Psychometric functions and temporal integration in electric hearing

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Temporal-integration functions and psychometric functions for detection were obtained in eight users of the Nucleus 22-electrode cochlear implant. Stimuli were 100-Hz, 200-μs/phase trains of biphasic pulses with durations ranging from 0.44 to 630.44 ms (1 to 64 pulses). Temporal-integration functions were measured for 21 electrodes. Slopes of these functions were considerably shallower than the 2.5 dB/doubling slopes typically observed in acoustic hearing. They varied widely across subjects and for different electrodes in a given subject, ranging from 0.06 to 1.94 dB/doubling of stimulus pulses, with a mean [standard deviation (s.d.)] value of 0.42 (0.38). Psychometric functions were measured for 11 of the same 21 electrodes. Slopes of psychometric functions also varied across subjects and electrodes, and were 2–20 times steeper than those reported by other investigators for normal-hearing and cochlear-impaired acoustic listeners. Slopes of individual psychometric functions for 1-, 2-, 4-, and 8-pulse stimuli ranged from 0.20 to 1.84 log d'/dB with a mean (s.d.) value of 0.77 (0.45). Psychometric-function slopes did not vary systematically with stimulus duration in most cases. A clear inverse relation between slopes of psychometric functions and slopes of temporal-integration functions was observed. This relation was reasonably well described by a hyperbolic function predicted by the multiple-looks model of temporal integration [Viemeister and Wakefield, J. Acoust. Soc. Am. **90**, 858–865 (1991)]. Psychometric-function slopes tended to increase with absolute threshold and were inversely correlated with dynamic range, suggesting that observed differences in psychometric-function slopes across subjects and electrodes may reflect underlying differences in neural survival. [S0001-4966(97)03506-6]

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INTRODUCTION

An important phenomenon observed in hearing and other sensory systems is that detection thresholds for brief stimuli improve with increasing stimulus duration. This phenomenon, termed temporal integration, has been described in audition for both normal-hearing and hearing-impaired listeners, for a variety of tonal and broadband stimuli [see Gerken *et al.* (1990), for a review]. Normal-hearing listeners demonstrate approximately 2.5 dB threshold improvement per doubling of stimulus duration for durations up to 200–300 ms. Temporal integration is reduced in the presence of cochlear hearing loss, with slopes shallower than 1 dB/doubling often observed (e.g., Gengel and Watson, 1971; Florentine *et al.*, 1988).

Classic models of temporal integration assume ''leaky'' (Plomp and Bouman, 1959; Zwislocki, 1960, 1969; Jeffress, 1967, 1968) or perfect (Green, 1960; Green and Swets, 1966) integration of stimulus energy with a time constant on the order of several hundred milliseconds. These models can account satisfactorily for the shapes of temporal-integration functions, but their long time constants grossly exceed the integration time constants necessary to explain temporal-resolution phenomena such as modulation detection and gap detection. Other models, that utilize shorter time constants (<10 ms), are able to account for various temporal-resolution data (Viemeister, 1979; Forrest and Green, 1987; Moore *et al.*, 1988); however, their predictions of temporal-integration functions at threshold are unrealistic. Thus, the assumption of a single time constant for integration of stimulus energy, whether short or long, appears unable to explain both temporal-integration and temporal-resolution phenomena. This dichotomy has been termed the ''integration-resolution paradox'' (Green, 1985; de Boer, 1975).

A solution to this paradox was proposed by Viemeister and Wakefield (1991), who reported data from two experiments suggesting that long time-constant integration does not underlie temporal integration but, instead, that multiple, short ''looks'' at the processed signal are combined to improve detection performance. An overview of the *multiple-looks* model is as follows: Signals within a single channel (e.g., critical-band filter) undergo a nonlinear transformation such as half-wave rectification, followed by leaky integration within a temporal window having a short time constant (~ 3 ms). The ongoing output of the short temporal window is stored in short-term memory. Multiple samples of the processed signal are available in short-term memory for use by the observer in making a decision related to signal detection or discrimination. In its simplest implementation, considered here, the samples or ''looks'' are assumed to be independent, optimally combined, and equally detectable. Performance (d') at a given stimulus intensity improves with n, the number of looks, according to the relation: $d'_n = \sqrt{n} d'_1$. In the

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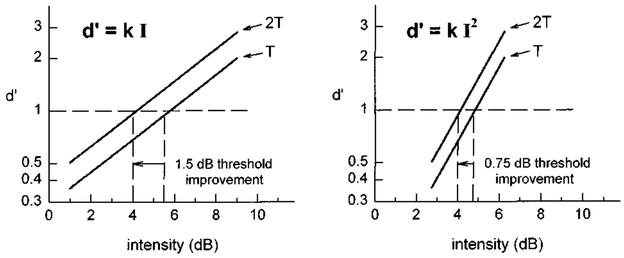

FIG. 1. Illustration of the relationship between psychometric function slope and predicted threshold improvement. In each panel, lower and upper solid lines represent psychometric functions for stimuli with durations of T and $2T$, respectively. Functions shown in the left panel are shallower (slopes of 1.0 log d'/dB) than those in the right panel (slopes of 2.0 log d'/dB). According to the simple version of the multiple-looks model, a doubling of stimulus duration improves performance (d') by $\sqrt{2}$ at all stimulus levels, resulting in an upward shift of the psychometric function. For a particular threshold criterion (e.g., $d'=1$, shown by the dashed horizontal line), improved performance corresponds to a decrease in threshold; however, the magnitude of threshold improvement is inversely proportional to the slope of the psychometric function. In this example, doubling stimulus duration results in 1.5-dB threshold improvement in the case of the shallower psychometric function (left panel), but only 0.75-dB threshold improvement in the case of the steeper function (right panel).

case of temporal integration, an increase in stimulus duration corresponds to an increase in the number of available looks; this results in improved performance at a given stimulus intensity or, for fixed performance, a reduction in ''threshold.''

An important prediction of the multiple-looks model of temporal integration is that the amount of threshold improvement associated with an increase in the number of looks depends on the slope of the psychometric function for a single look. As demonstrated in Fig. 1, steep psychometric functions will result in less threshold improvement than shallow psychometric functions, because the intensity difference corresponding to a constant ($\sqrt{n}$) improvement in performance (d') will be smaller in the case of a steeper function.[1] As noted by Viemeister and Wakefield (1991), this aspect of the theory is consistent, at least qualitatively, with the reduced temporal integration observed in cochlear hearing loss and with the dependence of temporal-integration slopes on stimulus frequency in normal-hearing listeners. However, direct evaluation of the dependence of temporal-integration slope on the slope of the psychometric function for a single look has proven to be difficult because the range of temporal-integration slopes observed in acoustic listeners is small and because the resolution with which psychometric-function slopes can be estimated is limited by normal sources of variability.

Existing reports of temporal integration in electric hearing indicate that slopes of temporal-integration functions vary considerably across subjects and for different stimulus conditions (Eddington *et al.*, 1978; Shannon, 1983, 1986, 1990; White, 1984; Pfingst *et al.*, 1991; Moon *et al.*, 1993; Pfingst and Morris, 1993). Given this, and assuming that the multiple-looks model is correct, then psychometric-function slopes for electric stimulation should also vary. Pfingst *et al.* (1991) considered the relation between psychometric-function slopes and temporal-integration slopes for behavioral data from implanted monkeys; however, their analyses appear to have been limited to qualitative observations, and these did not reveal any clear relation between the two measures. To our knowledge, psychometric functions have not been described in human listeners with cochlear implants.

The present study was undertaken with two goals in mind: One goal was to provide detailed descriptions of psychometric functions for detection and corresponding temporal-integration functions in a group of adult cochlear-implant users. The second goal was to determine whether psychometric-function slopes are predictive of temporal-integration function slopes in electric hearing, as suggested by the multiple-looks hypothesis.

I. METHODS

A. Subjects

Eight adult users of the Nucleus 22-electrode cochlear implant served as subjects. Onset of deafness was postlingual in seven subjects and prelingual in the remaining subject (AMA). Table I lists each subject's primary cause of deafness, years of deafness prior to implant surgery, age at implantation, depth of electrode-array insertion, and years of implant use at the time of data collection. As indicated, five of eight subjects were long-term users of the implant (5–7 years) at the time of testing. The other three (AMB, CXL, and SLB) had one year or less experience with their devices, but obtained considerable benefit from them in everyday use.

Experiments involved the presentation of electric stimuli on bipolar electrode pairs. Temporal-integration functions were obtained for 21 electrodes (1–3 electrodes in each subject); psychometric functions for detection were obtained for

TABLE I. Description of eight cochlear-implant subjects who participated in the present study. Subject identifying code, primary cause of deafness, years of deafness (implanted ear) prior to implantation, age at implantation, depth of electrode-array insertion (mm from the round window, with 25 mm representing complete insertion), and years of implant use at the time of the present testing are listed for each subject.

Subject	Cause of deafness	Years deaf	Age	Depth	Years use
AMA	Congenital	57	57	19.4	6
AMB	Progressive SNHL	1	49	25.0	1
CXL	Aminoglycocide toxicity	1.5	32	24.0	0.5
EES	Cogan's syndrome	4	54	17.0	7
FXC	Progressive SNHL	4	64	25.0	5
JPB	Progressive SNHL	4	52	24.0	5
SLB	Progressive SNHL	10	47	25.0	1
VVK	Sudden, After ear surgery	38	55	17.0	7

TABLE II. Detection threshold (THS), maximum acceptable loudness level (MAL) and dynamic range (DR) for each of 21 test electrodes in eight cochlear-implant subjects. Stimuli were 500-ms trains of 125-Hz, 205-μs/phase, biphasic pulses. Data represent means of values obtained at one or more timepoints within six months of data collection for the present study.

Subject	Electrode	THS (dB *re:* 1 μA)	MAL (dB *re:* 1 μA)	DR (dB)
AMA	rEL04	57.3	61.4	4.1
	rEL19	53.5	56.7	3.2
AMB	rEL06	48.1	56.0	8.0
	rEL12	47.1	56.6	9.5
	rEL20	47.6	57.6	10.0
CXL	rEL05	48.8	64.8[a]	>16.0
	rEL11	45.8	64.8[a]	>18.0
	rEL18	44.4	64.8[a]	>20.4
EES	rEL05	49.2	52.6	3.6
	rEL11	49.6	53.8	3.9
	rEL18	48.6	52.7	4.0
FXC	rEL05	49.3	55.2	6.0
	rEL11	50.9	57.7	6.7
	rEL18	52.3	55.9	3.6
JPB	rEL07	51.7	57.8	6.1
	rEL11	51.0	57.8	6.9
	rEL16	53.1	60.5	7.4
SLB	rEL21	53.6	57.6	4.1
VVK	rEL06	48.7	53.2	4.5
	rEL10	47.4	50.9	3.5
	rEL15	49.1	50.7	1.6

[a]MAL not reached at current–amplitude limits of receiver–stimulator.

