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Auditory Function and Speech Understanding in Listeners Who Qualify for EAS Surgery

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Abstract

Objective—For patients with relatively good low-frequency hearing and relatively poor high-frequency hearing, who met the pre-implant criteria for combined electric and acoustic stimulation (EAS), our aims were to i) assess deficits in low-frequency auditory function, ii) to identify measures which might be sensitive to changes resulting from the insertion of an intracochlear electrode array, and iii) to quantify the relationship between measures of auditory function and performance on tasks of speech and melody recognition.

Design—Measures of frequency selectivity, temporal resolution, and nonlinear cochlear function, along with measures of word, sentence, consonant, vowel, and melody recognition, were obtained from 5 normal-hearing and 17 hearing-impaired listeners. The hearing-impaired listeners had auditory thresholds at 500 Hz, ranging from 20 to 60 dB HL, and thresholds at 1 kHz, ranging from 60 to 100 dB HL.

Results—Nonlinear cochlear function was either reduced or absent. Frequency selectivity at 500 Hz was significantly reduced but still present in most patients. Temporal resolution, when measured at low modulation frequencies, was normal. Speech recognition in a modulated background revealed significantly poorer performance than normal. Speech and melody recognition varied over a large range. No measure of auditory function was correlated significantly with speech recognition. However, frequency selectivity was related to melody recognition.

Conclusions—(1) Patients who qualify for EAS surgery have a wide range of speech and melody recognition abilities. (2) A number of the psychophysical measures tested may prove more sensitive than the audiogram in determining the degree of damage inflicted by the intracochlear electrode array. (3) Speech recognition was not correlated with any of the measures of auditory function.

Individuals with relatively good low-frequency hearing and very poor high-frequency hearing have limited rehabilitation options. Amplification is of little benefit (e.g., Hogan & Turner, 1998), and cochlear implantation is not typically recommended because it has been thought that insertion of an electrode array would destroy the residual, low-frequency hearing. However, recent research has shown that an electrode can be inserted 10 or 20 mm into the cochlea without destroying hearing in the apical portion of the cochlea (e.g., Gantz et al., 2005; Kiefer et al., 2005). In these patients, speech intelligibility is significantly better in a combined electric and acoustic stimulation (EAS) condition than when stimulation is delivered by electric stimulation only (Gantz et al. 2005; Kiefer et al. 2005; Wilson et al., 2002).

Our objectives were to i) assess deficits in low-frequency auditory function in a little studied population with precipitously sloping, high-frequency hearing loss, ii) to identify measures which might be sensitive to changes resulting from the insertion of an electrode array into the basal region of the cochlea, and iii) to quantify the relationship between measures of auditory function and performance on tasks of speech and melody recognition. We will repeat this evaluation with patients who eventually undergo the partial insertion cochlear implant surgery associated with the EAS trials and report the results in a future publication.

Methods

Subjects

Five female subjects with normal hearing and 17 subjects (11 male, 6 female) with hearing loss were recruited for the study. The mean age of the hearing-impaired group was 68.5 years, with a range of 40 to 84 years. The mean age of the normal-hearing group was 24.2 years, with a range of 21 to 31 years. All subjects were paid an hourly wage for their participation. Subjects with hearing loss were chosen to match the audiologic criteria for participation in the FDA clinical trial of EAS as defined by the Med El Corporation. Figure 1 displays audiometric thresholds for all subjects.

General Laboratory Procedures

Stimuli used in the measurement of speech intelligibility were presented in the free field via a single loudspeaker placed in front of the subject (0° azimuth) at a distance of 1 meter. Stimuli used in the measurement of low-frequency acoustic processing were presented monaurally via Sennheiser HD250 stereo headphones. All psychophysical testing utilized an adaptive, three-interval, forced-choice paradigm with a decision rule to track 79.4% correct (Levitt, 1971). Stimuli were generated and produced digitally with a 20-kHz sampling rate. All gated stimuli were shaped with 10-msec \cos^2 rise/fall times. All test stimuli were temporally centered within the masker. Interstimulus intervals were 300 msec in all masking experiments. Testing was completed in a double-walled, sound-attenuating booth.

