, 1098–1107.
Buss, E., Porter, H. L., Leibold, L. J., Grose, J. H., Hall, J. W. (2016). Effects of self-generated noise on estimates of detection threshold in quiet for school-age children and adults. *Ear Hear, 37*, 650–659.
Causon, A., Verschuur, C., Newman, T. A. (2015). A retrospective analysis of the contribution of reported factors in cochlear implantation on hearing preservation Outcomes: *Otol & Neurotol*, *36*, 1137–1145.
Cosetti, M. K., Friedmann, D. R., Zhu, B. Z., Heman-Ackah, S. E., Fang, Y., Keller, R. G., Shapiro, W. H., Roland, J. T. Jr, Waltzman, S. B. (2013). The effects of residual hearing in traditional cochlear implant candidates after implantation with a conventional electrode. *Otol Neurotol, 34*, 516–521.
Crew, J. D., Galvin, J. J. III, Landsberger, D. M., Fu, Q. J. (2015). Contributions of electric and acoustic hearing to bimodal speech and music perception. *PLoS One, 10*, e0120279.
Davies-Venn, E., Nelson, P., Souza, P. (2015). Comparing auditory filter bandwidths, spectral ripple modulation detection, spectral ripple discrimination, and speech recognition: Normal and impaired hearing. *J Acoust Soc Am, 138*, 492–503.
de Jong, M. A. M., Briaire, J. J., Frijns, J. H. M. (2018). Learning effects in psychophysical tests of spectral and temporal resolution. *Ear Hear, 39*, 475–481.
Drennan, W. R., Anderson, E. S., Won, J. H., Rubinstein, J. T. (2014). Validation of a clinical assessment of spectral-ripple resolution for cochlear implant users. *Ear Hear, 35*, e92–e98.
Dreschler, W. A., & Plomp, R. (1980). Relation between psychophysical data and speech perception for hearing-impaired subjects. I. *J Acoust Soc Am, 68*, 1608–1615.
Dreschler, W. A., & Plomp, R. (1985). Relations between psychophysical data and speech perception for hearing-impaired subjects. II. *J Acoust Soc Am, 78*, 1261–1270.
Dubno, J. R., & Dirks, D. D. (1989). Auditory filter characteristics and consonant recognition for hearing-impaired listeners. *J Acoust Soc Am, 85*, 1666–1675.
Dubno, J. R., & Schaefer, A. B. (1992). Comparison of frequency selectivity and consonant recognition among hearing-impaired and masked normal-hearing listeners. *J Acoust Soc Am, 91*(4 Pt 1), 2110–2121.
Erixon, E., & Rask-Andersen, H. (2015). Hearing and patient satisfaction among 19 patients who received implants intended for hybrid hearing: A two-year follow-up. *Ear Hear, 36*, e271–e278.
Festen, J. M., & Plomp, R. (1990). Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing. *J Acoust Soc Am*, *88*, 1725–1736.
Festen, J. M., & Plomp, R. (1983). Relations between auditory functions in impaired hearing. *J Acoust Soc Am, 73*, 652–662.
Florentine, M., Buus, S., Scharf, B., Zwicker, E. (1980). Frequency selectivity in normally-hearing and hearing-impaired observers. *J Speech Hear Res, 23*, 646–669.
Fraysse, B., Macías, A. R., Sterkers, O., Burdo, S., Ramsden, R., Deguine, O., Klenzner, T., Lenarz, T., Rodriguez, M. M., Von Wallenberg, E., James, C. (2006). Residual hearing conservation and electroacoustic stimulation with the nucleus 24 contour advance cochlear implant. *Otol Neurotol, 27*, 624–633.
Fu, Q. J., Shannon, R. V., Wang, X. (1998). Effects of noise and spectral resolution on vowel and consonant recognition: Acoustic and electric hearing. *J Acoust Soc Am, 104*, 3586–3596.
Gantz, B. J., Turner, C., Gfeller, K. E., Lowder, M. W. (2005). Preservation of hearing in cochlear implant surgery: Advantages of combined electrical and acoustical speech processing. *Laryngoscope, 115*, 796–802.
Gfeller, K. E., Olszewski, C., Turner, C., Gantz, B., Oleson, J. (2006). Music perception with cochlear implants and residual hearing. *Audiol Neurootol, 11*(Suppl 1), 12–15.
Gifford, R. H., Grantham, D. W., Sheffield, S. W., Davis, T. J., Dwyer, R., Dorman, M. F. (2014a). Localization and interaural time difference (ITD) thresholds for cochlear implant recipients with preserved acoustic hearing in the implanted ear. *Hear Res, 312*, 28–37.
