Psychophysical recovery from pulse-train forward masking in electric hearing

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Psychophysical pulse-train forward-masking (PTFM) recovery functions were measured in fifteen subjects with the Nucleus mini-22 cochlear implant and six subjects with the Clarion cochlear implant. Masker and probe stimuli were 500-Hz trains of 200- or 77-μs/phase biphasic current pulses. Electrode configurations were bipolar for Nucleus subjects and monopolar for Clarion subjects. Masker duration was 320 ms. Probe duration was either 10 ms or 30 ms. Recovery functions were measured for a high-level masker on a middle electrode in all 21 subjects, on apical and basal electrodes in 7 of the Nucleus and 3 of the Clarion subjects, and for multiple masker levels on the middle electrode in 8 Nucleus subjects and 6 Clarion subjects. Recovery functions were described by an exponential process in which threshold shift (in μA) decreased exponentially with increasing time delay between the offset of the masker pulse train and the offset of the probe pulse train. All but 3 of the 21 subjects demonstrated recovery time constants on a middle electrode that were less than 95 ms. The mean time constant for these 18 subjects was 54 ms (s.d. 17 ms). Three other subjects tested on three electrodes exhibited time constants larger than 95 ms from an apical electrode only. Growth-of-masking slopes depended upon time delay, as expected from an exponential recovery process, i.e., progressively shallower slopes were observed at time delays of 10 ms and 50 ms. Recovery of threshold shift (in μA) for PTFM in electrical hearing behaves in the same way as recovery of threshold shift (in dB) for pure-tone forward masking in acoustic hearing. This supports the concept that linear microamps are the electrical equivalent of acoustic decibels. Recovery from PTFM was not related to speech recognition in a simple manner. Three subjects with prolonged PTFM recovery demonstrated poor speech scores. The remaining subjects with apparently normal PTFM recovery demonstrated speech scores ranging from poor to excellent. Findings suggest that normal PTFM recovery is only one of several factors associated with good speech recognition in cochlear-implant listeners. Comparisons of recovery curves for 10- and 30-ms probe durations in two subjects showed little or no temporal integration at time delays less than 95 ms where recovery functions have steep slopes. The same subjects exhibited large amounts of temporal integration at longer time delays where recovery slopes are more gradual. This suggests that probe detection depends primarily on detection of the final pulses in the probe stimulus and supports the use of offset-to-offset time delays for characterizing PTFM recovery in electric hearing.
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I. INTRODUCTION

This paper describes psychophysical forward-masking recovery functions obtained in cochlear implant listeners using a stimulus paradigm in which both masker and probe stimuli are trains of biphasic current pulses. We refer to this paradigm as ''pulse-train forward masking'' (PTFM). PTFM recovery functions are of interest because they are thought to reflect neural adaptation or persistence mechanisms located in neural pathways central to the cochlea (Shannon, 1990a, 1990b) and may affect the ability of cochlear-implant listeners to discriminate temporal envelope characteristics of the electrical stimulus. Such envelope cues are particularly important for discriminating speech through a cochlear implant, especially when minimal spectral cues are available (Van Tasell *et al.*, 1992; Shannon *et al.*, 1995). Individual differences in recovery rates from forward masking may be one of the factors underlying individual differences in cochlear implant users' speech recognition abilities.

It is important to distinguish PTFM from single-pulse forward masking (SPFM), which uses single electric pulses as masker and probe signals, since the two paradigms yield recovery functions with quite different recovery rates (Donaldson and Nelson, 1999). Although differences between PTFM and SPFM are not well understood, it is likely that the rapid recovery of SPFM provides a direct measure of short-term recovery processes in surviving auditory nerve fibers (Nelson and Donaldson, 2001), whereas PTFM may reflect more central temporal processes that could affect envelope resolution and temporal pattern recognition (Blamey and Dooley, 1993).

Psychophysical PTFM recovery functions for electrical stimulation have been studied by previous investigators (Shannon, 1983, 1986, 1990a; Chatterjee and Shannon, 1998; Chatterjee, 1999). Shannon's earlier work (Shannon,

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TABLE I. **Subjects**. Subject identifying code (N-Nucleus; C-Clarion), gender, age when tested for the present study, etiology of deafness in implanted ear (and electrode type for Clarion subjects), duration of bilateral severe-to-profound hearing loss prior to implantation, depth of electrode array insertion (mm from the round window, with 25 mm representing complete insertion), duration of implant use prior of the study, and percent-correct score on the NU-6 monosyllabic word test in quiet.

Subject code	m/f	Age	Etiology of deafness (EL type)	Dur. (yrs)	Depth (mm)	CI use (yrs)	NU 6 (% C)
N09	m	66	Meniere's disease	1	22	10	24
N13	m	61	progressive SNHL	4	24	9	70
N14	m	56	hereditary; progressive SNHL	1	25	7	68
N24	m	55	skull fracture; progressive SNHL	24	20	12	32
N28	m	59	meningitis	<1	25	2	28
N30	f	59	otosclerosis	10	25	1	40
N31	m	79	noise exposure; progressive SNHL	25	20	8	6
N32	m	31	maternal rubella; progressive SNHL	<1	23	2	70
N34	f	54	mumps; progressive SNHL	9	22	10	0
N35	m	49	measles, age 2	37	20	10	8
N36	f	73	hereditary; progressive SNHL	??	19	10	2
N37	f	70	hereditary, unknown	4	25	5	10
N38	f	65	measles, otosclerosis, prog SNHL	10	10	6	4
N39	f	79	hereditary; progressive SNHL	14	25	6	32
N41	f	66	hereditary; progressive SNHL	19	21.5	6	14
C05	m	48	unknown; sudden SNHL (1.2E)	1	25	4	52
C12	f	50	otosclerosis, progressive (1.2E)	13	25	2	
C13	m	81	noise-induced progressive (1.2E)	6	25	3	50
C14	m	66	hereditary, unknown (HFP)	48	25	2	76
C15	f	42	unknown progressive SNHL (HFP)	7	25	2	68
C16	f	49	hereditary; progressive SNHL (HF)	18	25	1	80

1983, 1986, 1990a) showed that PTFM recovery in electric hearing is similar to that seen in normal acoustic hearing (Plomp, 1964; Duifhuis, 1973; Jesteadt *et al.*, 1982; Nelson and Freyman, 1987; Nelson and Pavlov, 1989) once intensity is scaled appropriately to account for nonlinear cochlear processing. This similarity suggests that the same physiological mechanisms are responsible for acoustic and electric forward-masking recovery, and that those mechanisms must reside beyond the auditory nerve. As yet, there has been no rigorous examination of PTFM recovery characteristics at different stimulation levels and in different electrode regions; thus, it is not clear whether an acoustic recovery model describes recovery in electrical hearing. If a single model can accurately describe the characteristics of forward masking in both acoustic and electric hearing, then it seems likely that they share common physiological mechanisms.

Because Shannon's cochlear-implant listeners all had similar recovery functions but exhibited a wide range of speech recognition abilities, he reasoned that PTFM was unrelated to speech recognition. Later work (Chatterjee and Shannon, 1998; Chatterjee, 1999) confirmed that PTFM recovery rates in most cochlear implant listeners are similar to those in acoustic listeners, but also identified some implant listeners with very fast recovery and poor speech recognition. This association between fast PTFM recovery and poor speech recognition is counterintuitive, and is contrary to recent SPFM results which found listeners with the slowest recovery rates to have the poorest speech recognition (Brown *et al.*, 1990; Brown *et al.*, 1996; Nelson and Donaldson, 2001). Thus, the existing literature is inconclusive as to the relationship between PTFM and speech recognition in cochlear-implant listeners.

The present study was designed to examine characteristics of psychophysical PTFM recovery functions in a relatively large group of implant listeners, including the general form of the PTFM recovery function, the dependence of recovery-function shape and amount of masking on masker level, and the extent to which recovery characteristics vary across cochlear implant listeners and regions of the implanted array. Recovery functions were obtained for subjects with two different device types, for electrodes in different regions of the cochlea, for a range of masker levels, and for different probe durations. They were analyzed using an exponential model of recovery that is commonly used to describe recovery from acoustic stimulation. Recovery was characterized by recovery time constants and amounts of masking at specific time delays following masker offset. Possible relations between these PTFM measures and speech recognition were examined with the goal of clarifying earlier findings.

II. METHODS

A. Subjects

Subjects were 21 post-lingually deafened adults, 15 implanted with a Nucleus mini-22 device (Patrick and Clark, 1991), and 6 implanted with a Clarion C-I device (Schindler and Kessler, 1993). The Nucleus users were implanted with a 22-electrode straight array. The Clarion users were implanted with a 16-electrode Spiral array (1.2E), a 16-electrode HiFocus array (HF) or a 16-electrode HiFocus array with an electrode positioning system (HFP). Table I displays relevant information for each subject, including age, etiology of deafness, electrode type for Clarion users, duration of hear-

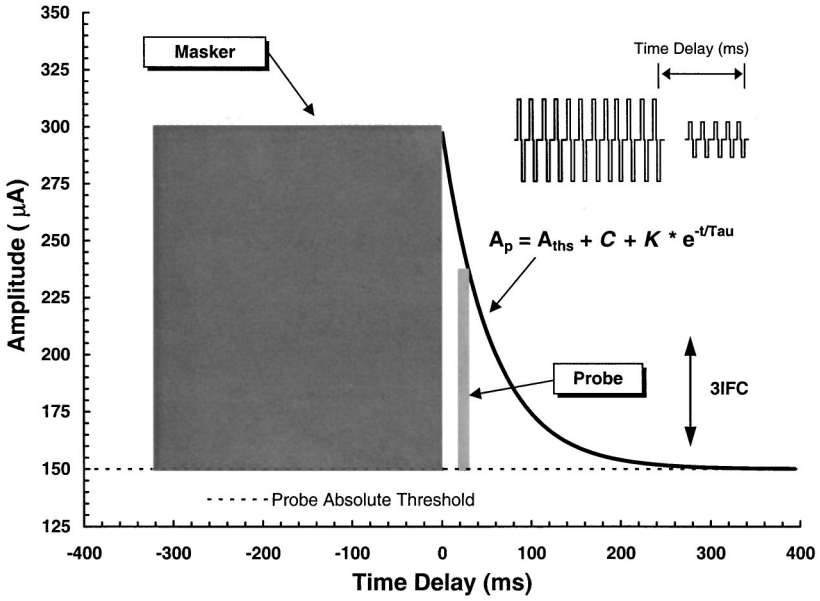

FIG. 1. Schematic diagram of the stimulus protocol used to measure pulse-train forward-masking recovery functions.

ing loss prior to implantation, insertion depth, duration of implant use prior to participation in the study, and score on the NU-6 monosyllabic word test in quiet.