Stimuli and Conditions

Experiment 1: Estimates of Frequency Resolution—Estimates of frequency resolution were assessed by deriving auditory filter (AF) shapes, using the notched-noise method (Patterson, 1976) in a simultaneous-masking paradigm. Each band of noise [0.4 times the signal frequency (f_s)] was placed symmetrically or asymmetrically around the 500 Hz signal (Stone & Moore, 1992). The signal was fixed at a level of 10 dB sensation level (SL), and the masker level was varied adaptively. The masker and signal were 400 and 200 msec in duration, respectively.

Experiment 2: Estimates of Temporal Resolution—Psychophysical estimates of temporal resolution were obtained by measuring amplitude modulation (AM) detection thresholds for modulation rates from 4 to 32 Hz, in octave steps. The 500 Hz carrier—which was fixed at a level of 20 dB SL—was gated with each 500 msec observation interval. The depth of the modulation was varied adaptively. Level compensation was applied to the modulated stimulus (see Viemeister, 1979).

An additional measure of temporal resolution was achieved by obtaining a speech reception threshold (SRT) for sentences from the Hearing in Noise Test (HINT; Nilsson et al., 1994) in two types of background noise. The steady-state (SS) noise was shaped to match the long-term spectrum of the HINT sentences. The modulated noise was constructed by imposing a 10 Hz square wave (SQ, 100% modulation depth) on the SS noise. The SS noise was fixed at an overall level of 70 dB SPL and the sentences were varied adaptively to achieve 50% correct

(see Bacon et al., 1998 for greater detail regarding stimuli). Twenty HINT sentences were used to calculate the speech threshold in dB signal-to-noise ratio (SNR) for each background noise (for more information on procedure, see Bacon et al., 1998). The difference in the thresholds for the SS and SQ noises provides a measure of masking release provided by the modulated masker. The degree of masking release demonstrates the listener's ability to "listen in the dips" to obtain information about the speech stimulus and is thought to reflect a measure of temporal resolution (see Bacon et al., 1998).

Experiment 3: Estimates of Nonlinear Cochlear Processing—Psychophysical estimates of cochlear nonlinearity were obtained by measuring masked thresholds for 500 Hz tonal signals in the presence of both positively scaled and negatively scaled Schroeder phase harmonic complexes (see Lentz & Leek, 2001). Positive-Schroeder (m+) and negative-Schroeder (m-) phase complexes have identical amplitude spectra but different phase spectra (Schroeder, 1970). Although m+ and m- complexes have identical flat envelopes, m+ complexes tend to produce less masking. Several researchers have hypothesized that the difference in masking effectiveness results from the m+ complexes producing a more peaked response along the BM, coupled with fast-acting compression (e.g., Carlyon & Datta, 1997; Recio & Rhode, 2000; see also Oxenham & Dau, 2001).

The overall level of the masker was fixed at 75 dB SPL (63.9 dB SPL per component), and the signal level was varied adaptively. The spectral range of the masker encompassed the frequency range between 200 and 800 Hz with a fundamental frequency of 50 Hz. The durations of the masker and signal were 400 and 200 msec, respectively. The signal was placed in the temporal center of the masker.

Experiment 4: Estimates of Speech Intelligibility and Melody Recognition—The test material included monosyllables, sentences, vowels, consonants, and simple melodies (see Spahr & Dorman, 2005, for details). All stimuli were presented at 70 dB SPL. Sentence stimuli were presented in quiet and in +10 dB SNR (4-talker babble). Only listeners with hearing loss were tested on measures of speech intelligibility.

Results and Discussion

Psychophysical Results

The masked thresholds in the presence of the different notched-noise conditions were used to derive filter shapes using a roex (p , k) model (Patterson et al., 1982). Figure 2A displays the derived AF shapes for the normal-hearing and 13 hearing-impaired listeners who completed the testing.* The AF shapes for the hearing-impaired listeners were broader than those of the listeners with normal hearing. Consistent with previous studies, the hearing-impaired listeners demonstrated extensive intersubject variation in AF shape (e.g., Laroche et al., 1992; Leek & Summers, 1993).

Comparisons across subjects were made in terms of equivalent rectangular bandwidth [(ERB), Glasberg & Moore, 1990] of the AF. The mean and standard deviation for the normal-hearing listeners' ERBs were 104 and 19 Hz, respectively (with a range of 78 to 120 Hz). The mean and standard deviation for the pre-implant listeners' ERBs were 183 and 56 Hz, respectively (with a range of 109 to 285 Hz). A one-way ANOVA on ranks revealed a significant difference in the width of the ERB (in Hz) between the normal-hearing and hearing-impaired listeners ($H = 7.9$, $p = 0.005$).