11 of these electrodes. The spatial separation between active and reference electrodes was set to agree with that used in subjects' speech-processor maps. This separation was 1.5 mm (7 subjects) or 0.75 mm (subject AMA). In this paper, research electrode (rEL) numbering is used, i.e., electrodes are numbered consecutively from the apical to basal end of the 22-electrode array, and electrode number refers to the basal member of the stimulating pair.

Electrodes were chosen to represent a range of absolute thresholds and dynamic ranges, and different regions of subjects' implanted arrays. Specifically, subjects were tested whose average dynamic ranges varied from narrow (<4 dB) to relatively wide (>8 dB) and, to the extent possible, test electrodes in a given subject were chosen to represent differing thresholds and dynamic ranges. Table II lists detection threshold (THS), maximum acceptable loudness level (MAL), and dynamic range (DR) for each electrode. These measures were obtained in response to a standard stimulus (500-ms train of 125-Hz, 205-μs/phase biphasic pulses) using an ascending method of adjustment. In the adjustment procedure, pulse trains are repeated continuously at a rate of 1/s and the experimenter slowly increases stimulus current amplitude until the subject indicates that the sound is just audible. This level is recorded and then remeasured in another ascending run. The mean of two or three such estimates is taken to be threshold. An estimate of MAL is subsequently obtained by increasing stimulus level above the threshold estimate until the subject indicates that stimulus loudness has reached a level that can only be tolerated for a short time. THS and MAL estimates for this standard stimulus are obtained periodically in our laboratory as part of a baseline characterization of subjects' electric hearing and to monitor for obvious changes in hearing sensitivity over time. Values in Table II represent mean data for each subject from one or more test dates over a time period within ± 6 months of data collection for the present experiments. They are presented here to provide the reader with an overview of the sensitivity and dynamic range characteristics of electrodes tested. Additional measures of THS and MAL were obtained as part of the present experiments, and are described below.

B. Stimuli

Stimuli for the present experiments were pulse trains comprised of 1, 2, 4, 8, 16, 32, or 64 biphasic pulses presented at a rate of 100 pulses/s. Individual pulses had a fixed pulse duration of 200 μs/phase, with a 44-μs interphase gap; thus, interpulse interval for the multiple-pulse stimuli was 9.56 ms, and train durations for the 1- to 64-pulse stimuli ranged from 0.44 to 630.44 ms. Current amplitude (pulse height) was always the parameter varied.

Experiments were controlled by a 50-MHz 80486 computer connected through a parallel port to a BTNI cochlear-implant interface (Shannon *et al.*, 1990). Stimulus amplitudes called for in the adaptive and fixed-level procedures (described below) were translated to the nearest current value that could be delivered by a particular subject's receiver–stimulator. These values corresponded to integer *current step units* (CSUs),[2] and were determined using calibration tables provided by Cochlear Corporation for each subject's implanted device. Stimuli were verified using a calibrated, Nucleus 22-electrode receiver–stimulator whose outputs could be monitored directly (*Implant-in-a-Box*, Cochlear Corporation).

C. Psychophysical procedures

Psychophysical procedures were selected that would permit collection of an entire temporal-integration function or psychometric function for detection in a single testing session. This was necessary to ensure that small shifts in subjects' hearing sensitivity across sessions did not invalidate estimates of temporal-integration slope or psychometric-function slope. Threshold data used to construct temporal-integration functions were obtained using an adaptive procedure; psychometric functions were obtained with a fixed-level procedure. Details of these procedures are given below.

Temporal-integration functions. Temporal-integration functions were constructed from threshold data for each of the seven stimuli. For each stimulus, preliminary estimates of threshold and maximum acceptable loudness were obtained using the ascending method of adjustment procedure described earlier (Sec. I A). These values were used to set the starting level and maximum-safe-stimulation level, respectively, for a 3IFC adaptive procedure that provided final threshold estimates comprising temporal-integration functions. In the adaptive procedure, three listening intervals were cued visually on a video monitor and the stimulus was presented in one of the intervals, chosen at random on each trial. The subject's task was to identify the interval containing the stimulus and to press the corresponding button on a three-button computer mouse. Correct-answer feedback was provided after each trial.

Stimulus level was set 1–3 dB above the preliminary (adjustment) threshold estimate at the start of each adaptive track. The first four reversals were obtained using a step size of either 2 or 4 CSUs (approximately 0.3 or 0.6 dB) and a two-down, one-up stepping rule. These initial trials were intended to quickly move the adaptive track to a level near detection threshold. Following the fourth reversal, step size was halved and a three-down, one-up stepping rule was assumed. This rule estimates the stimulus level necessary to obtain 79.4% correct responses (Levitt, 1971). Trials continued until eight additional reversals occurred. Threshold was taken to be the arithmetic mean of the current levels (dB *re:* 1 μA) at the final eight reversals.

Threshold estimates were obtained in ''sets,'' where a set consisted of one threshold estimate for each of the seven stimuli (1, 2, 4, 8, 16, 32, or 64 pulses), collected in order of increasing stimulus duration.[3] Three to four complete sets were obtained initially. Additional tracks were then obtained, if needed, to replace tracks in which reversals failed to converge or to provide additional threshold estimates if the first 3 to 4 estimates for a particular stimulus were unusually variable.[4] Temporal-integration functions were constructed from means of 3–5 threshold estimates for each stimulus. Data comprising a given function were typically obtained in a single 2-h session; however, it was occasionally necessary to combine data across two sessions. When this was the case, threshold data collected during a second session were evaluated for shifts in the subject's sensitivity. If such a shift was suspected, the original threshold estimates were discarded and another complete set of data was obtained.

Psychometric functions for detection. Psychometric functions for detection were obtained for the 1-, 2-, 4-, 8-, and 64-pulse stimuli, using a fixed-level, 2IFC procedure. In this procedure, two listening intervals were cued on a video monitor. The stimulus was presented in one of the intervals, chosen at random on each trial. Again, correct-answer feedback was provided after each trial.

Stimulus levels for a particular psychometric function were selected to span the range of near-chance to near-perfect performance in 5–10 steps. Levels could not be specified uniformly for all electrodes and stimuli (e.g., at fixed levels relative to the adaptive threshold), first, because the rate of performance increase with level varied across subjects and, second, because subjects' receiver–stimulators could deliver current levels only in discrete steps corresponding to integer CSUs. Instead, for a given psychometric function, the interval between adjacent stimulus levels was held constant at 1, 2, or 4 CSUs (approximately 0.15, 0.3, or 0.6 dB, respectively). Appropriate stimulus levels were initially estimated from the 3IFC threshold and were modified, if necessary, after an initial descending run was completed. Data were collected in blocks of 20 trials. The first data set consisted of one block of trials at each stimulus level, in descending order. Stimulus level order was alternated between ascending and descending in subsequent sets.[5] Four to six data sets (80–120 trials per point) were obtained in this manner, with all data for a particular psychometric function collected in a single, 2 to 3 h session.

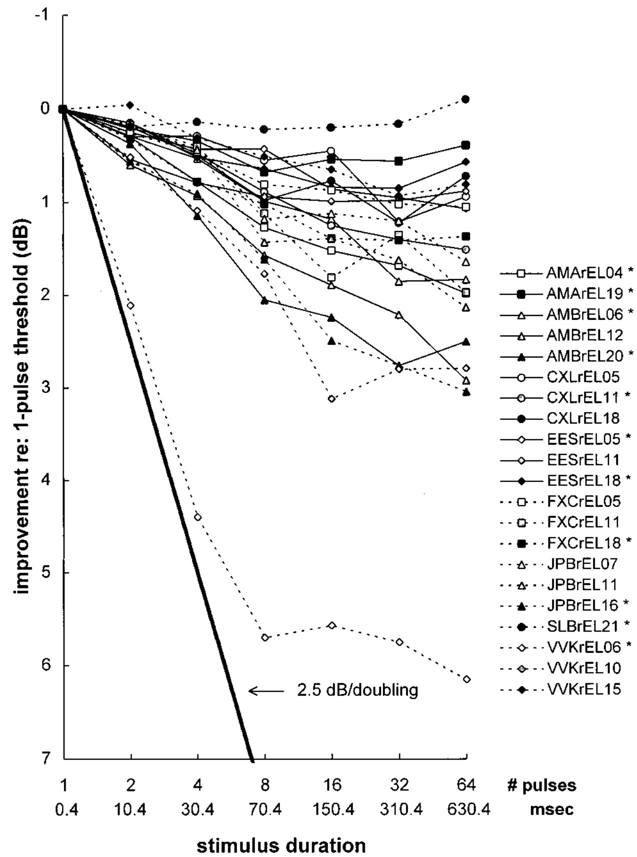

FIG. 2. Temporal-integration functions for 21 test electrodes in eight cochlear-implant subjects. All thresholds are expressed relative to the threshold for a single pulse in order to facilitate comparison of function shapes across electrodes. Different combinations of symbols and connecting lines represent different electrodes, as indicated in the legend; data from apical, middle, and basal electrodes are plotted as open, shaded, and filled symbols, respectively. Asterisks next to legend entries indicate electrodes for which psychometric functions were also obtained (see Fig. 6). The heavy, solid line represents the slope (2.5 dB/doubling of pulses) expected for normal-hearing listeners performing a similar, acoustic task.

Slope estimates for each psychometric function were obtained as follows: The mean percent-correct score and corresponding standard deviation were computed for the 4–6 blocks of trials obtained at each stimulus level, and the 90% confidence interval (CI) around each mean value was determined. Data points were included in psychometric-function fits if the lower limit of the CI was greater than 50% and the upper limit of the CI was less than 100%.[6] Mean percent-correct values were transformed to d' units, and a linear function was fit to the data in log d' versus dB coordinates by least-squares regression.

II. RESULTS AND DISCUSSION

A. Temporal-integration functions

Variability of temporal-integration slopes across subjects and electrodes. Temporal-integration functions for all 21 test electrodes are shown in Fig. 2. To facilitate comparison of function shapes across electrodes, thresholds for each

TABLE III. Slopes of short-duration segments of temporal-integration functions (1–8 pulses), estimated by linear regression of threshold (dB *re:* 1 μA) on stimulus duration (doublings of number pulses). Standard errors (se) of slope estimates and 90% confidence intervals (90% CI) are also given. Slopes are expressed as positive numbers (i.e., dB threshold improvement per doubling of number pulses). With one exception (SLB rEL12), significant r^2 values ($r^2 > 0.85$, $p < 0.01$) were associated with all slope estimates.

