Intensity discrimination and increment detection in cochlear-implant users[a)]

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Intensity difference limens (DLs) were measured in users of the Nucleus 22 and Clarion v1.2 cochlear implants and in normal-hearing listeners to better understand mechanisms of intensity discrimination in electric and acoustic hearing and to evaluate the possible role of neural adaptation. Intensity DLs were measured for three modes of presentation: gated (intensity increments gated synchronously with the pedestal), fringe (intensity increments delayed 250 or 650 ms relative to the onset of the pedestal), and continuous (intensity increments occur in the presence of a pedestal that is played throughout the experimental run). Stimuli for cochlear-implant listeners were trains of biphasic pulses; stimuli for normal-hearing listeners were a 1-kHz tone and a wideband noise. Clarion cochlear-implant listeners showed level-dependent effects of presentation mode. At low pedestal levels, gated thresholds were generally similar to thresholds obtained in the fringe and continuous conditions. At higher pedestal levels, however, the fringe and continuous conditions produced smaller intensity DLs than the gated condition, similar to the gated-continuous difference in intensity DLs observed in acoustic hearing. Nucleus cochlear-implant listeners did not show consistent threshold differences for the gated and fringe conditions, and were not tested in the continuous condition. It is not clear why a difference between gated and fringe thresholds occurred for the Clarion but not the Nucleus subjects. Normal-hearing listeners showed improved thresholds for the continuous condition relative to the gated condition, but the effect was larger for the 1-kHz tonal carrier than for the noise carrier. Findings suggest that adaptation occurring central to the inner hair cell synapse mediates the gated-continuous difference observed in Clarion cochlear-implant listeners and may also contribute to the gated-continuous difference in acoustic hearing. [DOI: 10.1121/1.1579007]

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I. INTRODUCTION

Information encoded in the fine structure of speech and other environmental sounds may be unavailable to cochlear-implant users due to the use of pulsatile stimuli by the speech processor. Thus, these listeners with electric hearing may rely strongly on information encoded in the stimulus envelope. To maximize performance of cochlear-implant listeners, it is important to maximize the perceptual resolution in both the intensity/amplitude and temporal domains. A number of studies have measured intensity discrimination in electric hearing. Some have measured intensity discrimination in animals (e.g., Pfingst *et al.*, 1983; Pfingst and Rai, 1990), whereas others have tested human cochlear-implant subjects (Hochmair-Desoyer *et al.*, 1981; Shannon, 1983; Dillier *et al.*, 1983; Busby *et al.*, 1992; Nelson *et al.*, 1996; Donaldson and Viemeister, 2000). All of these existing studies have employed a gated mode of presentation in which intensity increments are equal in duration to the pedestals (see Fig. 1), even though in everyday life, intensity changes are most commonly encountered in ongoing sounds.

Psychophysical studies in listeners with normal hearing have demonstrated that sensitivity to intensity increments depends upon mode of stimulus presentation. Viemeister and Bacon (1988) reported that over a wide range of levels, the Weber fraction ($10 \log \Delta I/I$, where ΔI is the intensity DL), measured with a continuous tonal pedestal, is on average about 4.6 dB smaller than the Weber fraction measured when the pedestal is gated with an increment of the same duration. Their result supported earlier findings that sensitivity to intensity increments is generally better for increments occurring in a continuous sound (Campbell and Lasky, 1967; Green, 1969; Zwicker and Fastl, 1972; Green *et al.*, 1979; Bacon and Viemeister, 1985). More recently, Moore and Peters (1997) studied the effects of gating the pedestal before the onset of the increment. They found an effect consistent in the direction but smaller than the gated-continuous difference reported by Viemeister and Bacon (1988), but the gated (no-fringe) condition was not used in their study.

[a)] Portions of these data were presented at the 141st Meeting of the Acoustical Society of America [M. Wojtczak, G. S. Donaldson, and N. F. Viemeister, J. Acoust. Soc. Am. **109**, 2464(A) (2001)].

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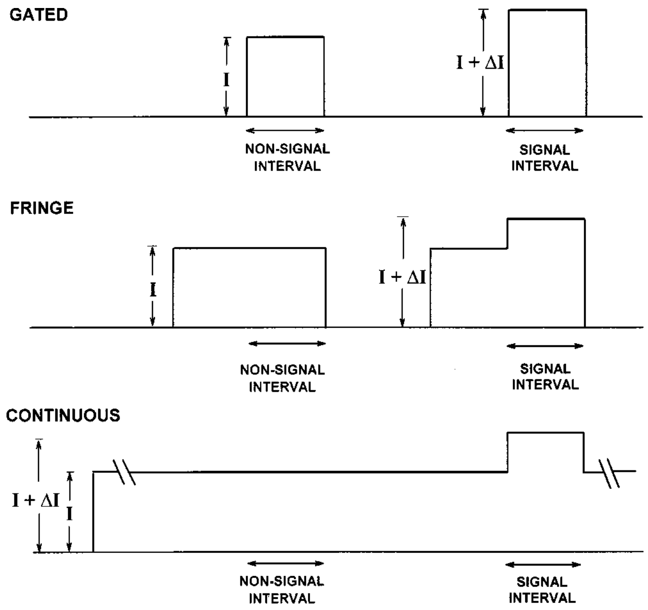

FIG. 1. A schematic illustration of the conditions in which intensity DLs were measured for cochlear-implant users and listeners with normal hearing. The top row shows the gated condition, in which the increment (ΔI) is gated on simultaneously with the pedestal (I); the middle row shows the fringe condition, in which the increment is delayed relative to the onset of the pedestal; and the bottom row shows the continuous condition, in which the pedestal is played continuously throughout the experimental run and the increment occurs during the signal interval.

The most compelling explanations for the gated-continuous difference involve neural adaptation (Smith and Zwislocki, 1975; Smith, 1977). They suggest that adaptation affects increment detection because it effectively decreases the internal response to the pedestal, while having no effect on the incremental response when the signal of a fixed intensity is added at different time delays relative to the onset of the pedestal. Assuming that the increment is detected when the internal response increases by some criterion factor relative to the response just before the increment, adaptation correctly predicts that delaying the onset of the increment will lead to a lower threshold. This explanation is closely related to the idea of a change-detection mechanism proposed by Macmillan (1971, 1973). This mechanism is assumed to be sensitive to signal onsets and offsets but not to be sensitive to the direction of a change. A constant criterion change in response necessary for detection would be in agreement with the above adaptation explanation. It is not clear whether the main source of adaptation is in the synapse between the inner hair cells and the spiral ganglion, as suggested by many physiological studies (Geisler *et al.*, 1979; Schwid and Geisler, 1982; Smith and Brachman, 1982; Meddis, 1986; Westerman and Smith, 1988; Javel, 1996), or if the dominant adaptation originates at a more central site of processing (Shannon and Otto, 1990).

