Temporal resolution in sensorineural hearing-impaired listeners

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Temporal masking curves were obtained from 12 normal-hearing and 16 hearing-impaired listeners using 200-ms, 1000-Hz pure-tone maskers and 20-ms, 1000-Hz fixed-level probe tones. For the delay times used here (> 40 ms), temporal masking curves obtained from both groups can be well described by an exponential function with a single level-independent time constant for each listener. Normal-hearing listeners demonstrated time constants that ranged between 37 and 67 ms, with a mean of 50 ms. Most hearing-impaired listeners, with significant hearing loss at the probe frequency, demonstrated longer time constants (range 58–114 ms) than those obtained from normal-hearing listeners. Time constants were found to grow exponentially with hearing loss according to the function $\tau = 52e^{0.011(\mathrm{HL})}$, when the slope of the growth of masking is unity. The longest individual time constant was larger than normal by a factor of 2.3 for a hearing loss of 52 dB. The steep slopes of the growth of masking functions typically observed at long delay times in hearing-impaired listeners' data appear to be a direct result of longer time constants. When iterative fitting procedures included a slope parameter, the slopes of the growth of masking from normal-hearing listeners varied around unity, while those from hearing-impaired listeners tended to be less (flatter) than normal. Predictions from the results of these fixed-probe-level experiments are consistent with the results of previous fixed-masker-level experiments, and they indicate that deficiencies in the ability to detect sequential stimuli should be considerable in hearing-impaired listeners, partially because of extended time constants, but mostly because forward masking involves a recovery process that depends upon the sensory response evoked by the masking stimulus. Large sensitivity losses reduce the sensory response to high SPL maskers so that the recovery process is slower, much like the recovery process for low-level stimuli in normal-hearing listeners.

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INTRODUCTION

Previous investigations of temporal resolution in the auditory system indicate that hearing-impaired listeners often perform more poorly on temporal-resolution tasks than do normal-hearing listeners when the stimulus has a broad frequency spectrum (Boothroyd, 1973; Irwin *et al.*, 1981; Fitzgibbons and Wightman, 1982; Tyler *et al.*, 1982; Giraudi-Perry *et al.*, 1982; Fitzgibbons and Gordon-Salant, 1986). This appears to be due to an overall bandwidth problem in which high-frequency broad-bandwidth channels, ones that are usually capable of good temporal resolution, are not functional because of cochlear hearing loss at high frequencies (Buss and Florentine, 1985). However, when the stimulus has a narrow frequency spectrum and temporal information is confined to specific frequency regions, evidence of abnormal performance on temporal resolution tasks by hearing-impaired listeners is not as common, nor is the interpretation of that evidence straightforward.

Typically, forward-masking experiments have been used to investigate frequency-specific temporal resolution in sensorineural hearing-impaired listeners. The results of those forward-masking experiments are somewhat equivocal. Work with fixed-level maskers (Gardner, 1947; Elliott, 1975; Tillman and Rosenblatt, 1975) indicates that the hearing-impaired listener demonstrates a more gradual rate of recovery from auditory stimulation. However, for the same high-level masker, normal ears demonstrate a large amount of masking, while hearing-impaired listeners demonstrate a small amount of masking. We know from research on normal ears that the rate of recovery from auditory stimulation is always more gradual for small amounts of masking than for large amounts of masking (Luscher and Zwislocki, 1947; Samoilova, 1959; Plomp, 1964; Duifhuis, 1973; Smiarowski and Carhart, 1975; Fastl, 1979; Widin and Viemeister, 1979; Jesteadt *et al.*, 1982). Therefore, if comparisons were made in terms of equal initial amounts of forward masking, the rate of recovery from auditory stimulation in the hearing-impaired ear may not be so different from that in the normal ear.

This investigation specifically examines the rate of recovery from auditory stimulation in normal and in sensorineural hearing-impaired listeners when the amounts of forward masking are comparable. Forward masking is measured with a fixed-probe procedure, regression-analysis procedures are used to estimate parameters of forward masking in individual listeners, and comparisons are then made of the parameter values obtained from hearing-impaired and normal-hearing listeners.

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I. METHODS

A. Procedures

In order to evaluate temporal resolution at specific frequency regions in the hearing-impaired ear, we examined forward masking of 20-ms, 1000-Hz tone bursts rather than forward masking of clicks or very short bursts of broadband noise. This choice of 20-ms tone bursts over shorter stimuli limited temporal specificity in favor of better frequency specificity. Since temporal resolution may be particularly important to the hearing-impaired listener for low-sensation-level signals, a fixed-probe-level forward-masking procedure was utilized to allow comparisons between normal and impaired listeners at comparable probe sensation levels.

Two groups of listeners participated in the experiment. The normal-hearing group consisted of 12 listeners with normal hearing at test frequencies from 250–8000 Hz. The hearing-impaired group consisted of 16 listeners with sensorineural hearing losses of various amounts. All of the hearing-impaired listeners underwent a battery of audiologic tests to rule out conductive hearing losses and retrocochlear dysfunction; they demonstrated results consistent with cochlear hearing loss.

Masker frequencies and probe frequencies were both 1000 Hz, except for one hearing-impaired listener who was tested at 1200 Hz. Masker duration was 200 ms, and probe duration was 20 ms, both durations specified as the time during which a stimulus exceeded 90% of peak amplitude. Both masker and probe were gated with 10-ms rise/decay times (time between 10% and 90% of peak amplitude). Delay time between masker and probe was specified as the time between masker offset and probe offset. The shortest delay time was 42 ms: 10-ms masker offset, 2-ms temporal separation, 10-ms probe onset, and 20-ms probe duration. At this 42-ms delay time, no physical overlap existed between masker and probe waveforms, since the temporal separation between masker offset and probe onset, at 10% of peak amplitude, was 2 ms. Intertrial intervals in the forced-choice procedure were 300 ms.

A four-interval four-alternative forced-choice adaptive procedure was used to determine the level of masking tone that was required to just mask a fixed-level probe tone. The adaptive procedure estimated the 71% correct threshold with a two-up one-down tracking procedure that averaged the last six out of ten level reversals, during which the level varied in 2-dB steps. In a single listening session, a complete temporal masking curve was obtained for one fixed probe level. A temporal masking curve consisted of consecutive masked thresholds for increasing delay times from 42–160 ms. Test sessions continued until at least three temporal masking curves were collected at each probe level. At least three probe levels were tested in all of the normal-hearing listeners; only two probe levels could be tested in some of the hearing-impaired listeners because of the severity of their hearing losses.

B. Data analysis

Assuming that the time course of recovery from adaptation in the forward-masking experiment can be adequately represented with an exponential recovery process, the general equation used to describe that process can take the form of Eq. (1), which is similar to the exponential equation used by Duifhuis (1973) and by Widin and Viemeister (1979) to model the decay of forward masking:

$$SL_p = k\,(SL_m + M)\,e^{-t/\tau}, \tag{1}$$

where SL_m and SL_p are masker and probe sensation levels, respectively, t is the delay time between masker offset and probe offset, and τ is the time constant of recovery from adaptation. The constant M defines sensitivity to adaptation, and k is the slope of the growth of masking, which for the initial analyses is assumed to be unity.[1]

In this study, a fixed-probe-level forward-masking procedure was employed, which obtains the masker level required to just mask a fixed-level probe tone. Therefore, the appropriate general equation to analyze these data, assuming $k = 1.0$, is the inverse of Eq. (1) as given by Eq. (2a):

$$SL_m = (SL_p * e^{t/\tau}) - M. \tag{2a}$$

Equation (2a) is similar to those used by Vogten (1978), Nelson and Turner (1980), and Cudahy (1982) to describe similar fixed-probe-level data. To facilitate data analysis, Eq. (2a) can be "linearized" by taking the natural logarithm of both sides of the equation, as shown in Eq. (2b):

$$\ln(SL_m + M) = \ln(SL_p) + t/\tau. \tag{2b}$$

This transformation simplifies parameter estimation so that standard least-squares curve-fitting procedures can be used to examine the validity of using a single time constant at all probe levels.