Subject	Electrode	Slope	se	90% CI
AMA	rEL04	0.43	0.032	0.36–0.52
	rEL19	0.22	0.029	0.13–0.30
AMB	rEL06	0.32	0.033	0.23–0.42
	rEL12	0.50	0.042	0.38–0.63
	rEL20	0.69	0.087	0.44–0.95
CXL	rEL05	0.16	0.042	0.04–0.29
	rEL11	0.30	0.042	0.18–0.42
	rEL18	0.33	0.046	0.19–0.46
EES	rEL05	0.15	0.040	0.03–0.27
	rEL11	0.31	0.063	0.12–0.49
	rEL18	0.23	0.033	0.13–0.33
FXC	rEL05	0.26	0.021	0.20–0.32
	rEL11	0.36	0.092	0.09–0.63
	rEL18	0.35	0.028	0.27–0.44
JPB	rEL07	0.38	0.095	0.10–0.66
	rEL11	0.46	0.137	0.06–0.86
	rEL16	0.52	0.045	0.39–0.65
SLB	rEL21	0.06	0.031	−0.03–0.15
VVK	rEL06	1.94	0.152	1.49–2.38
	rEL10	0.59	0.026	0.51–0.66
	rEL15	0.19	0.054	0.03–0.35

electrode are expressed relative to the threshold for a single pulse presented to the same electrode. The heavy, solid line in Fig. 2 has a slope of 2.5 dB/doubling; this corresponds to the slope of a temporal-integration function expected from a normal-hearing listener performing a similar, acoustic task (Gerken *et al.*, 1990; Carlyon *et al.*, 1990).

Figure 2 shows that the slopes of temporal-integration functions and, related to this, the maximum threshold improvement obtained with increasing stimulus duration, varied considerably across subjects and electrodes. At one extreme, the function obtained for electrode SLBrEL21 (topmost curve in Fig. 2) showed essentially no temporal integration. At the opposite extreme, electrode VVKrEL06 (bottom-most curve in Fig. 2) demonstrated nearly 6 dB of threshold improvement as the number of stimulus pulses increased from 1 to 8, with the temporal-integration slope for short-duration stimuli (1.94 dB/doubling) approaching the value expected in normal-hearing acoustic subjects (2.5 dB/doubling). Slopes of temporal-integration functions' initial segments were quantified by fitting a line to the 1-, 2-, 4-, and 8-pulse data by least-squares regression.[7] The resulting parameters are given in Table III. Slopes ranged from 0.06 to 1.94 dB threshold improvement per doubling of the number of pulses, with mean and median values of 0.42 and 0.33 dB/doubling, respectively. The shallowest of these slopes (0.06, electrode SLBrEL21) was not significantly different from zero ($p > 0.1$).

The same temporal-integration functions are replotted in Fig. 3, with each panel showing data for a single subject. Mean detection thresholds are shown as symbols connected by thin solid lines; linear functions fit to the 1-, 2-, 4-, and 8-pulse data (described above) are shown as heavy line segments.

Several features of Fig. 3 are noteworthy. First, it can be seen that the variability of threshold estimates, as represented by the size of error bars, was generally small. Electrode VVKrEL06 was an obvious exception to this, demonstrating high variability for the 2- and 4-pulse thresholds. We can offer no explanation for this variability: Subject VVK had no difficulty performing the adaptive threshold task, and there were no systematic shifts in this electrode's threshold estimates over time. The variability of threshold estimates for 1- and 8-pulse stimuli was considerably smaller; thus, it is unlikely that increased variability of the 2- and 4-pulse thresholds had a substantial effect on the overall shape of the temporal-integration function for this electrode, or on its unusually steep short-duration slope.

A second feature of Fig. 3 involves comparison of temporal-integration function slopes across electrodes for the seven subjects with multiple test electrodes. Subjects CXL, EES, FXC, and JPB exhibited relatively similar temporal-integration slopes on different test electrodes. Mean [standard deviation (s.d.)] slope estimates for these subjects were 0.26 (0.09), 0.23 (0.08), 0.33 (0.05), and 0.45 (0.07) dB/doubling, respectively. Somewhat larger slope differences across electrodes were exhibited by subjects AMA and AMB. AMA's electrodes rEL04 and rEL19 yielded slopes of 0.43 and 0.22, respectively, and the 90% confidence intervals of slope estimates for these electrodes were nonoverlapping (see Table III). AMB's electrodes rEL06, rEL12, and rEL20 yielded slopes of 0.32, 0.50, and 0.69 dB/doubling, respectively. Confidence intervals suggest that the temporal-integration slope for rEL06 was shallower than that for rEL20, but that other pairs of slopes (i.e., rEL06 versus rEL12, and rEL12 versus rEL20) were not significantly different. The largest interelectrode slope differences were exhibited by subject VVK, whose electrode rEL06 produced a temporal-integration function more than three times steeper (1.94 dB/doubling) than any other test electrode. Slopes for VVK's middle and apical electrodes (rEL10 and rEL15) fell within the range observed for other subjects (0.59 and 0.19 dB/doubling, respectively); however, 90% confidence intervals indicate significant slope differences between all three electrodes.

It will be shown later that short-duration temporal-integration slopes can be predicted relatively well by the slopes of corresponding psychometric functions for detection. In turn, it may be argued that psychometric-function slopes are determined by the characteristics of surviving neurons nearest the intracochlear stimulating electrodes. If this is the case, then the large differences in temporal-integration slopes exhibited by subject VVK across electrodes may reflect substantial differences in the characteristics of surviving neurons in different regions of the cochlea. Similar but less dramatic differences may account for the variation in temporal-integration slopes across electrodes in subjects AMA and AMB, and for differences in average temporal-integration slopes across subjects.

A final characteristic exhibited by the temporal-integration functions in Fig. 3 is a marked reduction in slope

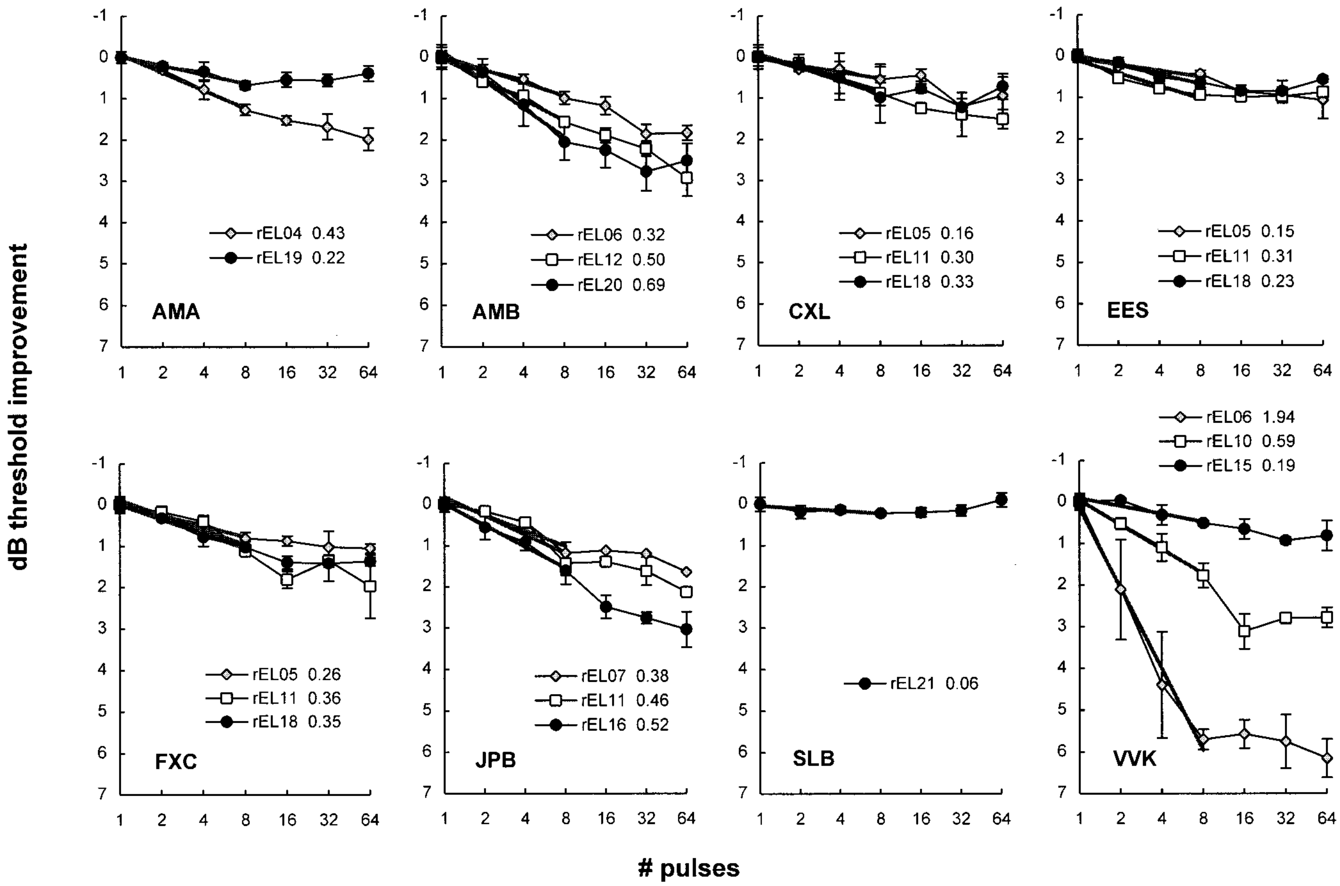

FIG. 3. Temporal-integration functions for 21 electrodes in eight cochlear-implant subjects, replotted from Fig. 2. Each panel shows data for 1–3 electrodes in a single subject whose subject code is given in the panel's lower-left corner. Mean detection thresholds are shown as symbols connected by thin solid lines; error bars represent values ± 1 s.d. from each mean. As in Fig. 2, data for apical, middle, and basal electrodes are plotted with open, shaded, and filled symbols, respectively. Heavy line segments represent linear functions resulting from least-squares regressions to the 1-, 2-, 4-, and 8-pulse data (see text). Electrode numbers and regression slopes are indicated in the symbol key for each panel.

for long-duration stimuli. Such a slope change is particularly evident in the functions for subject VVK's middle and basal electrodes (rEL06 and rEL10): The function for rEL06 possesses a sharp kneepoint at eight pulses, with slope decreasing from 1.94 dB/doubling of pulses for shorter stimuli to a slope that is nearly flat for stimulus trains with eight or more pulses. A similar kneepoint is seen at 16 pulses for rEL10. With one exception (JPBrEL16), least-squares linear-regression estimates of temporal-integration slopes between 16 and 64 pulses were not significantly different from zero ($p > 0.05$). It is not clear what mechanisms underlie the observed flattening of functions at 8–16 pulses.