For each of the 21 subjects, a psychophysical recovery function was obtained from an electrode near the middle of the array using a masker level above 70% of the masker dynamic range (DR) in decibels. For 8 Nucleus subjects and 6 Clarion subjects, recovery functions for the middle electrode were measured at additional masker levels (20% to 80% DR). For 7 Nucleus subjects and 3 Clarion subjects, recovery functions for a high-level masker (>70% DR) were measured for an apical electrode and a basal electrode in addition to the middle electrode.[1]

All Nucleus subjects were stimulated in bipolar mode, using an electrode separation of 1.5 mm (BP+1) or the narrowest separation greater than 1.5 mm that would allow maximum acceptable loudness to be achieved at realizable current amplitudes. Nucleus electrodes were numbered sequentially from 1–22, beginning with the most apical electrode. All Clarion subjects were stimulated in a monopolar mode. The Clarion Spiral electrode array (1.2E) incorporates 8 pairs of lateral and medial electrodes. Electrodes were numbered sequentially from 1–16, beginning with the most apical electrode, thus all odd-numbered electrodes were lateral electrodes and all even-numbered electrodes were medial electrodes. Electrodes in the Clarion HiFocus array were numbered 1–16, beginning with the most apical electrode.

B. Stimuli and procedures

1. PTFM recovery functions

Experiments were controlled by a computer connected through a parallel port to a specialized cochlear implant interface (Shannon *et al.*, 1990) for the Nucleus users, and through a special-purpose micro-processor that controlled the speech processor for the Clarion users (Clarion C-I Research Interface). For the Nucleus users, stimuli were trains of 500-Hz biphasic current pulses, with a per-phase duration of 200 μs and a delay between phases of 44 μs. 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 here. CSUs were converted to calibrated current amplitudes using user-specific tables provided by Cochlear Corporation. For the Clarion users, stimuli were trains of 500-Hz biphasic current pulses, with a per-phase duration of 77 μs and no delay between phases. Stimulus amplitudes were specified in integer *stimulus units* (SUs), which are logarithmic amplitudes steps of 0.15 to 0.30 dB. SU values were translated to calibrated amplitudes using a set of look-up tables developed in our laboratory. These tables compensate for nonlinearities in the current source that depend upon elecrode impedance and pulse rate. Electrode 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 IBM Think Pad computer. Calibrated amplitudes for a given electrode were calculated using the average of all beginning and ending impedance values for data collection sessions in which that electrode was tested.

Figure 1 illustrates the stimulation protocol used to obtain PTFM recovery functions. As shown in the figure, a 320-ms ''masker'' pulse train was presented first, followed at some time delay by a 10- or 30-ms ''probe'' pulse train. The current amplitude of the masker pulse train was fixed and the amplitude of the probe pulse train was varied adaptively to determine masked threshold. By varying the time delay between masker and probe pulse trains in different adaptive tracks, a recovery function was defined. In this report, time delay (ms) is specified as the time between the offset of the masker pulse train and the offset of the probe pulse train (Fig. 1 inset). This differs from previous reports which measured time delay between the offset of the masker pulse train and the *onset* of the probe pulse train (Shannon, 1990a; Chatterjee, 1999). Our specification of time delay was based on a comparison of recovery functions for 10- and 30-ms probe pulse trains in two cochlear implant listeners (see Appendix A), which indicated that earlier pulses in the 30-ms pulse train did not contribute substantially to detection of the probe

during recovery from forward masking. Masker and probe amplitudes were specified in microamperes (μA) of current, and masked thresholds for the probe were specified in terms of threshold shift (TS) in μA, i.e., the amplitude difference between the masked threshold of the probe ($\mathbf{A}_p$) and the unmasked threshold of the probe in quiet ($\mathbf{A}_{0p}$). This is similar to the normalized level scale used by Shannon (1990a), except that masked thresholds are not normalized to masker sensation level (in μA). Loudness balances between an acoustic stimulus in one ear and an electric stimulus in the other ear (Eddington *et al.*, 1978; Zeng and Shannon, 1992) indicate that equal ratio changes in acoustic intensity are balanced by equal linear amplitude changes in electrical current. This suggests that threshold shift in μA in electric hearing is equivalent to threshold shift in dB in acoustic hearing. Thus, if PTFM is a retrocochlear phenomenon, then the recovery process examined here should be similar to that seen in acoustic hearing.

2. Absolute thresholds and maximum acceptable loudness levels

Prior to obtaining recovery functions for a particular electrode, absolute detection threshold (THS) and maximum acceptable loudness level (MAL) were determined for both the 320-ms masker pulse train and for a 10- or 30-ms probe pulse train. THS was measured with a three-interval forced choice (3IFC) adaptive procedure similar to that used for measuring masked thresholds (described below). MAL was measured with an ascending method of limits procedure in which pulse trains, presented at a rate of 2/s, were slowly increased in amplitude until the subject indicated that loudness had reached a ''maximum acceptable'' level. Estimates for two consecutive ascending runs were averaged to obtain a single measure of MAL. THS and MAL were measured at the start of each test session for the particular electrode to be evaluated in that session, and THS was measured again at the end of each test session. Values of THS and MAL reported here represent the average of all measures obtained across sessions.

3. Masked thresholds

Forward-masked thresholds were obtained using a 3IFC adaptive procedure. The masker pulse train was presented in each of three listening intervals. The probe pulse train was presented in one of the three intervals, chosen randomly from trial to trial, at some fixed time delay following the masker. The subject's task was to choose the ''different'' interval by pressing the appropriate button on a three-button computer mouse. Stimulus intervals were cued on a video monitor, and correct-answer feedback was provided after each trial. The amplitude of the probe pulse train was initially set to a level 2 dB to 4 dB (depending on the probe dynamic range of the test electrode) above the anticipated masked threshold. For the first four reversals, probe level was altered according to a 1-down, 1-up stepping rule, with step size equal to 1 dB. In a few subjects with very small dynamic ranges, the initial step size was 0.5 dB. These initial reversals quickly moved the adaptive procedure into the target region for masked threshold. After the fourth reversal, step size was reduced, typically to one-fourth of the initial step size, and a 3-down, 1-up stepping rule was assumed. This stepping rule estimates the stimulus level corresponding to 79.4% correct discrimination (Levitt, 1971). Step size was constant for all remaining trials. Trials continued until a total of 12 reversals occurred. The mean of the final eight reversals was taken as the masked threshold estimate.

Masked thresholds were determined in this manner for nine time delays between 11 ms and 300 or 500 ms, in equal ratio steps, to define a complete forward-masking recovery function. Each point on the recovery function was based on the average of three to five forward-masked threshold estimates. Data were obtained in sets, where a single set included one adaptive track at each time delay. Three to five sets were obtained, with the order of time delays alternated for consecutive sets (short-to-long time delays alternated with long-to-short). This allowed any learning effects to be distributed across time delays. Most recovery functions were completed within a single test session. At the end of a session, absolute threshold for the probe pulse train was remeasured. Threshold shift was based on the average of thresholds measured before and after each session.

When masker level effects were investigated in the Nucleus subjects, a recovery curve for the highest masker level was obtained first, followed by recovery functions for the two lower masker levels. The complete recovery curve for the highest masker level was then repeated on the Nucleus subjects to demonstrate the reliability of our procedure. High-level recovery curves were not repeated for Clarion subjects. When recovery functions were obtained from apical, middle, and basal electrodes, data were obtained first on the middle electrode and then on the remaining two electrodes. The order of testing basal and apical electrodes varied across subjects.

4. Exponential fits to PTFM functions

Least-squares regression procedures were used to fit individual recovery functions with the equation

$$(\mathbf{A}_p - \mathbf{A}_{0p} - C) = K \cdot e^{-t/tau}, \tag{1}$$

where $\mathbf{A}_p$ is the forward-masked threshold of the probe (μA), $\mathbf{A}_{0p}$ is the unmasked probe threshold (μA), t is the masker-probe time delay (ms), *tau* is the time constant of recovery from forward masking (ms), and K and C are constants. Values of *tau* and K were determined using standard least-squares fitting procedures on threshold shift minus a C constant [left-hand side of Eq. (1)]. This was repeated for different values of C until the residual squared error between the fitted and the actual recovery curve was minimized. Equation (1) is the same equation used previously to characterize SPFM recovery functions (Nelson and Donaldson, 2001). The constant C was included in Eq. (1) to accommodate residual masking (incomplete recovery) observed in some recovery functions at moderate or long masker-probe delays. Such residual masking is commonly observed in acoustic forward-masking experiments (Abbas and Gorga, 1981; Markman, 1989; Oxenham and Moore, 1995), but is not well understood.

5. Speech recognition tests

All subjects were tested with three different sets of speech materials: medial vowels in /hVd/ context, medial consonants in /aCa/ context, and NU-6 monosyllabic words. Speech stimuli were presented through loudspeakers in a sound insulated room with the frequent speech peaks set to 60 dB SPL_A at the microphone of the speech processor.

Vowel and consonant recognition. Vowel and consonant recognition were assessed using a standard phoneme–confusion procedure. Vowel stimuli were 11 /hVd/ monosyllables spoken by three male talkers,[2] taken from the database of Hillenbrand *et al.* (1995). Vowels tested were /æ, ɑ, ɛ, e, ɚ, ɪ, i, o, ʊ, ʌ, u/ as in ''had, hod, head, hayed, heard, hid, heed, hoed, hood, hud, and who'd.'' Consonant stimuli were 19 /aCa/ disyllables spoken by three male and three female talkers, taken from the stimulus set of Van Tasell *et al*. (1992). Consonants tested were /p, t, k, b, d, g, f, θ, s, ʃ, v, ð, z, ʒ, m, n, r, l, j/. Digitized speech tokens were played out from computer memory, low-pass filtered at half the digitization rate, amplified and presented through the speakers. The stimulus was presented once on each trial, and the subject used a computer mouse to select his or her response from a list of possible alternatives displayed on a video screen. Correct-answer feedback was provided immediately after each stimulus presentation.

Vowel and consonant recognition data were obtained in separate test sessions. For each stimulus type, one practice block and five standard blocks of data were obtained. Practice blocks were comprised of two trials per vowel phoneme (33 trials) or three trials per consonant phoneme (38 trials). Standard blocks were comprised of six trials per phoneme (66 vowels or 114 consonants) presented in random sequence. A merged confusion matrix was created from the five standard blocks of data for a particular subject. Each merged matrix represented 30 observations (5 blocks×6 tokens) per stimulus. Merged confusion matrices were analyzed using sequential information analysis (SINFA) to obtain relative transmitted information (RTI) measures for overall vowel and consonant recognition, and for specific vowel and consonant features (Wang, 1976; Van Tasell *et al.*, 1992; Donaldson and Allen, 2002).

