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Comparison of the Spectral-Temporally Modulated Ripple Test with the Arizona Biomedical Institute Sentence Test in Cochlear Implant Users

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Abstract

Objectives—Although speech perception is the gold standard for measuring cochlear implant (CI) users' performance, speech perception tests often require extensive adaptation to obtain accurate results, particularly after large changes in maps. Spectral ripple tests, which measure spectral resolution, are an alternate measure that has been shown to correlate with speech perception. A modified spectral ripple test, the spectral-temporally modulated ripple test (SMRT) has recently been developed, and the objective of this study is to compare speech perception and performance on the SMRT for a heterogeneous population of unilateral CI users, bilateral CI users, and bimodal users.

Design—Twenty-five CI users (eight using unilateral CIs, nine using bilateral CIs, and eight using a CI and a hearing aid) were tested on the Arizona Biomedical Institute Sentence Test (AzBio) with a +8 dB signal-to-noise ratio, and on the SMRT. All participants were tested with their clinical programs.

Results—There was a significant correlation between SMRT and AzBio performance. After a practice block, an improvement of 1 ripple per octave for SMRT corresponded to an improvement of 12.1% for AzBio. Additionally, there was no significant difference in slope or intercept between any of the CI populations.

Conclusion—The results indicate that performance on the SMRT correlates with speech recognition in noise when measured across unilateral, bilateral, and bimodal CI populations. These results suggest that SMRT scores are strongly associated with speech recognition in noise ability in experienced CI users. Further studies should focus on increasing both the size and diversity of the tested participants, and on determining whether the SMRT technique can be used for early predictions of long-term speech scores, or for evaluating differences among different stimulation strategies or parameter settings.

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Conflicts of Interest

We declare no conflicts of interest.

Introduction

Originally developed as an aid for lip-reading, cochlear implants (CI) have rapidly progressed to a point where many users have a high level of speech perception and sound recognition (Wilson & Dorman 2007). Improvements in speech recognition in noise are a key goal both clinically and in many research studies. However, such measures often need extended experience to obtain asymptotic performance because they rely on a learned association between a stimulation pattern and a phoneme. This presents a problem: with no immediate measure of how a patient will perform with a particular map, it is difficult to determine how one should adjust the map.

Measures of spectral resolution, such as the traditional spectral ripple test (Henry & Turner 2003) or spectral tilt measures (Winn & Litovsky 2015), which do not rely on such learned associations, offer a solution to this problem. In general, it has been shown that better spectral resolution correlates with better speech recognition in noise for CI users (Drennan et al. 2016; Henry & Turner 2003; Holden et al. 2016; Won et al. 2007; however, see Langner et al. 2017). It has also been shown that simulating broad activation patterns in normal hearing listeners via a vocoder results in deterioration of both spectral resolution and vowel recognition (Litvak et al. 2007). Additionally, spectral resolution tests involve minimal learning (Drennan et al. 2016; Won et al. 2007), indicating the potential use for these tests after remapping in predicting which adjustments may result in optimal speech perception in noise.

Recently, a modified version of the traditional spectral ripple test, the Spectral-temporally Modulated Ripple Test (SMRT; Aronoff & Landsberger 2013) has been used in a number of studies (Vickers et al. 2016; Holden et al. 2016; Aronoff et al. 2016b; Kirby et al. 2015; Zhou 2017). The SMRT uses a spectral ripple with a ripple phase that drifts over time. Each ripple phase has a 5 Hz repetition rate, creating a detectable temporal modulation with a changing phase across the spectrum (see Supplemental Digital Content 1). Holden et al. (2016) previously found that SMRT scores correlate with speech perception in noise for a relatively homogenous group of users tested with a unilateral CI. Similarly, Zhou et al. (2017) also found a correlation between SMRT and speech recognition in noise for users tested with a unilateral CI. However, many CI users have two CIs or a CI and a contralateral hearing aid. SMRT involves frequency-specific temporal modulations that align across ears and the interaural place mismatches common for bilateral CI users (Aronoff et al. 2016a) may result in a misalignment of the temporal modulations across ears. This could potentially result in interference or spurious cues that could alter the relationship between SMRT and speech scores. For bimodal users, the hearing aid and CI are likely to alter the SMRT signal differently, also potentially resulting in interference or spurious cues when the two ears are combined that could alter the relationship between SMRT and speech scores.