Gifford, R. H., Hedley-Williams, A., Spahr, A. J. (2014b). Clinical assessment of spectral modulation detection for adult cochlear implant recipients: A non-language based measure of performance outcomes. *Int J Audiol, 53*, 159–164.
Glasberg, B. R., & Moore, B. C. (1989). Psychoacoustic abilities of subjects with unilateral and bilateral cochlear hearing impairments and their relationship to the ability to understand speech. *Scand Audiol Suppl, 32*, 1–25.
Glasberg, B. R., & Moore, B. C. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. *J Acoust Soc Am, 79*, 1020–1033.
Goehring, T., Archer-Boyd, A., Deeks, J. M., Arenberg, J. G., Carlyon, R. P. (2019). A site-selection strategy based on polarity sensitivity for cochlear implants: Effects on spectro-temporal resolution and speech perception. *J Assoc Res Otolaryngol, 20*, 431–448.
Golub, J. S., Won, J. H., Drennan, W. R., et al. (2012). Spectral and temporal measures in hybrid cochlear implant users: On the mechanism of electroacoustic hearing benefits. *Otol Neurotol*, *33*, 147–153.
Helbig, S., & Baumann, U. (2010). Acceptance and fitting of the DUET device—A combined speech processor for electric acoustic stimulation. *Adv Otorhinolaryngol, 67*, 81–87.
Henry, B. A., McDermott, H. J., McKay, C. M., et al. (1998). A frequency importance function for a new monosyllabic word test. *Aust J Audiol*, *20*, 79–86.
Henry, B. A., Turner, C. W., Behrens, A. (2005). Spectral peak resolution and speech recognition in quiet: Normal hearing, hearing impaired, and cochlear implant listeners. *J Acoust Soc Am, 118*, 1111–1121.
Holden, L. K., Firszt, J. B., Reeder, R. M., Uchanski, R. M., Dwyer, N. Y., Holden, T. A. (2016). Factors affecting outcomes in cochlear implant recipients implanted with a perimodiolar electrode array located in scala tympani. *Otol Neurotol, 37*, 1662–1668.
Holder, J. T., Reynolds, S. M., Sunderhaus, L. W., Gifford, R. H. (2018). Current profile of adults presenting for preoperative cochlear implant evaluation. *Trends Hear, 22*, 2331216518755288.
Hood, J. D., & Poole, J. P. (1971). Speech audiometry in conductive and sensorineural hearing loss. *Brit J Audiol*, *5*, 30–38.
Hopkins, K., & Moore, B. C. (2011). The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *J Acoust Soc Am, 130*, 334–349.
Horst, J. W. (1987). Frequency discrimination of complex signals, frequency selectivity, and speech perception in hearing-impaired subjects. *J Acoust Soc Am, 82*, 874–885.
Kelsall, D. C., Arnold, R. J. G., Lionnet, L. (2017). Patient-reported outcomes from the United States clinical trial for a hybrid cochlear implant. *Otol Neurotol, 38*, 1251–1261.
Kiefer, J., Pok, M., Adunka, O., Stürzebecher, E., Baumgartner, W., Schmidt, M., Tillein, J., Ye, Q., Gstoettner, W. (2005). Combined electric and acoustic stimulation of the auditory system: Results of a clinical study. *Audiol Neurootol, 10*, 134–144.
Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am, 116*(4 Pt 1), 2395–2405.
Kirby, B. J., Browning, J. M., Brennan, M. A., Spratford, M., McCreery, R. W. (2015). Spectro-temporal modulation detection in children. *J Acoust Soc Am, 138*, EL465–EL468.
Landsberger, D. M., Dwyer, R. T., Stupak, N., Gifford, R. H. (2019a). Validating a quick spectral modulation detection task. *Ear Hear, 40*, 1478–1480.
Landsberger, D. M., Stupak, N., Aronoff, J. M. (2019b). Spectral-temporally modulated ripple test Lite for Computerless Measurement (SLRM): A nonlinguistic test for audiology clinics. *Ear Hear, 40*, 1253–1255.
Landsberger, D. M., Padilla, M., Martinez, A. S., Eisenberg, L. S. (2018). Spectral-temporal modulated ripple discrimination by children with cochlear implants. *Ear Hear, 39*, 60–68.
Laroche, C., Hétu, R., Quoc, H. T., Josserand, B., Glasberg, B. (1992). Frequency selectivity in workers with noise-induced hearing loss. *Hear Res, 64*, 61–72.
Lawler, M., Yu, J., Aronoff, J. M. (2017). Comparison of the spectral-temporally modulated ripple test with the Arizona Biomedical Institute Sentence Test in cochlear implant users. *Ear Hear, 38*, 760–766.