NU-6 words. A single list of 50 words was presented using tape-recorded stimuli spoken by a single male talker. Subjects provided written responses, which were scored in terms of percent phonemes as well as percent words identified correctly.

Subjects used their own speech processors for all testing. Nucleus subjects had a Spectra speech processor programmed in the SPEAK strategy. Clarion subjects had a v1.2 or S-series speech processor programmed in the CIS strategy. Nucleus subjects adjusted the sensitivity controls on their processors to achieve comfortable loudness for the test stimuli. Clarion subjects adjusted the volume control, leaving the sensitivity control set to a level at which AGC compression would not be activated for the stimulus levels used (''10:30'' for the v1.2 processor; ''11:00'' for the S-series processor).

III. RESULTS

A. Characteristics of individual PTFM recovery functions

PTFM recovery functions obtained from the middle electrodes of three Nucleus subjects (N14r12, N32r12, and N13r11) are shown in Fig. 2. Each panel shows the data for one electrode at several masker levels. Four recovery curves are shown in panels (A) and (B): one for each of three different masker levels (at approximately 25%, 50%, and 75%

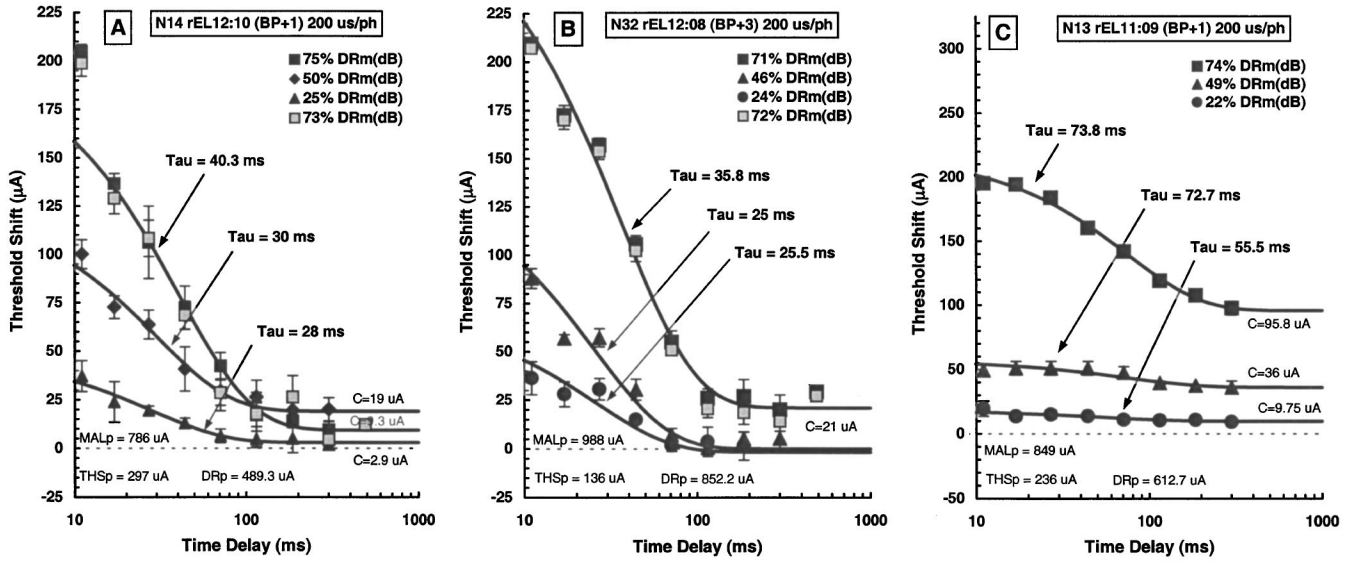

FIG. 2. Pulse-train forward-masking recovery functions are plotted in terms of threshold shift (TS) in microamps, as a function of the time delay between masker offset and probe offset. Data are from Nucleus subjects N14, N32, and N13, all with N-22 electrodes. These subjects demonstrated short time constants for the recovery process (tau<40 ms) and high speech recognition scores. Each panel contains recovery functions for a single electrode in the middle of the electrode array. Error bars indicate 1 standard deviation from the mean. The parameter is masker level, expressed as a percentage of the dynamic range of the masker pulse train that was available on each electrode. Threshold (THSp), maximum acceptable loudness level (MALp) and dynamic range (DRp) for the probe pulse train are given within each panel. Time constants for each recovery function are indicated by tau; residual constants are indicated by C (μA TS).

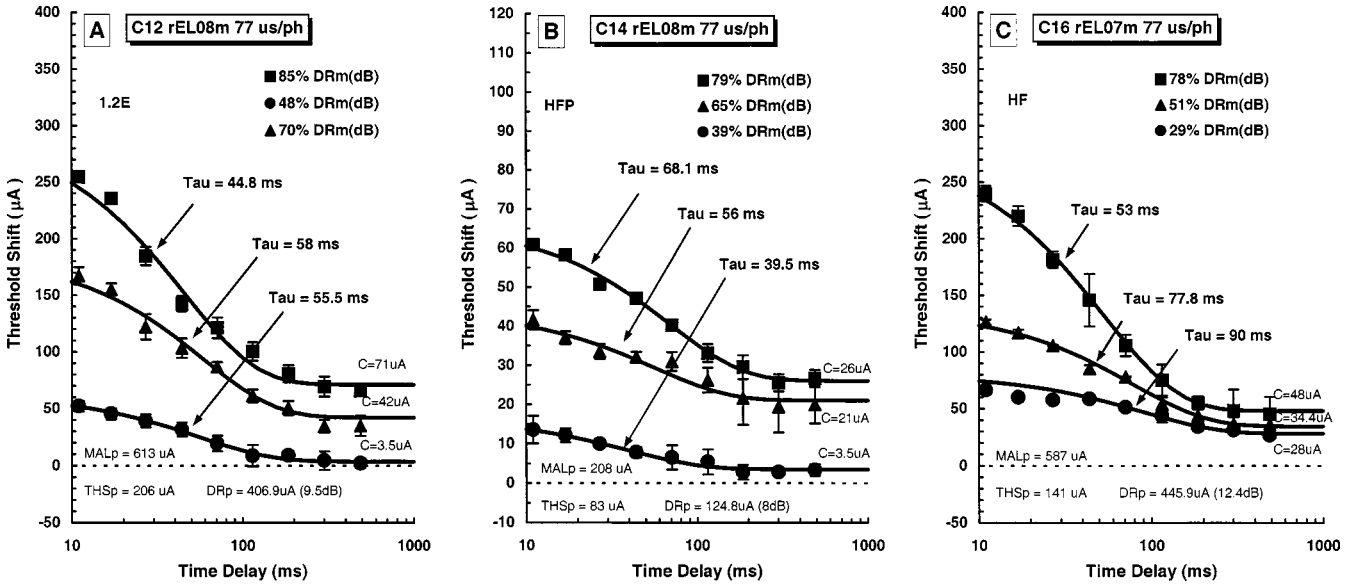

FIG. 3. Pulse train forward-masking recovery functions from a middle electrode in Clarion subjects C12, C14, and C16. C12 has a spiral electrode (1.2E). C14 has a high-focus electrode with a positioner (HFP). C16 has a high-focus electrode without a positioner. Each panel contains recovery functions for a single electrode in the middle of the electrode array. Error bars indicate 1 standard deviation from the mean. The parameter is masker level, expressed in the legend as a percentage of the dynamic range of the masker pulse train that was available on each electrode. Dynamic range (DRp in μA) for the probe pulse train is indicated by the hatched horizontal line at the top of the graphs, and is listed within each panel in μA and dB μA. Time constants for each recovery function are indicated by Tau; residual constants are indicated by C (TS in uA).

of DR in dB), and a retest for the highest masker level (Lm$>$70% of DR in dB). Only three recovery curves are shown in panel (C) because N13r11 was not retested at the highest masker level. The shapes of these functions are typical of recovery functions obtained from other Nucleus subjects. Recovery time constants [tau in Eq. (1)] are indicated next to each curve. Recovery rates for the two electrodes represented in panels (A) and (B) were among the fastest observed, with time constants ranging from 25 to 40 ms. The electrode in panel (C) had slightly longer time constants (55–74 ms). All three of the subjects represented in Fig. 2 scored high on speech recognition tests.

The PTFM recovery functions in Fig. 2 illustrate several characteristics common to the functions measured in other subjects. First, PTFM recovery curves were well fit by the exponential recovery process given by Eq. (1). Second, most of the recovery curves exhibited a residual threshold shift specified by the constant *C*. Third, recovery curves at the highest masker level exhibited good test-retest reliability, with repeat masked thresholds that were not significantly different from the original ones [e.g., shaded vs solid squares in Figs. 2(A) and (B)].

One atypical characteristic sometimes seen in PFTM recovery functions is illustrated in Fig. 2(A). At the shortest time delay (11 ms), when the probe pulse train immediately follows the masker pulse train, a large amount of threshold

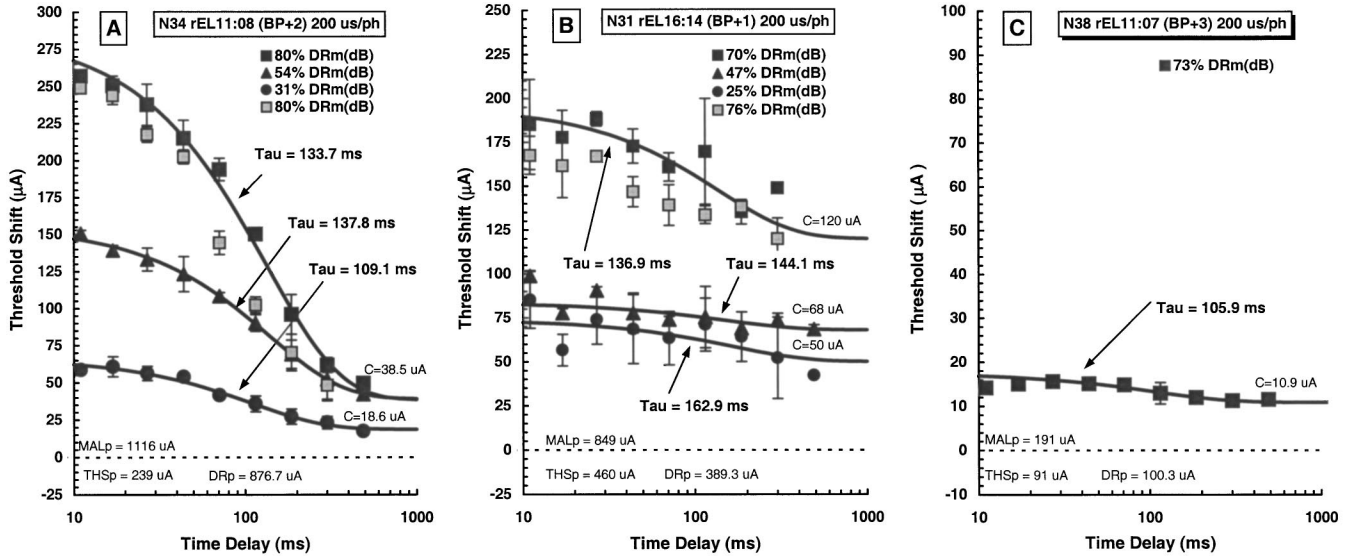

FIG. 4. Pulse-train forward-masking recovery functions from subjects N34, N31, and N38, who demonstrated long time constants for the recovery process ($tau>100$ ms) and low speech recognition scores. Legend as in Fig. 2.

shift is evident. This threshold shift greatly exceeds that predicted by the exponential recovery curve that describes masked thresholds at longer time delays. Excessive masking at 11 ms was observed for only one (middle) electrode in two subjects (N14r12 and C05r08), and then only at the highest of three masker levels.