One goal of the present study was to measure cochlear-implant listeners' sensitivity to intensity changes in an ongoing sound. To our knowledge, detection of increments in ongoing stimuli has never been measured in electric hearing. Another goal was to determine if the mechanism underlying the gated-continuous difference observed for normal-hearing listeners has its origin in peripheral or more central processing. Cochlear processing is by-passed in electric hearing. Thus, if neural adaptation underlies the gated-continuous difference in acoustic hearing and it stems primarily from depletion of neurotransmitter at inner hair cell synapses, then there should be no difference between gated and continuous thresholds in cochlear-implant users. If, on the other hand, adaptation underlying the gated-continuous difference originates at a more central site, then cochlear-implant listeners would be expected to exhibit a difference between gated and continuous thresholds. It should be noted that due to the absence of the basilar-membrane nonlinearity, the size of the observed difference might not match that for the normal-hearing listeners.

Two experiments were performed to compare increment detection in an ongoing sound with intensity discrimination for gated stimuli. In the first experiment, sensitivity to intensity increments was measured in cochlear-implant users under two conditions. In one case, the pedestal was gated synchronously with the increment (gated condition), whereas in the other its onset occurred a few hundred milliseconds before the increment (fringe condition). This experiment allowed us to evaluate whether the thresholds reported in various studies of intensity discrimination in electric hearing are representative of the listeners' ability to detect small intensity changes in ongoing stimuli, a situation most commonly encountered in daily life. Normal-hearing listeners were also tested in these two conditions for comparison. In the second experiment, cochlear-implant listeners were tested in the gated condition and in a condition in which the pedestal was played continuously throughout the experimental run (continuous condition). A diagram presenting the three conditions in which intensity DLs were measured is shown in Fig. 1. Our general hypothesis was that cochlear-implant listeners would demonstrate similar intensity DLs in all conditions, based on the assumption that peripheral adaptation underlies the gated-continuous difference in acoustic hearing.

II. EXPERIMENT 1

The purpose of this experiment was to determine whether delaying the onset of an intensity increment relative to the onset of the pedestal would facilitate increment detection. Intensity-discrimination and increment-detection thresholds were measured in cochlear-implant subjects and subjects with normal hearing. Normal-hearing listeners were included because the existing literature does not provide a clear picture of the dependence of intensity DLs on the duration of the preceding fringe.

A. Gated versus fringe conditions in electric hearing

1. Subjects

Four users of the Nucleus-22 cochlear implant (N28, N30, N31, N32) and three users of the Clarion-1.2 cochlear implant (C14, C16, C12) participated in the study. Table I provides information about the listeners, including their age, the duration of hearing loss before receiving an implant, etiology of hearing loss (when known), and duration of implant use. The last two columns specify the stimulation mode and the implant type. Subjects gave informed consent and were paid on an hourly basis for their participation. All seven subjects had prior experience performing psychophysical tasks

TABLE I. Subjects. Subject identifying code, gender, age when tested for the present study, etiology of deafness (implanted ear), duration of bilateral severe-to-profound hearing loss prior to implantation, duration of implant use prior to the study, test electrode, stimulation mode, and device and electrode type. Electrodes are numbered in research order (rEL), which increases from apex to base. Nucleus implants have 22 electrode contacts and a maximum of 21 bipolar electrode channels; Clarion implants have 16 electrode contacts arranged in radial pairs (SPRL electrode) or in a straight line (HF electrode). Bipolar mode indicates the separation between active and reference electrodes in the stimulating pair: BP+1, BP+2, and BP+3 represent electrode separations of 1.5, 2.25, and 3.0 mm, respectively. For Clarion subjects, electrode types are SPRL=standard spiral electrode; HF=HiFocus electrode; HF+EPS=HiFocus electrode with electrode positioning system.

Subject code	M/F	Age	Etiology of deafness	Dur. (years)	Cl use (years)	Electrode (rEL)	Stimulation mode	Device (electrode)
N28	M	63	Meningitis	<1	6	12	BP+1	Nucleus 22
N30	F	63	Otosclerosis	10	6	17	BP+2	Nucleus 22
N31	M	82	Noise exposure; progressive SNHL	25	12	16	BP+3	Nucleus 22
N32	M	34	Maternal rubella; progressive SNHL	<1	5	12	BP+2	Nucleus 22
C06	M	65	Unknown; progressive SNHL	12	3	8	monopolar	Clarion C-I (SPRL)
C12	F	49	Otosclerosis	13	2	8	monopolar	Clarion C-I (SPRL)
C14	M	65	Unknown; progressive SNHL	47	2	8	monopolar	Clarion C-I (HF+EPS)
C16	F	48	Unknown; progressive SNHL	18	10 mo.	7	monopolar	Clarion C-I (HF)
C18	M	67	Otosclerosis	33	1.5	7	monopolar	Clarion C-I (HF+EPS)

and were given at least 2 h of practice before data collection commenced. All experiments in the study were approved by the Human Subjects Committee of the University of Minnesota Institutional Review Board.

2. Conditions and stimuli

Stimuli for Nucleus-22 users were generated by a PC connected through a parallel port to a BTNI cochlear implant interface (Shannon *et al.*, 1990). Stimulus amplitudes were specified in integer current step units (CSUs), which are uneven amplitude steps that vary between 0.07 and 0.30 dB for the range of current amplitudes used in the present experiment. CSUs were converted to calibrated current amplitudes using user-specific tables provided by Cochlear Corporation.

Stimuli for Clarion subjects were generated by a PC that controlled a special-purpose interface provided by Advanced Bionics Corporation for the Clarion C-I intracochlear stimulator. Stimulus amplitudes were specified in integer stimulus units (SUs), which are logarithmic amplitude steps of 0.1 to 0.3 dB for the range of amplitudes used here.[1] SU values were converted to calibrated amplitudes using a set of tables developed in our laboratory. This calibration compensates for nonlinearities in the current source that depend upon electrode impedance and pulse rate. Electrical impedances for Clarion subjects were measured at the beginning and end of each data collection session using the SCLIN for Windows clinical software running on a PC. Calibrated amplitudes for each test electrode were based on average impedance values across data collection sessions for a given experiment.

Increment-detection thresholds were measured using trains of biphasic pulses presented to an electrode in the middle or midbasal portion of the array. The initial phase of each pulse was always cathodic (negative). For the Nucleus-22 subjects, pulse duration was 80 μs/phase and pulse rate was 800 pulses/s. Stimuli were presented to Nucleus subjects in bipolar mode, using the electrode separations listed in Table I. The initial (cathodic) pulse was presented to the more basal electrode of the pair. For the Clarion users, pulse duration was 77 μs/phase and pulse rate was 1000 pulses/s. Stimuli were presented in monopolar mode, with an intracochlear electrode referenced to a ground electrode on the case of the receiver–stimulator. In the gated condition, the pulse train had a duration of 100 ms and its amplitude was incremented in the signal interval over its entire duration. In the fringe condition, the pedestal was 750 ms long and the increment to be detected occupied the final 100 ms. Increments were generated in the simulation software by specifying higher-amplitude pulses during the final 100 ms of pedestal duration. Thresholds for detecting increments were measured for five amplitude levels of the pedestal defined using a reference amplitude of 1 μA. The pedestal levels were evenly spaced in 20-log (μA) steps across the dynamic range of each listener's hearing. Thus, for all listeners, thresholds were measured at levels corresponding to approximately the same percentages of dynamic range expressed in dB.