Estimations of the parameter values of Eq. (1), and estimates of how well those parameters fit the temporal masking curves, were obtained with an iterative or brute force parameter-estimation procedure similar in character to the type of procedure used by Jesteadt *et al.* (1982). We used a variant of what is commonly called the "simplex" least-squares parameter-estimation algorithm (Nedler and Mead, 1965), as described in detail by Caceci and Cacheris (1984).

II. RESULTS AND DISCUSSION

A. The single-time-constant assumption

Temporal masking curves obtained from four of the twelve normal-hearing listeners are shown in Fig. 1. These curves represent the masker level required to maintain a constant amount of masking as delay time between masker and probe is varied. Sensation level of the masker is plotted on a logarithmic scale as a function of delay time, with level of the probe as the parameter. This type of plot transforms exponential functions into straight lines. Each curve is labeled with its appropriate parameter value in dB SPL, with dB SL in parentheses by the lowest curve. The reciprocal of the slope of the best-fitting straight line for each temporal masking curve is the time constant for that curve.

Our first goal was to determine if temporal masking curves could be fit with a single time constant, irrespective of probe level, which is an assumption fundamental to the use of an exponential process to describe recovery from adaptation. To test that assumption, the data from each listener

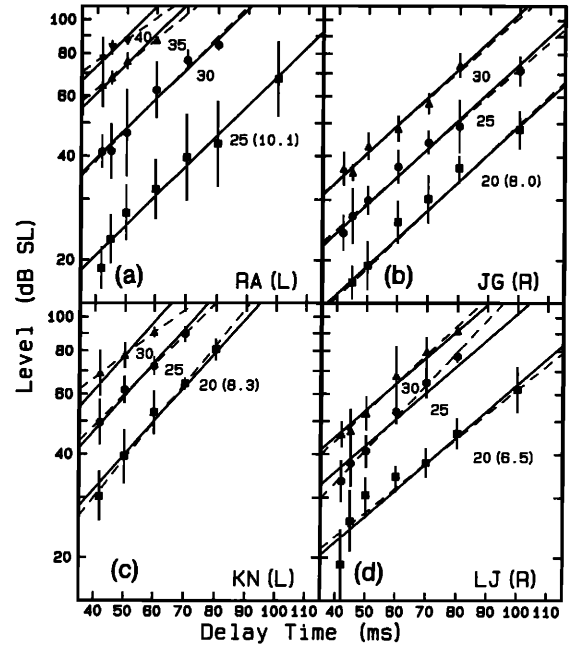

FIG. 1. Temporal masking curves obtained with the fixed-probe-level procedure for four of the normal-hearing listeners. The parameter is probe level in dB SPL, with probe sensation level indicated in parentheses for the lowest probe-level condition. Dashed lines are the "individual fits"; solid lines are the "parallel fits" (see text). The inverse of the slope of the solid lines is the level-independent time constant τ.

TABLE I. Variance accounted for by individual fits (R^2, I) and parallel fits (R^2, P) using Eq. (2c): Normal-hearing listeners. [Ltpp = Threshold SPL for a signal with duration of probe (20 ms); Ltpm = Threshold SPL for a signal with duration of masker (200 ms).]

Subject	Ltpp	Ltpm	R^2, I	R^2, P	F	(df)
CT(L)	12.0	7.0	0.94	0.93	0.20	(3,10)
DN(L)	12.5	7.0	0.98	0.98	0.47	(2, 9)
JG(R)	12.0	4.9	0.97	0.97	0.31	(2,15)
JI(L)	10.1	0.7	0.97	0.95	1.19	(2, 4)
KN(L)	11.7	3.9	0.99	0.97	6.92	(2, 6)[a]
LJ(R)	13.5	7.3	0.97	0.96	2.40	(2,14)
MK(L)	8.9	0.3	0.98	0.99	0.99	(2, 7)
MZ(L)	7.2	− 3.2	0.95	0.95	0.70	(3.16)
RA(L)	14.9	8.5	0.98	0.97	0.91	(2, 7)
TO(R)	18.0	12.4	0.91	0.84	3.62	(2, 9)
VS(R)	14.4	8.2	0.94	0.92	2.08	(3,21)
ZB(R)	18.5	12.3	0.99	0.98	12.91	(3,11)[a]
Means	12.8	5.9	0.96	0.95		
s.d.	3.3	4.6	0.03	0.04		

[a] The F ratio significant at $p = 0.05$.

were subjected to two regression analyses in which the intercepts of the functions were not constrained to be equal to SL_p as in Eq. (2b). Instead, the data were analyzed with Eq. (2c), where the intercept is a free parameter. To avoid confusion, A is used to represent that intercept. As defined in Eq. (2c), the reciprocal of the slope b of the least-squares straight-line fit specifies the time constant τ of each recovery curve,

$$\ln(SL_m) = \ln(A) + bt. \tag{2c}$$

In the first regression analysis, a least-squares fit to Eq. (2c) was performed on each temporal masking curve, allowing the slope and the intercept of that linear equation to vary at each probe level. We refer to this procedure as an *individual* fit, which represents the best possible linear fit to the data. Those fits are shown by dashed lines in Fig. 1. In the second regression analysis, a least-squares fitting procedure was used to obtain the best-fitting straight lines, all with the same slope, at several different masker levels (Seber, 1977). That procedure is referred to as a *parallel* fit (Nelson *et al.*, 1983). The parallel fit obtains the single slope term that best describes the data at all probe levels. Those fits are shown by solid lines in Fig. 1. Comparisons of the variance accounted for by the parallel-fitting procedure with the variance accounted for by the more traditional individual-fitting procedure, one that allows both the intercept and the slope of the best-fitting straight line to vary with probe level, can provide evidence for the validity of the assumption of a level-independent time constant.

The relative amounts of variance accounted for by the individual-fitting procedure (R^2, I) and the parallel-fitting procedure (R^2, P) are compared in Table I for the normal-hearing listeners. In ten of those listeners, the F ratios (Steel and Torrie, 1980) indicate that the individual fit was not significantly better than the parallel fit; in two (KN and ZB) it was. However, in those two "worst-case" listeners, the individual fit was observably different from the parallel fit at only one probe level [as seen in Fig. 1(c) for subject KN], and the difference was not in the same direction for the two listeners. We assume that the significant differences between the individual fit and the parallel fit in these two listeners are due to measurement error. These results indicate that, for normal-hearing listeners, a single time constant can adequately describe temporal masking curves at all probe levels tested, and that the assumption of a level-independent time constant is reasonable.

Temporal masking curves obtained from the hearing-impaired listeners were subjected to the same curve-fitting procedures used to examine the single time constant assumption in normal-hearing listeners. Temporal masking curves from two of the hearing-impaired listeners, together with sensitivity-curve insets for 200-ms test tones, are shown as examples in Figs. 2 and 3. A summary of the results of the parallel-fit analyses for the hearing-impaired listeners is included in Table II. Note that the results are grouped in Table II according to the outcome of the experiment. The first 11 listeners in Table II demonstrated significant hearing loss at the probe frequency and abnormal time constants. The next three (identified by a [b]) demonstrated significant hearing loss at the probe frequency but their time constants were normal. The final two (identified by a [c]) demonstrated normal hearing at the probe frequency and normal time constants, even though they also had sizable hearing losses at frequencies above the probe frequency.

