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AUDITORY TIME CONSTANTS FOR OFF-FREQUENCY FORWARD MASKING IN NORMAL-HEARING AND HEARING-IMPAIRED LISTENERS

DAVID A. NELSON ROSEMARY PAVLOV
University of Minnesota

Previous research has shown that frequency-specific estimates of auditory time constants for recovery from short-term adaptation can be made using a fixed-probe forward-masking procedure (Nelson & Freyman, 1987) if the masker and the probe stimuli are at the same frequency. This study examines the validity of time-constant estimates for off-frequency forward-masking conditions in which the masker frequency is below (900 Hz) or above (1100 Hz) the probe frequency (1000 Hz). Fixed-probe-level temporal masking functions were obtained from four normal-hearing and four hearing-impaired listeners. Auditory time constants were estimated with iterative least-squares procedures to derive parameter values for an exponential model of recovery from forward masking. After appropriate corrections were made for attenuation to the maskers provided by the auditory filter centered at the probe frequency, recovery from forward masking produced by either off-frequency or on-frequency maskers could be described by a single time constant. That time constant was around 50 ms in normal-hearing listeners and was larger in those hearing-impaired listeners who demonstrated moderate hearing loss at the probe frequency.

Since the pioneering work of Gardner (1947), Lüscher and Zwislocki (1946, 1947, 1949), Zwislocki and Pirodda (1952) and Zwislocki, Pirodda, & Rubin (1959), researchers have been concerned with the process of recovery from short-term adaptation in the auditory system. One of the fundamental properties of recovery from adaptation is that it proceeds in a proportional manner, so that a constant proportional amount of recovery (in dB) usually occurs in some fixed period of time, irrespective of the amount of adaptation produced by the adapting stimulus. That general result is demonstrated whether recovery is represented as a linear change in decibels of threshold shift as a function of a logarithmic change in recovery time (Jesteadt, Bacon, & Lehman, 1982; Kidd & Feth, 1981; Plomp, 1964), or as an exponential change in decibels of threshold shift as a function of some linear change in recovery time (Duifhuis, 1973; Nelson & Freyman, 1987). In the latter case, the process of recovery can be described by a *time constant*, which defines the time required for a proportionate amount of recovery to occur.

Psychophysical estimates of time constants for recovery from short-term adaptation have been made repeatedly using variants of the pure-tone forward-masking paradigm. Those estimates are around 50 ms for normal-hearing listeners (Cudahy, 1982; Duifhuis, 1973; Fastl, 1979; Nelson & Freyman, 1987) and have shown an increase of about a factor of 2 in listeners with significant sensorineural cochlear-type hearing losses, when equivalent amounts of masking are compared (Nelson & Freyman, 1987). All of those estimates employed masking tones and probe tones that were at the same frequency.

The same forward-masking procedures have been employed to obtain estimates of auditory frequency resolution by numerous investigators; for example, Nelson and Freyman (1984) used forward-masked psychophysical tuning curves (PTCs) to examine frequency resolution. Critical to the interpretation of those forward-masking measures of frequency resolution is the assumption that the time constant for recovery from adaptation remains the same when the masker and probe are not at the same frequency.

The validity of that assumption is supported by the finding that forward-masking recovery functions from auditory-nerve fibers in chinchillas are independent of masker spectral content (Harris & Dallos, 1979). They found identical recovery functions for 600-Hz and 800-Hz pure-tone maskers and for a broad-band masker, all masking 600-Hz probe tones. However, we are unaware of any direct psychophysical tests of that assumption. And with psychophysical measures, the possibility always exists that the psychophysical estimate of peripheral processing might reflect additional processing by more centrally located neural structures.

Consequently, we obtained estimates of forward-masking time constants for 1000-Hz probe tones using *off frequency* maskers at 900 and 1100 Hz, and compared them with time constants obtained with an *on-frequency* 1000-Hz masker. Because forward masking has been used to evaluate frequency resolution in hearing-impaired listeners (Nelson, 1988), we also wished to test the single-time constant hypothesis in hearing-impaired listeners.

Quantification of Recovery From Adaptation

The most typical way of measuring recovery from adaptation is to use a fixed-level adapting stimulus, or masking tone, and to measure the amount of threshold shift, or forward masking, produced by that masker at different recovery times (Duifhuis, 1973; Jesteadt et al., 1982). To quantify the recovery process in individual listeners, a mathematical model of the recovery process is useful, along with least-squares fitting procedures for

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parameter estimations. The value of that strategy, and the method by which it is accomplished, is illustrated below with previously published data from another investigator.