Whether the SMRT will have broad clinical applicability will depend in part on the strength of its association with speech perception in noise for a wide variety of patients. The goal of this study is to explore the relationship between SMRT scores and performance on the Arizona Biomedical Institute sentence test (AZBio) in noise for a group comprising unilateral CI users, bilateral CI users, and bimodal users.

Materials and Methods

Subjects

There were a total of 25 participants. Nine participants were tested with bilateral CIs, eight were tested with unilateral CIs, and eight were tested with a CI in one ear and a hearing aid in the other (see Table 1). In patients tested with a unilateral CI, the contralateral side was not blocked or altered in any way. Participants were all 18 years or older and native English speakers. Participants were chosen based on availability with no consideration or evaluation of previous CI performance. Although the majority of participants had no experience with SMRT, most had experience with AzBio in routine clinical testing. All participants had at least 6 months of CI listening experience.

Equipment

The stimuli were presented using either an Edirol UA-25 or MOTU 24I/O soundcard, amplified by a Behringer A500 Reference Amplifier, and presented in the sound field via a Pyle PCB5BK speaker placed 1 meter from the participant's head at ear-level. The same soundcard was always used for both the SMRT and AzBio testing for a given participant.

Stimuli and Procedures

Participants underwent testing with both AzBio and SMRT. AzBio consists of twenty-nine sentence lists, each with twenty sentences, ten from two female speakers and ten from two male speakers. The sentences range from four to twelve words and are spoken in a conversational style in a background of continuous ten-talker babble. For this study, the eight lists included in the Minimum Speech Test Battery were used. The noise was presented at 60 dB (A) and a +8 dB signal-to-noise ratio was used. Participants were asked to repeat the sentences to the best of their ability. The total number of words correct for all sentences was counted and divided by the total number of words in each list. Each subject was tested with two separate AzBio sentence lists and the sentence list selection was randomized across participants. No AzBio training in quiet or noise was provided to participants, although many of them had extensive experience with AzBio given its prevalence in clinical assessment.

SMRT consists of three spectrally rippled (i.e., amplitude modulated in the frequency domain) stimuli, two reference stimuli and one target stimulus. Each stimulus is generated with a 44.1 kHz sampling rate and is 500 ms with 100ms onset and offset linear ramps. The stimuli are composed of 202 pure tones with random starting phases, spaced every 1/33.33 octaves (from 100–6400 Hz). The amplitudes of the pure tones are temporally modulated by a half-wave rectified sinewave with a starting phase that differs systematically across pure tones. The temporal modulation of the stimulus is controlled by the frequency of that sinewave. As is standard for SMRT, the sinewaves used to add the temporal modulation had a frequency of 5 Hz. The shift in the starting phase of the modulating sinewaves across frequencies causes a drift in the ripples in the frequency domain (see Supplemental Digital Content 1).

The reference stimuli have ripple densities of 20 ripples per octave (RPO). The target stimulus initially has a ripple density of 0.5 RPO that is varied using a 1 up/1 down adaptive procedure with a step size of 0.2 RPO. Subjects are asked to “choose which of the three noises sounds different” and to use a keyboard to indicate whether it was the first, second, or third stimulus. The test is completed after ten reversals. Spectral-ripple thresholds (in RPOs) are calculated from the average of the last six reversals. For this study, stimuli were presented at a fixed intensity of 60 dB (A). Each participant was tested twice with the SMRT. No training was provided for the SMRT.

This study was approved by the University of Illinois at Urbana-Champaign Institutional Review Board.

Results

Robust statistical techniques were used to analyze the data (see the Appendix in the Supplemental Digital Content in Aronoff et al. 2016b; re-printed with permission as Supplemental Digital Content 2), including bootstrap analyses, least trimmed squares regressions and trimmed means. Overall, these techniques serve to minimize the problems that outliers and non-normality cause for traditional statistical techniques without resorting to non-parametric methods which ignore important magnitude information. Trimmed means retain some characteristics of means and some characteristics of medians. With medians, the upper and lower approximately 50% of the data are treated as ordinal values. The mean of the remaining interval data is then calculated. With the 20% trimmed means used here, the upper and lower 20% of the data are treated as ordinal values and the mean of the remaining interval data is calculated. Least trimmed squares regressions are similar to least squares regressions, except that they minimize a subset of the errors to reduce the effects of outliers.