*Three of the participants had quiet thresholds at 500 Hz that were too high, such that a 10 dB SPL signal could not be masked with the maximum permissible level of the masker (95 dB SPL).

The mean modulation detection thresholds are presented in Figure 2B. Modulation detection was found to be equivalent for the normal-hearing and hearing-impaired listeners ($F_{1,20} = 0.04$, $p = 0.85$). Thus, temporal resolution—as determined by modulation detection at relatively low rates—is essentially normal in this population of hearing-impaired listeners.

The results from the HINT in both the SS and square-wave (SQ) background noises are displayed in Figure 2C. Within the hearing-impaired group, there were 8 listeners who could not achieve 50% correct even at +20 dB SNR—these listeners' results are not shown. Figure 2C displays the mean normal-hearing SRTs as well as results for the 9 hearing-impaired listeners who completed the task. A two-way, repeated-measures ANOVA revealed that compared with normal-hearing listeners, hearing-impaired listeners demonstrated (i) significantly higher SRTs ($F_{1,20} = 212.75$, $p < 0.001$) and (ii) significantly reduced masking release with the SQ noise ($F = 56.99$, $p < 0.001$). Thus, the hearing-impaired listeners exhibited little or no benefit from listening in the “dips” of a modulated noise masker.

The mean Schroeder-masked thresholds for the five normal-hearing and the 16 hearing-impaired listeners who completed this experiment are displayed in Figure 2D. The maximum phase effect—defined as the difference in threshold between the peak (−1 scalar) and valley (+0.25 scalar) of the function—was computed and analyzed. A one-way ANOVA revealed a significant difference in the maximum phase effect between the normal-hearing and hearing-impaired listeners ($F = 54.2$, $p < 0.001$). The normal-hearing listeners displayed changes in threshold consistent with normal, nonlinear cochlear processing. In contrast, the hearing-impaired listeners exhibited little or no change in threshold as a function of scalar value. There are a couple of potentially confounding variables with the 500 Hz signal. First, several of the subjects' quiet thresholds at 500 Hz were higher than the normal-hearing listeners' masked thresholds. Thus, audibility played a role in a number of the cases. Second, because nonlinear cochlear processing is affected by hearing status up to one-half octave above CF (e.g., Davis, 1983), it is possible that thresholds at 750 Hz were responsible for this outcome. However, there was no correlation between thresholds at 750 Hz (or 500 Hz) and the Schroeder phase results. Thus, the audiogram alone may not provide a sensitive measure of auditory function in listeners with this type of hearing loss.

Speech and Melody Recognition

Speech and melody recognition scores are displayed in Figure 3. Of interest is the wide range of performance (as high as 80 percentage points) across the listeners on a given measure. In an attempt to relate speech and music performance to psychophysical function, measures of correlation were computed. The psychophysical metrics used for correlation were AF width in ERBs, AM detection sensitivity averaged across 8, 16, and 32 Hz, degree of masking release in dB, and maximum Schroeder phase effect (in dB). Each of the four psychophysical metrics was compared with performance on the tests of speech and melody recognition. Pearson product-moment correlations revealed no significant correlations between any of the psychophysical metrics and speech or melody performance with the exception of ERB (in Hz) versus melody recognition ($r = -0.78$, $p = 0.002$). This effect is understood given that the frequencies of the notes in all melodies ranged from 277 Hz to 622 Hz (with the average note equaling 440 Hz). The melodies were created without distinctive rhythmic information requiring the listener to identify each melody on the basis of pitch, rather than note duration or temporal spacing. Thus, a narrower AF at 500 Hz is associated with better frequency selectivity at 500 Hz, and hence, should also be associated with greater performance on a melody recognition task for which resolution of individual low-frequency notes and harmonics is required.

Conclusions

In the introduction, we identified three goals. The first was to assess deficits in low-frequency auditory function in listeners with steeply sloping high-frequency hearing loss. There were, in fact, significant deficits in frequency selectivity, masking release (the difference in SRT between the SS and SQ conditions), and nonlinear cochlear processing. Temporal resolution at low modulation rates was essentially equivalent to that observed in young normal-hearing listeners.