Jesteadt et al. (1982) have provided an extensive set of recovery curves from normal-hearing listeners, which they demonstrated could be described quite well by a mathematical model that represents recovery in decibels as a function of the logarithm of recovery time (Plomp, 1964). As an alternative, Nelson and Freyman (1987) have explored a model that represents recovery as an exponential process (Duifhuis, 1973), because it might be related more easily to neural synaptic-recovery mechanisms. The basic form of the exponential model is given in Equation (1a):

$$SL_p = k(SL_m + M)e^{-t/Tau} \quad (1a)$$

Where SL_p is the sensation level of the probe or amount of forward masking, SL_m is the sensation level of the masker, t is delay time between masker and probe, M is the sensitivity constant to forward masking, and Tau is the time constant of recovery from forward masking. The constant k is the slope of the growth of masking, which may be thought of as the ratio between the slope of the growth of sensory response to the masker (S_m) and the slope of the growth of sensory response to the probe (S_p), as in $k = S_m/S_p$ (Nelson & Freyman, 1987; Stelmachowicz, Lewis, Larson, & Jesteadt, 1987). Nelson and Freyman (1987) have proposed that it is reasonable to assume that the slope of the growth of masking (k) should be close to 1.0 when the masker and probe are at the same frequency, although no experiments have yet truly isolated growth of masking slopes from time constants.

The appropriateness of the exponential model for describing recovery from adaptation is demonstrated in Figure 1, where forward-masking recovery curves from Jesteadt et al. (1982) are replotted on the linear coordinates appropriate to the exponential recovery model. Amount of masking is shown on the ordinate along a logarithmic scale. Recovery time is represented on the abscissa along a linear scale. This type of plot requires a simple logarithmic transform of Equation (1a), given as Equation (1b):

$$\ln(SL_p) = \ln(k) + \ln(SL_m + M) - t/Tau \quad (1b)$$

On these coordinates, proportionate decreases in probe level (SL_p) with increases in delay time (t) are represented by a straight line. The proportionality constant is given by the slope of that line, and the time constant (Tau) is the reciprocal of that slope.

In order to obtain estimates of the parameter values of Equation (1) that best fit these data, an iterative parameter estimation procedure commonly called the "simplex" least-squares parameter estimation algorithm was used (Nelson & Freyman, 1987). The procedure adaptively searches for the parameter values that yield the least squared deviations of observed performance from model predictions. For the data in Figure 1, predictions were determined using Equation (1b). The estimated parameter values are given in Table 1, along with the variance accounted for by the fitting procedure (R^2).

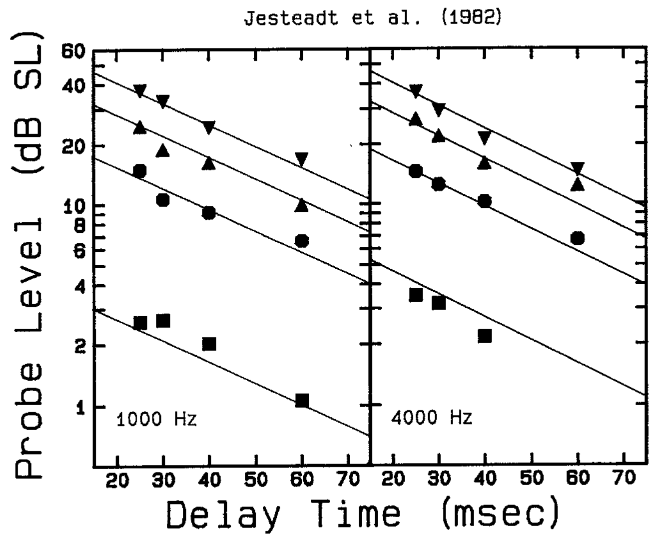

FIGURE 1. Forward-masking recovery curves at two different probe frequencies (Fp), 1000 Hz and 4000 Hz, replotted from Jesteadt et al. (1982) on coordinates appropriate to an exponential model of recovery (see text). The ordinate indicates sensation level (SL) of the probe signal, or amount of forward masking. The abscissa shows the time delay between masker offset and probe offset. Curves for four masker levels are shown: 20 dB SPL (squares), 40 dB SPL (circles), 60 dB SPL (triangles), and 80 dB SPL (inverted triangles). The straight lines are the best-fitting proportional recovery curves using Equation (1) and the fitting parameters given in Table 1 (k = var.).

As demonstrated in Figure 1 by the goodness of fit of the straight lines, the exponential model describes forward-masking recovery curves quite well over this range of delay times and over a range of masker levels from 20 to 80 dB SPL. Note also that the slope of the growth of masking is so close to unity that it can be effectively set to 1.0, with little change in the parameter estimates or the variance accounted for by the fit, as indicated in Table 1.[1]

[1]For those interested in comparing the precision of fitting recovery functions with different mathematical models, it is relevant that Jesteadt's model, which fits recovery functions in logarithmic time, can account for 99% of the variance as compared to 95% of the variance accounted for by the exponential model used here.

TABLE 1. Parameter estimates derived by fitting Equation (1) to recovery curves reported by Jesteadt et al. (1982) for a probe frequency (Fp) at 1000 and 4000 Hz. Two estimates are shown, one with the slope of masking as a free parameter (k = var.), and the other with the slope set to unity (k = 1.0).