To determine if performance improved from the first to second SMRT test, a percentile bootstrap pairwise comparison using 20% trimmed means was conducted comparing the first and second SMRT test. The results indicated a small but significant improvement for the second SMRT test (95% confidence interval: .06 to .93 RPO, 20% trimmed mean: 0.5 RPO). This indicates that a practice test is needed. As such, comparisons between SMRT and AzBio excluded the results from the first (i.e., practice) SMRT test.

A bootstrap pearson correlation with outlier correction based on the minimum generalized variance outlier detection method was calculated. There was a significant correlation between the SMRT scores and the AzBio scores ($r=0.83$, 95% confidence interval: 0.63 to 0.94; see Figure 1). The one outlier detected by the outlier detection method was the bilateral CI user with the highest SMRT score. A least trimmed squares regression was used to characterize the relationship between SMRT and AzBio scores. This indicated that an increase of one RPO on SMRT correlates with an increase of 12.1 percent on AzBio (slope=12.1, intercept = -5).

Bootstrap comparisons of least trimmed squares regressions were used to compare the relationship between SMRT and AzBio across groups. For these analyses, two groups were compared at a time. For example, a bootstrap sample was generated for both the bilateral

and the bimodal groups and a least trimmed squares regression analysis was conducted separately on each group. The slope for the bilateral group was subtracted from the slope for the bimodal group, creating a difference score for the slopes. The intercept for the bilateral group was also subtracted from the intercept for the bimodal group, creating a difference score for the intercepts. This process was repeated 599 times and the resulting difference scores were ordered by magnitude and the 95% confidence interval consisted of the 14th and 585th largest values. This same process was repeated comparing the bilateral and unilateral groups as well as the unilateral and bimodal groups. The results indicated that there was no significant difference between the slopes and intercepts for any of the groups (bilateral vs. bimodal groups: 95% confidence interval for slope = -56 to 27, 95% confidence interval for the intercept = -59 to 156; bilateral vs. unilateral groups: 95% confidence interval for slope = -17 to 16, 95% confidence interval for the intercept = -25 to 53; unilateral vs. bimodal groups: 95% confidence interval for slope = -24 to 32, 95% confidence interval for the intercept = -152 to 56).

The effects of participant characteristics were also analyzed. Although there were only a small number of participants with a prelingual onset of hearing loss, those individuals received similar scores as those with a postlingual onset of hearing loss (see Table 1). Additionally, the slope and intercept for the relationship between SMRT and AzBio scores were similar for the two groups (prelingual: slope = 11.1, intercept = -5.2; postlingual: slope = 12.8, intercept = -7.8). There was no significant correlation between the age of onset of hearing loss or length of CI use for either ear with either SMRT or AzBio scores.

Discussion

The results indicated that SMRT scores are correlated with speech perception in noise scores even with a diverse group of participants, including those tested with unilateral CIs, bilateral CIs, and a CI combined with a hearing aid. These results are consistent with previous work showing spectral resolution, as determined by spectral-ripple tasks, strongly correlate with speech perception in noise and in quiet (Holden et al. 2016; Litvak et al. 2007; Won et al. 2007; Zhou 2017) as well as the results from biologically inspired models (Chi et al. 1999).

Our results were similar to those found in Holden et al. (2016). Holden et al. (2016) included the same testing conditions as the current study but a much more homogenous group of participants, all tested with a unilateral CI. As with the results from the current study, they also found a significant correlation between SMRT and AzBio in noise (+8dB SNR in both studies). The range of SMRT and AzBio scores was largely similar across the two studies, although the range of SMRT scores was slightly larger in the current study. Holden et al. (2016) found a range of 1.5 to 6.2 RPO. In the current study, the range was 0.3 to 8.3 RPO (although excluding the outlier identified by the minimum generalized variance outlier detection method, it was more comparable, ranging from 0.3 to 6.3 RPO). Additionally, participants' AzBio scores spanned nearly the entire range in both studies (0 to 83 in the current study compared to 0 to 96% in Holden et al., 2016). However, both our mean SMRT scores (3.1 RPO) and mean AzBio scores (36%) were lower than those in Holden et al. (2016) (3.8 RPO and 52%, respectively), suggesting, on average, better performers in the Holden et al. (2016) study.

