Intensity discrimination and detection of amplitude modulation in electric hearing

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Wojtczak and Viemeister [J. Acoust. Soc. Am. **106**, 1917–1924 (1999)] demonstrated a close relationship between intensity difference limens (DLs) and 4-Hz amplitude modulation (AM) detection thresholds in normal-hearing acoustic listeners. The present study demonstrates a similar relationship between intensity DLs and AM detection thresholds in cochlear-implant listeners, for gated stimuli. This suggests that acoustic and cochlear-implant listeners make use of a similar decision variable to perform intensity discrimination and modulation detection tasks. It can be shown that the absence of compression in electric hearing does not preclude this possibility. [S0001-4966(00)04508-2]

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INTRODUCTION

Wojtczak and Viemeister (1999) investigated the relationship between intensity discrimination thresholds and 4-Hz amplitude modulation (AM) detection thresholds in normal-hearing acoustic listeners. Using continuous pure-tone pedestals and carriers spanning a wide range of levels, they found that intensity DLs were related to 4-Hz AM detection thresholds by the equation

$$10\log(\Delta I/I) = 0.44*(20\log m) + 1.7, \qquad (1)$$

where $\Delta I/I$ is the Weber fraction for intensity discrimination and m is the modulation index at threshold. They demonstrated that Eq. (1) generalizes to other low modulation frequencies by adjusting the additive constant term, and showed that it holds over a range of performance (d') levels. They also argued that Eq. (1) holds for a range of pedestal/carrier frequencies, for noise carriers, and for gated pedestals/carriers of varying durations. However, they noted that Eq. (1) does not describe the relationship between psychometric functions for intensity discrimination and AM detection when gated pedestals/carriers are used.

Equation (1) suggests that the same decision variable is used for intensity discrimination and AM detection tasks in acoustic hearing. Wojtczak and Viemeister (1999) examined several theoretical models of AM processing in an attempt to identify this decision strategy, but concluded that no existing model accounts convincingly for the empirical relationship that Eq. (1) describes. In this report, we examine the relationship between intensity discrimination and AM detection in cochlear-implant listeners, using gated stimuli. The relationship that we observe is similar to Eq. (1), suggesting that whatever decision strategy is used to perform intensity discrimination and modulation detection tasks in acoustic hearing also applies to electric hearing.

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I. PROCEDURE

Intensity DLs and 4-Hz AM detection thresholds were measured in three subjects with the Nucleus 22 cochlear implant. Three electrodes from different regions of the implanted array were tested in each subject. Electrode configuration was bipolar, with an electrode separation of 1.5 mm (BP+1) in subjects S1 and S3, and 2.25 mm (BP+2) in subject S2. Stimuli were 500-ms gated trains of 800-pps, 80-μs/ph biphasic pulses, spanning levels between 15% and 85% of the test electrode's dynamic range. Five identical levels of the standard stimulus were evaluated in both the intensity discrimination and AM detection tasks. Level was incremented or sinusoidally modulated by varying the current amplitude of pulses within the stimulus trains. Thresholds were obtained using a 3-down, 1-up 3-interval forced choice adaptive procedure that estimated 79.4% correct (Levitt, 1971), corresponding to a detection sensitivity of $d' = 1.63$.

Table I describes the subjects and shows the absolute thresholds and dynamic ranges (DRs) that were measured for each of the nine test electrodes in response to the standard stimulus (800 pps, 80-μs/ph, 500-ms pulse train).[1] Note that DRs are similar for electrodes within a given subject, but vary considerably across subjects. This suggests that the three subjects possess different numbers or patterns of surviving auditory neurons.

II. RESULTS

Figure 1 shows 4-Hz AM detection thresholds plotted as a function of current amplitude (dB μA) for each of the nine test electrodes. In each panel, individual threshold estimates are shown as shaded triangles and mean threshold values are shown by a thin solid line. For comparison, mean acoustic data obtained by Wojtczak and Viemeister (1999) for a 1-kHz continuous carrier are plotted in the upper-left panel.

The range of AM detection thresholds exhibited by the present subjects is generally similar to those reported in earlier cochlear-implant studies (Shannon, 1992; Busby *et al.*, 1993; Cazals *et al.*, 1994). Thresholds are also roughly simi-

TABLE I. Subjects.