PTFM recovery functions obtained from the middle electrodes of three Clarion subjects (C12r08, C14r08, and C16r07) are shown in Fig. 3. Each of the subjects has a different type of electrode array: C12 has a Spiral electrode (1.2E), C14 has a HiFocus electrode with a positioner, and C16 has a HiFocus electrode without a positioner. Qualita-

TABLE II. Recovery function parameters obtained from 8 Nucleus and 6 Clarion subjects at multiple masker levels on a middle electrode: subject code, research electrode number, and electrode type (Subj/Elect); stimulation mode (Mode); threshold (THS), maximum acceptable loudness level (MAL) expressed in μAmps of current; dynamic range (DR) for probe and masker stimuli (expressed in dB); masker level (Lm) expressed as percent dynamic range of the masker in dB (%DRm); time constant (tau); residual constant (C); goodness of fit (R^2). Average parameter values are shown in bold for each subject/electrode.

Subj/Elect	Mode	THSp (uA)	MALp (uA)	DRp (dB)	THSm (uA)	MALm (uA)	DRm (dB)	Lm (%DRm)	Tau (ms)	C (uA)	R^2
N09 rEL15:13	BP+1	139	459	10.4	124	310	7.9	75.9%	44.2	25.4	0.990
NUC	BP+1	143	437	9.7	120	305	8.1	53.5%	46.8	22.8	0.848
	BP+1	128	425	10.4	104	305	9.4	25.9%	45.3	10.0	0.849
		136.6	**440.4**	**10.2**	**116.1**	**306.8**	**8.4**				**0.896**
N13 rEL11:09	BP+1	233	845	11.2	157	591	11.5	74.2%	73.8	95.8	0.986
NUC	BP+1	238	855	11.1	146	542	11.4	49.0%	72.7	36.0	0.926
	BP+1	237	845	11.1	151	566	11.4	22.2%	55.5	9.8	0.360
		235.8	**848.5**	**11.1**	**151.6**	**566.3**	**11.4**				**0.757**
N14 rEL12:10	BP+1	301	780	8.3	171	647	11.5	75.0%	40.3	9.3	0.999
NuC	BP+1	290	789	8.7	166	662	12.0	49.8%	30.0	19.0	0.985
	BP+1	299	789	8.4	167	652	11.8	25.2%	28.0	2.9	0.985
		296.7	**786.0**	**8.5**	**168.3**	**653.4**	**11.8**				**0.990**
N28 rEL12:10	BP+1	157	396	8.0	126	305	7.7	79.3%	36.8	59.0	0.995
NUC	BP+1	155	385	7.9	129	303	7.4	52.9%	39.8	39.0	0.964
	BP+1	156	380	7.7	132	296	7.0	24.6%	59.9	13.5	0.839
		155.8	**386.9**	**7.9**	**129.2**	**301.4**	**7.4**				**0.933**
N30 rEL17:15	BP+1	174	557	10.1	126	432	10.7	75.6%	65.2	32.4	0.963
NUC	BP+1	177	565	10.1	130	423	10.2	51.6%	80.5	28.0	0.982
	BP+1	175	544	9.8	129	405	10.0	28.3%	33.3	5.7	0.978
		175.1	**555.2**	**10.0**	**128.4**	**419.7**	**10.3**				**0.974**
N32 rEL12:08	BP+3	131	1019	17.8	65	644	19.9	71.5%	35.8	21.0	0.985
NUC	BP+3	139	1039	17.5	65	636	19.8	46.2%	25.0	0.0	0.959
	BP+3	137	911	16.5	65	679	20.4	24.4%	25.5	−1.8	0.926
		135.8	**989.6**	**17.3**	**64.8**	**653.1**	**20.1**				**0.957**
N31 rEL16:14	BP+1	458	838	5.3	341	686	6.1	70.3%	136.9	120.0	0.824
NUC	BP+1	459	855	5.4	345	673	5.8	46.6%	144.1	68.0	0.698
	BP+1	463	855	5.3	340	682	6.0	24.6%	162.9	50.0	0.505
		460.1	**849.4**	**5.3**	**341.7**	**680.1**	**6.0**				**0.676**
N34 rEL11:08	BP+2	236	1103	13.4	195	609	9.9	80.1%	133.7	38.5	0.988
NUC	BP+2	238	1098	13.3	199	609	9.7	54.0%	137.8	39.1	0.998
	BP+2	243	1147	13.5	197	609	9.8	30.5%	109.1	18.6	0.988
		238.9	**1115.8**	**13.4**	**197.1**	**608.8**	**9.8**				**0.991**
C05 rEL08m	mono	104	400	11.7	52	330	16.1	87.0%	60.2	42.0	0.986
1.2E	mono	104	380	11.3	53	319	15.6	71.0%	60.5	16.0	0.979
	mono	98	361	11.3	42	319	17.5	50.4%	60.7	0.6	0.964
		101.9	**380.3**	**11.4**	**49.0**	**322.5**	**16.4**				**0.976**
C12 rEL08m	mono	199	572	9.2	106	574	14.7	85.5%	44.8	71.0	0.962
1.2E	mono	198	610	9.8	101	635	16.0	69.6%	58.0	42.0	0.957
	mono	221	659	9.5	102	642	15.9	48.3%	55.5	3.5	0.993
		205.9	**613.7**	**9.5**	**103.2**	**616.8**	**15.5**				**0.971**
C13 rEL08m	mono	131	348	8.5	69	351	14.1	87.0%	76.8	41.5	0.991
1.2E	mono	136	388	9.1	67	353	14.5	70.3%	78.8	22.5	0.933
		133.5	**367.7**	**8.8**	**67.7**	**352.0**	**14.3**				**0.962**
C14 rEL08m	mono	82	205	8.0	55	178	10.2	79.2%	68.1	26.0	0.983
HFP	mono	82	212	8.2	55	175	10.1	65.4%	56.0	21.0	0.868
	mono	84	206	7.8	57	164	9.1	39.1%	39.5	3.5	0.997
		82.7	**207.5**	**8.0**	**55.7**	**172.6**	**9.8**				**0.949**
C15 rEL08m	mono	69	116	4.5	32	61	5.8	71.2%	48.2	2.0	0.885
HFP	mono	68	117	4.7	33	77	7.4	43.8%	63.3	3.5	0.967
		68.6	**116.6**	**4.6**	**32.3**	**69.3**	**6.6**				**0.926**
C16 rEL07m	mono	147	632	12.7	149	495	10.5	78.2%	53.0	48.0	0.998
HF	mono	134	524	11.8	138	453	10.3	51.2%	77.8	34.4	0.945
	mono	144	612	12.6	141	507	11.1	28.8%	90.0	28.0	0.992
		141.5	**589.3**	**12.4**	**142.5**	**484.9**	**10.6**				**0.978**

tively, recovery curves from Clarion subjects are similar to those observed in Nucleus subjects, regardless of electrode type. These curves are well fit by exponential curves with time constants (tau) and residual constants (*C*) within the same range as seen in Nucleus subjects. All three of these subjects also performed well on the speech tests.

PTFM recovery functions from a middle electrode in three Nucleus subjects (N34r11, N31r16, and N38r11) are shown in Fig. 4. Two of these subjects (N34r11 and N31r16) exhibited extended PTFM recovery with long time constants at all three levels, and the third subject (N38r11) exhibited a long time constant for the one high-level masker that was tested. For N31r16 [Fig. 4(B)], residual masking was exceptionally high, with *C* constants between 50 and 120 μA. For N38r11 [Fig. 4(C)], the THS and MAL values were unusually low and only a small amount of threshold shift was produced by the PTFM masker. The three subjects represented in Fig. 4 also exhibited low speech scores. Comparison of time constants and speech scores for the subjects in Fig. 2 and Fig. 4 suggests that PTFM time constants are inversely related to speech recognition scores. As will be shown later, a simple inverse relationship does not exist. Rather, prolonged PTFM recovery appears to predict poor speech recognition, whereas apparently normal PTFM recovery may be observed in subjects with all levels of speech recognition.

B. Group tendencies in PTFM recovery functions

1. Masker level effects

The effect of masker level on PTFM recovery curves was examined for the middle electrodes of 8 Nucleus and 6 Clarion subjects. Parameters of the exponential fits obtained at different masker levels are given in Table II. For each test electrode (denoted by research electrode number, rEL), THS, MAL, and DR for the probe and masker stimuli are shown, together with fitting parameters *tau* and *C* for the exponential recovery process. Excellent exponential fits to the data were obtained at the highest masker level, as evidenced by coefficients of determination (R^2) that were typically above 0.98. Fits were less good at lower masker levels, but still provided an adequate characterization of the data.

Time constants for the recovery process (*tau*) were largely independent of masker level. As shown in Fig. 5(A), values for *tau* on the middle electrode varied considerably across subjects, from 25 ms to 163 ms, but did not vary systematically with masker level for most of the 8 Nucleus or 6 Clarion subjects tested at multiple levels. Thus, the PTFM recover process appears to be adequately described by an exponential recovery model [Eq. (1)] that produces level-independent time constants. As indicated in Fig. 5, two subjects (N31 and N34) demonstrated time constants greater than 95 ms, the upper 99% confidence limit of the mean (dashed line in Fig. 5).