	Fp = 1000 Hz		*Fp = 4000 Hz*	
Parameters	*k = var.*	*k = 1.0*	*k = var.*	*k = 1.0*
Tau	40.71ms	42.28	37.82	38.34
M	−7.15dB	−6.85	−4.87	−4.75
k	1.04	1.00	1.01	1.00
R^2	0.95	0.94	0.95	0.95

METHOD

Masking Paradigm

In a fixed-masker-level forward masking experiment the level of the probe tone at masked threshold varies over a wide range across different masker conditions. For example, in Figure 1 the level of the probe varied from 56 dB SPL for the most intense masker at the shortest delay time, down to 20 dB SPL for the least intense masker at the longest delay. Considering the well known increase in spread of excitation that occurs in the auditory system with increased stimulus intensity (e.g., Wegel & Lane, 1924; Zwicker & Jarszewski, 1982), those large changes in probe level correspond to large differences in the frequency regions of the cochlea that are stimulated, and to large differences in the numbers of nerve fibers that are probably excited by the probe tones.

Presumably, hearing-impaired listeners who exhibit frequency dependent hearing losses also have differential hair-cell dysfunctions along the cochlear partition. Therefore, the fixed-masker-level procedure may actually confound measures of recovery at different delay times with the spread of excitation into different regions of dysfunction. Consequently, we chose to employ the fixed-probe-level forward-masking paradigm of Nelson and Freyman (1987) to estimate time constants.

With the fixed-probe procedure a fixed-level probe tone is used as a test signal. With delay time as the independent variable, level of the masking tone is adjusted until sufficient adaptation is produced to mask the probe tone that follows the masker, that is, to produce a constant amount of forward masking. This fixed-probe procedure is preferred when one wishes to assess a particular frequency region of the auditory system, because a low probe sensation level assures that a small and localized population of neural elements will be excited by the test signal, and the fixed probe level ensures that the same population will be stimulated throughout the entire experiment. For normal-hearing listeners, Jesteadt et al. (1982) have shown that the two types of procedures yield the same results; however, for hearing-impaired listeners this is not known, and until it is shown that the two procedures yield the same result, it seems prudent to use the fixed-level probe procedure to test frequency regions of poor sensitivity that are near regions of good sensitivity.

Listeners

A total of 7 listeners participated in the experiment. Fixed-probe-level temporal masking functions were obtained from four normal-hearing ears and from four ears with cochlear hearing loss. One of the listeners had significant cochlear hearing loss in one ear and normal hearing in the other. All hearing-impaired listeners and three of the normal-hearing listeners were experienced at psychoacoustic listening tasks; all listeners were well practiced on forward masking experiments at the time of data collection. Absolute sensitivity thresholds for the normal-hearing (NM) and the hearing-impaired (HI) listeners are given in Table 2.

Stimuli

Probe tones were 1000-Hz tone bursts with durations of 20 ms, measured at 90% of peak amplitude. The masking tones were 200-ms tone bursts with frequencies of 900, 1000, or 1100 Hz. Maskers and probes were gated with 10-ms rise and decay times. Delay time between masker and probe was defined as the time between offset of the masker (90% of peak amplitude) and offset of the probe (Fastl, 1976; Lüscher & Zwislocki, 1949; Zwislocki et al., 1959). The shortest delay time was 42 ms, which included the 10-ms decay ramp of the masker, a 2-ms silent interval, the 10-ms rise ramp of the probe, and the 20-ms steady-state portion of the probe. A relatively long probe tone was used so that better frequency specificity could be achieved. Probe sensation levels were as low as possible (6–9 dB) in order to minimize the population of auditory nerve fibers excited by the probe tone.

Threshold Procedure

A four-alternative forced choice (4AFC) adaptive procedure was used to estimate the level of the masker

TABLE 2. Absolute sensitivity thresholds (dB SPL) for 200-ms tone bursts from normal-hearing (*NH*) and hearing-impaired (*HI*) listeners.

	Test Frequency					
Listener	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*8000 Hz*
NH:						
CT(L)	32	20	6	13	12	34
LJ(R)	23	15	9	6	10	12
RA(L)	30	11	8	15	27	26
ZB(R)	28	10	12	13	23	3
HI:						
LS(R)	71	41	26	40	54	77
DK(R)	38	29	37	55	44	8
RA(R)	34	23	51	57	81	77
EP(R)	38	56	57	54	23	16

needed to just mask a fixed-level probe tone (masked threshold) and to measure absolute sensitivity thresholds. During each 4AFC trial, the listener was presented with four observation periods, or listening intervals. Lights were used to indicate when the observation intervals were in progress. The probe stimulus was presented in only one randomly selected interval. A listener indicated which interval contained the test stimulus by pushing one of four response buttons, after which the correct-answer feedback was given.

A transformed up-down adaptive procedure (Levitt, 1971) was used to determine sensitivity thresholds and masked thresholds. A relatively large step size of 8 dB was used initially with a simple up-down stepping rule. This estimated the target region in the first three reversals. Then the adaptive procedure used 2-dB step sizes and a two-hit/one-miss stepping rule over the next six reversals to estimate masked threshold, defined by the mean of the masker levels visited during those reversals. Each masker-level threshold was repeated, during different sessions, until three consecutive threshold estimates showed minimal learning effects (defined as no consistent pattern of improvement in masked thresholds from one run to the next).