Subj	M/F	Age	Etiology of hearing loss	Years deaf	Years implanted	Electrodes tested	Threshold (dB *re*: 1 μA)	Dynamic range (dB μA)
S1	M	32	maternal rubella	27	2	e5	41.2	20.6
						e12	41.8	18.7
						e19	37.2	16.1
S2	F	60	otosclerosis	12	2	e4	48.0	11.0
						e17	45.6	10.1
						e21	49.3	10.1
S3	M	59	meningitis	3	3	e5	48.7	6.4
						e12	46.6	5.8
						e20	50.5	4.9

lar to the acoustic data for pure-tone carriers reported by Wojtczak and Viemeister (1999) and most others (see Kohlrausch, 1993, for a summary). Differences are apparent across subjects, however: Subjects S1 and S2 show steep functions with quite sensitive thresholds (-30 to -40 dB) at the highest stimulus levels, whereas subject S3 shows flatter functions with relatively insensitive AM thresholds (-10 to -20 dB) at all levels. None of the measured thresholds was limited by the resolution of current amplitude delivery in the subjects' devices; however, thresholds for three electrodes (CJP rEL5, CJP rEL12, and DAW rEL17) approached this limit at the highest carrier level.

Figure 2 shows corresponding intensity DLs $[10 \log(\Delta I/I)]$ for each of the nine test electrodes, plotted as a function of current amplitude (dB μA). As in Fig. 1, individual threshold estimates are shown as shaded triangles and mean thresholds are indicated by a thin solid line. All intensity discrimination thresholds were well below the resolution limits of the subjects' devices. Mean acoustic intensity DLs from Wojtczak and Viemeister (1999) for a 1-kHz continuous pedestal are shown in the upper-left panel.

Note that, for individual electrodes, the shapes of the mean intensity discrimination functions shown in Fig. 2 are similar to the shapes of AM detection functions shown in Fig. 1. That is, subjects S1 and S2 show steep functions with quite sensitive intensity DLs (-10 to -16 dB) at the highest pedestal levels, and subject S3 shows shallower functions with relatively large intensity DLs (-4 to -8 dB) at all pedestal levels. We have previously observed considerable variability across subjects and electrodes in the size and level dependence of intensity DLs in cochlear-implant subjects with the Nucleus 22 device (Nelson *et al.*, 1996; Donaldson and Nelson, 1997a,b). The data shown Fig. 2 are typical of those we have reported in earlier studies.

The unfilled square symbols in each panel of Fig. 2 represent intensity DLs predicted from the mean 4-Hz AM detection thresholds in Fig. 1, using Eq. (1). Note that predicted values are similar to the mean, measured DLs. This suggests that Eq. (1), derived from data for acoustic listeners and continuous pedestals/carriers, describes quite accurately the relationship between intensity DLs and modulation thresholds for cochlear-implant listeners and gated pedestals/carriers.

In Fig. 3, the intensity DLs from Fig. 1 are replotted as a function of the corresponding AM detection thresholds from Fig. 2. The upper-left, upper-right, and lower-left panels show data for subjects S1, S2, and S3, respectively. In each of these panels, data for individual test electrodes are plotted with different symbols, and a single linear regression