Threshold change expressed as percent dynamic range. In Fig. 2, it was shown that the amount of threshold improvement associated with temporal integration is considerably smaller in electric hearing than in acoustic hearing. This finding seems to imply that temporal integration has less influence on the detection of short-duration sounds in the electric case. However, if threshold improvement is expressed as a proportion of dynamic range in both acoustic and electric hearing, a different view is obtained. Consider that the dynamic range of normal, acoustic hearing is roughly 100 dB. Temporal integration at a rate of 2.5 dB per doubling of stimulus duration results in threshold improvements of 10 dB, or about 10% of dynamic range, as signal duration increases by a factor of 16 (e.g., from 10 to 160 ms). In the electric case, dynamic range may be 5 dB or less. A temporal-integration slope of 0.5 dB/doubling (typical of the short-duration slopes seen here) translates to only 2-dB change in absolute threshold for the same 16-fold increase in signal duration; however, this 2-dB change corresponds to 40% of a 5-dB dynamic range. Both dynamic range and slopes of temporal-integration functions are variable in electric hearing (e.g., see Tables II and III). As shown below, threshold improvement due to temporal integration, expressed as a percentage of dynamic range, may also vary considerably across subjects and electrodes.

The present temporal-integration data are replotted in Fig. 4, with thresholds normalized to the threshold for the longest-duration stimulus (64-pulse or 630.4-ms train), and with threshold change (in dB) expressed as a percentage of the dynamic range (in dB) for each electrode. Computations were based on the dynamic range values listed in Table II. Recall that these were obtained with stimuli (500-ms, 125-Hz 205-μs/phase pulse trains) relatively similar to the 64-pulse temporal-integration stimulus. The heavy, solid line in Fig. 4 represents data that would be expected for a normal-hearing acoustic listener, based upon a 100-dB dynamic range and a temporal-integration slope of 2.5 dB/doubling of signal duration for durations less than 320 ms.

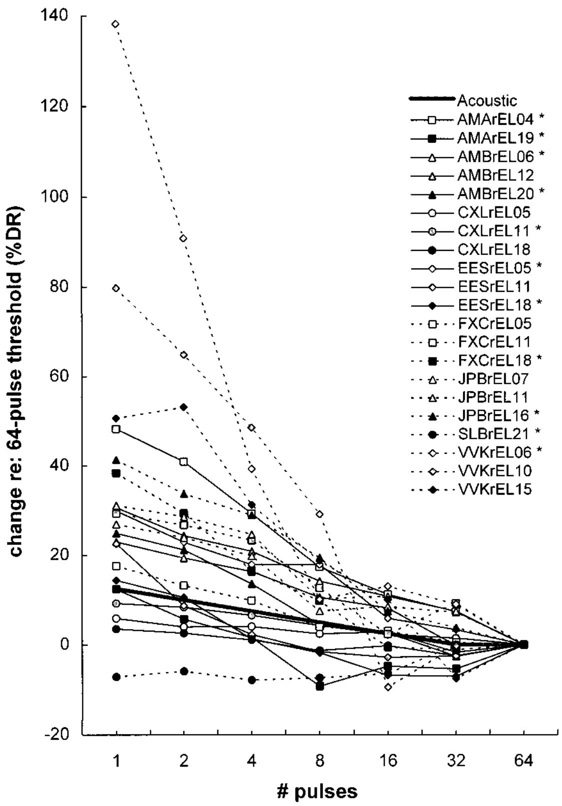

FIG. 4. Temporal-integration functions for 21 electrodes in eight cochlear-implant subjects, shown with thresholds normalized to the threshold for the longest (64 pulse) stimulus and with threshold change expressed as a percentage of the dynamic range for each electrode. Dynamic range values are taken from Table II. Data for individual electrodes are represented by the same symbol-line combinations as in Fig. 2. The heavy, solid line (without symbols) represents data that would be expected for a normal-hearing acoustic listener.

Figure 4 underscores the variability of temporal-integration behavior in electric hearing, both across subjects and for different electrodes in a given subject. Some subjects and electrodes (e.g., CXLrEL18) exhibit less temporal integration (expressed in percent dynamic range) than would be expected in acoustic hearing; however, many others exhibit considerably greater integration than that observed in the acoustic case. Electrode VVKrEL06 again demonstrates the greatest temporal integration, with a maximum threshold shift (approximately 6 dB, see Fig. 2) that is almost 40% greater than the corresponding dynamic range for a 500-ms stimulus (4.5 dB, see Table II). Whereas VVKrEL06 appears to possess unusual characteristics, many other electrodes demonstrate threshold shifts equivalent to 20% or more of dynamic range as stimulus duration decreases from 64 to 4 or fewer pulses. In comparison, an acoustic listener would exhibit threshold shifts corresponding to 10%–15% of dynamic range, depending upon stimulus parameters and the measured value of dynamic range.

The data in Fig. 4 have potentially important implications with respect to cochlear-implant subjects' detection of short-duration speech cues. Many speech processors encode the intensity level of an acoustic stimulus by varying current amplitude, and the input-output function used to map acoustic intensity level to current amplitude for a particular electrode is determined by measuring threshold and comfortable loudness levels for a relatively long-duration (e.g., 500-ms) stimulus. Figure 4 indicates that, for the stimulus parameters used here, the current amplitude necessary to reach threshold for a brief (<40 ms) electric stimulus may correspond to the current at any level from 0% to 50% (or more) of an electrode's dynamic range for a long-duration stimulus. In the extreme case of electrode VVKrEL06, the current amplitude at threshold for a one-pulse stimulus is higher than the current amplitude at MAL for a long-duration stimulus; thus, the use of an input-output function based upon threshold and dynamic range measures for a long-duration stimulus would ensure that a single-pulse stimulus would never be heard.

Consonant discrimination depends strongly on the listener's ability to distinguish differences in the amplitude or spectral characteristics of brief (e.g., <50 ms) acoustic cues embedded in the ongoing speech waveform. Speech processors that use low stimulation rates (e.g., 250 Hz or less in the Nucleus SPEAK and MPEAK processors) encode such cues with relatively few pulses per stimulated electrode. This may result in degraded consonant discrimination in those listeners (like VVK) who have one or more electrodes with steep temporal-integration functions and narrow dynamic ranges. Relatively little is known about the effects of stimulus parameters such as pulse rate, pulse duration, and electrode configuration on temporal-integration behaviors for electric stimuli; thus, it is difficult to predict whether consonant discrimination would be enhanced or degraded by particular speech-processing strategies. Effects of stimulus parameters on temporal-integration slope and dynamic range are likely to vary across individuals; thus, temporal integration may be one of several factors responsible for differences in speech-recognition ability across subjects and for different speech-processing strategies.

Dynamic range as a function of stimulus duration. Our consideration of temporal integration in terms of the dynamic range of individual electrodes led us to question whether dynamic range, itself, is influenced by stimulus duration. To address this question, we evaluated maximum acceptable loudness (MAL) levels for three electrodes in each of four subjects (AMB, EES, FXC, and JPB) using pulse-train stimuli that were identical to those used in constructing temporal-integration functions. MAL estimates were obtained using the ascending method of limits described previously, with stimuli presented continuously at a rate of 1/s. Dynamic range was computed by subtracting the mean 3IFC threshold for each stimulus (data shown in Figs. 2 and 3) from the corresponding, measured MAL. Resulting data are shown in Fig. 5.

Each panel in Fig. 5 displays data for a single electrode: Mean 3IFC-thresholds and MAL estimates are shown as shaded circles and shaded triangles, respectively, referred to the left-hand axis; dynamic range values are indicated by solid diamonds, referred to the right-hand axis. It is evident that the effects of train duration on MAL and dynamic range varied across subjects and electrodes, for the 12 electrodes tested. In general, MAL decreased or remained relatively constant as train duration increased. However, the relative slopes of threshold-duration functions and MAL-duration