During forward-masking threshold measurements, the masker was present for the first 200 ms of all four listening intervals, and in one interval the masker was followed by a 20-ms probe. A 300-ms intertrial interval of silence was maintained for all conditions to minimize long-term adaptation or fatigue effects. During each test session, a range of delay times was tested in the following order: 42, 50, 60, 70, 80, 100, and 120 ms. Then the 42-ms delay time was repeated so that any order effects could be noted.

RESULTS AND DISCUSSION

Input-Level Temporal Masking Functions

Temporal masking functions obtained at three different masker frequencies from 4 normal-hearing listeners are shown in Figure 2. Because the probe level was fixed in this experiment, the temporal masking functions reflect the proportionate change in masker level that is required to obtain the same amount of forward masking as the delay time between masker and probe is increased. For example, the data for the 1000-Hz on-frequency masker for listener RA(L) (circles) show that in order to forward mask the 20-dB SPL probe tone, a masker level of about 18 dB sensation level (SL) was required at very short (42 ms) delay times. Masker levels increased proportionately with increased delay time, indicated by the straight line, until at a delay time of 120 ms, a masker level of about 88 dB SL was required before sufficient adaptation was produced to mask the probe tone.

These temporal masking functions are essentially the inverse of the recovery functions shown in Figure 1. They can be represented by the simple inverse of Equation (1a), which is shown in Equation (2a):

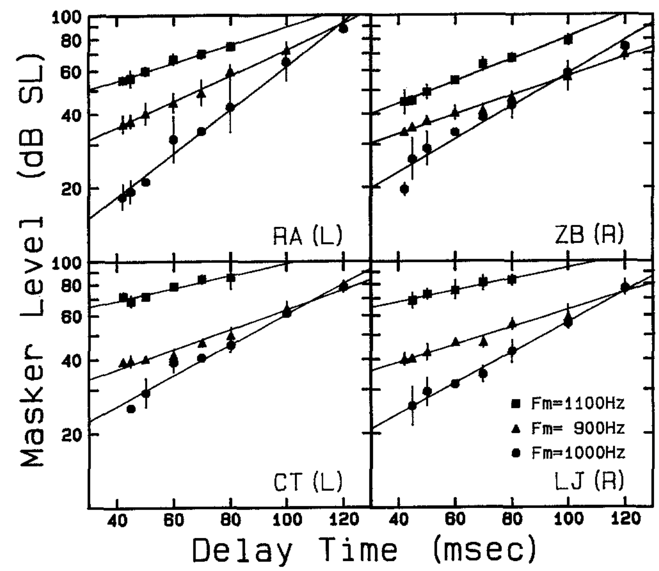

FIGURE 2. Temporal masking functions from four normal-hearing listeners. The masker sensation level (SL) required to mask a 20-dB SPL 1000-Hz probe tone (6-7 dB SL across listeners) is plotted on the ordinate as a function of the delay time between masker offset and probe offset. Data are shown for three different masker frequencies: 1000 Hz (circles), 900 Hz (triangles), and 1100 Hz (squares). Masker levels are shown on a logarithmic scale to demonstrate how masker level increases proportionately with delay time. This is shown on these coordinates by the best-fit straight-line functions. The reciprocals of the slopes of those lines define the time constants that best describe each function. Steeper slopes indicate shorter time constants. Vertical error bars indicate one standard deviation above and below the mean across retests.

$$SL_m = (SL_p{}^* e^{t/Tau}) - M \qquad (2a)$$

Equation (2a) adequately describes temporal masking functions from normal-hearing and hearing-impaired listeners (Nelson & Freyman, 1987), but only for on-frequency maskers. To facilitate data analysis, it can be "linearized" by taking the natural logarithm of both sides of the equation, as shown in Equation (2b):

$$\ln(SL_m - M) = \ln(SL_p) + t/Tau \qquad (2b)$$

The bottom function in each panel of Figure 2 is for the 1000-Hz on-frequency masker. This is the condition in which Jesteadt et al. (1982) found the same results for the fixed-masker and the fixed-probe procedures. The on-frequency temporal masking functions shown in Figure 2 can be characterized by model parameters that are entirely consistent with those obtained from the Jesteadt et al. fixed-masker-level data. This is evidenced by the results of parameter estimations for the 1000-Hz on-frequency temporal masking functions, using Equation (2b), which are given in Table 3. For example, in the case of RA(L), the 1000-Hz function is well fit ($R^2 = 0.98$) by a time constant (Tau) of 42.9 ms and a sensitivity constant (M) of −3.5 dB. The values of 42.3 and −6.85 for the data of Jesteadt et al. (1982) estimated using Equation (1), as indicated in Table 1, confirm their finding that the two

TABLE 3. Time constants (Tau) and sensitivity constants (M) derived from the 1000-Hz on-frequency maskers. Also shown are the additional filter attenuation constants (A_f) that are required to fit the off-frequency functions with the 1000-Hz Tau and M values shown. The proportion of variance accounted for by the simplex fit is given by R^2. The ratio between probe frequency and the 10-dB bandwidth of the three-point psychophysical tuning curve defined by the filter attenuation constants is given for each listener by Q_{10}. Absolute sensitivity thresholds at 1000 Hz for 200 ms tone bursts are given by L_{tpm} (dB SPL). Results are shown for normal-hearing listeners (NH) and hearing-impaired listeners (HI).