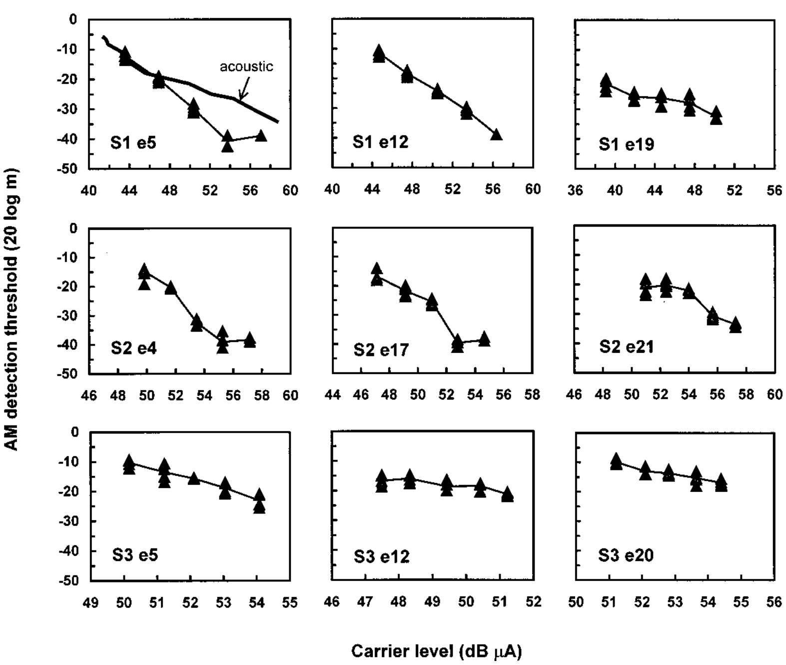

FIG. 1. 4-Hz AM detection thresholds as a function of carrier level. Individual threshold estimates are shown as shaded triangles; mean data are indicated by the solid line (without symbols). Each panel represents data for one electrode; each row of panels represents data from a different subject. Acoustic data for a 1-kHz carrier from Wojtczak and Viemeister (1999) are shown in the upper-left panel. These data are scaled along the *x* axis so as to match the cochlear-implant data in terms of percent dynamic range in dB, by assuming an acoustic threshold of 5 dB SPL and an acoustic maximum acceptable loudness of 95 dB SPL.

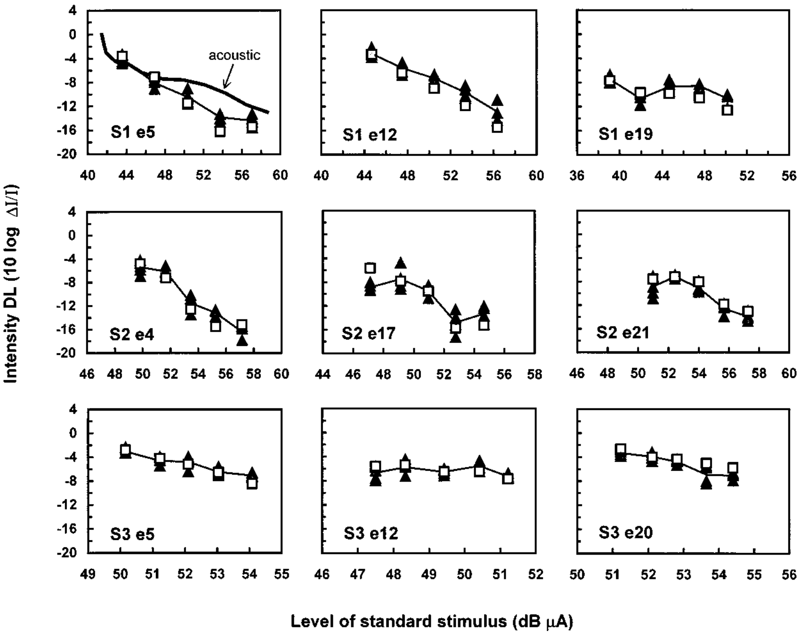

FIG. 2. Intensity DLs as a function of the level of the standard stimulus. Panels and symbols as in Fig. 1. Open squares represent intensity DLs predicted from the mean AM detection thresholds in Fig. 1, using Eq. (1).

line is fit to the combined data from all three electrodes. The data for each subject show a strong, linear relationship between intensity DLs and 4-Hz AM detection thresholds. Slopes of all three regression functions are similar (0.33–0.36) and the intercepts are all close to zero. In each case, AM detection thresholds account for a large (77%–93%) and highly significant proportion ($p<0.0001$) of the variance observed in the intensity DLs.

The data for subjects S1, S2, and S3 are combined in the lower-right panel of Fig. 3. Here, different symbols represent the data for different subjects. The dark line in this panel is the best-fitting linear regression function for the combined subject data

$$10\log(\Delta I/I)=0.36*(20\log m)+0.9. \tag{2}$$

The lighter gray line in this panel represents Eq. (1). Both the slope and y intercept of Eq. (2) are significantly smaller than their counterparts in Eq. (1) ($p<0.005$); however, it is apparent from Fig. 3 that these differences are small.