Importantly, while Holden et al. took steps to limit the acoustic hearing for their participants, the current study specifically included a group of bimodal patients. Given that an aim of this study is to provide evidence for the clinical utility of the SMRT, a broad range of patients, similar to what would be found in a typical clinic, were included. Notably, the linear fit for the current data and that from Holden et al. (2016) is strikingly similar, as shown in Figure 1. This, coupled with the lack of a significant difference between the slopes and intercepts between any of the groups, suggests that the relationship between SMRT and AzBio is similar across different CI populations. Further research is needed to determine if a similar relationship would be found if other hearing impaired populations are tested.

Although the results from this study and others suggest that measures of spectral resolution are significantly correlated with performance on speech tests, the correlation only accounts for a portion of the variability in performance on speech tests. This is likely because a number of other factors that affect speech understanding, such as implant experience and age of implantation (e.g., Lazard et al. 2012; Eapen et al. 2009), may not have a comparable effect on spectral resolution. However, as spectral resolution is improved by adding additional channels, both vocoder and CI studies show an improvement in speech perception performance (Shannon et al. 1995; Fishman et al. 1997; Friesen et al. 2001). It is possible that the correlation between spectral resolution and speech perception may be caused by spectral resolution affecting the upper limit of speech perception performance.

Potential limitations of the SMRT

One limitation of the SMRT found in this study is that, despite the relatively simple nature of the task for SMRT, the significant improvement from the first to the second SMRT test suggests that, at minimum, a practice test is needed. However, it is possible that learning continues over additional tests. This suggests that the test-retest reliability for the SMRT needs to be further examined.

Another possible limitation of the SMRT is that it may have an upper range that could limit the utility of the test for extremely high performing participants. Excluding the one outlier, both the current study and Holden et al. (2016) had a maximum SMRT score of approximately 6 RPO. Although this may have reflected limitations in the samples in each study, the similarity across the two studies suggests that this may reflect a true limitation of the SMRT with CI users. When normal hearing listeners were tested (without vocoders) in Aronoff & Landsberger (2013), scores were typically above 8 RPO, suggesting that the 6 RPO upper limit may reflect limitations induced by the CI processor, such as the bandwidth of the frequency bands.

The correlation between SMRT and AzBio is also likely to be affected by a number of factors not specifically manipulated in this study. For example, there may be effects of factors such as pre/postlingual deafness, pre/postlingual implantation, native language, etc. Although the similarities between the results found here and those in Holden et al. (2016) suggest that the correlation is likely to be found for a wide range of participants, many of these factors were not manipulated in either study.

Possible cues used for SMRT by CI users

CI processors will invariably distort the cues in the acoustic SMRT stimuli. However, the temporal cue caused by the 5 Hz modulation that changes in phase across frequencies would be expected to be at least partially retained after processing. Because multiple ripples that fall within one filter will be added together and the temporal modulation for adjacent ripples is slightly offset in time, the expectation is that the greater the ripple density, the greater the temporal smearing of the amplitude modulation within a frequency band. Similarly, the more channel interaction, resulting in signals from multiple filters adding together at the neural level, the more temporal smearing will occur. With increasing temporal smearing, the modulation depth of the amplitude modulation is reduced, increasing the difficulty of detecting it.

To investigate if this occurs with CI processors, electrodograms were recorded using a 16 channel map programmed on an Advanced Bionics Harmony processor using Bionic Ear Programming System (BEPS+; Advanced Bionics, Valencia, CA). The map used a continuous interleaved sampling (CIS) processing strategy without current steering, with a phase duration of 48 μ s and a pulse rate of 657 pulses per second. The Standard Extended Low clinical frequency allocation was used, which ranged from 238 to 8054 Hz (see Table 2 for the corner frequencies).

Because the amplitude modulation rate for each ripple is 5 Hz, versions of the electrodograms were also generated that were low-pass filtered at 10 Hz using a 4th order butterworth filter to highlight the temporal modulation in different channels. The top portion of Figure 2 shows the effect of increasing the ripple density. With a ripple density of 0.5 RPO, a clear amplitude modulation can be seen, shifted in time across channels. As predicted, increasing the ripple density decreased the amplitude modulation depth within each channel. The top portion of Figure 3 shows the effect of simulated increased channel interaction, by averaging the amplitude of the signal from each electrode over one, three, five, or seven electrodes. As predicted, increased simulated channel interaction also results in a reduction of the amplitude modulation depth. This is consistent with previous vocoder data indicating that increasing spectral smearing, by decreasing the number of vocoder channels, results in poorer SMRT scores (Aronoff & Landsberger 2013). Electrodograms for a wide range of SMRT stimuli are available in Supplemental Digital Content 1 and the raw data underlying the electrodograms are available in Supplemental Digital Content 3.