		Masker Frequency							
		1000 Hz			900 Hz		1100 Hz		
Listener	L_{tpm}	Tau (ms)	M (dB)	R^2	A_f (dB)	R^2	A_f (dB)	R^2	Q_{10}
NH:									
CT(L)	6	49.2	−11.1	0.95	−9.7	0.87	−43.3	0.88	7.94
LJ(R)	9	51.6	−10.9	0.99	−13.3	0.89	−44.0	0.95	10.19
RA(L)	8	42.9	−3.5	0.98	−17.3	0.98	−36.8	0.96	11.76
ZB(R)	12	48.6	−7.2	0.93	−8.7	0.71	−22.7	0.95	6.27
Mean	8.8	48.1	−8.2	.96	−12.2	0.86	−36.7	0.94	9.04
Sdev	(2.5)	(3.7)	(3.6)		(3.9)		(9.9)		(2.4)
HI:									
LS(R)	26	58.2	−0.3	0.98	−11.4	0.97	−39.3	0.96	8.86
DK(R)	37	51.2	−5.1	0.98	−5.9	0.96	−15.8	0.98	4.29
RA(R)	51	69.3	−9.6	0.96	−1.7	0.99	−4.2	0.87	1.21
EP(R)	57	83.8	−1.7	0.97	−3.4	0.96	−1.7	0.92	1.15

types of experiments yield the same results; in this case the parameter estimates are nearly identical, at least for normal-hearing listeners and for on-frequency 1000-Hz maskers.

For off-frequency maskers there are no previous data for comparison, and the process of quantifying recovery from adaptation is more complex, as will become evident below.

With off-frequency maskers, a higher masker level is required to produce the same amount of forward masking as the 1000-Hz masker. This is shown in Figure 2 for maskers at 900 and 1100 Hz by filled triangles and squares, respectively. For example, for RA(L) at a delay time of 42 ms, 36 dB SL is required for a 900-Hz masker and 55 dB SL is required for an 1100-Hz masker. Presumably, the higher masker levels are needed because the auditory filter centered at the probe frequency attenuates the off-frequency maskers. Consequently, the levels for those maskers must be increased until they produce the same effective excitation in the auditory filter, and presumably, the same amount of adaptation as the 1000-Hz on-frequency masker.

For the purposes of this experiment, one might refer to the masker levels shown in Figure 2 as the input levels required to achieve a constant output from the auditory filter. The constant output presumably leads to a constant amount of adaptation or forward masking at 1000 Hz. With the single-time-constant assumption, it is the amount of adaptation produced by the constant output of the auditory filter, and the recovery from that adaptation, that are reflected in forward-masking recovery curves.

Examination of the proportionate changes in input levels with delay time, shown by straight lines in Figure 2, reveals a more gradual change in input level with increased delay time for the off-frequency maskers than for the on-frequency masker. The best-fitting straight lines indicate apparent time constants of 82.3 ms for the 900-Hz masker and 120.2 ms for the 1100-Hz masker. This type of analysis of the input levels could easily lead to the interpretation that time constants for recovery from forward masking are longer for off-frequency maskers than for on-frequency maskers.

Temporal masking functions obtained from 4 hearing-impaired listeners are shown in Figure 3. The same proportionate change in masker level with delay time is seen in these functions. Those from LS(R) appear the same as those in Figure 2 from normal-hearing listeners; the on-frequency function is steep and the off-frequency

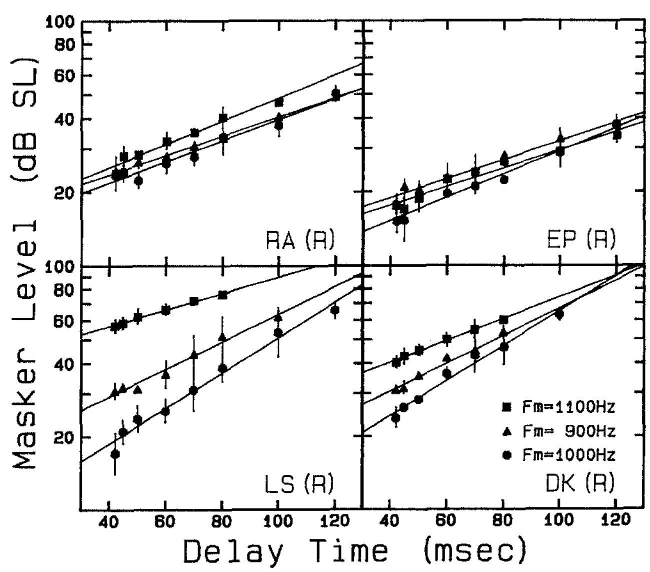

FIGURE 3. Temporal masking functions from four hearing-impaired listeners. Legend as in Figure 2, except the probe levels were at 7–9 dB SL (across listeners).