3. Procedure

Each experimental session began by measuring the listener's absolute threshold and maximum acceptable loudness level (MAL) for the 100-ms pulse train used in the subsequent intensity-discrimination task. The threshold was measured using an adaptive 2-down, 1-up, three-interval forced-choice (3IFC) procedure that estimated the 70.7%-correct

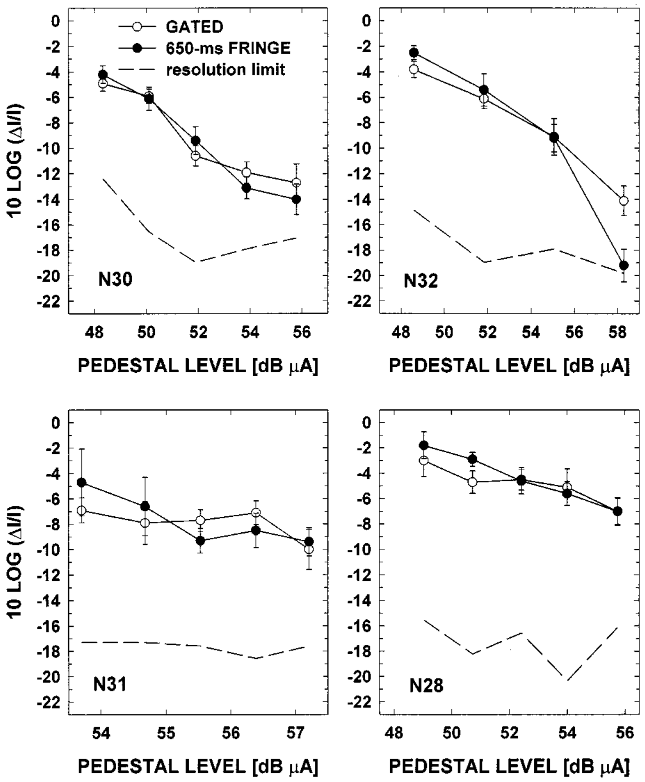

FIG. 2. Intensity DLs in Nucleus-22 users, measured in the gated (open circles) and 650-ms fringe (filled circles) conditions. The dashed line indicates the amplitude resolution limit of the cochlear implant.

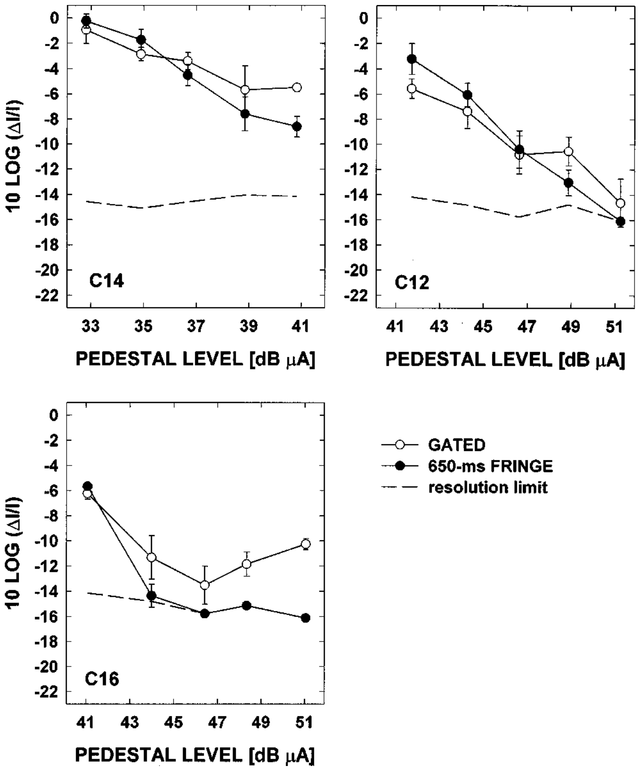

FIG. 3. Intensity DLs in Clarion users, measured in the gated (open circles) and 650-ms fringe (filled circles) conditions. The dashed line indicates the amplitude resolution limit of the cochlear implant.

point on the psychometric function (Levitt, 1971). The MAL was measured using an ascending method of adjustment. The difference between the level (in dB *re*: 1 μA) corresponding to the MAL and the level corresponding to the absolute threshold determined the listener's dynamic range for the tested stimulus. The estimated difference was used to compute five levels of the pulse train corresponding to 17%, 33%, 50%, 67%, and 83% of the dynamic range in dB, for which intensity discrimination was measured. Intensity DLs were measured using an adaptive 3IFC procedure similar to that used for absolute threshold. The observation intervals were separated by a 250-ms silent interval. On each trial, the increment (signal) occurred randomly in one of the three intervals. Initially the increment was large enough to be clearly detectable. After two consecutive correct responses the amplitude of the incremented portion of the pulse train was decreased by 2 units (CSUs for Nucleus users; SUs for Clarion users), and after an incorrect response it was increased by 1 unit. Visual feedback was provided after each response. The run was terminated after 12 reversals were obtained. Threshold was computed as the mean of the last eight reversals. Threshold amplitude increments were converted into Weber fractions in dB $(10 \log \Delta I/I)$, where I is proportional to the squared current amplitude (A^2) and represents electric power with a unit of $\mu A^2 \times \mathrm{ohm}$. The power increment ΔI is proportional to $2A\,\Delta A + (\Delta A)^2$, where ΔA represents the increment in current amplitude. The final threshold estimate was obtained by averaging four to six Weber fractions in dB obtained from separate runs.

4. Results

Figure 2 shows intensity DLs for individual Nucleus subjects. DLs are expressed in terms of the Weber fraction in dB and plotted as a function of pedestal level in dB *re:* 1μA. Error bars represent one standard deviation around the mean. Figure 3 shows the data obtained for individual Clarion subjects.

For all of the cochlear-implant listeners, Weber fractions tend to decrease with increasing pedestal level. This trend has been reported in the past studies of intensity discrimination in electric hearing (Shannon, 1983; Dillier *et al.*, 1983; Busby *et al.*, 1992; Nelson *et al.*, 1996; Donaldson and Viemeister, 2000). The present data show that a decrease in the Weber fraction with level is observed not only for gated stimuli (open symbols) but also when the increment occurs in an ongoing sound (filled symbols).

Apart from this general trend, slightly different patterns of results emerge for the two groups of cochlear-implant users. Overall, the Nucleus subjects (Fig. 2) do not appear to exhibit any systematic differences in sensitivity to intensity increments between the gated and fringe conditions. This observation is supported by statistical analysis, which showed no significant effect of condition across pedestal levels and subjects (ANOVA, $F = 0.41$, $p = 0.522$). Despite that general result, listener N32 exhibited a 5.1-dB smaller intensity DL for the fringe condition, and this difference may have been artificially limited by device resolution (see below in this section). The significance of this finding is unclear; it is possible that a similar pattern could be observed in other Nucleus users if a larger sample were tested. Note that for subject N32, data were obtained at only four pedestal levels due to possible voltage compliance limitations at levels exceeding 60 dB re: 1 μA.