For bimodal users, the properties of the acoustic signal are also critical. The bottom portions of Figures 2 and 3 show acoustic SMRT stimuli. For comparison with the electrodograms, a version of the stimuli was also generated that were band-pass filtered with a 4th order butterworth filter using the corner frequencies from Table 2. The signals were then low-pass filtered at 10 Hz with a 4th order butterworth filter to examine the effects of increasing the RPO of the stimuli or increasing spectral smearing. Both the low pass filtered electrodograms and the low pass filtered acoustic signals show similar patterns. The similarity likely results from the preservation of envelope information in CIS-based strategies. This suggests that amplitude modulation detection may be key for both the CI and HA ear for the bimodal participants.

Given the reliance on detecting amplitude modulations for the SMRT, it is possible that, in addition to differences in spectral resolution, differences in amplitude modulation sensitivity could also affect SMRT performance. However, such differences are also likely to influence speech perception. Single-channel amplitude modulation detection has been found to correlate with speech perception (Fu 2002; Luo et al. 2008). Additionally, removing channels with poor amplitude modulation sensitivity can improve speech perception (Zhou & Pfingst 2012).

Although both spectral resolution and temporal amplitude modulation sensitivity could potentially account for the correlation with speech recognition (Friesen et al. 2001; Won et al. 2007; Fu 2002; Luo et al. 2008; Zhou & Pfingst 2012) it is not possible to distinguish the contributions of each based on the current experiment. Future studies will need to independently manipulate these factors to determine how they each contribute. Although the role of spectral resolution and temporal amplitude modulation sensitivity may differ across participants, the result of the current study suggest that, if they do, their effects are similar on both SMRT and speech recognition abilities.

Differences between SMRT and traditional ripple tests

Although both traditional ripple discrimination tests and SMRT scores are expressed in ripples per octave, numbers from the two tests are not interchangeable. Studies using traditional ripple tests with CI users have typically found average score of less than 3 RPO (Henry et al. 2005; Drennan et al. 2014; Anderson et al. 2011; Won et al. 2007). In contrast, studies using SMRT with CI users, including the current study, have typically found average scores greater than 3 RPO (Holden et al. 2016; Zhou 2017). These differences in scores likely reflect differences in both the stimuli and the tasks. Although both the traditional ripple test and the SMRT have amplitude modulations in the frequency domain, the SMRT also provides a temporal cue that varies across the spectrum and has a low modulation rate. These temporal modulations are not used in the traditional ripple test. In terms of task, the traditional ripple discrimination test typically asks participants to distinguish two ripples that differ in phase. In contrast, the SMRT asks participants to distinguish a stimulus with few RPOs, where the within-channel temporal modulation is likely audible, from a stimulus with a high ripple density, where the within-channel temporal modulation is unlikely to be preserved or audible. These differences may explain the different ranges of scores in the two tasks and suggest that the scores are unlikely to be interchangeable.

Conclusion

The results indicated that SMRT scores are strongly associated with speech recognition in noise ability in a diverse group of experienced CI users, including those using unilateral CIs, those with bilateral CIs, and those using a CI combined with a hearing aid. This increases the likelihood that SMRT may become a useful tool to evaluate map changes in the clinic, but further studies will be needed to provide a definitive answer.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

SMRT scores significantly correlate with AzBio in noise scores. Each data point represents one participant. The solid line reflects a linear fit of the data from the current study. The dashed line reflects a linear fit of the data from Holden et al. (2016).

Figure 2.

Electrodograms (top panel) and acoustic signals (bottom panel) for SMRT stimuli demonstrating the effects of increased ripple density on the amplitude modulation in different frequency bands.

Figure 3.

Electrodegrams (top panel) and acoustic signals (bottom panel) for SMRT stimuli demonstrating the effects of increased spectral smearing on the amplitude modulation in different frequency bands. For the electrodegrams, channels were slightly shifted in time to align pulses across channels so they could be added together.

Table 1

Participant characteristics.