functions are elevated, indicating normal recovery and sharp tuning. This is notable because the significant hearing losses at frequencies surrounding the 1000-Hz probe frequency (see Table 2) apparently do not affect performance at the probe frequency, where the absolute sensitivity threshold of 26 dB SPL is near normal. Temporal masking functions from listener DK(R) are slightly closer together, presumably reflecting slightly poorer tuning associated with the higher sensitivity threshold of 37 dB SPL at 1000 Hz. Listeners RA(R) and EP(R), with sensitivity thresholds of 51 and 57 dB SPL, show significantly flatter temporal masking functions; the off-frequency and on-frequency curves are close together, which is consistent with significantly poorer tuning characteristics.

Again, if time constants were estimated from these input masker levels, one would reach the conclusion that off-frequency time constants are longer than on-frequency time constants, and that the longer time constants demonstrated by listeners with significant sensitivity losses and poor tuning might be due to the loss of sharp tuning mechanisms.

Normalized Temporal Masking Functions

Considering that neural recovery functions reported by Harris and Dallos (1979) did not differ with stimulus spectral content, the interpretation that time constants are longer for off-frequency maskers may not be valid. Their results showed that the recovery process was the same when each of the stimulus spectra evoked the same firing rate, that is, when the output level of the auditory filter was held constant (see their Figure 7). From this we reasoned that it is very likely that recovery from adaptation is dependent upon the output level, not the input level, of the auditory filter; if we could specify the masker levels for the off-frequency maskers in terms of their equivalent output levels, then the resulting temporal masking functions might reflect a common recovery process with a single time constant that is independent of masker frequency.

Recall that the fixed-probe-level forward masking procedure obtains the masker level (input level) that is required to mask a constant SL probe tone (output level). This is true for both on-frequency and off-frequency maskers regardless of delay time, that is, an off-frequency masker produces the same amount of forward masking, the same output level, as an on-frequency masker. So, at any time delay, the fixed-probe-level forward masking experiment produces a constant output from the auditory filter, just as in the physiological experiment. However, the psychophysical experiment cannot directly measure a change in the output level as a function of recovery time as in the physiological experiment. The psychophysical experiment can only measure a change in the input level as a function of recovery time. Because, for a given time delay, the input level is greater for an off-frequency masker than an on-frequency masker, most likely because the auditory filter attenuates the input level for the off-frequency maskers, a transformation from input level to equivalent output level is needed to obtain a psychophysical time-constant estimate that is similar to that obtained physiologically.

To accomplish a transformation from input levels to equivalent output levels, we must make an assumption about the order in which auditory filtering and adaptation processes occur in the auditory system. If we assume that the auditory filtering process occurs before the adaptation and recovery processes, then the input levels measured for off-frequency maskers are attenuated by the auditory filter, whereas those measured for the on-frequency masker are not, or at least not as much. In the fixed-probe-level experiment, input levels for off-frequency maskers would have to be increased sufficiently to overcome the effective attenuation provided by the auditory filter in order to produce the same amount of masking as on-frequency maskers.[2]

One way to convert input levels for off-frequency maskers to equivalent output levels for on-frequency maskers is to assume that the output of the auditory filter is the same when an off-frequency forward masker produces the same amount of forward masking as an on-frequency masker. The off-frequency masker levels can then be normalized by the difference between off-frequency and on-frequency input levels at some short delay time (Schroder & Cudahy, 1983), which is essentially an estimate of the attenuation provided by the auditory filter for each off-frequency masker. Then the recovery process for longer delay times can be examined to determine if it is reasonable to conclude that the time constant for recovery from forward masking is independent of masker frequency.

However, normalization based on the difference between the functions at a short delay time is subject to any biases unique to one delay time. Therefore, we chose to normalize with a procedure that would allow equal weight to the differences between the masker levels at every delay time, a procedure that uses least-squares parameter estimation techniques to derive attenuation constants for a simple model of how the filtering processes might behave.

Given the assumption that the auditory filter attenuates the masker input level before adaptation and recovery occur, then that attenuation can be represented by additive *attenuation constants* (A_f) for each off-frequency masker in the general equation that describes temporal masking functions, as indicated in Equation (3):

$$\ln(SL_m - M - A_f) = \ln(SL_p) + t/Tau \qquad (3)$$

Our assumptions dictate that estimates of Tau and M must be made from the 1000-Hz on-frequency temporal mask-

[2]The assumption that auditory filtering occurs before adaptation in the auditory system is strongly supported by data from Kidd and Feth (1981), Moore and Glasberg (1981), and Nelson and Freyman (1984). However, it should be note here that Lutfi (1984, 1988) argues in the reverse (see also Moore, 1985 and Lutfi, 1985).

ing functions using Equation (2b). Estimates of the attenuation constants (A_f) for each off-frequency masker can then be made by substituting into Equation (3) the values of Tau and M obtained already for the 1000-Hz on-frequency masker (Table 3) and solving for values of A_f.