In contrast to the data from Nucleus users, the data from Clarion users do show some systematic differences between the intensity DLs measured with the gated pedestal and those measured with the preceding fringe (Fig. 3). The main effect of condition was significant (ANOVA, $F=36.61$, $p<0.001$). For listeners C14 and C12, the intensity DLs measured at two lowest levels with the 650-ms fringe are slightly higher than those measured with the gated pedestal. At the two highest levels, the intensity DLs for the 650-ms fringe fall below those for the gated pedestal. For subject C16, the intensity DLs measured in the fringe condition are consistently lower than those measured in the gated condition, except at the lowest pedestal level.

Because cochlear implants deliver current in quantized steps, they sometimes impose a limitation on users' intensity resolution. In Figs. 2 and 3, the dashed lines show Weber fractions that would be estimated if a subject consistently detected the smallest current increment that could be generated for a given pedestal amplitude. It is clear that device resolution sometimes prohibited assessment of the listeners' ''real'' intensity DLs in the fringe condition.[2] This occurred for subjects N32 and C12 at the highest pedestal level and for subject C16 at the three highest levels. Despite this limitation, it appears that for Clarion users, the 650-ms fringe causes a reduction in intensity DL (and thus the Weber fraction) at higher pedestal levels.

It is not clear why a similar difference in the intensity DLs measured with and without the preceding fringe was not observed in the Nucleus users. Small differences in the parameters of pulse trains used for Nucleus versus Clarion users are unlikely to explain the discrepancy. Also, the fact that the Clarion users were generally stimulated with lower current amplitudes does not seem to provide an explanation, since there is some overlap of current amplitudes tested in Nucleus and Clarion subjects and, at similar levels, different results are still observed (e.g., compare Nucleus user N30 for levels around 48–51 dB *re*: 1 μA and Clarion user C16 for the same range of levels). The most obvious difference was in the mode of stimulus presentation (medial monopolar for Clarion subjects versus bipolar for Nucleus subjects). We do not know whether differences in electrode coupling can account for the observed discrepancy between the two groups. We will return to this issue in the Discussion.

Overall, the present data indicate that at medium and high stimulus levels the Weber fractions reported in previous cochlear-implant studies may underestimate intensity resolution for ongoing sounds. In particular, our data show that when a pedestal presented at medium to high levels has been on for 650 ms before an increment occurs, intensity DLs may be reduced significantly relative to the gated case. Assuming that neural adaptation underlies the improvement in intensity DLs when a preceding fringe is added, this result suggests that adaptation central to the inner hair cell synapse may play a role in the gated-continuous difference observed in normal hearing.

B. Gated versus fringe conditions in normal hearing

As mentioned in the Introduction, it is believed that in normal hearing, the difference between the intensity DL measured with the gated pedestal and the intensity DL measured with the continuous pedestal stems from neural adaptation. It is not clear how much time is needed from the onset of the pedestal for the adaptation to cause a significant decrease in the intensity DL. Most studies of increment detection in normal-hearing listeners used pedestals that were played continuously throughout the experimental run and compared the observed thresholds with those for pedestals gated with the increments. Scharf *et al.* (1992) studied the effect of the duration of a preceding fringe on increment detection, but they did not use fringe durations shorter than 1 s. Moore and Peters (1997) used shorter fringe durations (10 and 200 ms) but they did not measure intensity DLs using the gated (no-fringe) paradigm. The current experiment measured intensity DLs in normal-hearing subjects as a function of fringe duration.

1. Subjects

Three listeners with normal hearing participated in the study. Their absolute thresholds were within 10 dB of laboratory norms at octave frequencies between 250 and 8000 Hz. One listener (S1) was the first author, and the two other listeners were paid for their services. The listeners had previous experience in various psychoacoustic tasks.

2. Conditions and stimuli

Intensity DLs were measured for a gated condition, a continuous condition, and two fringe conditions. In the fringe conditions, the pedestal onset preceded the increment onset by 250 ms in one case and 650 ms in another. The increment was always 100 ms in duration. The pedestals and increments were gated with 5-ms raised-cosine ramps. Thresholds were measured for two types of stimuli, a 1-kHz tone and a noise that was low-pass filtered at 5 kHz with a 6-dB/oct attenuation outside the passband. The tone was presented at a level of 58 dB SPL and the noise was presented at a spectrum level of 20 dB SPL measured at 1 kHz.

For all conditions except the continuous-noise condition, the stimuli were generated digitally on a NeXT computer using a 16-bit D/A converter and a sampling rate of 44.1 kHz. The intensity increment in a tonal pedestal was produced by in-phase addition of a 100-ms 1-kHz tone to the pedestal. For the noise pedestal, the increment was obtained by adding an independent sample of the noise to the pedestal. The continuous noise pedestal was produced by an analog noise generator (General Radio 1381). The increment was obtained by mixing the continuous pedestal with a computer-generated 100-ms burst of noise. Fixed analog attenuators were used to achieve the desired levels of presentation. Stimuli were presented monaurally through Sony MDR-V6 headphones.

3. Procedure

An adaptive 3IFC 2-down, 1-up procedure was used to measure intensity DLs in the three normal-hearing subjects.

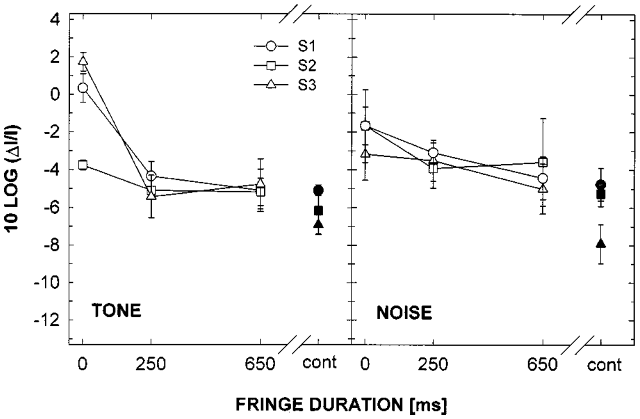

FIG. 4. Individual thresholds for intensity discrimination for three listeners with normal hearing, plotted as a function of the duration of a fringe preceding the increment. The left panel shows data for a 1-kHz tone, and the right panel shows data for a wideband noise, low-pass filtered at 5 kHz. The filled unconnected symbols represent intensity DLs measured with a continuous pedestal.