The second goal was to identify measures that might be sensitive to changes resulting from the insertion of an intracochlear electrode array. Frequency selectivity, while poor, could get worse after partial insertion implant surgery. Though temporal resolution was normal, it is feasible to believe that sensitivity to modulation could also get worse after surgery. Speech masking release was small but present for six subjects. Thus, it could also be a useful measure. Nonlinear cochlear processing as measured with Schroeder phase maskers is not a useful tool at 500 Hz; this measure, however, might be useful at lower test frequencies.

The third goal was to quantify the relationship between measures of auditory function and performance on tasks of speech and melody recognition. The results suggest that there was no relationship between speech recognition and any of the psychophysical measures of auditory function. There was a significant correlation between frequency selectivity at 500 Hz and melody recognition.

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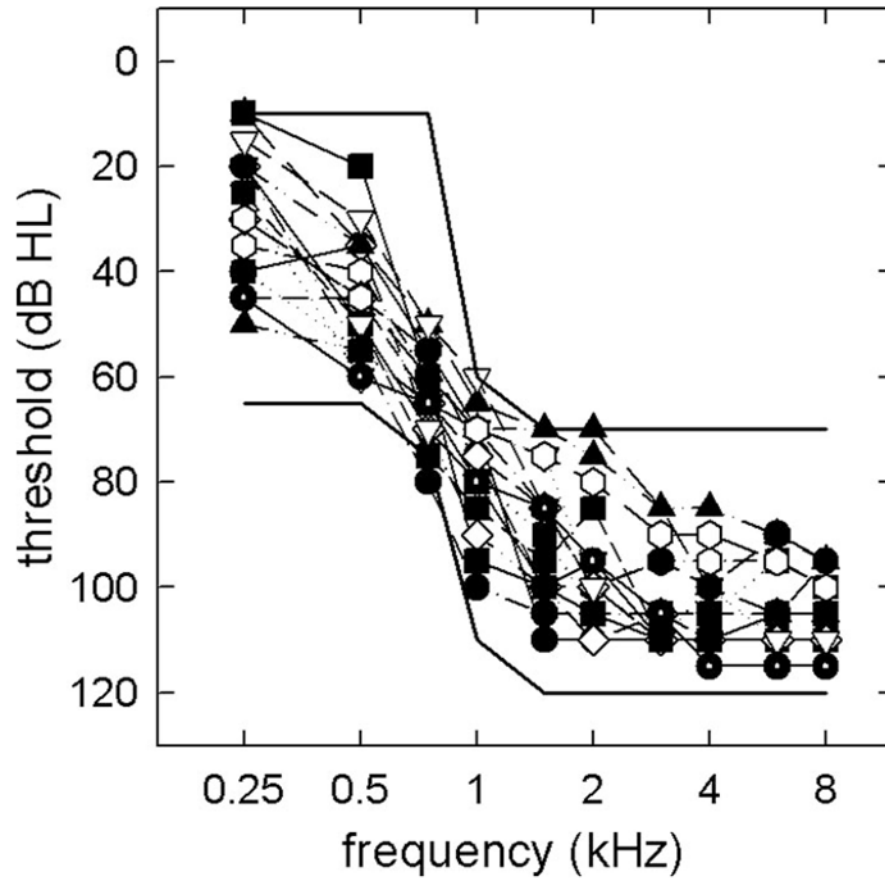
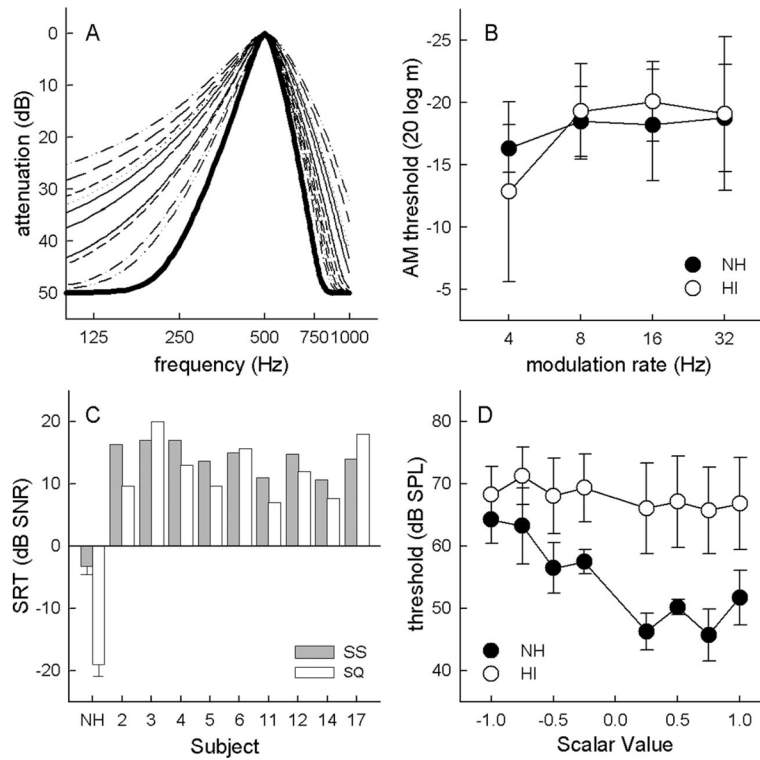