Parameter Estimates: Normal-Hearing Listeners

Again, parameter estimation was done with an iterative estimation procedure commonly called the "simplex" least-squares parameter estimation algorithm (Nelson & Freyman, 1987). First the 1000-Hz functions were subjected to a simplex fit with Tau and M as free parameters using Equation (2b). Then simplex fits were done on the 900-Hz and 1100-Hz off-frequency temporal masking functions. During those fitting procedures the values of Tau and M, obtained previously for the 1000-Hz function, were substituted into Equation (3) and the filter attenuation constants (A_f) were allowed to vary. Finally, the original masker levels were normalized by subtracting the M and A constants from each data point to yield what we call equivalent filter output levels, and the data were replotted along with the straight line representing the single time constant Tau. The values of the parameters of Equation (3) that were estimated in this way are given in Table 3 for each of the four normal-hearing and four hearing-impaired listeners.

Normalized temporal masking functions from four normal-hearing listeners are shown in Figure 4. As in the previous figures, data for the three different masker frequencies are represented by different symbols. In contrast to the input level functions shown in Figure 2, these equivalent output level functions overlie one another and can be described by a single time constant. That time constant is given in Table 3 for each subject and represented by the slope of the straight line in each panel of Figure 4.

The R^2 values in Table 3 indicate that the two free parameters in Equation (2b) can account for 93–99% of the variance in the 1000-Hz on-frequency data. Time constants (Tau) ranged from 42.9 to 51.6 for these four normal-hearing listeners; these compare favorably with the average time constant of 49.7 ms reported earlier by Nelson and Freyman (1987). Sensitivity constants (M) ranged from −3.5 to −11.1, and are also consistent with previous estimates (Nelson & Freyman, 1987).

Filter attenuation constants (A_f) varied among listeners, of course, because those constants are thought to represent the attenuation to the off-frequency masker provided by the auditory filter. As indicated in Table 3, the attenuation constants ranged from −8.7 dB to −13.3 dB for the 900-Hz maskers and from −22.7 dB to −44 dB for the 1100-Hz maskers. This implies a steeper auditory filter slope above the probe frequency than below. From these attenuation constants an estimate of the filter bandwidth can be made at 10 dB above the masker level at the center of the filter, and the relative width of the filter can be expressed as a ratio to the center frequency of the filter, a measure referred to as Q_{10} dB. The Q_{10} values ranged

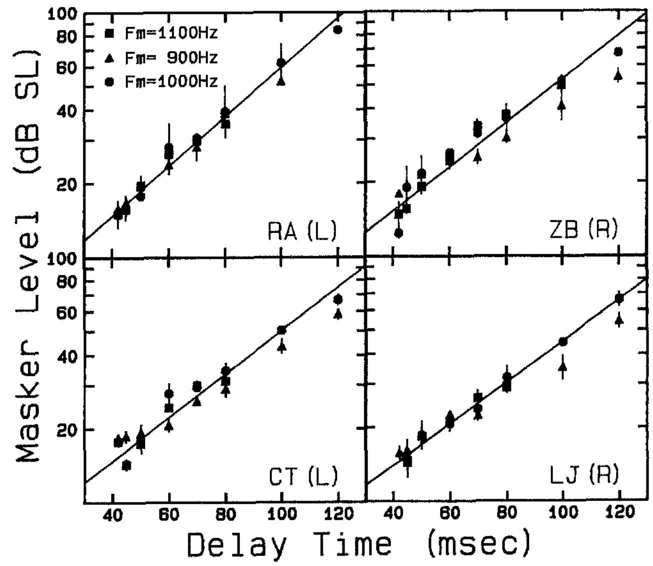

FIGURE 4. Normalized temporal masking functions from 4 normal-hearing listeners. Masker levels for off-frequency maskers have been normalized to have the same effective output levels at the 1000-Hz probe frequency as the on-frequency maskers (see text for details for the normalization procedure). Normalized masker levels on the ordinate are shown in dB SL for the 1000-Hz masker. The straight line in each panel is the best-fitting function for the 1000-Hz masker, with the slope of that function specifying the 1000-Hz time constant. The graph demonstrates how well the time constant for the 1000-Hz on-frequency masker describes the temporal masking functions for the 900- and 1100-Hz off-frequency maskers, after appropriate normalization to account for attenuation of those off-frequency maskers by the auditory filter.

from 6.27 to 11.76 for these four normal-hearing listeners, with a mean value of 9.04 that is consistent with values reported by other investigators (Hoekstra & Ritsma, 1977; O'Loughlin & Moore, 1981; Stelmachowicz & Jesteadt, 1984; Weber, Johnson-Davis, & Patterson, 1980).