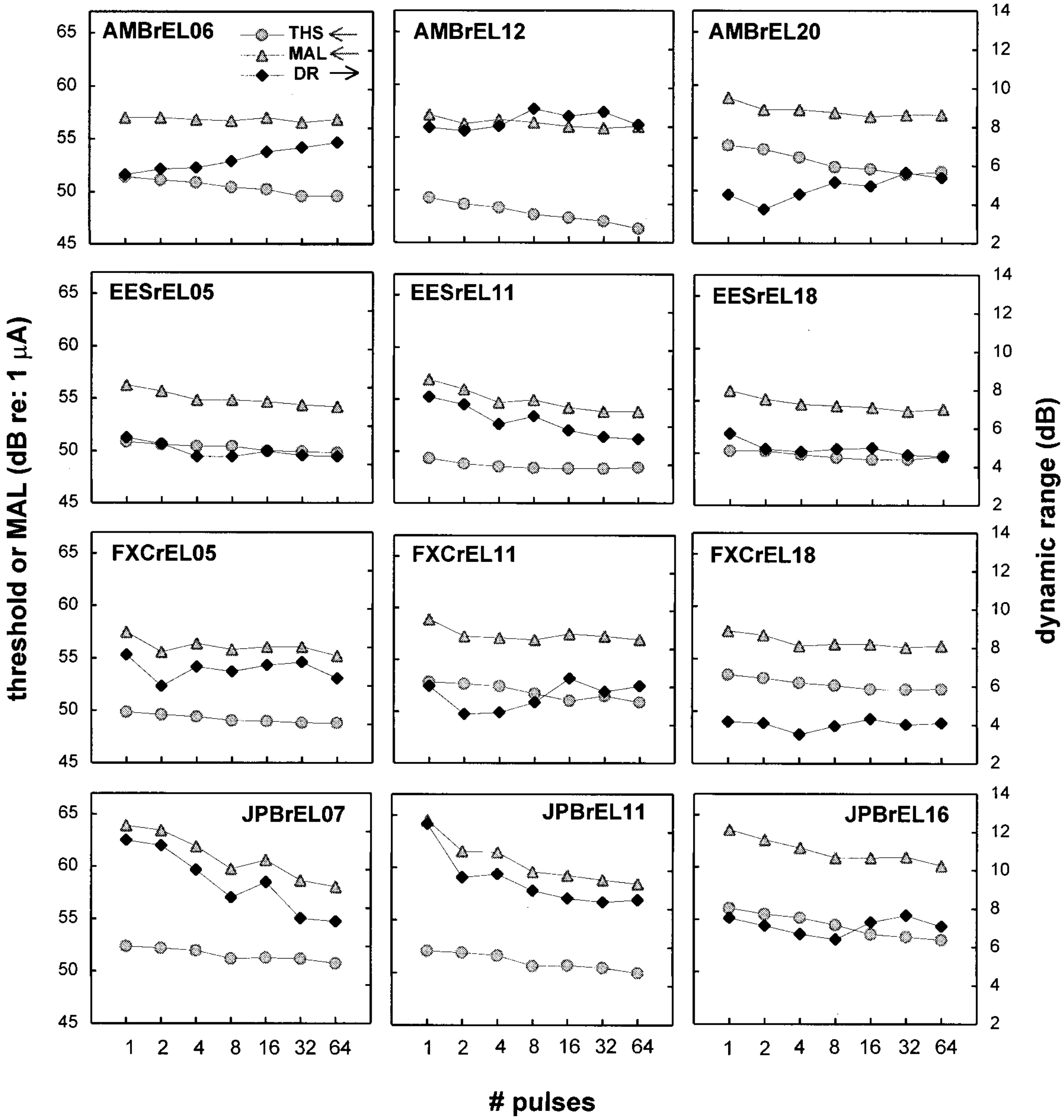

FIG. 5. Threshold, maximum acceptable loudness (MAL), and dynamic range measures as a function of stimulus duration for three electrodes each in four subjects. Each panel shows data for a different electrode, as indicated. Thresholds, represented by shaded circles, are mean 3IFC data replotted from Figs. 2 and 3; MALs, represented by shaded triangles, were obtained using an ascending method-of-limits procedure described in the text. Threshold and MAL data are referred to the left-hand axis. Dynamic range measures computed from threshold and MAL values are shown as solid diamonds, referred to the right-hand axis.

functions varied, with MAL-duration functions being steeper (e.g., JPBrEL07), shallower (e.g., AMBrEL12) or similar in slope (e.g., FXCrEL18) to the threshold-duration functions. This produced dynamic ranges that decreased, increased, or remained relatively constant as the stimulus train was lengthened. In short, stimulus duration had an inconsistent effect on dynamic range for the stimulus parameters used here.

B. Psychometric functions

Figure 6 shows fitted psychometric function data for 11 test electrodes, obtained with the 1-, 2-, 4-, 8-, and 64-pulse stimuli. The data are linear in log d' versus dB coordinates, as plotted. The 64-pulse data were not used in predictions of temporal-integration slopes according to the multiple-looks hypothesis (see below), but are shown for completeness.[8] Details of Fig. 6 are discussed below.

Certainty of slope estimates. Table IV summarizes slope estimates and related statistics for the same psychometric functions. Slopes were computed for 54 of 55 data sets: In one instance (SLBrEL21, one-pulse stimulus), a valid slope estimate could not be obtained because percent-correct responses met the criteria for inclusion in the fitted function at only two levels of the signal. This occurred even though signal levels were sampled at the smallest possible current increments, i.e., 1-CSU steps. Considerable uncertainty was associated with psychometric-function slope estimates for the individually fit (1-, 2-, 4-, 8-, or 64-pulse) functions, as

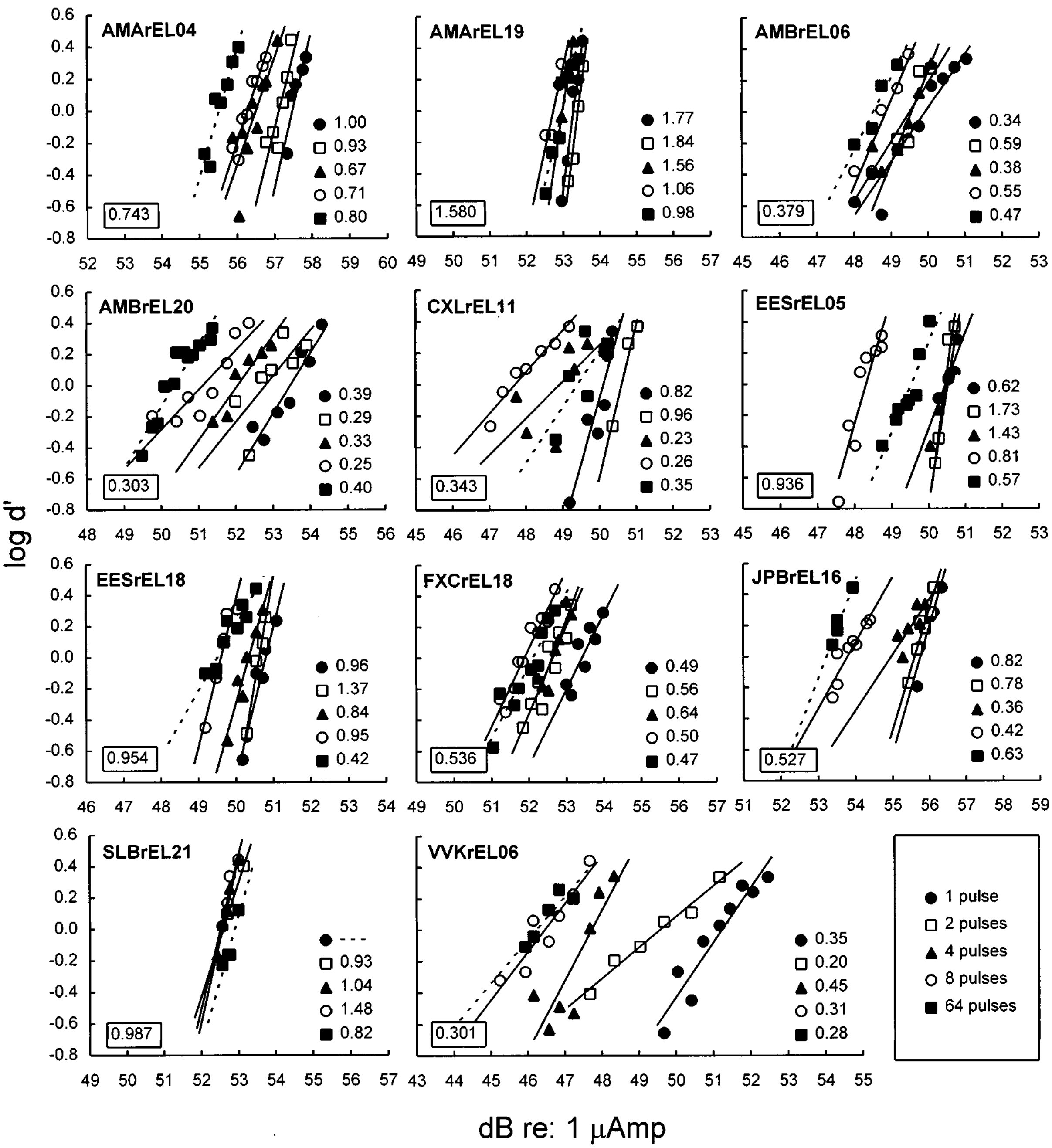

FIG. 6. Psychometric functions for detection for 11 electrodes from eight cochlear-implant subjects. Each panel represents data for a single subject and electrode, as indicated in the panel's top-left corner. Psychometric-function data for 1-, 2-, 4-, and 8-pulse stimuli are shown as filled circles, open squares, filled triangles, and open circles, respectively. Solid lines represent linear regression fits to these short-duration data. Data points and fitted functions for the 64-pulse stimulus are shown as filled squares and dashed lines, respectively. Slope estimates for individual psychometric functions are listed in the lower-right corner of each panel, and the composite slope estimate obtained by simultaneously fitting the 1-, 2-, 4-, and 8-pulse data (see text) is given in the box in each panel's lower-left corner. (Composite functions are not plotted). The scaling of x and y axes has been held constant across panels to emphasize differences in psychometric-function slopes, although the origin varies with electrode.

reflected by their large standard error (se) values and large coefficients of variation (CVs). Coefficients of variation averaged 22% for the 1-, 2-, 4-, and 8-pulse conditions and 19% for the 64-pulse condition. Moreover, large standard errors coupled with the small number of data points comprising individual functions often resulted in unacceptably large confidence intervals (90% CI limits). The certainty of composite slope estimates [comp (1–8)] was considerably better: For these functions, the mean CV was 12%, and confidence intervals were much narrower. Recall that composite slopes were computed by simultaneously fitting the 1-, 2-, 4-, and 8-pulse data sets with four functions having identical slopes and variable y intercepts (see Sec. I). Composite slope estimates were generally similar to the mean slope estimates for the four short-duration conditions [*mean* (1–8)]; however, given that underlying psychometric-function slopes are constant with signal duration, the composite estimates likely provide a more accurate estimate of the ''true'' slope for a

TABLE IV. Individual and composite psychometric-function slopes obtained for 11 electrodes in eight cochlear-implant users. Individual functions for the 1-, 2-, 4-, 8-, and 64-pulse stimuli were estimated by least-squares linear regression fits of the data for a particular stimulus to the equation $\log d' = \alpha' x + b$, where d' is detection performance, x is stimulus amplitude (dB *re:* 1 μA), and b is a sensitivity constasnt. Composite slope stimates [comp (1–8)] were obtained by simultaneously fitting four functions $\log d' = \alpha' x + b_i$, with a common slope α' and variable sensitivity constants b_i, to the 1-, 2-, 4-, and 8-pulse data for each electrode. Standard errors of slope estimates [se(α')], coefficients of variation [CV(%)], and 90% confidence intervals (90% CI) are listed for each function. For each electrode, the mean of individual short-duration slopes (1-, 2-, 4-, and 8-pulses) is also given [mean (1–8)].