As indicated by the F ratios in Table II, in 14 of the 16 hearing-impaired listeners, the relative amount of variance accounted for by the parallel fit (R^2, P) was not significantly different from that accounted for by the individual fit (R^2, I). From this, we conclude that temporal masking curves from these hearing-impaired listeners can also be ade-

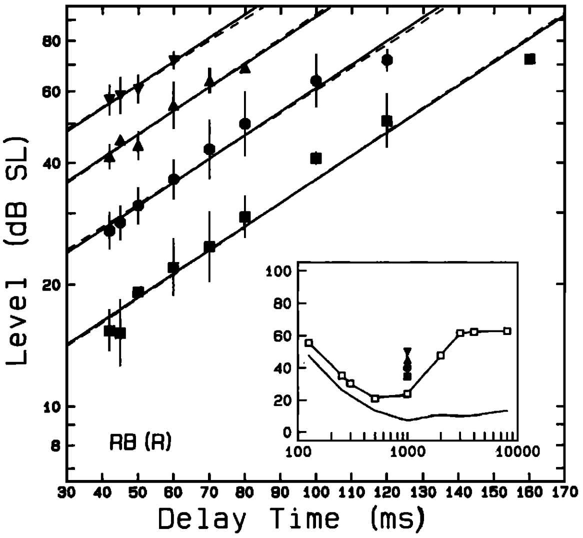

FIG. 2. Temporal masking curves from hearing-impaired listener RB(R). Legend as in Fig. 1. The sensitivity curve (inset) shows thresholds for 200-ms test tones. The filled symbols in the inset indicate the probe levels that were tested.

TABLE II. Variance accounted for by individual fits (R^2, I) and parallel fits (R^2, P) using Eq. (2c): hearing-impaired listeners.

Subject	Ltpp	Ltpm	R^2, I	R^2, P	F	(df)
DA(L)	56.9	53.7	0.95	0.95	0.28	(2,18)
EP(R)	60.9	57.9	0.98	0.98	1.77	(1, 8)
GR(R)	57.8	54.8	0.97	0.97	0.0005	(1, 9)
HD(R)	56.8	53.1	0.92	0.92	0.0005	(1, 8)
HK(R)	27.5	23.8	0.97	0.96	2.43	(2,16)
LC(R)	46.8	43.0	0.91	0.90	1.69	(1,13)
MR(L)	23.4	18.7	0.96	0.95	2.98	(1,10)
RA(R)	55.6	53.0	0.96	0.96	0.28	(1, 8)
RB(R)	29.2	24.2	0.97	0.97	0.09	(3,19)
SJ(R)	26.0	19.2	0.97	0.96	1.51	(2,12)
IW(L)	61.0	58.3	0.96	0.88	22.66	(1,12)[a]
DK(R)[b]	41.1	37.5	0.97	0.97	0.11	(2, 7)
MR(R)[b]	21.4	17.1	0.98	0.94	21.50	(1, 8)[a]
LS(R)[b]	31.3	23.4	0.97	0.97	1.58	(2,14)
TK(L)[c]	14.0	5.5	0.98	0.97	1.17	(2,15)
XB(L)[c]	13.1	5.4	0.94	0.92	1.25	(1, 5)

[a] F ratio significant at $p = 0.05$.
[b] Hearing loss at the probe frequency and normal time constants.
[c] Normal hearing at the probe frequency, normal time constants, and significant hearing losses at frequencies higher than the probe.

quately described by a single time constant that is independent of probe level.

Temporal masking curves from two of the hearing-impaired listeners did not follow this trend. In one listener, MR(R), the individual fit accounted for significantly more variance than did the parallel fit, which suggests that a single time constant may not be appropriate to describe the results. However, an examination of the time constants obtained with the individual fits indicates that both time constants are within the range of normal time constants, as was the time constant obtained with the parallel fit. For listener IW(L), the individual fits also accounted for significantly more variance than the parallel fit. In this case, the time constants obtained with the individual fits (214 and 117 ms at 9 and 14 dB SL_p) cannot be well described by a single time constant, although both fall outside the range of normal.

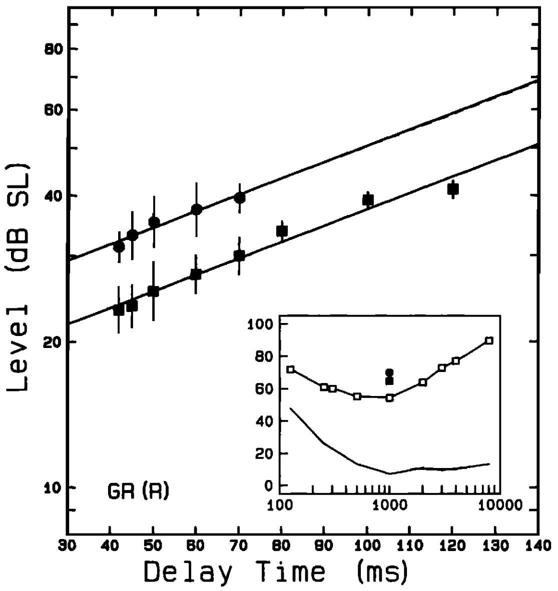

FIG. 3. Temporal masking curves from hearing-impaired listener GR(R).

B. Time constants and hearing loss

The relation between time constants and amount of hearing loss was determined by obtaining an objective estimate of the time constant for each listener, and then examining the regression between time constants and hearing loss. Objective estimates of time constants were accomplishing by a simplex fit to Eq. (1), with $k = 1.0$, for each listener's temporal masking curves. The estimated time constants resulting from those fits are shown in the top panel of Fig. 4 (values given in Tables III and IV). Time constants are plotted as a function of the amount of hearing loss at the probe

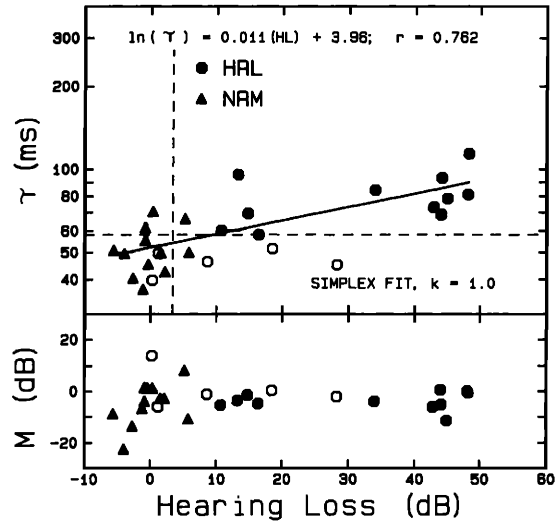

FIG. 4. Scattergrams of time constants τ and sensitivity constants M as a function of hearing loss. Parameters estimated with the slope of the growth of masking $k = 1.0$. Normal performance cutoff criteria are indicated by the dashed lines. Triangles: normal-hearing listeners. Octagons: hearing-impaired listeners. Parameters of the linear regression between τ and hearing loss are given in the top panel. Open symbols: data not included in the regression analysis (see text).

TABLE III. Model parameters for Eq. (1) with unit slope and variable slope (k): normal-hearing listeners.