When the off-frequency masker levels were normalized by subtracting estimates of M and A_f, the variance accounted for by the straight line, defined only by SL_p and the on-frequency Tau, ranged from 71–98% (given by R^2 in Table 3). From Figure 4, we see that the fits are satisfactory for all functions, except perhaps the 900-Hz function for ZB(R), which appears to deviate consistently at long delay times as reflected by an R^2 value of 0.71.

This finding, that off-frequency temporal masking functions overlie on-frequency functions when normalized by filter attenuation constants that are consistent with filtering characteristics found by others, indicates to us that for normal-hearing listeners, recovery from forward masking can be represented by a single time constant that is independent of the masker frequency, at least over the range of masker frequencies examined here.

Parameter Estimates: Hearing-Impaired Listeners

Normalized temporal masking functions obtained from the hearing-impaired listeners are shown in Figure 5.

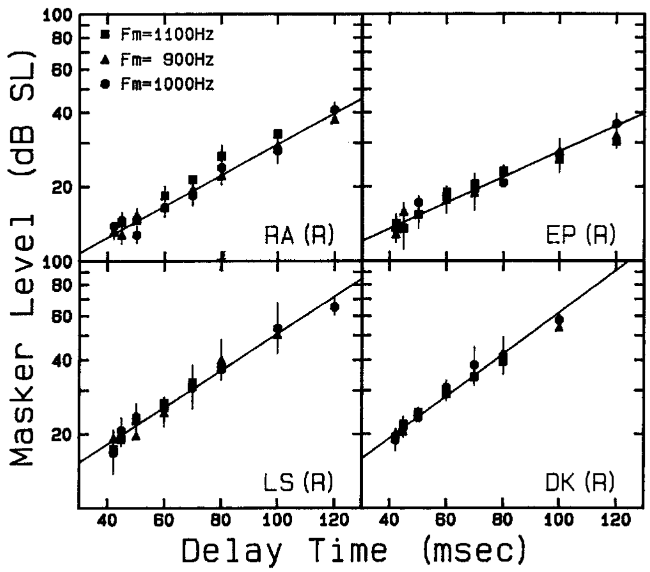

FIGURE 5. Normalized temporal masking functions from four hearing-impaired listeners. Legend as in Figure 4.

Here we see that the time constants derived from the 1000-Hz on-frequency functions represent the off-frequency functions even better than in normal-hearing listeners. The R^2 values in Table 3 ranged from 0.87 to 0.99. Two of the hearing-impaired listeners, LS(R) and DK(R), behaved very much like the normal-hearing listeners, in that their time constants, sensitivity constants, and filter attenuation constants were within the range of normal. Their Q_{10} values of 8.9 and 4.3 were also within the range of normal, although Q_{10} for DK(R) is near the conservative limits for normal [9.04 − 2(2.42) = 4.2]. This is not surprising, because their sensitivity losses at the probe frequency were relatively mild (17 and 28 dB, respectively). The other two hearing-impaired listeners, RA(R) and EP(R), demonstrated time constants longer than normal and sensitivity constants no different from normal, which are consistent with their moderate hearing losses of 42 and 48 dB, respectively (Nelson & Freyman, 1987). Their attenuation constants are smaller than normal, reflecting poorer tuning as specified by their Q_{10} values of 1.21 and 1.15. These Q_{10} values are less than any reported by Stelmachowicz, Jesteadt, Gorga, & Mott, (1985); however, simultaneous masking was used in that study and their 100-Hz-wide narrow-band noise maskers had different envelopes from the pure-tone maskers used in the present study. The importance of those differences remains undetermined.

From these findings it appears that temporal masking functions from hearing-impaired listeners can also be represented satisfactorily by a single time constant irrespective of the masker frequency.

SUMMARY

These results demonstrate that an exponential model of recovery from forward masking can describe the recovery process adequately. Using a fixed-probe-level forward masking procedure similar to that used to obtain forward-masked psychophysical tuning curves, temporal masking functions obtained with on-frequency and off-frequency maskers superficially indicate that the time course for recovery from forward masking is more gradual for off-frequency maskers, presumably reflecting a longer "apparent" time constant for recovery from adaptation. After appropriate corrections to the off-frequency masker levels are made—corrections accomplished with the addition of filter attenuation constants to the exponential model—the time constant derived from the on-frequency temporal masking function can adequately describe both on-frequency and off-frequency functions. These results are consistent with auditory-nerve temporal masking functions obtained under similar conditions, which demonstrate a time constant that is independent of spectral content of the masker.

These findings hold for both normal-hearing and hearing-impaired listeners. The main differences between temporal masking functions obtained from the two types of listeners can be described by longer time constants and smaller filter attenuation constants for hearing-impaired listeners who exhibit moderate hearing losses at the probe frequency. Longer time constants indicate poorer than normal temporal resolution. Smaller attenuation constants indicate poorer than normal frequency resolution.

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Request for reprints should be sent to David A. Nelson, University of Minnesota, Dept. of Otolaryngology Medical School, 2630 University Ave S.E., Minneapolis, MN 55414.