For the tonal pedestal, the increment was adjusted in steps of 4 dB $[10\log(\Delta I/I)]$ until four reversals were obtained. The step size was then reduced to 2 dB for the subsequent eight reversals. The same stepping rule was applied for the noise, except that in this case the level of the added sample of noise rather than the Weber fraction was varied adaptively. Visual feedback indicating the correct interval was provided after each trial. The block terminated after 12 reversals were completed. The threshold was computed as the mean of the last eight reversals. The final threshold estimate was obtained by averaging thresholds from three single runs. All conditions were first run using the tonal pedestal and then the same conditions were repeated using the noise pedestal. The order in which the experimental conditions were tested for a given type of stimulus was different for different listeners.

4. Results

Figure 4 shows individual data for the normal-hearing listeners. Weber fractions are plotted as a function of fringe duration, where 0-ms fringe corresponds to the gated condition. Data for the gated and fringe conditions are represented by open symbols; data obtained for the continuous pedestal are represented by the filled symbols at the right of each panel.

For the tonal pedestal (left panel), the decrease in intensity DL was largest between the gated case and the 250-ms fringe condition. Increasing the fringe duration from 250 to 650 ms did not appear to further affect the detection of the increment. The average difference between the intensity DL measured with the gated pedestal and the intensity DL measured with the 650-ms fringe averaged across the listeners was 4.4 dB $(F=587,\ p<0.001)$, which is very close to the 4.6-dB gated-continuous difference reported by Viemeister and Bacon (1988). The average decrease in threshold between the 650-ms fringe condition and the continuous condition was only 1.1 dB and was not statistically significant $(F=11.05,\ p=0.006)$. In contrast to our result, Scharf *et al.* (1992) found that for a 4-kHz tone, intensity DLs continued to decrease as fringe duration increased up to 30 s. In Fig. 4, the intensity DL measured with a 650-ms preceding fringe is already very similar to that measured with a continuous pedestal. We have no explanation for the discrepancy between the present results and their data. Scharf *et al.* used a higher frequency (4 kHz) than that used in the present study (1 kHz). However, as shown by Bacon and Viemeister (1994), the frequency dependence of adaptation may have no effect on the way the adapting stimulus behaves as a masker. Bacon and Viemeister compared intensity DLs measured in the same subjects using a 1-kHz tone and a 16-kHz tone for gated and continuous pedestals, respectively. They found that despite very strong loudness adaptation for the 16-kHz tone (that decayed to inaudibility), similar differences between gated and continuous thresholds were observed for the two pedestal frequencies.

The data shown in the right panel of Fig. 4 were obtained for the noise pedestal. A decrease of 2.1 dB in average intensity DL was observed between the gated condition and the 650-ms fringe condition, but this decrease was not statistically significant $(F=2.88,\ p=0.083)$. However, the gated intensity DLs were significantly different from those obtained with a continuous pedestal $(F=40,\ p<0.001)$. The average gated-continuous difference for the low-pass-filtered noise was 4.2 dB. Thus, it appears that with increasing fringe duration, intensity DLs decrease at a slower rate for noise stimuli than for tones. Using noise pedestals, Scharf *et al.* found essentially no change in intensity DLs with increasing fringe duration up to 30 s. Assuming that adaptation is the primary mechanism underlying the change in sensitivity to intensity increments between the gated and continuous conditions, it appears that for any given fringe duration, less adaptation is produced by noise than by tonal stimuli.

For listeners with normal hearing, the Weber fractions were measured only at one selected pedestal level that was slightly below the level corresponding to the middle of these listeners' dynamic range. Generally, the observed Weber fractions were comparable or worse than the Weber fractions observed for cochlear-implant users for midrange pedestal levels. However, a direct comparison is difficult since it cannot be made at equivalent levels of pedestal presentation, and it is not clear to what extent the acoustic stimuli can be considered equivalent to the pulse-train stimuli used with implant users.

III. EXPERIMENT 2

In this experiment, the gated and continuous paradigms were used to test five cochlear-implant users in the intensity-discrimination and increment-detection tasks. This experiment further investigated the role of long-term stimulation in improving sensitivity to intensity increments. In particular, it tested whether a continuous pedestal would produce gated-continuous differences similar to those observed in normal hearing.

A. Subjects

Five users of the Clarion cochlear implant participated in this experiment. Three of them served as subjects in experiment 1. More detailed information about the listeners is given in Table I. The listeners had earlier experience in psy-

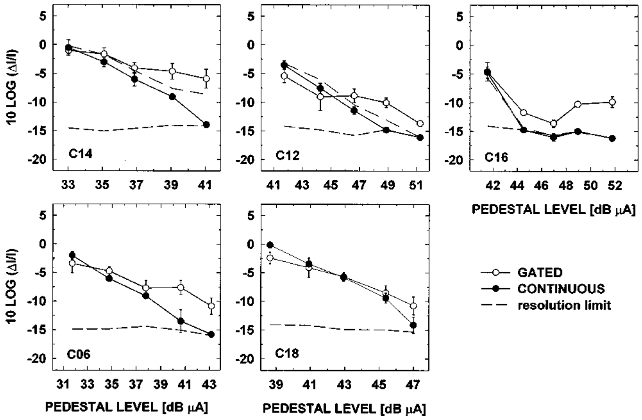

FIG. 5. Intensity DLs measured in Clarion users for a pedestal gated with the increment (open symbols) and a pedestal played continuously throughout the run (filled symbols). The dashed-dotted line in the upper row represents thresholds for the 650-ms fringe, replotted from Fig. 3. The dashed line shows the resolution limit of the device.

chophysical tasks and were given at least 2 h of practice in the intensity-discrimination and increment-detection tasks. Subjects gave informed consent and were compensated for their services.

B. Stimuli and procedure

The stimuli and the procedure used in this experiment were identical to those used for the Clarion users in experiment 1. The only difference was that instead of using a fixed-duration fringe preceding the intensity increment, the pedestal was present continuously throughout the run. Three observation intervals and the correct-response interval were signaled visually on each trial. A 100-ms increment in pulse-train intensity appeared randomly in one of the observation intervals. Although intensity DLs for the gated pedestal were previously measured in experiment 1 for three of the listeners, new data were collected from them for this condition along with the data for the continuous pedestal. This was done to ensure that any differences between the intensity DLs obtained using the two experimental paradigms did not result from changes in the listeners' performance across sessions. In this experiment, only three separate threshold estimates were averaged to obtain the final threshold.

C. Results

Figure 5 shows data for the five users of the Clarion cochlear implant. At the lowest level, intensity DLs measured with the continuous pedestal (filled symbols) are similar to or fall slightly above the DLs measured with the gated pedestal (open symbols). As the pedestal level increases, the intensity DLs generally decrease. An exception occurs for listener C16, whose thresholds decrease for low and medium levels, and then increase slightly at high levels.