Fig. 1. Quiet thresholds for the 17 hearing-impaired listeners in the current study. Bold lines outline the range of acceptable thresholds for candidacy in the MED EL clinical trial of EAS.

**Fig. 2.**

Estimates of psychophysical low-frequency acoustic processing. A, AFs for the individual hearing-impaired listeners as well as the mean normal-hearing listeners (in bold); B, mean AM detection thresholds for the normal-hearing and hearing-impaired listeners; C, mean normal-hearing and individual hearing-impaired listeners' SRT for the SS and SQ noise backgrounds; D, mean Schroeder-phase masked thresholds for the normal-hearing and hearing-impaired listeners.

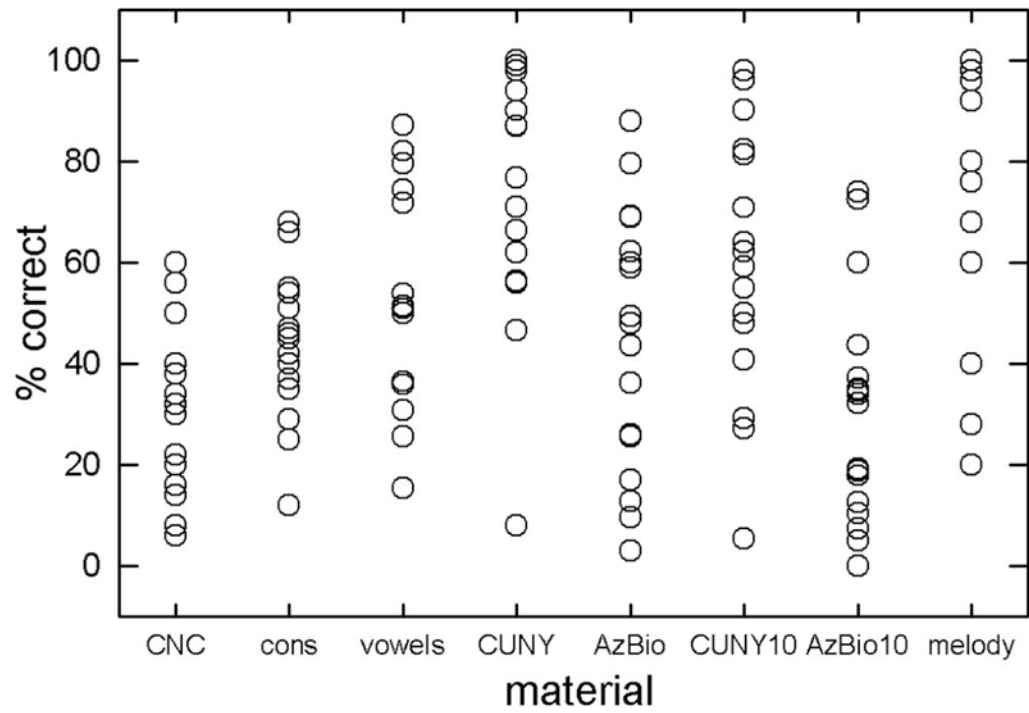


Fig. 3. Individual performance scores on measures on CNC word recognition, consonants, vowels, CUNY, and AzBio sentences in quiet and +10 dB SNR and melody recognition.