Electrode	No. pulses	α'	se(α')	CV(%)	90% CI	Electrode	No. pulses	α'	se(α')	CV(%)	90% CI
AMArEL04	1	1.00	0.28	28	0.35–1.66	EESrEL18	1	0.96	0.12	12	0.71–1.21
	2	0.93	0.24	26	0.41–1.45		2	1.37	0.18	13	0.86–1.89
	4	0.67	0.17	25	0.35–0.99		4	0.84	0.11	13	0.61–1.07
	8	0.72	0.09	13	0.54–0.89		8	0.95	0.16	17	0.56–1.33
	64	0.80	0.12	15	0.55–1.05		64	0.42	0.06	13	0.32–0.53
	comp (1–8)	0.74	0.09	12	0.59–0.89		comp (1–8)	0.95	0.07	7	0.83–1.08
	mean (1–8)	0.83					mean (1–8)	1.03			
AMArEL19	1	1.77	0.17	10	1.37–2.17	FXCrEL18	1	0.49	0.37	31	0.32–2.06
	2	1.84	0.24	13	1.14–2.54		2	0.56	0.09	15	0.40–0.73
	4	1.56	0.10	6	1.28–1.84		4	0.64	0.12	19	0.39–0.89
	8	1.06	0.32	30	0.14–1.98		8	0.50	0.05	8	0.41–0.59
	64	0.98	0.15	15	0.68–1.29		64	0.47	0.06	13	0.35–0.59
	comp 1–8	1.58	0.13	8	1.35–1.81		comp (1–8)	0.54	0.04	8	0.47–0.60
	mean (1–8)	1.56					mean (1–8)	0.53			
AMBrEL06	1	0.34	0.04	11	0.28–0.41	JPBrEL16	1	0.82	0.15	19	0.49–1.14
	2	0.59	0.22	38	−0.06–1.23		2	0.78	0.13	17	0.51–1.06
	4	0.38	0.09	24	0.18–0.57		4	0.36	0.14	38	0.07–0.65
	8	0.55	0.11	20	0.30–0.80		8	0.42	0.08	18	0.27–0.57
	64	0.47	0.10	21	0.19–0.75		64	0.63	0.10	16	0.33–0.92
	comp (1–8)	0.38	0.04	9	0.32–0.44		comp (1–8)	0.53	0.07	13	0.40–0.62
	mean (1–8)	0.46					mean (1–8)	0.60			
AMBrEL20	1	0.39	0.06	16	0.26–0.51	SLBrEL21	1	[a]	[a]	[a]	[a]
	2	0.29	0.11	39	0.06–0.52		2	1.07	0.14	13	0.45–1.00
	4	0.33	0.06	18	0.21–0.46		4	1.04	0.08	8	0.84–1.23
	8	0.25	0.05	21	0.15–0.36		8	1.48	0.41	28	−1.13–4.09
	64	0.40	0.05	11	0.32–0.48		64	0.82	0.18	21	0.31–1.33
	comp (1–8)	0.30	0.04	12	0.24–0.37		comp (1–8)	0.99	0.09	9	0.81–1.16
	mean (1–8)	0.32					mean (1–8)	1.20			
CXLrEL11	1	0.82	0.16	20	0.47–1.17	VVKrEL06	1	0.35	0.05	13	0.27–0.43
	2	0.96	0.20	21	−0.28–2.20		2	0.20	0.02	8	0.16–0.23
	4	0.23	0.14	60	−0.06–0.53		4	0.45	0.11	25	0.22–0.67
	8	0.26	0.03	11	0.20–0.33		8	0.31	0.05	17	0.20–0.41
	64	0.35	0.15	43	0.03–0.67		64	0.28	0.07	25	0.11–0.44
	comp (1–8)	0.34	0.07	22	0.21–0.47		comp (1–8)	0.30	0.03	11	0.25–0.36
	mean (1–8)	0.57					mean (1–8)	0.32			
EESrEL05	1	0.62	0.21	34	0.01–1.23						
	2	1.73	0.28	16	0.93–2.54						
	4	1.43	1.26	88	2.24–5.10						
	8	0.81	0.13	16	0.55–1.07						
	64	0.57	0.09	15	0.40–0.74						
	comp (1–8)	0.94	0.17	18	0.63–1.24						
	mean (1–8)	1.15									

[a]A valid fit could not be obtained because only two data points met the criterion for inclusion.

given electrode. The assumption of invariant slopes is considered below.

Variability of slopes across stimulus conditions and electrodes. Figure 6 illustrates several important aspects of psychometric-function slopes. (Here, we focus on the slopes for 1- to 8-pulse stimuli; slopes of 64-pulse functions are considered briefly below.) First, it can be seen that slopes for the short-duration stimuli varied markedly across electrodes and subjects. Slope estimates for the individually fit 1-, 2-, 4-, and 8-pulse psychometric functions ranged from 0.20 to 1.84 $\log d'$/dB μA, with a mean (s.d.) value of 0.77 (0.45) $\log d'$/dB μA. Composite slope estimates computed from the same 1- to 8-pulse data ranged from 0.30 to 1.58 with a mean (s.d.) value of 0.69 (0.40) $\log d'$/dB μA. These individual and composite slopes are 2–20 times steeper than psychometric-function slopes reported for detection of tones in quiet by normal-hearing and cochlear-impaired acoustic listeners, which range from 0.08 to 0.15 $\log d'$/dB SPL (Carlyon *et al.*, 1990; Viemeister and Wakefield, 1991).

A second aspect of the data shown in Fig. 6 involves differences in slope estimates across the four short-duration conditions. For most electrodes, psychometric function slopes were relatively constant across these stimuli, varying by 33% or less from their mean value. Electrode AMBrEL20, for example, yielded slopes of 0.39, 0.29, 0.33, and 0.25 $\log d'$/dB for the 1-, 2-, 4-, and 8-pulse conditions, respectively, and all four individual slope estimates fell within 22% of their mean value (0.32). Greater variability was exhibited by electrodes EESrEL05 and VVKrEL06. For these electrodes, individual slope estimates differed from the mean short-duration slope by as much as 51% and 40%, respectively; however, slopes did not vary systematically with stimulus duration. Electrodes CXLrEL11 and JPBrEL16 yielded slope estimates that were steeper for the shortest-duration stimuli (single pulses or 2-pulse trains) than for stimuli with slightly longer durations (4- and 8-pulse trains); however, the apparent decrease in psychometric function slope with stimulus duration demonstrated by these electrodes was not statistically significant.[9]

Psychometric-function slopes obtained for the 64-pulse stimulus were generally similar to those obtained for the short-duration stimuli. However, there was one clear exception: For electrode EESrEL18, the 64-pulse psychometric-function slope of 0.42 log d'/dB was considerably shallower than the slopes estimated for the four short-duration stimuli, which averaged 1.03 log d'/dB. Current levels spanned by psychometric functions (and mean 3IFC thresholds, see Fig. 2) were similar across these conditions; thus, level-dependent changes in neural-response characteristics cannot account for this finding. We can offer no other explanation.

Perhaps the most important aspect of the psychometric functions shown in Fig. 6 is the variation of composite slope estimates across electrodes. As noted above, composite slopes ranged from 0.30 to 1.58 log d'/dB and were considerably steeper than those reported in acoustic hearing. Composite slopes were similar for pairs of test electrodes in two subjects: AMB's electrodes rEL06 and rEL20 yielded slopes of 0.38 and 0.30 log d'/dB, and EES's electrodes rEL05 and rEL18 yielded slopes of 0.94 and 0.95 log d'/dB. In contrast, composite slope estimates for AMA's electrodes rEL04 and rEL19 differed considerably, with respective values of 0.74 and 1.58 log d'/dB. As mentioned earlier, differences in neural survival may underlie the observed differences in psychometric function slopes across subjects and electrodes. Specific factors that may mediate these survival-related differences are considered below (Sec. III C).

Correlations of slopes with absolute threshold and dynamic range. Sensitive absolute thresholds and wide dynamic ranges have been associated with increased survival of spiral ganglion cells and myelinated peripheral processes, especially when threshold and dynamic range measures are obtained with long phase-duration stimuli (Pfingst *et al.*, 1981; Pfingst and Sutton, 1983; Pfingst *et al.*, 1985; Kawano *et al.*, 1994). Thus, if differences in neural survival are responsible for differences in psychometric-function slopes across subjects and electrodes, then it might be expected that the psychometric-function slopes would vary systematically with one or both of these measures.

To evaluate this possibility, we computed correlations between psychometric-function slopes and two different measures of absolute threshold and dynamic range. Threshold and dynamic range data for 205-μs/phase (125 Hz, 500 ms) pulse trains, listed in Table II, were available for all 11 electrodes.[10] In addition, threshold and dynamic range data for a longer phase-duration stimulus (1260 μs/phase, 125 Hz, 300 ms), measured as part of another experiment, were available for six electrodes (AMBrEL06, AMBrEL20, EESrEL05, EESrEL18, FXCrEL18, and JPBrEL16). As noted, above, neural survival may be better predicted by threshold and dynamic range measures at long phase durations; thus, correlations were performed for this subset of the data as well. Scatterplots of composite psychometric-function slopes (from Table IV) versus threshold and dynamic range measures for short and long phase-duration stimuli are shown in Fig. 7. Heavy line segments represent least-squares linear regression fits to the data; corresponding regression parameters and correlation coefficients are indicated in each panel.

Psychometric-function slopes tended to increase with absolute threshold for both the 205- and 1260-μs/phase conditions, although correlations were relatively weak ($r = 0.479$ and $r = 0.680$, respectively) and failed to reach statistical significance ($p \sim 0.13$ in each case). Dynamic range was more strongly predictive of psychometric-function slope: A moderate negative correlation was obtained for the 205-μs/phase condition ($r = -0.65$, df$=8$, $p = 0.04$), and a strong negative correlation ($r = -0.89$, df$=4$, $p < 0.05$) was obtained for the 1260-μs/phase condition. Although these correlations were based upon a small number of electrodes, they nonetheless suggest a link between slopes of psychometric functions and neural survival.

To summarize, the data shown in Fig. 7 indicate that psychometric-function slopes tend to increase with absolute threshold and are inversely related to dynamic range. This supports our suggestion that the observed variability of psychometric-function slopes across subjects and electrodes may be primarily attributable to differences in auditory-nerve survival.

C. Evaluation of the multiple-looks hypothesis

As discussed earlier, the simple version of the multiple-looks hypothesis predicts an inverse relation between psychometric-function slopes and slopes of the short-duration segments of temporal-integration functions. In terms of the present data, the predicted relation is described by the hyperbolic function

$$10 \log\left(\frac{I_{2T}}{I_T}\right) = \frac{-0.1505}{\alpha'}, \qquad (1)$$

where $10 \log(I_{2T}/I_T)$ is the slope of the temporal-integration function in units of dB threshold improvement per doubling of stimulus pulses and α' is the slope of the psychometric function in $\log d'$ versus dB coordinates. The derivation of Eq. (1) is given in the Appendix.