	Simplex fit, $k = 1.0$			Simplex fit, k = var			
Subject	τ	M	R^2	τ	M	k	R^2
CT(L)	61.4	−3.84	0.7755	50.2	−12.03	1.42	0.8938
DN(L)	45.6	1.07	0.9719	44.5	0.57	1.05	0.9735
JG(R)	55.4	1.65	0.9635	52.9	0.44	1.10	0.9676
JI(L)	40.5	−13.44	0.7761	32.5	−22.83	1.69	0.8877
KN(L)	36.8	−6.49	0.9562	38.8	−4.89	0.90	0.9556
LJ(R)	45.9	−6.34	0.9324	49.0	−4.75	0.87	0.9300
MK(L)	49.8	−22.43	0.7014	49.2	−24.36	1.05	0.7333
MZ(L)	51.0	−8.77	0.8749	45.4	−12.29	1.29	0.9106
RA(L)	42.8	−2.66	0.7743	65.6	20.08	0.47	0.9425
TO(R)	66.6	8.22	0.8680	77.4	10.54	0.84	0.8732
VS(R)	50.0	−2.61	0.8687	60.1	0.85	0.70	0.8837
ZB(R)	50.1	−10.84	0.9717	50.9	−10.48	0.97	0.9714
Means	49.7	−5.54	0.8696	51.4	−4.93	1.03	0.9102
s.d.	8.5	7.93	0.0935	11.9	12.76	0.33	0.0665

frequency for the 20-ms probe tone. Data for both normal-hearing and hearing-impaired listeners are indicated.

The cutoff criterion for normal performance on either task (mean plus one standard deviation) is given by a dashed line. From this, we see that 11 of the 14 hearing-impaired listeners, whose sensitivity thresholds at the probe frequency were above the normal cutoff criterion, demonstrated time constants that were above the cutoff criterion for normal time constants. This observation, alone, might lead one to qualitatively conclude that listeners with cochlear hearing loss take longer to recover from auditory stimulation and therefore should perform poorly on tasks that require temporal analysis.

However, the relation between time constants and hearing loss appeared strong enough to attempt a more quantitative description. As indicated by the scattergram, the relationship between the size of the time constant and the amount of hearing loss is positive and fairly strong, with a correlation coefficient of 0.76, but it is not perfect, as is discussed below. The linear regression between time constants and hearing loss is shown by the solid line in the top panel of Fig. 4, with the parameters of that regression indicated at the top of the graph. The regression analysis indicates that, when the slope of the growth of masking k is unity, the time constant τ grows exponentially with hearing loss HL according to Eq. (3a)

$$\tau = 52.5e^{0.011(\mathrm{HL})} . \tag{3a}$$

However, it should be noted that not all of our listeners with significant hearing loss demonstrated abnormal time

TABLE IV. Model parameters for Eq. (1) with unit slope and variable slope (k): hearing-impaired listeners.

	Simplex fit, $k = 1.0$			Simplex fit, k = var			
Subject	τ	M	R^2	τ	M	k	R^2
DA(L)	93.3	−5.18	0.9019	92.1	−5.57	1.03	0.9060
EP(R)	80.8	−0.08	0.7456	127.6	5.41	0.61	0.9718
GR(R)	78.4	−11.46	0.9516	79.7	−11.18	0.97	0.9504
HD(R)	68.8	0.65	0.8972	90.3	7.13	0.62	0.9328
HK(R)	69.4	−1.61	0.8614	94.3	5.26	0.60	0.9451
LC(R)	84.5	−3.75	0.6855	154.4	7.49	0.44	0.8848
MR(L)	60.3	−5.40	0.9204	87.3	11.46	0.49	0.9497
RA(R)	73.2	−6.03	0.9525	80.9	−3.70	0.85	0.9527
RB(R)	58.1	−4.94	0.9160	72.1	−0.75	0.68	0.9632
SJ(R)	95.9	−3.71	0.9462	103.0	−2.98	0.94	0.9497
IW(L)	113.7	−0.67	0.6336	211.9	7.04	0.53	0.8488
Means	79.7	−3.83	0.8556	108.5	1.78	0.71	0.9323
s.d.	16.6	3.43	0.1135	41.7	6.99	0.21	0.0373
DK(R)[b]	45.2	−2.18	0.8020	59.2	2.21	0.65	0.8824
LS(R)[b]	51.7	0.29	0.9403	64.0	4.73	0.67	0.9687
MR(R)[b]	46.3	−1.13	0.9224	60.8	3.63	0.61	0.9463
TK(L)[c]	49.9	−6.13	0.9503	48.7	−7.02	1.05	0.9526
XB(L)[b]	39.7	13.66	0.9231	42.0	14.70	0.89	0.9192

[b] and [c] as in Table II.

constants. Evidence of the less than perfect relationship between hearing loss at the probe frequency and the size of the time constant is seen in the results of three of the hearing-impaired listeners who demonstrated normal time constants, even though they had significant hearing losses at the probe frequency (identified by open symbols in Fig. 4 and by a [b] in Tables II and IV). This suggests that in some hearing-impaired listeners the mechanisms underlying sensitivity loss may not be the same mechanisms that are responsible for lengthened time constants. Stated differently, some pathologies that produce sensorineural hearing loss may also result in slow recovery, while others may not.

This latter finding is supported further by retest results for listener LS(R) after a 32-dB increase in sensorineural hearing loss at the probe frequency. Despite the large change in sensitivity, the time constant did not change proportionately. It was 51.7 before the sensitivity change and 58.9 ms afterward. Such a dramatic change in hearing sensitivity without a concomitant change in time constants emphasizes the possible independence of underlying mechanisms that account for sensitivity loss and recovery from auditory stimulation.

Finally, our assumption that this fixed-probe-level procedure should obtain good frequency specificity is supported by the results of the two hearing-impaired listeners whose sensitivity thresholds were normal at the probe frequency but who demonstrated significant hearing losses at frequencies above the probe frequency. Both listeners (indicated in Fig. 4 by open symbols and in Tables II and IV by a [c]) demonstrated time constants that were normal, which suggests that this particular temporal-resolution task is quite frequency specific and that hearing losses at frequencies above the probe frequency have very little influence on this fixed-probe measure of the time course of forward masking.

C. Sensitivity to adaptation and hearing loss

In these experiments, both the masking tones and the probe tones were at the same frequency, and are presumably subject to the same underlying physiologic mechanisms, such as auditory filters, which might differentially affect the growth of sensory response to the masker or the probe, thereby affecting the slope of the growth of masking. This reasoning does not provide us with any obvious, *a priori*, reasons to expect the slope k of the growth of masking at $t = 0$ to be other than 1.0, for either normal-hearing or hearing-impaired listeners, except for off-frequency listening arguments appropriate with high-level simultaneous masking, which are unlikely to occur in this nonsimultaneous masking task. Therefore, it seemed appropriate to examine M, which we refer to as a sensitivity constant, while holding $k = 1.0$ in Eq. (1).

In the context of Eq. (1), sensitivity constants indicate the intercepts of the growth of masking functions, in dB SL, at a delay time of $t = 0$. For example, a sensitivity constant M of -5 means that the threshold of the probe tone was not raised above quiet threshold until the masker level had reached 5 dB SL, i.e., $SL_m = 5$ dB for $SL_p = 0$.