For all of the listeners, continuous thresholds decrease at a faster rate with increasing level than gated thresholds. As a consequence, at high levels, intensity DLs measured with the continuous pedestal are lower (often substantially) than intensity DLs measured with the gated pedestal. Thus, at high levels all five of the Clarion users exhibit a clear gated-continuous difference. The maximum size of the gated-continuous difference could not be estimated because intensity DLs for the continuous pedestal were limited by amplitude resolution of the cochlear implant. Even with this limitation, however, the gated-continuous difference was as large as 8 dB for C14 and 6.4 dB for C16. In contrast to the normal-hearing data of Viemeister and Bacon (1988), the present data appear to indicate that in electric hearing, the gated-continuous difference in Weber fractions is not constant across a range of suprathreshold pedestal levels but continues to increase over the entire dynamic range. All of the listeners reported that the continuous pedestal decayed in loudness during the experimental run, frequently to inaudibility. This strongly suggests an involvement of long-term adaptation. It should be noted that this adaptation could not originate from the depletion of neurotransmitter at the inner hair cell synaptic site, since hair cells are by-passed in electric hearing. Instead, the data suggest that a strong adaptation of more central origin affects increment detection in cochlear-implant listeners.

Since three of the listeners (C14, C12, and C16) participating in this experiment also completed experiment 1, their data can be compared for the 650-ms fringe condition (the dashed-dotted line in Fig. 5) and the continuous condition (filled symbols in Fig. 5). This comparison reveals a similar pattern of differences between the Weber functions obtained for the gated condition and the functions obtained for the fringe and continuous conditions. At higher levels the Weber fractions observed for the continuous pedestal are slightly lower than those measured with the fringe (when the latter were not limited by the amplitude resolution of the implant). The Weber fractions observed in the gated condition were highly repeatable (the average differences in dB between the sets of gated thresholds shown in Figs. 3 and 5 are 0.68, 1.06, and 0.82, for C14, C12, and C16, respectively). This indicates that the observed decrease in the intensity DL (continuous versus fringe condition) was unlikely the result of training effects.

IV. DISCUSSION

In cochlear-implant users, intensity discrimination expressed in terms of the Weber fraction improves with increasing stimulus level, similar to what is observed for listeners with acoustic hearing. In normal hearing, a decrease in the Weber fraction with increasing pedestal level is thought to reflect nonlinear spread of excitation on the basilar membrane (see Viemeister, 1988). Intensity-discrimination data from cochlear-implant users suggest nonlinear spread of excitation across the neural population despite the lack of basilar-membrane processing. A possible explanation for the nonlinear spread observed in electric hearing was offered by Nelson *et al.* (1996). They suggested that at low levels of stimulation, only sparsely populated neurons close to the electrode respond. Assuming that some criterion increase in the total spike count is necessary for increment detection, a relatively large change in stimulus level is required to achieve the criterion increase. At moderate and high levels, the current spreads into the modiolus and activates the spiral nerve bundle located farther away from the electrode. Consequently, the rate-intensity functions become steeper and a smaller change in stimulus intensity is sufficient to reach the criterion increase in total spike count.

Experiment 1 revealed that at high stimulus levels, a 650-ms fringe preceding an increment in stimulus intensity improves increment detection in users of the Clarion cochlear implant but does not affect increment detection in users of the Nucleus-22 implant. As noted earlier, the mode of stimulation was different for the two groups of implant users. Monopolar stimulation, used by Clarion subjects in this study, is known to produce a broader excitation pattern than bipolar stimulation, used by the Nucleus-22 subjects. This has been demonstrated physiologically at peripheral (Brown *et al.*, 1996; Kral *et al.*, 1998) and central sites including the auditory cortex (Bierer and Middlebrooks, 2002). However, monopolar stimulation may result in lower average response probabilities for auditory-nerve fibers (Pfingst *et al.*, 1997; Miller *et al.*, 2002). Intuitively, lower response probabilities would be more likely to reduce rather than increase adaptation, and thus lead to less facilitation of increment detection in the Clarion users. Our data showed the opposite effect, namely a larger gated-fringe difference in Clarion users than in Nucleus users. A notion that broader patterns of excitation produce more adaptation at central sites would be consistent with our findings, but we are not aware of any documented evidence that would support this notion.

The results of experiment 2 suggest that strong long-term adaptation occurs in cochlear-implant users despite the lack of peripheral processing involving inner hair cell synaptic transmission. Strong loudness decay of the continuous stimulus, often to inaudibility, supports this conjecture. Even though no direct link between loudness decay and the size of the gated-continuous difference has been identified, both effects are believed to reflect adaptation (Scharf *et al.*, 1992; Bacon and Viemeister, 1994). The slightly smaller difference between intensity DLs obtained in the gated versus fringe conditions (Fig. 3) compared with that difference for the gated versus continuous conditions (Fig. 5) may suggest that adaptation is not complete after 650 ms of stimulus presentation. Also, none of the subjects reported loudness decay in the task using the 650-ms fringe.

A. Predictions based on subtractive adaptation (constant ΔI)

As mentioned before, it is not clear exactly how adaptation would aid increment detection. Bacon and Viemeister (1994) considered two models of adaptation. One model assumed subtractive adaptation. According to this model, the excitation produced by the masker/pedestal would be subtracted due to adaptation and, independent of masker level, would fall to some fixed excitation level below absolute threshold. Since a long exposure to the pedestal frequently renders it inaudible, the task becomes effectively a detection-in-quiet task. Thus, the model of subtractive adaptation predicts that a constant level of the signal (added to the pedestal in order to produce an increment) is required to reach threshold. Bacon and Viemeister plotted their threshold increments in terms of the level of the ''added'' signal and found that subtractive adaptation did not predict their data correctly. Rather than being constant, the signal level necessary to produce a threshold increment increased in proportion to the pedestal level.

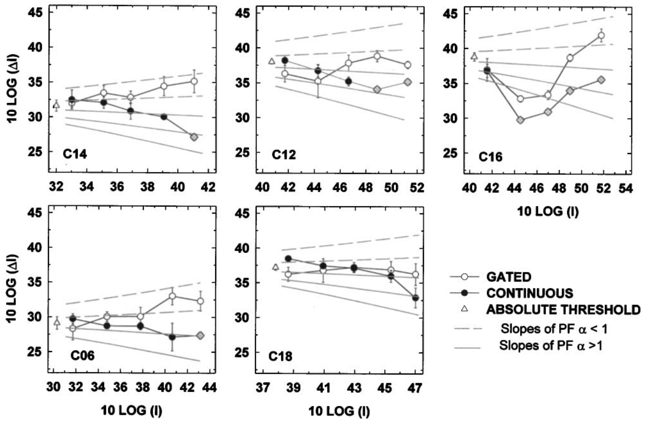

FIG. 6. Thresholds from Fig. 5 replotted in terms of 10 log (ΔI) as a function of pedestal level for the gated (open circles) and the continuous (filled circles) pedestal. The leftmost unconnected open symbols represent thresholds for absolute detection of the pulse train. Thresholds limited by the resolution of the cochlear implant are represented by gray diamonds. Gray lines represent predictions based on Eq. (1). The predictions were obtained for exponents α equal 0.7, 0.9, 1.1, 1.3, and 1.5, where exponent 0.7 is represented by the upper dashed line, and exponent 1.5 is represented by the lowest solid line. For listener C06 the line representing the exponent of 1.5 is not included.