Li, B., Hou, L., Xu, L., Wang, H., Yang, G., Yin, S., Feng, Y. (2015). Effects of steep high-frequency hearing loss on speech recognition using temporal fine structure in low-frequency region. *Hear Res, 326*, 66–74.

Litvak, L. M., Spahr, A. J., Saoji, A. A., Fridman, G. Y. (2007). Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners. *J Acoust Soc Am, 122*, 982–991.

Moore, B. C. (2007). Masking, frequency selectivity and basilar membrane nonlinearity. In *Cochlear Hearing Loss* (pp. 45–91). John Wiley & Sons, Ltd.

Moore, B. C. J. (2001). Dead regions in the cochlea: diagnosis, perceptual consequences, and implications for the fitting of hearing aids. *Trends Amplif*, *5*, 1–34.

Narne, V. K., Prabhu, P., Van Dun, B., et al. (2018). Ripple glide direction discrimination and its relationship to frequency selectivity estimated using notched noise. *Acta Acust United Ac*, *104*, 1063–1074.

O'Connell, B. P., Hunter, J. B., Haynes, D. S., Holder, J. T., Dedmon, M. M., Noble, J. H., Dawant, B. M., Wanna, G. B. (2017). Insertion depth impacts speech perception and hearing preservation for lateral wall electrodes. *Laryngoscope, 127*, 2352–2357.

Peterson, G. E., & Lehiste, I. (1962). Revised CNC lists for auditory tests. *J Speech Hear Disord, 27*, 62–70.

Phillips, S. L., Gordon-Salant, S., Fitzgibbons, P. J., Yeni-Komshian, G. (2000). Frequency and temporal resolution in elderly listeners with good and poor word recognition. *J Speech Lang Hear Res, 43*, 217–228.

Pillsbury, H. C., Dillon, M. T., Buchman, C. A., et al. (2018). Multicenter US clinical trial with an electric-acoustic stimulation (EAS) system in adults: Final outcomes. *Otol Neurotol*, *39*, 299–305.

Plant, K., & Babic, L. (2016). Utility of bilateral acoustic hearing in combination with electrical stimulation provided by the cochlear implant. *Int J Audiol, 55*(Suppl 2), S31–S38.

Preminger, J., & Wiley, T. L. (1985). Frequency selectivity and consonant intelligibility in sensorineural hearing loss. *J Speech Hear Res, 28*, 197–206.

Roland, J. T. Jr, Gantz, B. J., Waltzman, S. B., Parkinson, A. J.; Multicenter Clinical Trial Group. (2016). United States multicenter clinical trial of the cochlear nucleus hybrid implant system. *Laryngoscope, 126*, 175–181.

Rom, D. M. (1990). A sequentially rejective test procedure based on a modified Bonferroni inequality. *Biometrika*, *77*, 663–665.

Santa Maria, P. L., Domville-Lewis, C., Sucher, C. M., Chester-Browne, R., Atlas, M. D. (2013). Hearing preservation surgery for cochlear implantation—Hearing and quality of life after 2 years. *Otol Neurotol, 34*, 526–531.

Santa Maria, P. L., Gluth, M. B., Yuan, Y., Atlas, M. D., Blevins, N. H. (2014). Hearing preservation surgery for cochlear implantation: A meta-analysis. *Otol Neurotol, 35*, e256–e269.

Saoji, A. A., & Eddins, D. A. (2007). Spectral modulation masking patterns reveal tuning to spectral envelope frequency. *J Acoust Soc Am, 122*, 1004–1013.

Saoji, A. A., Litvak, L., Spahr, A. J., Eddins, D. A. (2009). Spectral modulation detection and vowel and consonant identifications in cochlear implant listeners. *J Acoust Soc Am, 126*, 955–958.

Shannon, R. V., Fu, Q.-J., Galvin, J. (2004). The number of spectral channels required for speech recognition depends on the difficulty of the listening situation. *Acta Otolaryngol Suppl*, *552*, 50–54.

Sheffield, S. W., Jahn, K., Gifford, R. H. (2015). Preserved acoustic hearing in cochlear implantation improves speech perception. *J Am Acad Audiol, 26*, 145–154.

Sheft, S., Risley, R., Shafiro, V. (2012). Clinical measures of static and dynamic spectral-pattern discrimination in relationship to speech perception. In T. Dau, M. L. Jepsen, T. Poulsen, et al., eds. *Proceedings of ISAAR 2011: Speech Perception and Auditory Disorders*. 3rd International Symposium on Auditory and Audiological Research. (*pp.* 481–488). Nyborg, Denmark.