Sensitivity constants M, obtained using a simplex fit with $k = 1.0$, are given in Table III for the normal-hearing listeners and Table IV for the hearing-impaired listeners. For both groups, sensitivity constants are plotted as a function of hearing loss in the bottom panel of Fig. 4. The group mean sensitivity constant is -5.5 dB for the normal-hearing listeners, with a range across subjects from -22.4 to $+8.2$ dB. The group mean sensitivity constant for the 11 hearing-impaired listeners with significant hearing loss at the probe frequency and abnormal time constants is -3.8 dB, with a range from -11.5 to $+0.7$ dB. The mean of the sensitivity constants for hearing-impaired listeners is not significantly different from the mean for normal-hearing listeners ($p = 0.0005$); therefore, one would not expect any variation in sensitivity constants with hearing loss, an expectation that is confirmed by the plot of sensitivity constants M in the bottom panel of Fig. 4. From this, we conclude that our hearing-impaired listeners are not more sensitive to adaptation than normal-hearing listeners.

The degree to which Eq. (1) can describe the normal-hearing data with only two free parameters (τ and M), and with both independent variables t and SL_p being considered, is given in Table III by R^2 under the column labeled simplex, $k = 1.0$. On the average, 87% of the variance was accounted for by the two parameters. In eight of those listeners, the two parameters accounted for more than 80% of the variance. In the remaining four, the fits were less exciting, but still better than 70% of the variance was accounted for.

The total proportion of variance accounted for by τ and M for the hearing-impaired listeners is shown in Table IV. On the average, 86% of the variance was accounted for by the two parameters for the first eleven listeners in Table IV, those with substantial hearing loss at the probe frequency. For eight of those listeners, and for the remaining five listeners at the bottom of Table IV, the two parameters accounted for more than 80% of the variance. Fairly good fits to the data, for most listeners, can be obtained with a slope of 1.0 in both normal-hearing and in hearing-impaired listeners.

These results suggest that temporal masking curves from both normal and hearing-impaired listeners can be described with some precision by Eq. (1). The major difference between the two types of listeners is the time constant τ which is larger in hearing-impaired listeners than in normal-hearing listeners. A comparison of the sensitivity constants M shows that the two groups are not different on the average. These results indicate that hearing-impaired listeners are not more or less susceptible to forward masking than normal-hearing listeners. Given a probe sensation level that is the same for both types of listeners, and given a presumed slope of the growth of masking of 1.0 at an extrapolated delay time of zero, the hearing-impaired listeners do not require more or less masker sensation level to mask that probe, but they do require slightly longer times to recover from stimulation.

D. Slope of the growth of masking

Throughout the comparison of the normal-hearing and hearing-impaired data, and the calculations of time constants and proportionality constants, the slope of the relation between SL_p and SL_m, i.e., the slope of the growth of masking k, was restricted to unity. Given that restriction, we were able to achieve satisfactory fits for most of the listeners. However, the fits for some of the listeners were less than perfect. Examination of the percentage of total variance accounted for in individual temporal masking curves, assuming $k = 1.0$ in Eq. (1), showed that in 7 out of 28 listeners less than 80% of the variance could be accounted for. This indicates that the restriction of the slope of the growth of masking to 1.0 might be considered to be a severe restriction for a small proportion of listeners. Much better predictive accuracy should be achievable simply by including a third free parameter in the equation, namely, the slope of the growth of masking that is represented in Eq. (1) as k.

In general, the slope of the growth of masking (k) can be thought of as a ratio between the slope of the growth of sensory response to the masker, at the masker frequency (S_{mf}), and the slope of the growth of sensory response to the probe, at the probe frequency (S_{pf}), as in $k = S_{mf}/S_{pf}$. Assuming the detection criterion to be constant, any mechanism that affects one slope slightly more than the other could be reflected in the slope of the growth of masking k. In this case, the masker and probe frequencies are identical. Therefore, any physiological gain mechanism that is fundamentally frequency dependent, such as an auditory filter, should not introduce differential effects on S_{mf} or S_{pf}, and the proposed relation reduces to $k = S_m/S_p$. On the other hand, in these forward-masking experiments, the masker sensation level SL_m is always larger than the probe sensation level SL_p that is to be adapted (forward masked) to threshold. This circumstance often involves widely disparate stimulus levels, with the masker more intense than the probe. If the underlying system is nonlinear, the masker and the probe could essentially be at different operating levels and thereby be subject more or less to that nonlinearity, which might alter the slope of the growth of response to one relative to the other.

Consequently, a more detailed evaluation of the slope of the growth of masking in individual subjects was carried out by allowing k in Eq. (1) to vary as a third free parameter during the simplex fits. As expected, better precision was achieved by including the slope term than by forcing the slope to unity. The estimated parameters and the percentage of variance accounted for are given in Table III for the normal-hearing listeners and in Table IV for the hearing-impaired listeners under the column labeled simplex, $k =$ var. In 16 out of all 28 listeners, the percentage of variance accounted for with the slope term as a free parameter was greater, by at least 1%, than with the slope term fixed at unity. Given this increased precision, the effects of the slope term on the parameter estimates varied among listener groups.

For the normal-hearing listeners, the resulting parameter estimates are plotted in Fig. 5. As seen in the top panel of Fig. 5 (and listed in Table III), time constants τ tended to be more variable across subjects with k as a free parameter (s.d. of 11.9 vs 8.5), but the average time constant across subjects did not change significantly (mean of 51.4 vs 49.7), and the average sensitivity constant M did not change significantly (mean of -4.9 vs -5.5). The slopes of the growth of masking k, shown in the bottom panel of Fig. 5, tended to

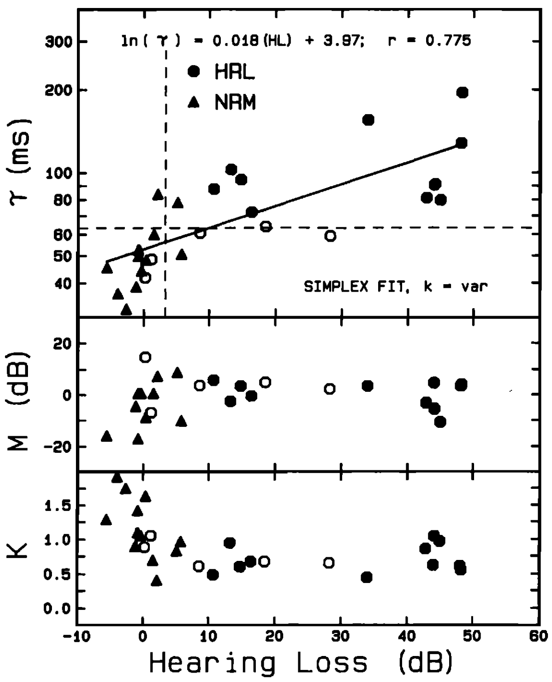

FIG. 5. Scattergrams of time constants τ, sensitivity constants M, and growth of masking slopes k as a function of hearing loss. Parameters estimated with the slope of the growth of masking $k =$ var, i.e., as a free parameter. Legend as in Fig. 4.

vary around a slope of 1.0 for the normal-hearing listeners, and the average slope of masking (1.03) was not significantly different from a slope of 1.0 ($p = 0.05$). When a slope term is included in Eq. (1), neither time constants nor sensitivity constants change significantly and the slope stays near unity. We regard this as evidence to support the general use of a unity slope term in Eq. (1) for composite data from normal-hearing listeners.