Therefore, they considered a different model that was based on attenuative adaptation. The assumption was that the response to the pedestal and the response to the pedestal-plus-increment are both attenuated by the same factor that is inversely proportional to the pedestal level. In this case, the level of the added signal must increase in proportion to the pedestal level in order to produce excitation necessary for absolute detection of that signal. This approach accurately described the behavior observed in Bacon and Viemeister's data. Bacon and Viemeister demonstrated that the result predicted by attenuative adaptation could also be predicted by subtractive adaptation preceded by a logarithmic nonlinearity. A compressive nonlinearity presumably is not operating at the stages of auditory processing that are central to the cochlea, and thus it is not present in the processing by the auditory system of cochlear-implant users. If the model of subtractive adaptation preceded by a nonlinearity is correct, then subtractive adaptation should predict the results obtained in electric hearing, i.e., the level of the signal that must be added to the pedestal to produce a just-detectable increment should be constant across the listener's dynamic range. Figure 6 shows the intensity-discrimination thresholds replotted from Fig. 5 and expressed in terms of the power increment in dB $(10 \log \Delta I)$. The thresholds in Fig. 6 can also be thought of as the levels of the signal orthogonal to the pedestal that produce just-noticeable increments when the signal is added to the pedestal.

As in Fig. 5, the filled symbols represent the data for the continuous pedestal and the open symbols represent the gated condition. The leftmost unconnected symbols show thresholds for detecting the pulse train in quiet. It appears that none of the listeners required a constant level of the added signal to produce the threshold increment in the continuous condition. As the pedestal level increased, a relatively small albeit consistent decrease in threshold increment was observed except for the cases where the intensity DL was limited by the resolution of the device. This result does not support the idea of subtractive adaptation. The data are also inconsistent with the idea of attenuative adaptation as described by Bacon and Viemeister. Some listeners show an increase in threshold level that may be roughly proportional to the pedestal level (C14, C12, C06, and C16 at mid to high levels) but only for the gated condition, for which long-term adaptation does not occur or at best is negligible. The increase in threshold $\Delta A\,[\mathrm{dB}\,re\!:\!1\,\mu\mathrm{A}]$ (and thus also ΔI) with increasing level of the pedestal was also observed in other studies that measured intensity discrimination as a function of level using gated pedestals (Shannon, 1983; Nelson *et al.*, 1996).

B. Explanation in terms of Laming's theory

Similar to the acoustic data (e.g., Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Bacon and Viemeister, 1994), there is a trend for intensity DLs measured in electric hearing to be larger in the continuous than in the gated condition at low pedestal levels, but the trend is reversed at higher pedestal levels. As shown by Hanna *et al.*, this result can be predicted by Laming's theory (Laming, 1986), at least qualitatively. The theory, originally developed to explain the phenomenon of negative masking (discussed in the following section), assumes that a nonlinear (square-law) transformation combined with differential coupling operates on near-threshold stimuli. Related to this is the assumption that a system responds to changes in amplitude/intensity rather than the absolute amplitude of a signal, and thus it is compatible with the idea of a change detector (MacMillan, 1971, 1973; Hafter *et al.*, 1997). Laming's approach correctly predicts steeper psychometric functions and larger intensity DLs observed for the continuous versus gated pedestals near absolute threshold. As explained by Hanna *et al.* (1986), applying Laming's assumptions to the gated condition would lead to the mean value for the decision variable that would be proportional to $(I+\Delta I)^2$ in the signal interval, and the mean value proportional to I^2 in the nonsignal interval. Consequently, under the assumption of a constant variance, d' would be proportional to the difference between the two variables, which is $2I\Delta I+(\Delta I)^2$. In the continuous (or, more generally, nongated) condition, the mean value of the decision variable would be proportional to $(\Delta I)^2$ in the signal interval and to zero in the nonsignal interval, resulting in d' being proportional to just $(\Delta I)^2$. Any value of $(\Delta I)^2$ would lead to a higher d' (and thus, to a lower threshold) in the gated versus nongated condition. This is generally observed in the data for the lowest pedestal level shown in Fig. 5 (the exception is subject C16).

At higher pedestal levels, the square-law transformation would be applied only in the nongated condition, where ΔI is always near threshold. In the gated condition, each onset is considered a change in intensity. Since these changes are suprathreshold, the square-law nonlinearity does not apply. As a result, lower thresholds (higher d' for a given ΔI) should be observed in the nongated versus gated condition. This trend is observed in the data at higher pedestal levels.

C. Negative masking

For the continuous pedestal, the level of the signal in Fig. 6 decreases below the threshold for detection of that signal in quiet. This phenomenon has been observed in acoustic hearing for tonal stimuli and has been dubbed ‘‘negative masking’’ because the presence of a simultaneous masker appears to lower the threshold for detecting the signal instead of raising it (Hanna *et al.*, 1986; Viemeister and Bacon, 1988; Bacon and Viemeister, 1994). There are, however, some differences between the negative masking in acoustic hearing and the negative masking observed in electric hearing. In acoustic hearing, this phenomenon has been observed exclusively for the gated thresholds and at masker levels near absolute threshold. At higher masker levels, thresholds for detecting the signal are elevated by the presence of the masker in both the gated and continuous condition.

In the listeners with cochlear implants, the signal levels necessary to reach intensity DLs at low pedestal levels for the two conditions fall around the threshold measured in quiet, with the tendency for the threshold to be higher for the continuous pedestal than for the gated pedestal. As the masker level increases, the signal levels at threshold for the gated masker stay near or increase above the absolute threshold. In contrast, the signal levels measured with the continuous masker fall progressively further below absolute threshold as masker level increases. In some cases there is an upturn in the data for the continuous condition at high levels (C12, C06, C16), but it almost certainly results from the limited amplitude resolution of the cochlear implant (see Fig. 5). Thus, at high levels no negative masking is observed for the gated masker and an increasing amount of negative masking is observed for the continuous masker. This result is *not* predicted by Laming's theory, which does not predict any negative masking for the continuous condition.