Probe dynamic ranges for subjects' middle electrodes varied from 4.5 to 17.8 dB (47 to 904 μA). Figure 5(B) shows time constants plotted as a function of dynamic range for the probe pulse train, expressed in μA. There was no simple relationship between tau and DR. Subjects with shorter time constants (filled symbols) exhibited dynamic ranges from small to very large.

2. Growth of masking

If an exponential model with a level-independent time constant is truly appropriate for describing the PTFM recovery process, then the model should accurately predict the rate at which forward masking grows with masker level at all time delays. To evaluate characteristics of growth of masking (GOM), parameter *K* in Eq. (1) was expressed as a linear function of masker sensation level $(\mathbf{A}_m - \mathbf{A}_{0m})$, as follows:

$$K = b + n \cdot (\mathbf{A}_m - \mathbf{A}_{0m}). \quad (2)$$

Substituting Eq. (2) for *K* in Eq. (1) yields the following:

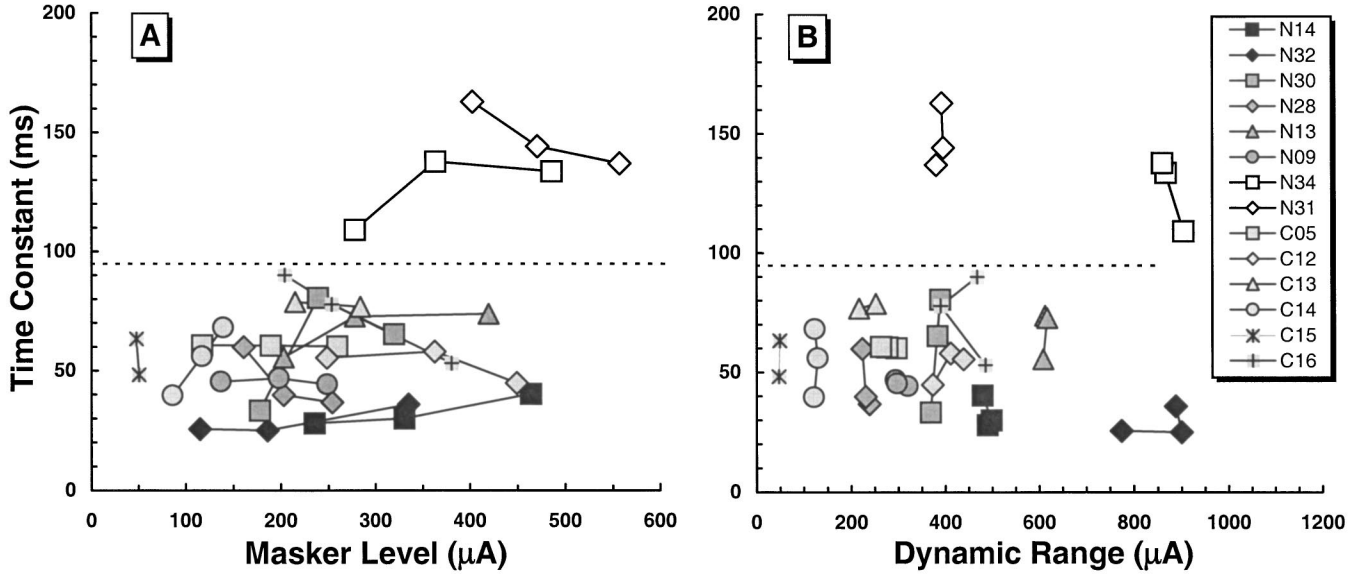

FIG. 5. Time constants for the recovery process on middle electrodes, from 8 Nucleus and 6 Clarion subjects, as a function of masker level [panel (A)] and as a function of dynamic range for the probe pulse train [panel (B)]. Time constants were obtained from exponential fits to the pulse-train forward-masking recovery functions. The dashed line indicates 99% confidence limits above the mean; time constants above this line are identified by unfilled symbols.

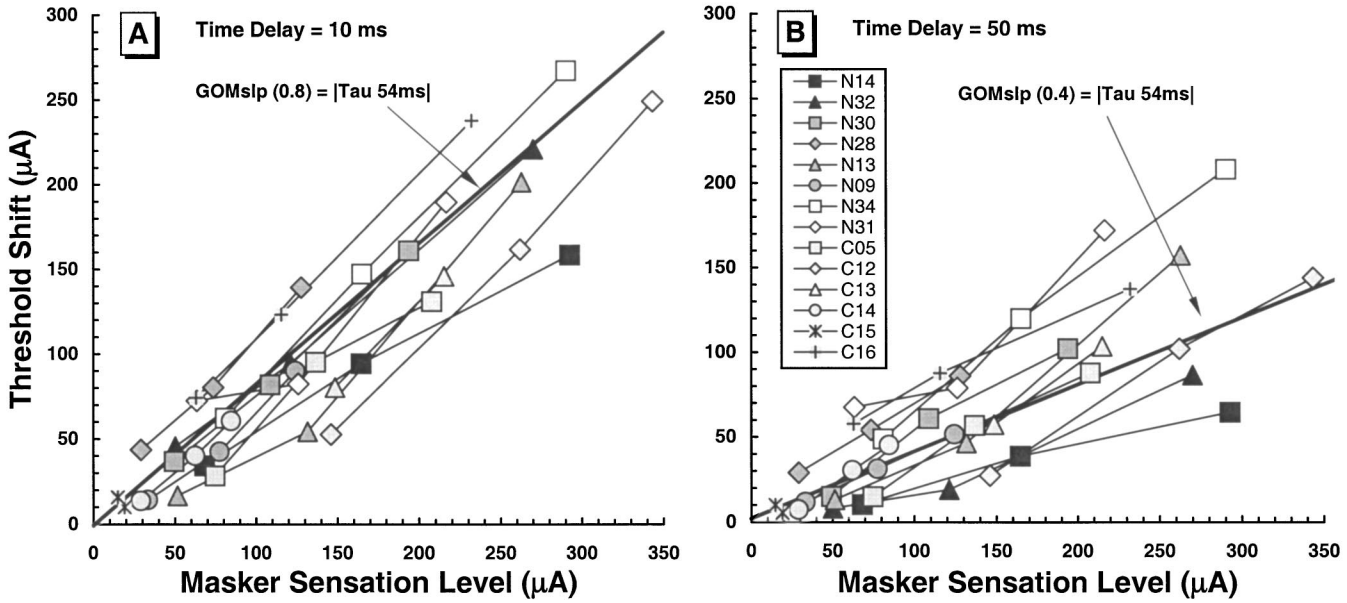

FIG. 6. Amount of masking as a function of masker sensation level, calculated for time delays of 10 ms [panel (A)] and 50 ms [panel (B)]. The growth of masking functions predicted by Eq. (3) for a time constant of 54 ms are shown by the solid lines, which have slopes of 0.8 and 0.4 for the 10- and 50-ms time delays, respectively.

$$(\mathbf{A}_p - \mathbf{A}_{0p} - C) = [b + n(\mathbf{A}_m - \mathbf{A}_{0m})] \cdot e^{-t/tau}. \quad (3)$$

This shows that for a time delay of $t = 0$ ms, the growth rate of masking is equal to *n*, and the sensitivity to masking is equal to *b*. For other values of *t*, Eq. (3) shows that the rate of growth of masking is inversely related to *tau*. Growth of masking slopes were evaluated for several values of *t* in order to determine if the expected dependence of growth rate on *tau* was actually reflected in the data.

Figures 6(A) and (B) show GOM functions for time delays of 10 and 50 ms, respectively. In each graph, threshold shifts calculated from the fitted recovery curves at time delays of 10 or 50 ms are plotted as a function of masker sensation level. The GOM functions at 50 ms exhibit lower slopes than those at 10 ms, which is consistent with Eq. (3). For comparison, the GOM functions predicted from Eq. (3) using a time constant of 54 ms are shown by solid lines in Figs. 6(A) and (B). Recall that 54 ms was the average time constant for 18 subjects with apparently normal rates of recovery on a middle electrode. For both 10- and 50-ms time delays, the general trend of the slopes of the GOM functions are well described by the solid line. A linear fit across all electrodes to the amount of masking at a 10-ms delay as a function of masker sensation level indicates that, on average, forward masking at a 10-ms delay begins when the masker is slightly above its detection threshold (0.9 μA SL). These results suggest that, for most subjects, effective masking due to a pulse-train masker tends to grow monotonically with the sensation level of the masker (in μA), and that forward masking begins when masker amplitude is at absolute threshold. This outcome adds further support to the validity of an exponential model for describing recovery from PTFM in electric hearing.

3. Effects of electrode location

Parameters for recovery curves obtained from three regions of the same electrode array (apical, middle, and basal) at a single masker level (>70% DR) in 7 Nucleus and 3 Clarion subjects, are given in Table III. Parameters for recovery curves obtained on a middle electrode at a single masker level (>70% DR) in an additional 8 Nucleus and 3 Clarion subjects are also listed. To examine whether recovery function parameters differed significantly for electrodes located in the apical, middle, or basal regions of the electrode array, single factor repeated-measures ANOVAs were performed on the measures of *tau* and threshold shift at $t = 10$ ms or $t = 50$ ms. None of the resulting F-ratios approached statistical significance for either group. This indicates that neither the recovery from PTFM nor the amount of threshold shift at a 10- or 50-ms time delay varied consistently with electrode region. Repeated-measures ANOVAs similarly showed that neither absolute threshold nor probe dynamic range varied systematically with electrode location.

Figure 7 shows the time constants obtained from different electrode regions, plotted as a function of masker level. In addition to subjects N31 and N34, one additional subject (N38) who was tested only on a middle electrode exhibited a long time constant. Thus, out of 15 Nucleus and 6 Clarion subjects tested on a middle electrode, only three exhibited time constants longer than 95 ms. As shown in Fig. 7, two of the subjects with long time constants on a middle electrode (N31 and N34) also exhibited long time constants on a basal electrode. One of those subjects (N34) exhibited long time constants on all three electrodes. In addition, three subjects (N13, N30, C14) exhibited long time constants on an apical electrode only, with normal time constants on a middle and basal electrode.

TABLE III. Recovery function parameters obtained from apical, middle or basal electrodes at the highest masker level (Lm>70% DR) in 21 subjects. Column 1 shows the subject code and electrode pair stimulated (m=monopolar). Rows 1–21: 7 Nucleus subjects tested on apical, middle and basal electrodes. Rows 22–29: 8 additional Nucleus subjects tested on a middle electrode. Row 30–38: 3 Clarion subjects tested on apical, middle and basal electrodes. Rows 39–41: 3 additional Clarion subjects tested on a middle electrode.