Parameter estimates, with k as a free parameter, for the hearing-impaired listeners are also plotted in Fig. 5. Contrary to the normal-hearing listeners, allowing k to vary did significantly affect the parameter estimates. First of all, there were no significant effects on sensitivity constants. The average sensitivity constant M was 1.8, which was not significantly different from the -3.8 sensitivity constant obtained previously with $k = 1.0$. On the other hand, it appeared that including a slope term did affect estimates of time constants in the hearing-impaired listeners. The time constants increased remarkably, with the average time constant changing from 79.7 to 108.5 ms. The slopes of the growth of masking k were less than 1.0 for 10 out of 11 listeners with hearing loss at the probe frequency. Contrary to the normal-hearing listener's data, for these listeners the average slope of masking (0.71) was significantly different from a slope of 1.0, and was significantly flatter than the mean slope (1.03) for the normal-hearing listeners. This means that to produce the most precise fit with hearing-impaired data, a slope term should be included in Eq. (1). When that is done, the sensitivity constants do not change but the time constants are longer and the slope of the growth of masking estimated in this way (at $t = 0$) is more gradual.

As indicated by the scattergram in the top panel of

Fig. 5, when the slope of the growth of masking is allowed to vary, the quantitative relationship between the size of the time constant and the amount of hearing loss is still a fairly strong positive one (correlation coefficient of 0.78). The linear regression between time constants and hearing loss is shown by the solid line, and the parameters of the regression analysis are indicated at the top of the graph. That regression indicates that, when the slope of the growth of masking (k) is allowed to vary, the time constant (τ) grows exponentially with hearing loss (HL) according to Eq. (3b)

$$\tau = 53.0e^{0.018(\mathrm{HL})} . \tag{3b}$$

The major difference between Eqs. (3a) and (3b) is in the slope of the relation between time constants and hearing loss, which changes from 0.011 to 0.018. Including a slope term k for the growth of masking in Eq. (1) yields longer time constants, more so for the larger time constants, so that the effect of hearing loss on time constants appears somewhat greater.

From these data, we have no way of estimating the rate of growth of sensory response to either the masker or the probe alone; however, a flatter slope of the growth of masking in hearing-impaired listeners does suggest that there might be differential mechanisms operating on the sensory response to masker and probe in these listeners. That the slope of masking (k) is less than 1.0 suggests that either the slope of the growth of response to the probe (S_p) is larger (steeper) than normal, or that the slope of the growth of response to the masker (S_m) is smaller (flatter) than normal. This follows from the assumption that $k = S_m/S_p$.

It is tempting to speculate that the mechanism underlying abnormal loudness recruitment associated with cochlear hearing loss is the same mechanism responsible for the steeper rate versus intensity functions seen for tones near to the characteristic frequency of neural fibers in damaged cochleas (Harrison, 1981). And, further, that it is the same mechanism that leads to a steeper probe response growth rate S_p for low-SL probe tones relative to the masker response growth rate S_m for the higher SL masking tones required in this forward-masking task.

On the other hand, a mechanism that reduces the slope of the growth of response to the masker S_m could also account for the more gradual slope of the growth of masking k in these hearing-impaired listeners. Since the hearing-impaired listeners were tested at higher SPLs, due to the requirements of their hearing losses, one might look to high-SPL mechanisms to explain a more gradual slope of growth of masker response S_m. Unfortunately, it is next to impossible to obtain forward-masked thresholds from normals for probe SPLs that are comparable to those used with hearing-impaired listeners.

Finally, these fits of growth of masking functions for the hearing-impaired listeners should be interpreted with caution, because 9 of the 16 listeners could only be tested at two probe levels and the validity of slope estimates from only two data points is questionable. The data from listeners tested at only two probe levels can be identified in Table II by the value of 1 for the first degree of freedom.

E. Temporal resolution deficits

We have demonstrated that listeners with cochlear hearing loss tend to have longer time constants than normal-hearing listeners, that their sensitivity to forward masking is not different from normal, and that their time constants grow exponentially with the amount of hearing loss. Subsequently, they are poorer than normal on this type of temporal-resolution task. However, we have not addressed how those lengthened time constants translate into deficiencies in auditory analysis, deficiencies that may have deleterious effects on the ability to discriminate complex acoustic signals like speech. The most direct way is to examine the detectability limits implied by lengthened time constants, i.e., the time and intensity relations of detectable sequential stimuli. Those detectability limits can be most easily appreciated by examining the **masked thresholds** that are predicted from the results reported here. These are shown in Fig. 6(a) by the generalized forward-masking (or adaptation) recovery curves for a typical normal-hearing listener and for a hearing-impaired listener, IW(L).

The curves in Fig. 6 (and Fig. 9) were generated using Eq. (1) with values for τ and M determined by our results. For this illustration, the mean values in Tables I and III ($k = 1.0$) were used to represent parameter values for a typical normal-hearing listener, and individual parameter values for listener IW(L) in Tables II and IV ($k = 1.0$) were used for the hearing-impaired example. We chose listener IW(L) because her time constant was the longest obtained by any of our hearing-impaired sample ($\tau = 113.7$ ms) and her hearing loss was also the largest (52 dB for 200-ms tones). We also elected to plot predicted data for delay times (t's) between 2 and 800 ms to illustrate the more general, and somewhat idealized, form of the exponential recovery curve that we have shown to represent our data quite well. This

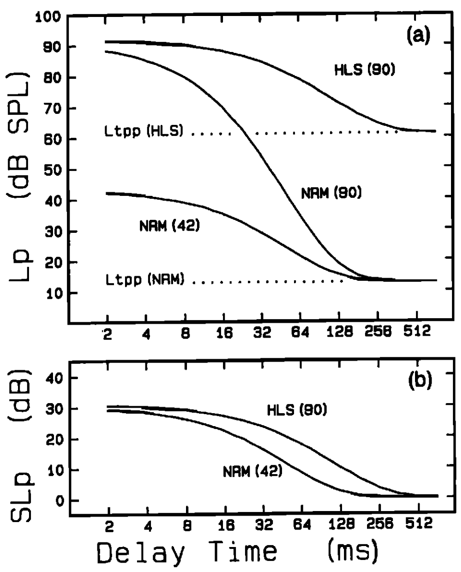

FIG. 6. Generalized forward-masking (or adaptation) recovery curves from Eq. (1) for a "typical" normal-hearing listener (NRM) and for one hearing-impaired listener (HLS). (a) Masked thresholds; and (b) the amount of masking. Curves are shown for two masker SPLs (90) and (42). Dotted lines indicate sensitivity thresholds.

simplified form of the recovery curve was chosen to illustrate our points, even though our results only directly apply for delay times longer than 40 ms, and Eq. (1) only includes a single time constant, where a second, shorter, time constant has been shown to be more appropriate for delay times shorter than our 40 ms (Duifhuis, 1973; Widin and Viemeister, 1979).

For the typical normal-hearing listener, recovery from adaptation to a 90-dB SPL masker follows the time course of the solid curve labeled NRM(90) in Fig. 6(a). Masked thresholds in the normal ear recovered from around 90 dB SPL right after masker termination down to about 13 dB SPL at 256 ms, which is more than 77 dB of recovery. For the hearing-impaired listener, recovery from the same stimulus follows the more gradual time course of the solid curve labeled HLS(90).

The first point to be made about hearing-impaired recovery curves is that they do not simply follow the time course of recovery of the normal curve down to hearing-loss threshold levels, as would be the case if the sensitivity loss were a pure attenuative factor on the signal alone and recovery were simply dependent upon the SPL of the masker. In terms of masked thresholds, the recovery curve from the impaired ear is obviously extended in time, and indicates that a wide range of sequential stimuli, that are detectable for the normal ear, are not detectable for the impaired ear. As shown by the solid curve labeled HLS(90) in Fig. 6(a), masked thresholds in the impaired ear recovered from around 90 dB SPL right after masker termination down to about 64 dB SPL by 256 ms, which is only about 26 dB of recovery in the same period of time. Stated differently, the normal ear recovered 26 dB by 25 ms, while the impaired ear required 256 ms to recover by the same amount, an order of magnitude difference in the time required to achieve the same amount of recovery.