D. Explanation based on psychometric functions for detection

An interesting possible account for the observed data is in terms of the underlying psychometric functions for detection. Assume, as suggested by Tanner (1956), that the discriminability of an intensity change is equal to the difference between the detectabilities of the incremented pedestal and the pedestal alone

$$d'_{\mathrm{disc}}(\Delta I)=d'_{\mathrm{det}}(I+\Delta I)-d'_{\mathrm{det}}(I). \tag{1}$$

The psychometric function for detection both in acoustic hearing (Egan *et al.*, 1969) and in electric hearing (Donaldson *et al.*, 1997; Donaldson and Viemeister, 2001) can be well described by $d'_{\mathrm{det}}(I)=kI^{\alpha}$, where α is the slope of the psychometric function on log–log coordinates. These equations lead to

$$d'_{\mathrm{disc}}(\Delta I)=k[(I+\Delta I)^{\alpha}-(I)^{\alpha}]. \tag{2}$$

Predictions based on Eq. (2) are shown in Fig. 6. Dashed lines represent predicted thresholds for α values of 0.5 and

0.7, and solid lines represent predicted thresholds for α values of 1.1, 1.3, and 1.5. The predictions were obtained by solving Eq. (2) for ΔI and adjusting d'_{disc}/k so that ΔI equals the observed detection threshold when $I=0$. As demonstrated in Fig. 6, for $\alpha>1$, Eq. (2) predicts increasing negative masking as the pedestal level increases. For $0<\alpha<1$, it predicts an increasing amount of masking with increasing level. Although this appears promising, the values for α that could provide at least a rough account of the data appear to disagree with the data on detection. Donaldson and Viemeister (2001) obtained detailed psychometric functions for detection of 300-ms, 100-pulses/s trains in 10 adults with Nucleus-2 implants. Generally, the slopes of the psychometric functions decreased with increasing pulse width. For 80-μs/phase pulses, close to the values used in the present study, the estimates of α ranged from approximately 1.2 to 8, with a mean of 3. These slopes, which are much larger than those for acoustic hearing, predict considerably more negative masking than shown by the data. Furthermore, since these predictions are based on psychometric functions for gated stimuli they technically are appropriate only for the gated pedestals. In that condition, the data, except for those of C16, show little or no negative masking.

It is not clear how to explain the discrepancy between the predictions of Eq. (2) and the data. The most likely possibility is that Eq. (1) is incorrect. Perhaps because of the limited range over which d'_{det} can be measured, the validity of Eq. (1) has not been empirically assessed either in acoustic or electric hearing. The observation that intensity discrimination cannot be predicted from the psychometric function for absolute detection may be tapping something fundamental about the mechanisms involved in the two tasks. It may suggest that intensity discrimination is based on change detection, whereas absolute detection is mediated by a different mechanism. Far less likely is the possibility that the differences in implant type, pulse rate, stimulus duration, and individual differences account for the discrepancy between the predictions and the slopes resulting from the data of Donaldson and Viemeister.

E. Adaptation in response to auditory and electric stimulation

The size of the gated-continuous difference in the upper part of the dynamic range of hearing is larger for Clarion users than it is for normal-hearing listeners. This may reflect stronger adaptation due to electrical stimulation of the nerve. Kiang and Moxon (1972) demonstrated that neurons are driven to respond at higher rates with electrical stimulation than with auditory stimulation. Shannon (1983) observed strong loudness decay in cochlear-implant users for sinusoids with frequencies higher than 300 Hz. He suggested that stronger adaptation occurs when neurons are driven electrically because they are driven to higher rates and have less time for recovery. In contrast, neurons driven with auditory stimulation respond stochastically at lower rates and have more time to recover. Consequently, auditory stimulation causes less adaptation. Shannon's observations were not, however, supported by the study of Brimacombe and Eisenberg (1984), who generally did not observe loudness decay in cochlear-implant listeners stimulated with high-frequency sinusoids (even as high as 16 kHz). Only three of their 17 subjects showed loudness decay. Those three subjects lost their hearing at earlier ages and did not use hearing aids for a longer time than subjects who could sustain the perception of a tone for at least 2 min. For this reason, Brimacombe and Eisenberg concluded that neural degeneration was a probable cause of loudness decay. The Clarion users participating in the present study reported a considerable decay in stimulus loudness during each block of trials, often to inaudibility, but there was no apparent relationship between the degree of loudness decay and years of deafness. As in normal-hearing listeners, no direct link between loudness decay and the size of the gated-continuous difference was found in the Clarion users. It may appear as if two different mechanisms underlie the two phenomena. More likely, however, loudness adaptation and the gated-continuous difference are a result of different types of adaptation that occur at different levels of processing and are characterized by different time constants. Loudness decay may be a result of a long-term adaptation occurring at central sites, whereas the gated-continuous difference may reflect short-term adaptation determined more peripherally.

V. FINAL REMARKS AND CONCLUSIONS

The gated-continuous difference observed for tones in listeners with normal hearing does not change significantly for fringe durations longer than 650 ms. In fact, the gated-continuous difference and the difference measured with a 250-ms fringe are already very similar. In listeners with electric hearing, a larger difference in intensity DLs is observed for the gated versus continuous condition than for the gated versus 650-ms fringe condition. This may be due to the difference in the type of stimulus. This possibility is supported by the noise data collected from normal-hearing subjects, which show no significant decrease in the Weber fraction between the gated and the 650-ms fringe condition, and a significant decrease between the 650-ms fringe and the continuous condition. For noise stimuli, excitation is distributed across neurons with different CFs. Broader distribution of excitation and lower level of stimulation at specific CFs may produce less adaptation and a slower temporal course of adaptation compared with that for tones. In cochlear-implant listeners, neurons were driven at higher rates by the electric pulse trains due to increased synchrony and, at least with monopolar stimulation, a broader distribution of excitation across neurons was likely produced compared with that produced by acoustic stimulation by tones. These differences could contribute to the more sizable gated-continuous difference in the Clarion users.

It is likely that in acoustic hearing, peripheral synaptic adaptation and adaptation occurring at more central sites of processing both play a role in facilitating detection of intensity changes in an ongoing stimulus. It may be that the time course of synaptic adaptation is faster than that for central adaptation, and that synaptic adaptation becomes complete at shorter fringe durations.

In summary, the following conclusions can be drawn from our experiments:

(1) Cochlear-implant users exhibit an increased sensitivity to intensity increments after a prolonged exposure to the stimulus. Thus, DLs reported in other studies that measured intensity discrimination in cochlear-implant users with gated pedestals may underestimate these listeners' ability to detect small changes in current amplitude of an ongoing stimulus. This may be true particularly when the exposure times exceed 650 ms and the level of stimulus presentation is relatively high in the listener's dynamic range.

(2) The gated-continuous difference in sensitivity to intensity increments depends on the level in the listener's dynamic range. At high levels, the listeners' ability to detect small changes in the current amplitude after prolonged exposure to a stimulus may be limited by the amplitude resolution of the cochlear implant.

(3) Strong long-term adaptation is observed in cochlear-implant users. It reveals itself through strong loudness decay and through an increased sensitivity to intensity increments. This adaptation, combined with a change-detection mechanism, may be the primary cause of the gated-continuous difference in intensity-discrimination thresholds.

(4) Adaptation originating at sites central to the synapse between the IHCs and the spiral ganglion is likely to be a strong contributing factor in creating the gated-continuous difference in normal hearing.

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[1] Nominal amplitude steps for the Clarion C-l device are a constant 0.3 dB across amplitude. However, the actual step size decreases with increasing electrode impedance and at high current amplitudes where the current source begins to saturate. At current levels used in the present study, the current source was essentially linear.

[2] During the track when the listener correctly detected the increment on three consecutive trials at the resolution limits of the device, the program assumed an incorrect response, counted it as a reversal, and continued presentations at the same level. If the subject always responded correctly when this smallest current increment was presented, then his discrimination threshold was computed to be half of the size of this resolution step.

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