Shpak, T., Most, T., Luntz, M. (2014). Fundamental frequency information for speech recognition via bimodal stimulation: Cochlear implant in one ear and hearing aid in the other. *Ear Hear, 35*, 97–109.

Smith, Z. M., Parkinson, W. S., Long, C. J. (2013). Multipolar current focusing increases spectral resolution in cochlear implants. *Conf Proc IEEE Eng Med Biol Soc, 2013*, 2796–2799.

Smoorenburg, G. F. (1992). Speech reception in quiet and in noisy conditions by individuals with noise-induced hearing loss in relation to their tone audiogram. *J Acoust Soc Am, 91*, 421–437.

Spahr, A. J., Dorman, M. F., Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., Loiselle, L. M., Oakes, T., Cook, S. (2012). Development and validation of the AzBio sentence lists. *Ear Hear, 33*, 112–117.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., Lewis, D. E. (2001). Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults. *J Acoust Soc Am, 110*, 2183–2190.

Strelcyk, O., & Dau, T. (2009). Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing. *J Acoust Soc Am, 125*, 3328–3345.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *J Speech Hear Res, 28*, 455–462.

Summers, V., & Leek, M. R. (1998). FO processing and the separation of competing speech signals by listeners with normal hearing and with hearing loss. *J Speech Lang Hear Res, 41*, 1294–1306.

Summers, V., Makashay, M. J., Theodoroff, S. M., Leek, M. R. (2013). Suprathreshold auditory processing and speech perception in noise: Hearing-impaired and normal-hearing listeners. *J Am Acad Audiol, 24*, 274–292.

Supin A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B. (1994). Frequency resolving power measured by rippled noise. *Hear Res, 78*, 31–40.

Supin A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B. (1998). Ripple density resolution for various rippled-noise patterns. *J Acoust Soc Am, 103*, 2042–2050.

Supin A. Y., Popov, V. V., Milekhina, O. N., Tarakanov, M. B. (1999). Ripple depth and density resolution of rippled noise. *J Acoust Soc Am, 106*, 2800–2804.

Thibodeau, L. M., & Van Tasell, D. J. (1987). Tone detection and synthetic speech discrimination in band-reject noise by hearing-impaired listeners. *J Acoust Soc Am, 82*, 864–873.

Thornton, A. R., Abbas, P. J., Abbas, P. J. (1980). Low-frequency hearing loss: Perception of filtered speech, psychophysical tuning curves, and masking. *J Acoust Soc Am, 67*, 638–643.

Turner, C., Gantz, B. J., Reiss, L. (2008). Integration of acoustic and electrical hearing. *J Rehabil Res Dev, 45*, 769–778.

Turner, C. W., Gantz, B. J., Karsten, S., Fowler, J., Reiss, L. A. (2010). Impact of hair cell preservation in cochlear implantation: combined electric and acoustic hearing. *Otol Neurotol, 31*, 1227–1232.

Tyler, R. S., Hall, J. W., Glasberg, B. R., Moore, B. C., Patterson, R. D. (1984). Auditory filter asymmetry in the hearing impaired. *J Acoust Soc Am, 76*, 1363–1368.

Vermeire, K., Punte, A. K., Van de Heyning, P. (2010). Better speech recognition in noise with the fine structure processing coding strategy. *ORL J Otorhinolaryngol Relat Spec, 72*, 305–311.

Verschuur, C., Hellier, W., Teo, C. (2016). An evaluation of hearing preservation outcomes in routine cochlear implant care: Implications for candidacy. *Cochlear Implants Int, 17*(Suppl 1), 62–65.

Vickers, D., Degun, A., Canas, A., Stainsby, T., Vanpoucke, F. (2016). Deactivating cochlear implant electrodes based on pitch information for users of the ACE strategy. In P. van Dijk, D. Başkent, E. Gaudrain, et al., eds. *Physiology, Psychoacoustics and Cognition in Normal and Impaired Hearing*. Advances in Experimental Medicine and Biology (pp. 115–123). Springer International Publishing.

Vinay, & Moore, B. C. J. (2007). Prevalence of dead regions in subjects with sensorineural hearing loss. *Ear Hear*, *28*, 231–241.

Warren, R. M., Bashford, J. A. Jr, Lenz, P. W. (2005). Intelligibilities of 1-octave rectangular bands spanning the speech spectrum when heard separately and paired. *J Acoust Soc Am, 118*, 3261–3266.

Won, J. H., Drennan, W. R., Rubinstein, J. T. (2007). Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *J Assoc Res Otolaryngol, 8*, 384–392.

Zhou, N. (2017). Deactivating stimulation sites based on low-rate thresholds improves spectral ripple and speech reception thresholds in cochlear implant users. *J Acoust Soc Am, 141*, EL243–EL248.