These general characteristics of recovery curves, predicted from our fixed-probe-level results, are also consistent with forward-masking data collected by other investigators with the more traditional fixed-masker-level procedure. This is evidenced in Fig. 7, which shows forward-masking recovery curves obtained by Tillman and Rosenblatt (1975)

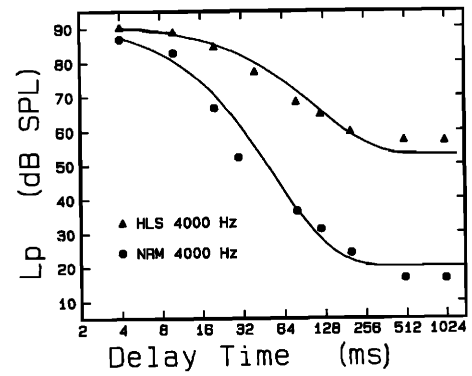

FIG. 7. Forward-masking (adaptation) recovery curves obtained by Tillman and Rosenblatt (1975). The two curves compare the recovery process for a group of ten normal-hearing listeners (NRM) with that for a group of ten hearing-impaired listeners (HLS). The solid curves are exponentials with time constants of 55 ms for NRM and 110 ms for HLS.

from a group of normal-hearing and a group of ten sensorineural hearing-impaired listeners who demonstrated no appreciable tone decay. The masker was a 90-dB SPL, 600-Hz-wide band of noise centered at 4000 Hz with a duration of 4 s. The probe was a 20-ms, 4000-Hz tone burst. Delay time is expressed as the time between masker offset and probe offset. Here we see that the normal-hearing listeners demonstrate steeper recovery, over a much wider range of levels, than the hearing-impaired listeners, just as predicted by our results. For comparison, we have also plotted two exponential recovery curves, one with a 55-ms time constant for the normal-hearing group and the other with a 110-ms time constant for the hearing-impaired group. The exponential recovery curves describe the main features of the two sets of data, with the most prominent differences being accounted for by time constants that differ by a factor of 2.0. Therefore, we feel confident that the predictions of Eq. (1), with the parameters obtained from our fixed-probe-level results, are consistent with previous data.

Although the normal ear, depicted in Fig. 6, recovered by an order of magnitude faster and showed over 50 dB more recovery than the abnormal ear in the same period of time, it is certainly not appropriate to ascribe these types of differences to a temporal resolution mechanism and call it a **temporal resolution deficit**, since it is obvious that the **sensitivity deficit** alone, indicated by the dotted lines in Fig. 6, precludes detection below 61 dB SPL for this listener. While appropriate for considering which signals are detectable at various post-stimulus times in the two types of ears, as we will return to later, this type of plot of recovery curves does not differentiate temporal resolution deficits from sensitivity deficits. In order to consider deficits solely related to a temporal-resolution mechanism, it is necessary to factor out deficits attributable to a loss in sensitivity.

To do this, we first consider a fundamental characteristic of forward masking and its recovery over time. Due to the exponential nature of the recovery process in forward masking, the rate of recovery (in dB per unit time) is faster for greater amounts of masking, i.e., the larger the sensory response [$(SL_m + M)$ in Eq. (1)], the faster is the rate of recovery. This is demonstrated quite clearly by the recovery curves in Fig. 8 for normal-hearing listeners, replotted from the recent work of Jesteadt *et al.* (1982), where successive curves are shown for 20, 40, 60, and 80 dB SPL, 300-ms tonal maskers. The lower stimulus elicits a lower sensory response, which exhibits more gradual recovery.

This is illustrated further in Fig. 6(a) by comparing the slopes of the recovery curve for the 90-dB SPL stimulus, NRM(90), with the slopes of the curve for the 42-dB SPL stimulus, NRM(42). Notice that the time course of recovery for the hearing-impaired listener exposed to 90 dB SPL, HLS(90), is very similar to the time course of recovery for the normal-hearing listener exposed to 42 dB SPL, NRM(42). It appears that the recovery curves from normal and impaired ears may both be dependent on the magnitude of the sensory response evoked by the stimulus, rather than on the level of the physical stimulus (SPL).

To examine that possibility further, the 42-dB SPL stimulus level in Fig. 6 was chosen because it produced the same

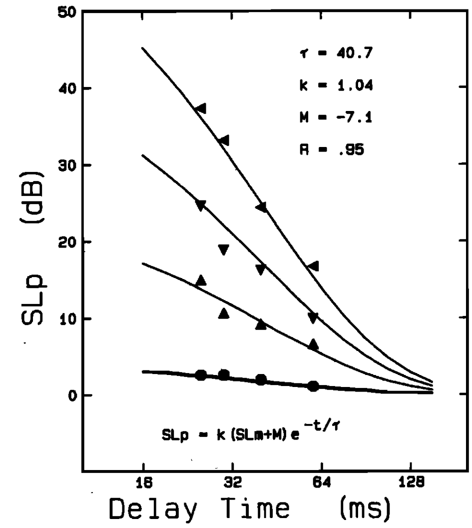

FIG. 8. Forward-masking (adaptation) recovery curves obtained by Jesteadt *et al.* (1982) from normal-hearing listeners at tonal masker levels of 20, 40, 60, and 80 dB SPL (from bottom to top). A fit of the data to Eq. (1) yielded the indicated parameter estimates. Progressively steeper recovery curves with increases in masker level illustrate a fundamental property of forward masking, i.e., higher masker levels yield faster recovery in dB per unit time.

sensory response [$(\mathrm{SL}_m + M) = 31$ dB] in the hearing-impaired listener as it did in the average normal-hearing listener. With sensory response equated in this way, a comparison of the two functions should only show differences related to temporal resolution, as is illustrated in Fig. 6(b), where the **amount of masking** is plotted as a function of recovery time. With sensory response equated in this way, the only difference between the curves is a horizontal shift, which simply reflects the different time constants of the two curves. We see that the rate of recovery (in dB per unit time) is the same for the two curves, the major effect being a delayed recovery process that can be specified as the ratio of the two time constants. In terms of the amount of masking at different delay times, the difference between the two curves never exceeds 10 dB (at 80 ms the difference is 9.2 dB), not nearly as great as the 77-dB difference exhibited when comparing masked thresholds. Stated differently, the impaired ear required delay times that were longer than normal by a factor of 2.3, the ratio of the impaired to the mean normal time constant (113.7/49.7).

By comparing recovery curves at equivalent sensory response levels, as Fig. 6(b), we can examine the effects of hearing losses on the temporal-resolution mechanism somewhat independently of the sensitivity loss. In this case, differences in the amount of masking between normal and impaired ears at any particular delay time are much smaller than the differences in masked thresholds shown earlier. This type of comparison, at equivalent amounts of masking, provides a way to examine temporal effects with sensitivity effects factored out, which, of course, is equivalent to fitting an exponential function to temporal masking data expressed as amount of masking, as was done earlier in this paper to estimate the time constant τ.

As is illustrated in Fig. 6(b), the time constant tells us about the temporal resolving capabilities of the system under evaluation, quite independent of sensitivity effects. Deficiencies in those temporal resolving capabilities, or temporal-resolution deficits, can be expressed conveniently as ratios of "abnormal" to "normal" time constants. For listener IW, the temporal-resolution deficit was 2.3. From the equations at the top of Figs. 4 and 5, we see that, for the listeners tested here, temporal-resolution deficits are dependent upon hearing loss (HL) and can be expressed as $e^{0.011(\mathrm{HL})}$ when $k = 1.0$ or as $e^{0.018(\mathrm{HL})}$ when $k = \mathrm{var}$.