III. DISCUSSION

The present data suggest that the empirical relationship between intensity DLs and AM detection thresholds reported by Wojtczak and Viemeister [Eq. (1)] is approximately correct in both acoustic and electric hearing. This result is at first surprising, given that stimulus coding properties are known to differ substantially in the two modes. For example, at the level of the auditory nerve it is known that electric stimulation produces steeper rate-level functions, smaller dynamic ranges, and less variable spike counts than acoustic stimulation (Moxon, 1971; Hartmann *et al.*, 1984; Javel, 1990; Javel and Viemeister, 1999). In addition, factors such as loss of cochlear compression and altered patterns of neural

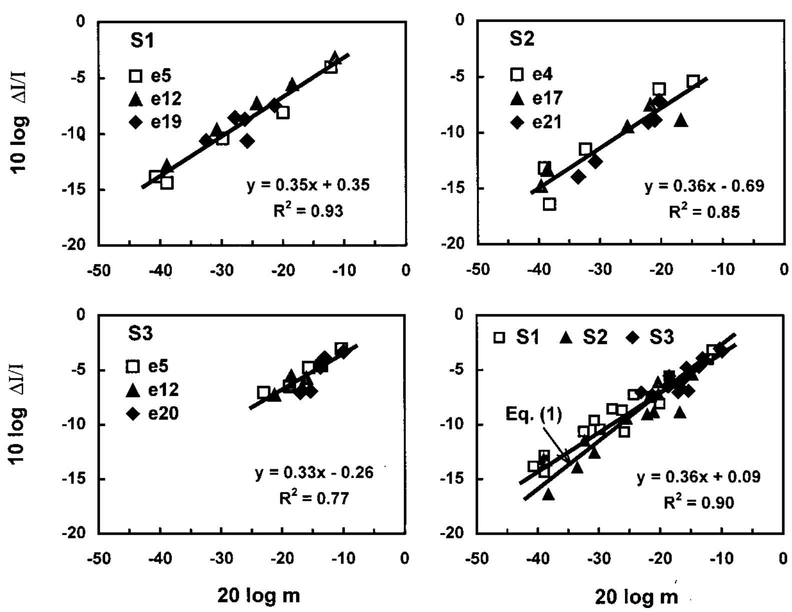

FIG. 3. Intensity DLs as a function of AM detection thresholds. Data for subjects S1, S2, and S3 are shown individually in the upper-left, upper-right, and lower-left panels, respectively, and are plotted together in the lower-right panel.

recruitment almost certainly affect psychophysical measures of intensity coding in the electric case (e.g., Zeng and Shannon, 1994; Zeng *et al.*, 1998).

A possible explanation for the present finding is that both acoustic and cochlear-implant listeners use a similar decision statistic for performing intensity discrimination and modulation detection tasks. Specifically, if the decision variables applied in acoustic and electric hearing are related by a monotonic transform such as compression, and the noise that limits performance occurs before the decision statistic is ''computed,'' then they will produce identical performance (Eagan, 1975). This would not only explain the similarity between Eqs. (1) and (2) but would also explain the similarity between the Weber fractions and between the modulation thresholds. The requirement that the internal noise precede the monotonic transformation presents a potential problem, since compression is observed prior to hair-cell transduction and other possible sources of internal noise in acoustic hearing. However, this requirement is too restrictive, since some decision variables can produce identical performance even when the noise *follows* the transform.

For example, assume that the decision variable is the effective peak value of the transformed, processed stimulus and that an internal noise is added *after* the peak is computed. Then

$$d'_{\Delta I}=\frac{f(I+\Delta I)-f(I)}{\sigma},\quad d'_m=\frac{f(I(1+m)^2)-f(I)}{\sigma},$$

where $d'_{\Delta I}$ and d'_m are performance measures for intensity discrimination and AM detection, respectively, f is a monotonically increasing function, and σ is the standard deviation of the decision variable.

For equal ''threshold'' performance,

$$f(I+\Delta I)-f(I)=f(I(1+m)^2)-f(I).$$

This equation is satisfied if

$$I+\Delta I=I(1+m)^2,$$

or, equivalently,

$$\frac{\Delta I}{I}=2m+m^2.$$

The last equation, when expressed in logarithmic form, is similar to Eqs. (1) and (2). The important point, however, is that this equation does not depend on $f(\ )$. This demonstrates that the relationship between intensity discrimination and AM detection need not be affected by compression. It does not imply, however, that compression *cannot* affect the relationship. Indeed, it is possible that the small differences between the slopes and between the intercepts for acoustic and electric hearing [Eq. (1) vs Eq. (2)] may be the result of compression. Another possibility is that these differences reflect the use of gated stimuli in the present experiment as compared to the continuous carriers and pedestals used by Wojtczak and Viemeister. Finally, it should be noted that we are not suggesting that intensity discrimination and modulation detection, considered separately, are not affected by $f(\ )$. Clearly, in this demonstration $d'_{\Delta I}$ and d'_m depend on $f(\ )$.