Subj/Elect	Mode	THSp (uA)	MALp (uA)	DRp (dB)	THSm (uA)	MALm (uA)	DRm (dB)	Lm (%DRm)	Tau (ms)	C (uA)	R^2	TS(10 ms)/ DRp(uA)	TS(50 ms)/ DRp(uA)
N13 rEL07:02	BP+4	239	525	6.8	169	491	9.3	70.6%	112.6	65.5	0.919	0.44	0.38
N13 rEL11:09	BP+1	233	845	11.2	157	591	11.5	74.2%	73.8	95.8	0.986	0.33	0.26
N13 rEL16:11	BP+4	273	767	9.0	180	581	10.2	75.7%	52.8	91.2	0.976	0.36	0.27
N14 rEL06:04	BP+1	412	833	6.1	246	796	10.2	75.1%	25.0	5.8	0.935	0.56	0.12
N14 rEL12:10	BP+1	301	780	8.3	171	647	11.5	75.0%	40.3	9.3	0.999	0.33	0.13
N14 rEL20:18	BP+1	411	809	5.9	229	730	10.1	74.0%	21.7	19.0	0.980	0.49	0.12
N28 rEL05:03	BP+1	339	550	4.2	156	410	8.4	75.0%	58.8	6.4	0.909	0.23	0.13
N28 rEL12:10	BP+1	157	396	8.0	126	305	7.7	79.3%	36.8	59.0	0.995	0.58	0.36
N28 rEL20:18	BP+1	410	811	5.9	193	571	9.4	77.9%	42.7	6.4	0.987	0.28	0.12
N30 rEL04:02	BP+1	329	1088	10.4	178	892	14.0	73.2%	127.6	68.9	0.994	0.34	0.27
N30 rEL17:15	BP+1	174	557	10.1	126	432	10.7	75.6%	65.2	32.4	0.963	0.42	0.27
N30 rEL21:19	BP+1	299	1388	13.3	226	850	11.5	78.4%	53.6	108.3	0.997	0.34	0.21
N31 rEL12:10	BP+1	643	1029	4.1	438	869	6.0	76.1%	71.1	107.8	0.994	0.41	0.35
N31 rEL16:14	BP+1	458	838	5.3	341	686	6.1	70.3%	136.9	120.0	0.824	0.50	0.45
N31 rEL21:19	BP+1	688	1083	3.9	443	897	6.1	79.0%	107.4	80.0	0.990	0.40	0.34
N32 rEL05:01	BP+3	140	1738	21.9	71	699	19.9	77.7%	41.0	51.3	0.996	0.18	0.09
N32 rEL12:08	BP+3	131	1019	17.8	65	644	19.9	71.5%	35.8	21.0	0.985	0.25	0.10
N32 rEL19:15	BP+3	88	724	18.3	44	565	22.3	73.4%	48.9	31.8	0.995	0.33	0.17
N34 rEL06:02	BP+3	294	1283	12.8	221	717	10.2	82.2%	107.6	67.5	0.976	0.31	0.23
N34 rEL11:08	BP+2	236	1103	13.4	195	609	9.9	80.1%	133.7	38.5	0.988	0.31	0.24
N34 rEL17:13	BP+3	241	608	8.0	173	523	9.6	74.8%	110.9	52.0	0.963	0.45	0.36
N09 rEL15:13	BP+1	139	459	10.4	124	310	7.9	75.9%	44.2	25.4	0.990	0.28	0.16
N24 rEL11:08	BP+2	368	1038	9.0	218	791	11.2	74.4%	33.9	50.0	0.990	0.35	0.16
N35 rEL12:07	BP+4	225	1656	17.3	229	1221	14.5	88.8%	22.2	85.0	0.997	0.64	0.15
N36 rEL11:08	BP+2	262	981	11.5	217	801	11.3	79.9%	60.9	145.0	0.983	0.54	0.38
N37 rEL11:09	BP+1	505	933	5.3	282	703	7.9	74.2%	18.2	42.0	0.997	0.18	0.11
N38 rEL11:07	BP+3	91	191	6.5	53	122	7.2	73.2%	105.9	10.9	0.973	0.17	0.15
N39 rEL12:10	BP+1	217	641	9.4	146	694	13.6	75.4%	75.3	71.0	0.996	0.64	0.44
N41 rEL12:10	BP+1	360	852	7.5	246	649	8.4	78.1%	85.5	65.0	0.976	0.36	0.28
C05 rEL02m	mono	102	341	10.5	51	273	14.6	82.3%	50.2	25.0	0.980	0.42	0.25
C05 rEL08m	mono	104	400	11.7	52	330	16.1	87.0%	60.2	42.0	0.986	0.44	0.30
C05 rEL14m	mono	72	314	12.8	42	250	15.6	83.6%	67.7	30.3	0.951	0.45	0.31
C12 rEL02m	mono	242	663	8.8	118	694	15.4	85.0%	33.8	70.0	0.985	0.72	0.34
C12 rEL08m	mono	199	572	9.2	106	574	14.7	85.5%	44.8	71.0	0.962	0.67	0.39
C12 rEL14m	mono	232	646	8.9	110	711	16.2	82.8%	37.7	73.5	0.995	0.72	0.36
C14 rEL02m	mono	75	120	4.1	51	98	5.7	78.8%	99.4	4.3	0.877	0.35	0.27
C14 rEL08m	mono	82	205	8.0	55	178	10.2	79.2%	68.1	26.0	0.983	0.49	0.37
C14 rEL14m	mono	83	153	5.3	43	110	8.1	78.4%	48.4	5.0	0.924	0.30	0.17
C13 rEL08m	mono	131	348	8.5	69	351	14.1	87.0%	76.8	41.5	0.991	0.67	0.48
C15 rEL08m	mono	69	116	4.5	32	61	5.8	71.2%	48.2	2.0	0.885	0.21	0.12
C16 rEL07m	mono	147	632	12.7	149	495	10.5	78.2%	53.0	48.0	0.998	0.49	0.28

4. Comparisons across electrode types

An examination of recovery curves from subjects with different types of implanted electrodes did not reveal any systematic differences in recovery characteristics. Earlier (Fig. 3), recovery curves were shown for subjects with each of the three types of Clarion electrodes. The recovery curve parameters fit to these curves fall within the range shown earlier for Nucleus subjects. The only obvious difference is that dynamic ranges (in μA) are smaller for subject C14 [panel (B)] than for the other subjects. C14 has a HiFocus electrode and a positioner (HFP), which presumably resides closer to the modiolar wall than the Spiral electrode (1.2E) or the HiFocus electrode without the positioner (HF). Recovery curve parameters for the two Clarion subjects with HFP electrodes, C14 and C15 (see Table III) were not different from those of other subjects, even though their THS and MAL values were noticeably smaller. Because Clarion subjects were stimulated in monopolar mode and Nucleus subjects were stimulated in bipolar mode, our findings suggest that electrode coupling (bipolar versus monopolar) has no major effect on PTFM recovery.

C. Correlations with speech recognition scores

Table IV shows correlation coefficients between word and phoneme recognition scores and PTFM time constants or threshold shifts at 10- and 50-ms time delays. All of the coefficients for tau vs speech scores are negative, indicating that higher speech scores are associated with smaller time constants. However, the coefficients are all small in magnitude, ranging from -0.13 to -0.38; none account for more than 14% of the variance. The coefficients for threshold shift

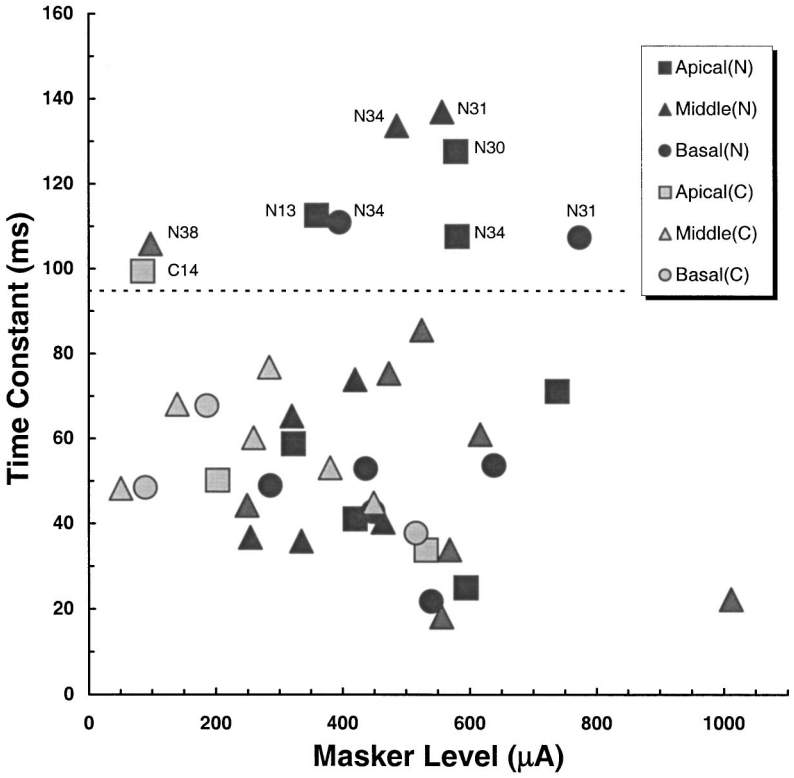

FIG. 7. Time constants for the recovery process at the highest masker level (>70% DRdB) on apical (squares), middle (triangles), and basal (circles) electrodes, plotted as a function of masker level. The dashed line indicates the 99% confidence limit. Time constants above this line are identified by their subject codes.

at 10 or 50 ms vs speech scores are even smaller. These results indicate that measures of PTFM are unable to explain the variance observed in speech recognition scores.

Figure 8 shows scattergrams of some the relationships summarized in Table IV. The relationships between recovery time constants and speech scores are shown in Figs. 8(A), (B), and (C). Subjects with time constants in the "normal" range (<100 ms) exhibit speech scores ranging from poor to excellent. Among these subjects, two subjects with very short time constants (N35 and N37) exhibit very poor speech scores, similar to a subject (N3) identified by Chatterjee (1999). On the other hand, the three subjects with prolonged time constants on a middle electrode (N31, N34, and N38) all exhibit poor speech scores. These results suggest that normal recovery from PTFM is a necessary but not sufficient requirement for good speech recognition. That is, prolonged PTFM recovery in itself may eliminate the possibility of good speech recognition, but other factors such as poor spatial resolution must be responsible for the low speech scores observed in some subjects with normal PTFM recovery rates.