F. Combined temporal-resolution deficits and sensitivity deficits

While the time constant provides an estimate of the temporal-resolution deficit, it essentially "hides" the sensitivity deficit. In order to consider the true effects a hearing loss might have on the ability to detect sequential signals, both types of deficits must be considered.

The combined deficit is schematized in Fig. 9, where we plot predicted masked thresholds for the typical normal ear, NRM(90), along with those from the impaired ear, HLS(90). Here, the shaded areas between the two curves illustrate the combined temporal-resolution and sensitivity deficits. Over the range of delay times actually measured in our experiments, the shaded areas show the time and intensity conditions that cannot be detected by the impaired ear but can by the normal. The total area is substantial, representing a large total deficit, but most of it is due to the sensitivity loss and to the fact that recovery is dependent upon the magnitude of the sensory response to the masker not to the masker SPL. Large sensitivity losses reduce the sensory response to high-SPL maskers, so that the sensory response is less than it is for normals exposed to the same high-SPL masker, and, consequently, the recovery process is dramatically slower

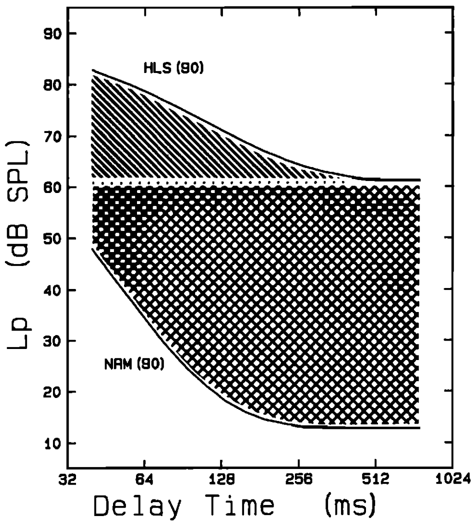

FIG. 9. Generalized recovery curves from Eq. (1) for the range of delay times used in these experiments. The shaded area illustrates the combined temporal-resolution and sensitivity deficits in an impaired ear. The area emphasizes the range of times and intensities for which sequential signals are detectable by the normal ear but are not detectable by the impaired ear.

than it is for normals, much slower than would be indicated by a comparison of time constants alone.

From this discussion, it appears that the effects of hearing loss on temporal resolution are significant. Time constants grow exponentially with the amount of hearing loss and can be up to 2.3 times poorer than normal for hearing losses over 50 dB. However, the most dramatic effect on the region of detectability of sequential signals is due to the sensitivity loss and to the fact that recovery from forward masking is inherently an exponential process that is dependent upon the magnitude of sensory response elicited by the masker, i.e., the fastest recovery occurs for the largest sensory response. Since sensitivity loss limits sensory response, it also produces a recovery process that is much longer than normal.

III. CONCLUSIONS

Exponential equations for predicting temporal masking curves are used to compare forward masking in normal-hearing and hearing-impaired listeners. One form of the equation contains only two free parameters: τ, the time constant of recovery from forward masking or adaptation, and M, a proportionality constant for forward masking. A second form includes a third parameter k, the slope of the growth of masking. Stepwise regression analyses of forward-masking data from 12 normal-hearing and 16 hearing-impaired listeners lead to the following conclusions.

Single time constants, τs, can adequately describe fixed-probe-level temporal masking curves obtained from individual normal-hearing or hearing-impaired listeners. These time constants appear to be independent of level over the range of probe levels investigated (5–30 dB SL). Time constants from normal-hearing listeners ranged from 37–67 ms with a mean of 50 ms.

Time constants demonstrate a strong positive relation with hearing losses at the probe frequency ($r = 0.76$), given by $\tau = e^{0.011(\mathrm{HL})}$ for $k = 1.0$, and by $\tau = e^{0.018(\mathrm{HL})}$ for $k =$ var. Listeners with significant hearing loss at the probe frequency generally demonstrate time constants in excess of 67 ms. That relation is not perfect, since a few listeners with significant hearing loss at the probe frequency also showed normal time constants, suggesting that some other characteristic of the hearing disorder besides sensitivity at the probe frequency might be important as well.

This technique for estimating time constants appears to be frequency (or place) specific, since the hearing-impaired listeners with sizable sensitivity losses at high frequencies and normal hearing at the probe frequency demonstrated normal time constants.

A sensitivity constant for forward-masking M describes the sensation level of the masker that is required to begin to mask the probe tone, irrespective of the delay time between masker and probe. This sensitivity constant can be derived by extrapolating forward-masking functions to a delay time of zero. There is no significant difference between the mean sensitivity constants determined in this way for normal-hearing and hearing-impaired listeners, although those constants tend to vary more among normal-hearing listeners. From this, it appears that hearing-impaired listeners, as a group, do not require different amounts of masking than normal-hearing listeners to mask comparable sensation-level probe tones.

Group data for both types of listeners, and most of the individual data, can be adequately described by a growth of masking slope k of 1.0, as long as the time constant is known and its effects are removed. With the two-parameter equation, shown in Eq. (2a), the slope of the growth of masking is determined solely by the time constant, and longer time constants result in steeper **apparent** slopes of the growth of masking. If the time constant is not factored out, those listeners with the longest time constant will appear to have the steepest slope of the growth of forward masking. Since we have shown that hearing-impaired listeners do have longer time constants, they will also appear to demonstrate steeper growth of masking functions at any particular delay time.

When a third free parameter, the slope of the growth of masking k, is allowed in the fitting procedure, slopes of individual growth of masking functions are not significantly different from 1.0 for normal-hearing listeners, while they are significantly less than 1.0 for hearing-impaired listeners. From this, we conclude that the slopes of the growth of forward masking are not steeper than normal in hearing-impaired listeners; if anything their slopes may be slightly flatter than normal.

Temporal-resolution deficits grow exponentially with hearing loss (HL) according to the function $e^{0.011(\mathrm{HL})}$ for $k = 1.0$ and $e^{0.018(\mathrm{HL})}$ for $k =$ var. Those deficits can be expressed as ratios of obtained to normal time constants, being as large as 2.3 for a hearing loss greater than 50 dB. In addition to having to deal with elevated sensitivity thresholds, the listener with sensorineural hearing loss must also deal with a significant temporal-resolution deficit.

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[1]The rationale for the assumption that $k = 1.0$, during the initial analyses, is as follows: In our conceptualization of forward masking, the term k, the slope of the growth of masking, is assumed to be a function of the growth rate of neural response to *both* the masker and the probe, as in $k = S_{\mathrm{mf}}/S_{\mathrm{pf}}$, where S_{mf} is the slope of the growth of neural response with masker level, S_{pf} is the slope of the growth of neural response with probe level; neural response might be specified in spikes per second. Because both the masker and the probe tone are at the same frequency, we expect the slope of the growth of neural response to the masker and the probe to be the same. Therefore, there is no *a priori* reason to expect the slope of the growth of masking k to be different from unity. Of course, the *observed* slope of the growth of forward masking is less than 1.0. We propose that this is due to the fact that recovery from adaptation produced by the masker is an exponential process, as in Eq. (1), and that the *observed* slope of the growth of masking has $e^{-t/\tau}$ built into it. Since, in a masking experiment, there is no way to obtain direct estimates of S_{mf} or S_{pf}, we have chosen to assume that they are equal and to express any proportional changes as a change in the time constant τ, by setting $k = 1.0$ during our initial fitting procedures. Later, we allow k to vary and obtain estimates of both k and τ.

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