Subject	Age	Gender	Hearing Loss Onset	Pre/post lingual onset of hearing loss	Cause	Cochlear implant	Cochlear implant experience	Hearing Aid	SMRT (RPO)	AZBio (% correct)
I02	63	Female	2 y/o	Prelingual	Meningitis	Advanced Bionics (bilateral)	4 years (left), 7 years (right)	-----	4.9	53.3
I03	72	Female	Congenital	Prelingual	Unknown	Advanced Bionics (bilateral)	14 years (left), 9 years (right)	-----	2.8	6.8
I16	51	Female	6 mo	Prelingual	Rubella	Advanced Bionics (bilateral)	2 months (right), 9 years (left)	-----	0.5	3.3
I26	45	Female	Congenital	Prelingual	Congenital	Advanced Bionics (bilateral)	2 years (bilateral)	-----	8.3	76.7
I30	26	Female	Congenital	Prelingual	Congenital	Cochlear (right)	21 years	None	3.1	21.8
I44	54	Male	Congenital	Prelingual	Congenital	Cochlear (right)	5 years	Starkey (left)	4.2	76.5
I04	58	Female	39 y/o	Postlingual	Autoimmune	Advanced Bionics (bilateral)	2 years (left), 2 years (right)	-----	5	80.4
I05	58	Male	5 y/o	Postlingual	Congenital	Advanced Bionics (bilateral)	13 years (bilateral)	----	1.4	8.8
I17	74	Male	66 y/o	Postlingual	Unknown	Advanced Bionics (right)	3 years	Audiibel (left)	2.3	17.4
I18	48	Male	20 y/o	Postlingual	Unknown	Cochlear (bilateral)	3 years (left), 11 years (right)	-----	5	74.9
I19	65	Male	44 y/o	Postlingual	Unknown	Med-El (bilateral)	8 months (bilateral)	-----	1.6	3.7
I20	59	Female	53 y/o	Postlingual	Autoimmune	Cochlear (left)	6 years	None	4.8	47.1
I23	50	Female	20 y/o	Postlingual	Ototoxicity	Cochlear (right)	13 years	* Unknown	1.4	17.8
I24	85	Male	65 y/o	Postlingual	Noise Exposure	Advanced Bionics (right)	7 years	* Phonak (left)	0.5	1.1
I29	65	Female	63 y/o	Postlingual	Noise Exposure	Cochlear (left)	6 months	ReSound (right)	5.6	44.6
I31	55	Male	37 y/o	Postlingual	Trauma	Cochlear (bilateral)	16 years (left), 2 years (right)	-----	2.5	11.2
I32	64	Female	39 y/o	Postlingual	Familial	Cochlear (left)	2 years	None	5.3	83.3
I33	69	Male	44 y/o	Postlingual	Familial	Med-El (left)	2 years	Oticon (right)	3	38.1
I45	68	Female	18 y/o	Postlingual	Genetic/progressive	Advanced Bionics (left)	5 years	Phonak (right)	6.3	77
I46	81	2/1/17	~75 y/o	Postlingual	Chemotherapy	Advanced Bionics (left)	1 year	Oticon (right)	2.3	7.9
I47	70	Female	30 y/o	Postlingual	Familial	Cochlear (right)	2 years	Phonak (left)	2	44.2
I22	50	Female	Unknown	Unclear	Chronic otitis	Cochlear (left)	1 year	None	1.6	20.2
I25	18	Female	Childhood	Unclear	Unknown	Med-El (right)	5 years	* Oticon (left)	0.3	0
I27	66	Male	Childhood	Unclear	Meningitis/otitis	Cochlear (right)	9 years	None	2.1	21.6

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Subject	Age	Gender	Hearing Loss Onset	Pre/post lingual onset of hearing loss	Cause	Cochlear implant	Cochlear implant experience	Hearing Aid	SMRT (RPO)	AZBio (% correct)
I48	67	Female	Birth (left), 59 y/o	Mixed	Congenital/ototoxicity	Advanced Bionics (left)	8 years	Phonak (right)	1.6	49.8

* Tested without hearing aid.

Table 2

Corner frequencies for maps used to generate electrodograms.

Channel	Lower bound (Hz)	Upper bound (Hz)
1	238	442
2	442	510
3	510	646
4	646	714
5	714	850
6	850	986
7	986	1189
8	1189	1393
9	1393	1597
10	1597	1937
11	1937	2277
12	2277	2617
13	2617	3093
14	3093	3704
15	3704	4316
16	4316	8054