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[1]Absolute thresholds were measured with an adaptive task, and maximum acceptable loudness levels (MALs) were measured using an ascending method of limits procedure, as described in Nelson *et al.*, 1996. Dynamic range was computed as the decibel difference between the average MAL and threshold values.

Busby, P. A., Tong, Y. C., and Clark, G. M. (**1993**). ''The perception of temporal modulations by cochlear implant patients,'' J. Acoust. Soc. Am. **94**, 124–131.

Cazals, Y., Pelizzone, M., Saudan, O., and Boex, C. (**1994**). ''Low-pass filtering in amplitude modulation detection associated with vowel and consonant identification in subjects with cochlear implants,'' J. Acoust. Soc. Am. **96**, 2048–2054.

Donaldson, G. S., and Nelson, D. A. (**1997a**). ''Effects of pulse duration on discrimination of current amplitude by Nucleus cochlear-implant users,'' Abstracts of the 20th Midwinter Research Meeting, Association for Research in Otolaryngology, p. 78 (unpublished).

Donaldson, G. S., and Nelson, D. A. (**1997b**). ''Intensity resolution for pulse amplitude and pulse duration: Individual differences and stimulus-parameter effects,'' Abstracts of 1997 Conference on Implantable Auditory Prostheses (Asilomar, CA), p. 24 (unpublished).

Eagan, J. P. (**1975**). *Signal Detection Theory and ROC Analysis* (Academic, New York).

Hartmann, R., Topp, G., and Klinke, R. (**1984**). ''Electrical stimulation of the cat cochlea: Discharge pattern of single auditory fibers,'' Adv. Audiol. **1**, 18–29.

Javel, E. (**1990**). ''Acoustic and electrical encoding of temporal information,'' *Models of the Electrically Stimulated Cochlea*, edited by J. M. Miller and F. A. Spelman (Springer, New York), pp. 247–292.

Javel, E., and Viemeister, N. F. (**2000**). ''Stochastic properties of cat auditory nerve rsponses to electric and acoustic stimuli and application to intensity discrimination,'' J. Acoust. Soc. Am. **107**, 908–921.

Kohlrausch, A. (**1993**). ''Comment on 'Temporal modulation transfer functions in patients with cochlear implants [J. Acoust. Soc. Am. **91**, 2086–2104 (1992)],' '' J. Acoust. Soc. Am. **93**, 1649–1650.

Levitt, H. (**1971**). ''Transformed up–down methods in psychoacoustics,'' J. Acoust. Soc. Am. **49**, 467–477.

Moxon, E. C. (**1971**). ''Neural and Mechanical Responses to Electric Stimulation of the Cat's Inner Ear,'' Doctoral thesis, MIT.

Nelson, D. A., Schmitz, J. L., Donaldson, G. S., Viemeister, N. F., and Javel, E. (**1996**). ''Intensity discrimination as a function of stimulus level with electrical stimulation,'' J. Acoust. Soc. Am. **100**, 2393–2414.

Shannon, R. V. (**1992**). ''Temporal modulation transfer functions in patients with cochlear implants,'' J. Acoust. Soc. Am. **91**, 2156–2164.

Wojtczak, M., and Viemeister, N. F. (**1999**). ''Intensity discrimination and detection of amplitude modulation,'' J. Acoust. Soc. Am. **106**, 1917–1924.

Zeng, F.-G., and Shannon, R. V. (**1994**). ''Loudness-coding mechanisms inferred from electric stimulation of the human auditory system,'' Science **264**, 564–566.

Zeng, F.-G., Shannon, R. V., and Hellman, W. S. (**1998**). ''Physiological processes underlying psychophysical laws,'' *Psychophysical and Physiological Advances in Hearing*, edited by A. R. Palmer, A. Rees, A. Q. Summerfield, and R. Meddis (Whurr, London), pp. 473–481.