Figure 8 shows a scatterplot of psychometric-function slope versus temporal-integration slope for the 11 electrodes for which both measures were obtained. Data are plotted on log-log axes, resulting in linearization of the hyperbolic function predicted by the multiple-looks hypothesis (solid line). A point representing mean data reported by Carlyon *et al.* (1990) for four normal-hearing acoustic listeners is also shown. Carlyon *et al.* estimated temporal-integration slopes by measuring subjects' thresholds for a single 5-ms, 4-kHz tone pulse and for trains of ten such pulses; they also measured psychometric-function slopes for the same stimuli. The

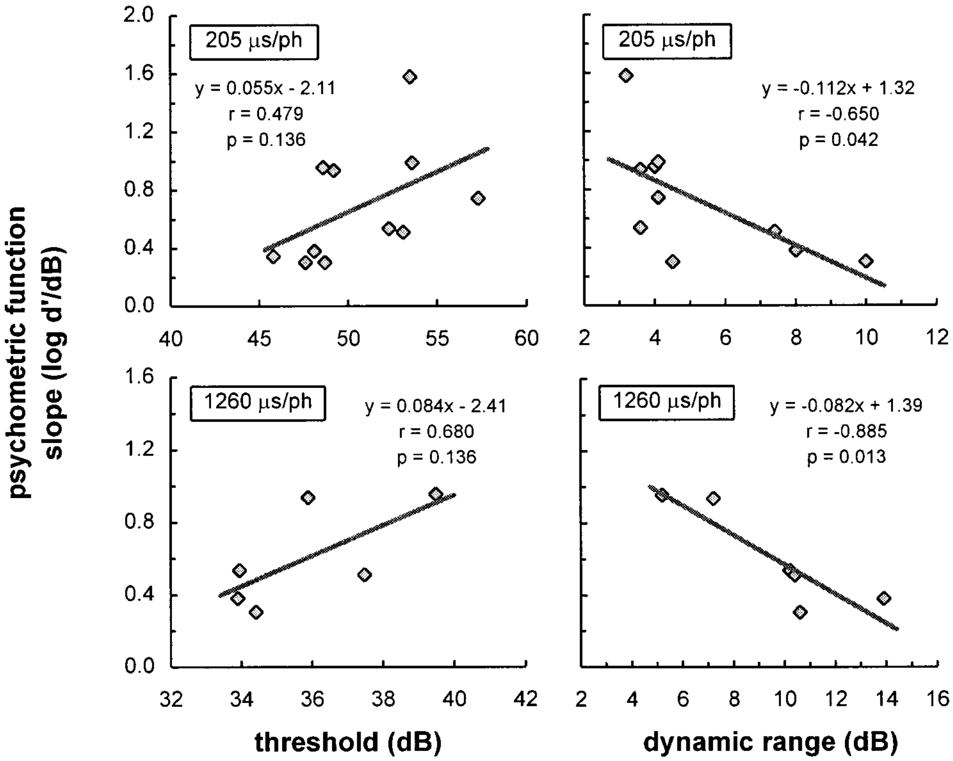

FIG. 7. Scatterplots of composite psychometric-function slope for short-duration (1-, 2-, 4-, and 8-pulse) stimuli versus absolute threshold and dynamic range. Threshold and dynamic range values in the upper panels are for stimuli with short pulse durations (205 μs/phase). Threshold data represent 11 electrodes in eight subjects; dynamic range data represent ten electrodes in seven subjects. Corresponding data in the lower panels are for stimuli with long pulse durations (1260 μs/phase), and represent six electrodes in four subjects. Heavy lines in each panel represent least-squares linear regression fits to the plotted data. Regression parameters and corresponding correlation coefficients are also given.

data point shown here, which is most comparable to the present data, is for pulse trains with 5-ms interpulse gaps.

The present cochlear-implant data conform fairly closely to the line predicted by the simple version of the multiple-looks model, and the prediction line accounts for 68% of the total variability in these data.[11,12] The data point representing acoustic data from Carlyon *et al.* (1990) also falls close to the multiple-looks prediction line. There is clearly some error in the multiple-looks' prediction of the present data; however, the model does a reasonable job of describing the observed relation between psychometric-function slope and temporal-integration slope over a relatively wide range of slope values.

III. GENERAL DISCUSSION

A. Comparisons with other published data

Temporal-integration functions obtained from cochlear-implant listeners have been reported in several previous studies. Shannon (1983, 1986) reported thresholds as a function of burst duration for 1000-Hz sinusoids, for one or more electrodes in each of five subjects. Slopes of temporal-integration functions were approximately 2.5 dB/doubling of stimulus duration for three subjects; one function reported for a fourth subject had a slope of approximately 1.5 dB/doubling. Five functions were reported for a fifth subject, and these demonstrated two distinct patterns: Three functions were nearly flat (slopes ~0.4 dB/doubling); the other two showed considerably steeper slopes, but only at very short durations. More recently, Shannon (1990) reported approximately 20 temporal-integration functions from six implanted subjects. Stimulus conditions were not specified, but were presumably the same for all functions. Function slopes varied considerably, from approximately 2.5 dB/doubling to nearly flat. It is difficult to directly compare temporal-integration slopes obtained by Shannon (1983, 1986) with the present data, since stimuli used in the two studies differed in waveshape (sinusoidal versus pulsatile), frequency (1000 Hz versus 100 Hz) and pulse duration (~500 μs vs 200 μs). These parameters have all been shown to affect temporal-integration slopes (White, 1984; Pfingst *et al.*, 1991; Moon *et al.*, 1993; Pfingst and Morris, 1993). The data reported by Shannon (1990) suggest the same general degree of intersubject variability in temporal-integration slopes as that observed in the present study.

Moon *et al.* (1993) reported temporal-integration functions that are more directly comparable to the present data. They tested five subjects with the Nucleus implant, using 100-Hz pulse trains comprised of 1–30 biphasic pulses. Slopes of temporal-integration functions became steeper with increasing pulse duration: 96-μs/phase pulse trains produced temporal-integration functions with a mean slope of 0.22 dB/doubling, whereas 1536-μs/phase pulse trains yielded functions with a mean slope of 0.81 dB/doubling. These values are roughly consistent with the mean temporal-

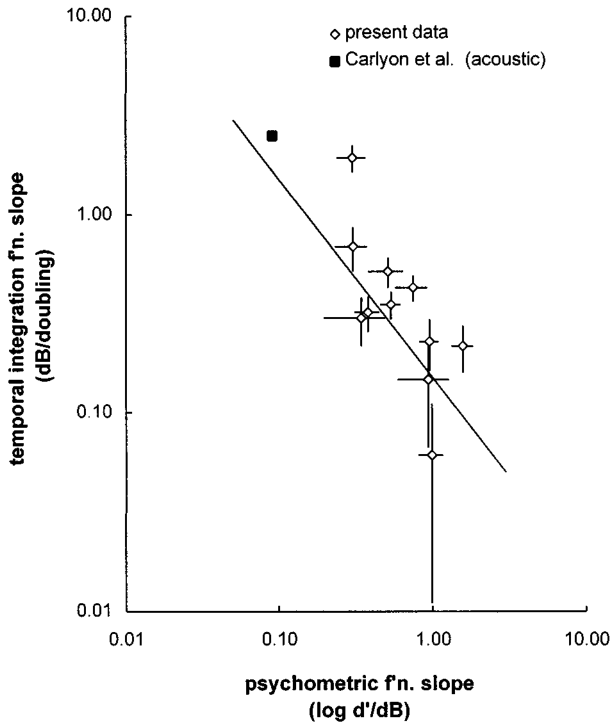

FIG. 8. Scatterplot of temporal-integration slope versus psychometric-function slope for 11 electrodes in eight cochlear-implant subjects for which both measures were obtained. Psychometric-function slopes (log d'/dB) are the composite short-duration slopes obtained by simultaneously fitting the 1-, 2-, 4-, and 8-pulse data for each electrode with four linear functions having a common slope and variable y intercepts (comp 1–8 slopes in Table IV). Temporal-integration slopes (dB threshold improvement per doubling of number pulses) are those listed in Table III. Horizontal and vertical error bars represent ± 2 standard errors of slope estimates for psychometric functions and temporal-integration functions, respectively. A point representing mean data reported by Carlyon *et al.* (1990) for normal-hearing acoustic listeners is also shown (see text). The solid line represents the equation predicted by the multiple-looks hypothesis [Eq. (1) in the text].

integration slope of 0.42 dB/doubling obtained in the present study for 100-Hz trains of 200-μs/phase biphasic pulses. Note that if the multiple-looks model is correct, Moon *et al.*'s finding that temporal-integration slopes increase with pulse duration predicts that psychometric-function slopes should *decrease* with increasing pulse duration. For example, Eq. (1) predicts that temporal-integration slopes of 0.22 and 0.81 dB/doubling (as reported by Moon *et al.* for 96- and 1536-μs/phase pulses) should correspond to psychometric-function slopes of 0.68 and 0.19 log d'/dB, respectively. Moon *et al.* did not measure psychometric functions in their study.

Pfingst *et al.* (1991) have similarly observed that temporal-integration functions become steeper with increasing phase-duration of pulse-train stimuli (500-μs/phase versus 5-ms/phase). Although psychometric functions were also obtained, these investigators were unable to detect a systematic effect of phase duration on psychometric-function slopes. As mentioned earlier, it appears that their analyses were limited to qualitative observations. Given this, and considering that detailed analyses of the present data were necessary to demonstrate a relation between psychometric-function and temporal-integration slopes, their findings are neither surprising nor inconsistent with the present results.

B. Support for the multiple-looks model

The present data generally support the multiple-looks hypothesis of temporal integration. Specifically, they demonstrate an inverse relation between slopes of psychometric functions for detection and slopes of temporal-integration functions that is approximately described by Eq. (1). Equation (1) also predicts the relation between psychometric-function slopes and temporal-integration slopes in acoustic listeners; thus, it accounts relatively well for both electric and acoustic data over a wide range of psychometric-function and temporal-integration slope values.

Deviations of the present data from Eq. (1) may stem largely from the inherent difficulty of measuring psychometric-function slopes and temporal-integration slopes accurately. Both measures are prone to variability imposed by changes in listeners' judgements over time, fluctuations in absolute hearing sensitivity, and statistical limitations of the psychophysical measurement procedures (e.g., binomial variability). Of course, deviations could also stem from factors that are not accounted for by the simple form of the multiple-looks model, or from violations of its assumptions that individual ''looks'' at the stimulus are independent, equally detectable, and optimally combined.

Additional tests of the multiple-looks model are possible in implanted listeners. For example, as mentioned in the previous section, Pfingst *et al.*, (1991) and Moon *et al.* (1993) have shown that temporal-integration functions increase with biphasic pulse duration in electric hearing, suggesting that slopes of psychometric functions for detection must decrease with pulse duration. If so, and the model is correct, then changes in psychometric-function slope with pulse duration should quantitatively predict changes in temporal-integration slope according to Eq. (1). Importantly, data for a range of pulse durations could be obtained on the same test electrodes, permitting a more direct test of the model than that provided in the present study.