Figure 8(D) shows threshold shift at a time delay of 50 ms plotted against percent transmitted information for the consonant envelope feature (Van Tasell *et al.*, 1992). Threshold shift is expressed as a percentage of the dynamic range (μA) of the probe pulse train. If extended forward masking were preventing the detection of a consonant following an intense vowel, this correlation would be expected to be strongly negative. As indicated in Fig. 8(D), there is no relationship between the two variables. Table IV shows that small correlation coefficients are obtained for threshold shifts at 10 ms as well.

TABLE IV. Correlations between pulse-train time constants (tau), threshold shift (TS in μA) at 10-ms or 50-ms time delays (all from a middle electrode), and various speech recognition scores (15 Nucleus and 6 Clarion subjects).

		Pulse train tau	TS (10 ms)	TS (50 ms)
/aCa/ consonants				
	Stimulus (RTI)	−0.29	−0.07	−0.07
	Envelope (RTI)	−0.23	−0.07	−0.11
	Place (RTI)	−0.30	−0.08	−0.07
NU-6 words				
	Phonemes (%C)	−0.38	0.04	0.01
	Words (%C)	−0.32	−0.02	−0.09
Hillenbrand vowels				
	Stimulus (RTI)	−0.23	0.00	0.00
	*F*1 Frequency (RTI)	−0.22	−0.08	−0.05
	*F*2 Frequency (RTI)	−0.31	0.08	0.00
	Duration (RTI)	−0.13	−0.06	−0.05

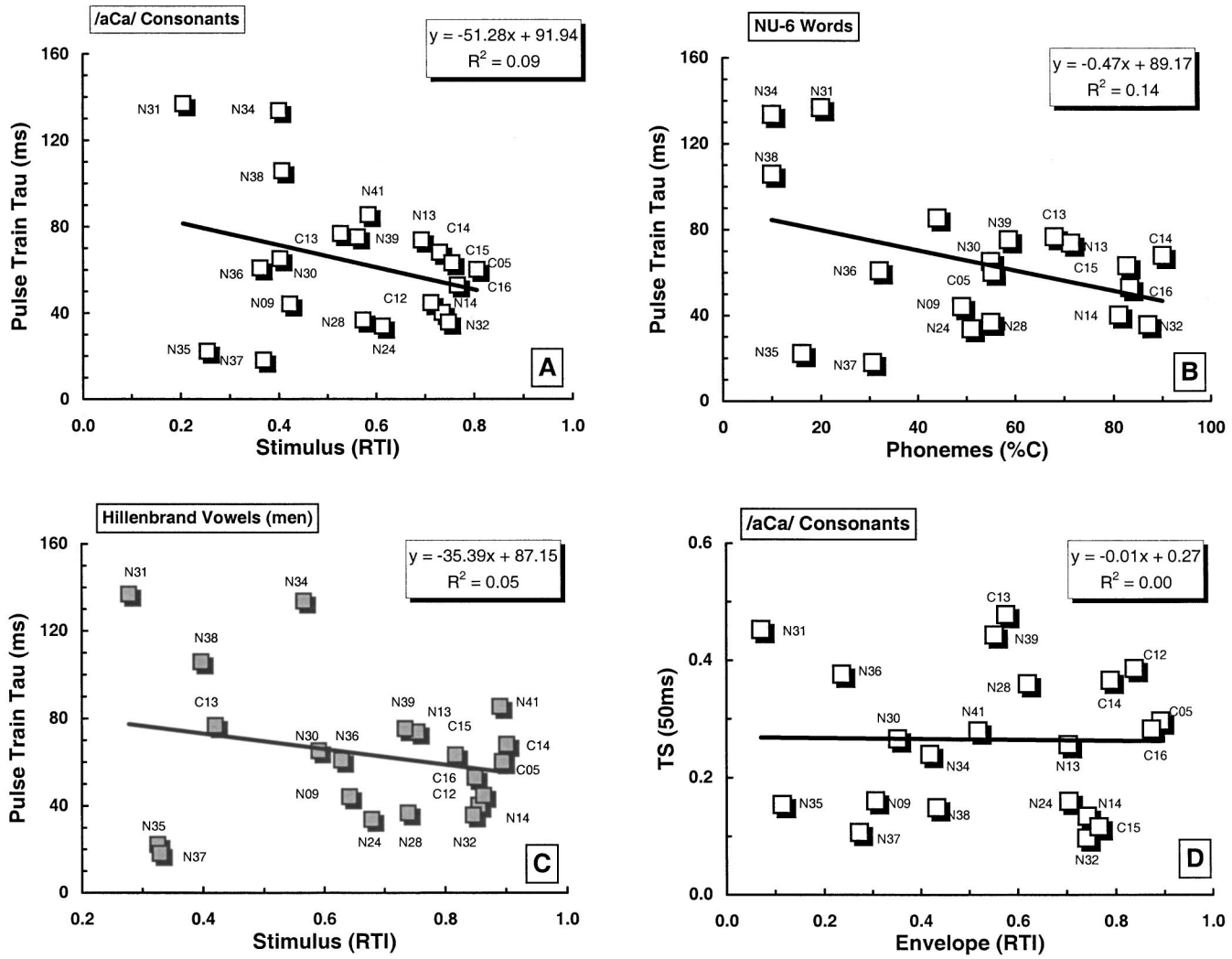

FIG. 8. Scattergrams of time constants (tau), or threshold shifts (TS in %DRuA) at a time delay of 50 ms, and different speech recognition scores. Time constants and threshold shifts are for pulse-train forward masking recovery functions obtained from a middle electrode with a masker level above 70% DRdB. Speech scores are given as percent correct (%C) phoneme scores or relative transmitted information (RTI).

IV. DISCUSSION

A. Exponential recovery process

An important finding of this study is that recovery from psychophysical pulse-train forward masking can be accurately described by a recovery process in which the amount of threshold shift produced by a masker pulse train recovers exponentially in time. The recovery process requires only a single time constant to account for PTFM data obtained over a wide range of masker amplitudes. In this study, the average recovery time constant for 18 subjects with apparently normal PTFM recovery was 54 ms, with a standard deviation of 17 ms. This means that approximately 99% of subjects in a similar cochlear implant population would be expected to demonstrate forward-masking time constants shorter than 95 ms.

Previous measures of pulse-train forward masking in electric hearing have found that recovery occurs over the same period of time as seen in the current study (Shannon, 1990a, 1990b; Chatterjee and Shannon, 1998; Chatterjee, 1999). Shannon specified recovery with a slightly different model (dB of threshold shift versus log delay time), which is another model used to describe recovery in acoustic hearing (Plomp, 1964; Jesteadt *et al.*, 1982). Nelson and Freyman (1987) showed that both models describe the recovery process in acoustic hearing equally well. We have evaluated some of Shannon's (1990a) data using the same exponential coordinates as in the present study, and using offset-to-offset rather than offset-to-onset time delays. Shannon's recovery curves do not differ qualitatively from those seen here, and the time constants are within the range of time constants seen here. Similarly, Chatterjee's (1999) published recovery curves, evaluated using offset-to-offset time delays, reveal time constants within the range of those seen here, except for one subject (N3) with a time constant of 11 ms (using our coordinates). For this subject, the recovery curves were well fit with two recovery processes, the faster one with an 11-ms time constant and the longer one with a 79-ms time constant.

A recent study of single-pulse forward masking (SPFM) from our laboratory (Nelson and Donaldson, 2001) used the same exponential recovery process to describe SPFM recovery curves, except that two time constants were evident, one a fast-recovery time constant under 10 ms and the other a

long time constant in the same range as those seen here for PTFM. Because the fast time constants were in the same range as those obtained from electrophysiologic measures of recovery in the whole-nerve action potential (Brown *et al.*, 1990; Brown *et al.*, 1996), it is likely that the fast SPFM time constant reflects refractory characteristics at the level of the auditory nerve and that the long time constant reflects recovery characteristics of more central processes. For SPFM, the fast-recovery time constant was also level independent and GOM slopes were determined by the fast time constant. In both of these studies, forward masking was specified as a threshold shift measured in terms of microamperes of current, i.e., recovery was described by an exponential decline in the difference between masked threshold and absolute threshold over time.

The traditional approach in acoustic hearing specifies forward masking as a threshold shift measured as a ratio of masked threshold to absolute threshold, i.e., recovery was described by an exponential decline in the ratio between masked threshold and absolute threshold over time, expressed in decibels (Duifhuis, 1973; Nelson and Freyman, 1987; Nelson and Pavlov, 1989). Almost all of the forward-masking recovery functions reported in studies of acoustic hearing have time constants shorter than 95 ms, except those obtained from hearing-impaired ears (Nelson and Freyman, 1987). Earlier studies in hearing-impaired subjects did not account for the fact that cochlear nonlinearities are present in normal-hearing ears and absent in hearing-impaired ears. Recent evidence indicates that forward-masking recovery time constants from normal-hearing and hearing-impaired ears are similar if non-linearities in normal-hearing ears are taken into account (Nelson and Schroder, 2001). Thus, recovery from forward masking is similar for normal and impaired acoustic hearing, and as we see here, it is also similar for acoustic and electric hearing.

In the acoustic case, stimulus amplitude must be transformed compressively by a decibel-like conversion process (a compressive nonlinearity within the cochlea), and then the compressed amplitude produces a neural effect that recovers exponentially with time. In the electric case, stimulus amplitude produces a direct neural effect (without any compression) that then recovers exponentially with time. It appears that the neural responses produced by either acoustic or electric stimulation are subjected to the same post-stimulatory recovery processes. This suggests that neural recovery is mediated by adaptation or persistence processes that occur at, or central to, the eighth nerve.

These observations suggest that linear units of electrical stimulation are comparable to logarithmic units of acoustic stimulation. In fact, loudness matches obtained in listeners with acoustic hearing in one ear and electric hearing in the opposite ear indicate that linear changes in μAmps of current are proportional to decibels of acoustic sound pressure (Eddington *et al.*, 1978; Zeng and Shannon, 1992). Thus, the use of linear μAmps of current as the input to a neural adaptation or persistence mechanism in electric hearing is consistent with the use of decibels as the input to the same mechanism in acoustic hearing.

In summary, both the form of the recovery curve described by Eq. (3) and the range of time constants obtained across subjects and electrodes in the present study, are consistent with data from previous psychophysical studies of forward masking in both acoustic hearing and electric hearing. These results support the notion that PTFM in electric hearing and pure-tone forward masking in acoustic hearing are mediated by the same physiological mechanisms.