C. Neural factors underlying variability of psychometric-function slopes

Perhaps the most important finding of the present study is that slopes of psychometric functions for detection vary considerably across implant listeners and for different regions of implanted cochleas. The relations discussed earlier, namely the tendency of psychometric-function slopes to increase with absolute threshold, and the inverse correlation between psychometric-function slopes and dynamic range, indicate that differences in psychometric-function slopes across subjects and electrodes may be mediated by differences in the types and relative numbers of surviving cochlear neurons.

A possible explanation for these findings is that low thresholds and wide dynamic ranges reflect the existence of peripheral processes (so-called *dendrites*) in the vicinity of the stimulating electrodes. Threshold detection is presumably mediated by a relatively small number of neural elements among those closest to the stimulating electrodes; thus, the population neural response to a threshold stimulus should stem primarily from dendritic processes when these exist. Available physiologic data suggest that electrical stimulation of auditory-nerve fibers at their dendritic processes results in shallower rate-intensity functions than stimulation at their central processes (axons) (van den Honert and Stypulkowski, 1984; Javel, 1990). Thus, relatively shallow rate-intensity (RI) functions should characterize neural responses to threshold-level stimuli in regions of good dendritic survival. Other factors (e.g., the stochastic properties of neural responses) being constant, shallow RI functions would be expected to result in shallow psychometric-function slopes.

A second factor to be considered is the spatial density of neural elements stimulated at threshold. Because degeneration occurs in a peripheral-to-proximal sequence (e.g., Spoendlin, 1975; Leake and Hradek, 1988) and loss of dendritic processes is typically greater than loss of spiral ganglion cell bodies in deafened human ears (e.g., Hinojosa and Marion, 1983; Suzuka and Schuknecht, 1988), neural density may be relatively lower for surviving dendrites than for corresponding axons. If so, then growth of the population neural response at threshold should be more gradual in the case of dendritic survival. Both shallow rate-intensity functions and reduced spatial density of surviving neurons are consistent with the relations we have observed here between psychometric function slope and measures of threshold and dynamic range.

IV. CONCLUSIONS

Slopes of temporal-integration functions vary considerably across cochlear-implant listeners and, in some cases, for different electrodes in a particular cochlea. For the stimuli used here (100-Hz trains of 200-μs/phase biphasic pulses), temporal-integration slopes in implanted listeners are substantially shallower than the 2.5 dB doubling typically reported for acoustic listeners.

Slopes of psychometric functions for detection also vary widely across implant listeners, and for different electrodes in some cochleas. Psychometric-function slopes may be primarily determined by the characteristics of surviving auditory neurons in stimulated regions of the cochlea.

Temporal-integration slopes vary inversely with psychometric-function slopes. This inverse relation is relatively well-described by a hyperbolic function predicted by a simple version of the multiple-looks model of temporal integration. The multiple-looks model appears to account for a wide range of temporal-integration slopes in cochlear-implant and acoustic listeners on the basis of differences in psychometric-function slopes, and is generally supported by the present data.

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APPENDIX: DERIVATION OF EQ. (1)

Equation (1) relates slopes of temporal-integration functions to slopes of psychometric functions for detection, according to assumptions of the multiple-looks model of temporal integration. It is derived as follows:

According to the simple form of the multiple-looks hypothesis, $d'_n = \sqrt{n} d'_1$, where d'_n is the detectability of n, independent, optimally combined looks and d'_1 is the detectability of a single look. Assuming $n = bT$, where T is the duration of the stimulus and b is a constant determined by the duration of a look, it follows that

$$d'_T = \sqrt{bT} d'_1 .$$

We assume that the psychometric function for one look can be described as $d'_1 = kI^{\alpha}$. Thus, $d'_T = \sqrt{bT} kI^{\alpha}$, where k, b, and α are assumed not to depend on n (or T).

The "threshold" value of I is

$$I_T = mT^{-1/2\alpha},$$

where m is a constant determined by the constants k and b, and by the value of d' used to define threshold. For each doubling of duration,

$$\frac{I_{2T}}{I_T} = 2^{-1/2\alpha}$$

and

$$10 \log\left(\frac{I_{2T}}{I_T}\right) = -\frac{1}{2\alpha} (3.01) = -\frac{-1.505}{\alpha}.$$

Note that α is the slope of the psychometric function for detection in $\log d'$ versus $\log I$ coordinates. Psychometric-function slopes (α') for the present data were computed in coordinates of $\log d'$ versus $10 \log I$. Thus, $\alpha = 10 * \alpha'$, and the equation can be rewritten

$$10 \log\left(\frac{I_{2T}}{I_T}\right) = -\frac{-0.1505}{\alpha'}.$$

[1]The multiple-looks model is not unique in predicting a relation between the form of the psychometric function and temporal integration. As noted by a reviewer, a scheme in which a nonlinearity precedes a temporal integrator and internal noise *could* predict such a relation. However, the relation between the nonlinearity and the form of the psychometric function is uncertain: The uncertainty arises because properties of the internal noise are unknown. In contrast, the simple version of the multiple-looks model, that is discussed here, makes a direct prediction and requires no assumptions about internal noise. Furthermore, there is experimental evidence that the nonlinearity-integration scheme is not tenable as a general account of temporal integration (Viemeister and Wakefield, 1991).

[2]Current step units (CSUs) are logarithmic units of current amplitude utilized in the Nucleus 22-electrode device. Decibel values equivalent to 1

CSU vary as a function of stimulus level. They generally ranged from 0.1 to 0.3 dB for the stimulus levels used in the present study.

[3]Collection of complete sets insured that any effects of learning or of time-varying subject state were distributed more-or-less uniformly across stimulus conditions. Random stimulus order would have been preferable in this respect; however, testers could more reliably choose appropriate starting and maximum-safe-stimulation levels when stimuli were tested in a short-to-long sequence, and subjects generally preferred this stimulus order.

[4]The 3 to 4 data sets (21–28 tracks) initially obtained for a particular temporal-integration function typically included 1 or 2 tracks that required replacement because reversals converged poorly and, thus, did not provide a reliable estimate of threshold. In contrast to this, unusual variability of initial thresholds was only a problem for a few stimuli across all 21 functions. Frequently, there was enough time remaining in a subjects's scheduled session to collect an additional, partial set of data (in short-to-long stimulus order) after the first 3 to 4 complete sets had been obtained. In such cases, we typically made use of the available time to collect an additional track for each of the short-duration (1-, 2-, 4-, and 8-pulse) stimuli or for each stimulus that yielded initial thresholds that were slightly more variable than others.

[5]The descending–ascending procedure was convenient because it allowed us to determine appropriate stimulus levels on the basis of an initial descending run. Some subjects demonstrated hysteresis in their performance near the middle of the psychometric function for ascending versus descending runs; thus, it seemed appropriate to alternate between these two conditions. We have subsequently compared psychometric function slopes ($\log d'$/dB) estimated with the descending–ascending procedure to slopes obtained when stimuli were completely randomized across level, and found no systematic differences.

[6]Since psychometric functions were often steep and the size of level increments was limited by the resolution of the implant receiver–stimulator, percent-correct performance sometimes increased from chance to perfect levels in only 3 to 4 steps. Thus, it was important to include as many data points as could be justified in the psychometric-function fits. Use of the confidence-interval criterion allowed us to include points close to chance or perfect performance if the variability of block-to-block percent-correct scores was small. By the same token, it forced us (appropriately) to exclude points in the 60%–90% correct range (which would typically be included) if the corresponding confidence interval was large. The confidence-interval criterion was first used by Buus and Florentine (1991), who showed that it tends to bias resulting slope estimates slightly toward shallower values. The reader is referred to their paper for further discussion of this point.

[7]Gerken *et al.* (1990) have shown that the short-duration portions of acoustic temporal integration functions are approximately linear when plotted in coordinates of log duration versus log amplitude.

[8]Note that the relative position of psychometric functions along the abscissa of each panel in Fig. 6 does not always agree with the corresponding temporal-integration function. For example, in the data for CXLrEL11, the one-pulse psychometric function is positioned to the left of the two-pulse psychometric function, suggesting (incorrectly) that the one-pulse threshold was lower than the two-pulse threshold. These discrepancies reflect changes in absolute sensitivity that occurred between the test sessions during which psychometric functions were collected. To insure that such sensitivity shifts did not contaminate the data, temporal-integration functions that were collected over two sessions were monitored for sensitivity shifts, and psychometric functions were always obtained within a single test session (see Sec. I).

[9]Simultaneous fits to the 1-, 2-, 4-, and 8-pulse data were performed using both model I regression (one slope and four intercepts) and model II regression (four slopes and four intercepts). Model II regression did not account for significantly greater variability than model I regression in either case. This indicates that there were no significant differences among the four short-duration slope-estimates for either electrode.

[10]Electrode CXLrEL11 did not reach MAL at the output limits of the receiver–stimulator for the 205-μs/phase stimulus. Because an accurate estimate of dynamic range could not be obtained, this electrode was excluded from the correlation of psychometric function slope versus dynamic range (upper right panel, Fig. 7).

[11]Because both temporal-integration slopes and psychometric-function slopes were estimated with error, it was appropriate to compute the percentage of *total* (x plus y) variability accounted for by the multiple-looks prediction line. This computation was performed on the log-transformed data (as plotted in Fig. 8). To determine the ''residual'' variability (D^2), the distance from each data point to the prediction line was computed along a vector whose angle was determined by the relative magnitudes of the x and y errors for that point. (If variability was greater in the y dimension, the vector was more nearly vertical; if variability was greater in the x dimension, the vector was more nearly horizontal.) D^2 was taken to be the sum of the squared distances obtained in this manner. The total variability (D_0^2) was computed by determining a weighted sum-of-squares for the x values and a weighted sum of squares for the y values, and summing these quantities. The proportion of variability explained by the prediction line was taken to be $1-(D^2/D_0^2)$.

[12]Elimination of the data point for electrode VVKrEL06 increased the percentage of variability accounted for by the multiple-looks prediction line from 68.3% to 75.0%. (This electrode's temporal-integration slope was considerably different than that for other electrodes, and could be viewed as an outlier.) The approximate significance (p value) associated with 68.3% explained variability is 0.15; that associated with 75.0% variability is 0.07. Significance values must be viewed as approximate because a theoretical prediction line rather than the best-fitting regression line was used to account for variability.

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