B. Relationship to speech recognition

Our findings suggest that ''normal'' recovery from PTFM (i.e., tau $<$95 ms) does not, by itself, predict good speech recognition through a cochlear implant. Among our 21 subjects, the 18 with normal time constants on a middle electrode varied widely in their speech recognition abilities. Two of these subjects had very fast PTFM recovery yet exhibited poor speech recognition. This outcome was also seen in one subject (N3) tested by Chatterjee and Shannon (1998). In our data set, prolonged recovery from PTFM ($>$95 ms) on both middle and basal electrodes predicted poor speech recognition but prolonged recovery on only an apical electrode did not. This suggests that adequate PTFM recovery may be more important in middle and basal regions of the cochlea where consonant envelope cues are transmitted and less important in apical regions that primarily code vowel formant information. These finding suggest a model wherein PTFM recovery is only one of several psychophysical ''requirements'' for good speech recognition. It seems certain that another requirement would be adequate spatial resolution, since it has been repeatedly shown that some degree of spectral resolution is critical for speech recognition through a cochlear implant (Nelson *et al.*, 1995; Hanekom and Shannon, 1996; Collins *et al.*, 1997; Donaldson and Nelson, 2000; Henry *et al.*, 2000).

Shannon (1990a) measured PTFM recovery rates similar to the ''normal'' recovery rates shown here (i.e., $<$95 ms) in a group of cochlear implant subjects with disparate speech recognition scores. He concluded that recovery from forward masking was unrelated to speech perception. Whereas this appears to be true for the majority of implant users with PTFM time constants $<$95 ms, Shannon may not have sampled the small proportion of implant users with prolonged forward masking. This group included 3 of 21 subjects tested in our study, suggesting that a small proportion of the implant population may fall into this category.

It is possible that the small segment of cochlear implant listeners with prolonged PTFM time constants have widespread deficiencies in auditory processing rather than a specific deficit in forward-masking recovery. This might be expected if prolonged PTFM recovery is a reflection of widespread or severe auditory degeneration. If so, then subjects with prolonged PTFM time constants may also have poor spatial resolution, further limiting their potential for speech recognition.

V. CONCLUSIONS

Recovery from psychophysical pulse-train forward masking can be described by an exponential recovery pro-

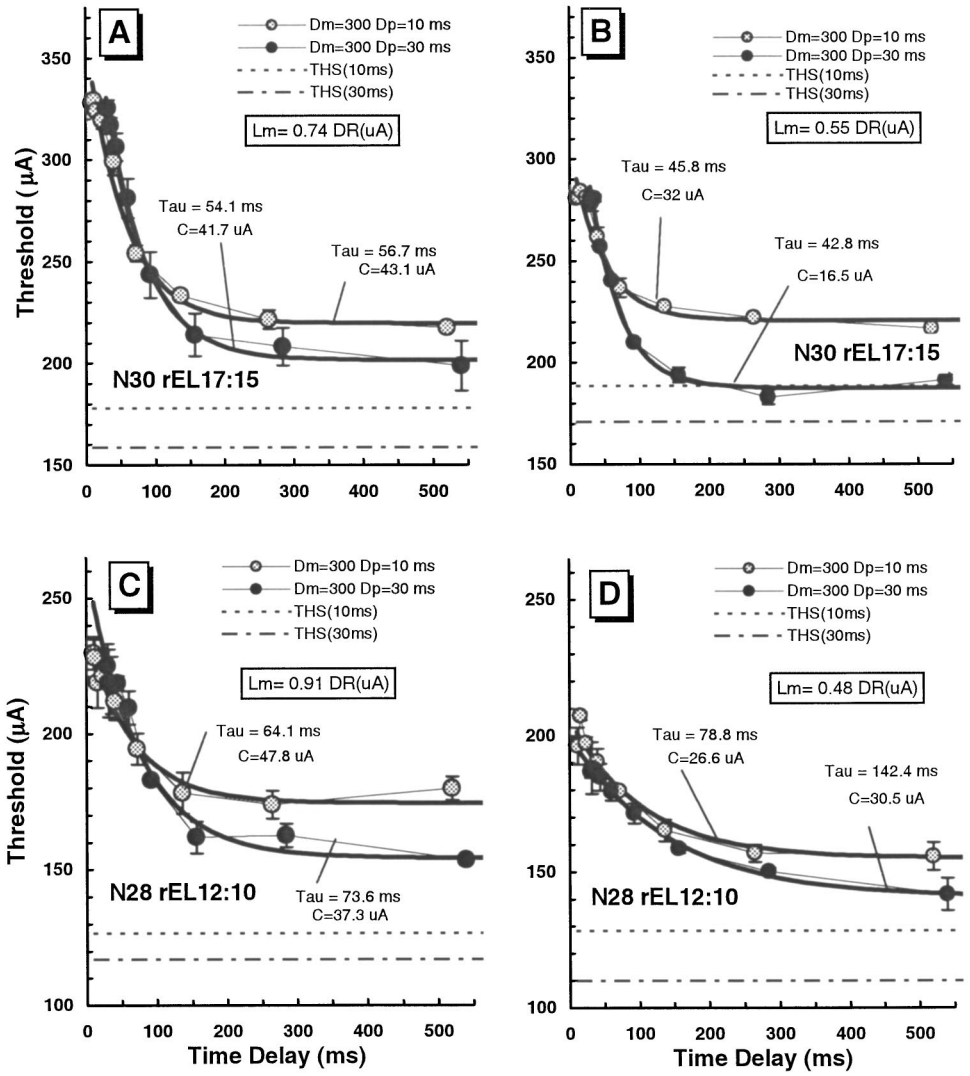

FIG. 9. Pulse-train forward masking functions from two subjects for probe durations of 10 and 30 ms, at two masker levels throughout the masker dynamic range (DR). Threshold of the probe (μA) is plotted against the time delay in ms between masker and probe offsets (note the linear scale on the *x* axis).

cess in which the amount of threshold shift (in μA) for a pulse-train signal recovers exponentially in time. Time constants for 18 subjects with ''normal'' PTFM recovery averaged 54 ms with a standard deviation of 17 ms. Time constants are independent of masker level and do not vary systematically with electrode location.

Response to the masker grows monotonically with masker level (in μA). Growth rates at longer time delays are less than 1.0, and are determined by the level-independent time constant. This behavior is consistent with an exponential recovery process.

The addition of a constant residual threshold shift improves the exponential fit to most PTFM recovery curves, consistent with the existence of cumulative fatigue during the experiment or a distraction component.

The PTFM recovery process is similar to that seen with acoustic stimulation. The same recovery model describes acoustic stimulation, the range of time constants is similar for acoustic stimulation, and similar residual constants are needed to obtain good fits for acoustic stimulation. Essentially, recovery of threshold shift (in microamps) in electric hearing is equivalent to recovery of threshold shift (in decibels) in acoustic hearing. The primary difference is in the input of the recovery model; acoustic stimulation requires an additional compressive transform before the recovery process. These findings are consistent with the idea that linear microamps of electrical stimulation to the auditory nerve are equivalent to acoustic decibels, as suggested by loudness balancing experiments that show a log-linear relationship between acoustic and electrical stimuli.

PTFM recovery parameters obtained from Clarion users were not significantly different than those obtained from Nucleus users, even though maximum acceptable loudness levels and dynamic ranges were significantly smaller in those Clarion users with a HiFocus electrode and electrode positioning system.

Small negative correlations between PTFM time constants and speech recognition scores did not approach statistical significance. Long time constants were associated with poor speech scores; however, short time constants were not strictly associated with good speech scores. Instead, subjects with short time constants demonstrated a wide range of speech recognition performance. This suggests that normal PTFM recovery is only one of several psychophysical abilities needed for good speech recognition in cochlear implant subjects. Adequate spatial resolution is almost certainly another critical factor.

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APPENDIX: PTFM RECOVERY FOR 10- AND 30-ms PROBE DURATIONS

If recovery from PTFM is governed by neural adaptation or persistence that recovers or decays gradually following masker offset, then the earlier pulses in the probe must be subjected to more adaptation or persistence than the later pulses. Assuming that detection involves integration of probe excitation over time (temporal integration), then it follows that responses to earlier pulses would contribute less to probe detection than responses to later pulses. This reasoning suggests that when large amounts of adaptation or persistence exist, and recovery or decay is occurring rapidly, the end of the probe pulse train determines detection threshold. If so, then it is most appropriate to specify the time delay between masker and probe pulse trains as the time between masker and probe offsets (rather than the time between masker offset and probe onset).

To examine this issue more closely, PTFM recovery functions were obtained from two subjects (N30 and N28) for two different probe durations. In one case the probe duration was 10 ms, consisting of five biphasic pulses separated by 2 ms (as in the main experiment, above). In the other case the probe duration was 30 ms, consisting of 15 biphasic pulses separated by 2 ms. All other conditions were the same as those described above for the main experiment. The data were actually collected using the same offset-to-onset delays between masker and probe for the 10- and 30-ms conditions, but the recovery curves were displayed and fitted using the corresponding offset-to-offset time delays. Use of the 10-ms probe allowed examination of shorter (offset-to-offset) time delays than was possible with the 30-ms probe.

The PTFM recovery curves obtained at two masker levels and two probe durations are shown in Fig. 9. For both subjects, masked thresholds at time delays shorter than about 100 ms were the same for the 10- and 30-ms probe durations. This means that the extra 10 pulses in the 30-ms probe did not contribute to detection, i.e., little or no temporal integration was observed during the steep recovery portion of the recovery function. In contrast, masked thresholds at time delays longer than 100 ms were considerably lower for the 30-ms probe duration than the 10-ms probe duration. The same was true for quiet thresholds for the probe pulse trains (dashed lines in Fig. 9). At these longer time delays, recovery from adaptation was very gradual, such that responses to early and late portions of the probe were similar. Responses to the additional 10 pulses in the 30-ms probe contributed significantly to detection, therby reducing the probe level at masked (or quiet) threshold.

These results strongly support the specification of PTFM time delay as the time between masker offset and probe offset, since the later pulses in the probe determine detection at time delays less than 100 ms. However, these findings do not resolve the question of whether PTFM is due to adaptation that recovers over time or to neural persistence that decays over time (Oxenham, 2001). In either case, earlier pulses would contribute less to detection than later pulses, due to reduced sensitivity or due to greater persistence at the beginning of the probe train.

[1]Facial nerve stimulation restricted electrode selection in two subjects (N31 and N30). For these subjects, test electrodes were distributed across the range of stimulable electrodes.

[2]Only male talkers were used for vowel testing because female talkers exhibit wide, sometimes overlapping, ranges of formant frequencies for a given vowel. This prevents categorization of formant frequencies for purposes of information transmission analyses.

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