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Informational Masking in Listeners with Sensorineural Hearing Loss

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ABSTRACT

Measures of energetic and informational masking were obtained from 46 listeners with sensorineural hearing loss. The task was to detect the presence of a sequence of eight contiguous 60-ms bursts of a pure tone embedded in masker bursts that were played synchronously with the signal. The masker was either a sequence of Gaussian noise bursts (energetic masker) or a sequence of random-frequency 2-tone bursts (informational masker). The 2-tone maskers were of two types: one type that normally tends to produce large amounts of informational masking and a second type that normally tends to produce very little informational masking. The two informational maskers are called "multiple-bursts same" (MBS), because the same frequency components are present in each burst of a sequence, and "multiple-bursts different" (MBD), because different frequency components are presented in each burst of a sequence. The difference in masking observed for these two maskers is thought to occur because the signal perceptually segregates from the masker in the MBD condition but fuses with the masker in MBS. In the present study, the effectiveness of the MBD masker, measured as the signal-to-masker ratio at masked threshold, increased with increasing hearing loss. In contrast, the signal-to-masker ratio at masked threshold for the MBS masker changed much less as a function of hearing loss. These results suggest that sensorineural hearing loss interferes with the ability of the listener to perceptually segregate individual components of complex sounds. The results from the energetic masking condition, which included critical ratio estimates for all listeners and auditory filter characteristics for a subset of the listeners, indicated that increasing hearing loss also reduced frequency selectivity at the signal frequency. Overall, these results suggest that the increased susceptibility to masking observed in listeners with sensorineural hearing loss is a consequence of both peripheral and central processes.

INTRODUCTION

The defining complaint of listeners with sensorineural hearing loss is difficulty communicating in noise. In quiet environments where the listener's task is to attend to a single sound source, the difficulty in sound reception imposed by hearing loss may be minimal and amplification, if needed, is often very effective. However, real-world listening environments may be much more complex and often contain many sources of sound. The listener must sort out which sounds are important and deserve attention and which are unwanted and should be ignored. Because real-world acoustic environments are often dynamic and uncertain, sounds and their sources must constantly be monitored and judgments made about the way attention should be allocated. In contrast to performance in quiet single-source environments, performance in complex multisource environments may be much

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worse for listeners with sensorineural hearing loss and amplification may not always provide significant benefit.

In this study we examined the performance of listeners with sensorineural hearing loss in listening situations that were complex, uncertain, and contained multiple sounds. The procedures were modifications of those used in previous work aimed at studying central factors in masking (Kidd et al. 1994), specifically, what is called "informational masking" [see Watson (1987) for a review]. In contrast to peripheral masking (also called "energetic masking"), informational masking occurs despite a neural representation of the signal in the periphery that presumably is sufficiently robust to solve the task. Therefore, informational masking is thought to reflect limitations in central processing of the peripheral neural representation of sounds.

Watson et al. (1975, 1976) demonstrated that the amount of informational masking was related to the degree of uncertainty produced by the stimulus configuration. Low-uncertainty conditions, i.e., those in which the pattern of frequencies and levels was fixed throughout blocks of trials, produced small amounts of informational masking. Conditions in which the stimulus configuration varied randomly across trials produced greater uncertainty and larger amounts of masking. For listeners with normal hearing, Neff (1995) has shown that stimulus manipulations that promote perceptual segregation of the signal from the masker can reduce the amount of informational masking. In her work, the task was the detection of a signal tone embedded in a set of simultaneous masker tones that were chosen randomly on each presentation to create a high degree of spectral uncertainty (Neff and Green 1987; Neff et al. 1993; Neff and Dethlefs 1995). The signal was made more audible in a variety of ways including amplitude modulation of the signal, dichotic presentation of the signal and masker, asynchronous onset of signal and masker, and use of a narrow band noise signal that has a distinctly different perceptual quality than the tonal maskers (Neff 1995). Comparable effects have been shown by Kidd et al. (1994, 1998) for randomized sequences of multitone maskers when signals and maskers differ in temporal structure or spatial location. These stimulus manipulations exploit well-known grouping and segregation principles (Bregman 1990; Yost 1991; Darwin and Carlyon 1995) and support the idea that perceptual segregation of the signal from the masker(s) may substantially reduce informational masking.

There has been relatively little study of central factors in masking in listeners with sensorineural hearing loss. This may be due to the assumption that, because the site of lesion is known to be peripheral (i.e., usually cochlear), the impairments observed in the performance of psychophysical tasks can be explained by the degraded representation of the stimulus in the auditory nerve, e.g., by reduced resolution in the frequency and time domains or perhaps a lack of coincidence at early shared receptor sites (Carney 1994). This assumption has not been adequately tested, however, and it has not been demonstrated that peripheral factors alone are sufficient to account for the difficulties experienced by listeners with cochlear hearing loss in complex acoustic environments.

Very few studies have investigated the perceptual organization of sounds in multisource environments in listeners with cochlear hearing loss. Grose and Hall (1996) used two tasks: detection of a temporal gap embedded in alternating tone sequences and identification of tonal melodies embedded in competing melodies. In the latter case, the listener was required to perform the task in the presence of nonenergetic maskers. On both tasks, the listeners with sensorineural hearing loss consistently performed more poorly than the listeners with normal hearing suggesting that "cochlear hearing loss deleteriously affects the processes underlying the perceptual organization of sequential stimuli" (Grose and Hall 1996, p. 1149). In a study by Rose and Moore (1997), normal-hearing and hearing-impaired listeners made judgments about the frequency boundary [in ΔERB units (ERB = equivalent rectangular bandwidth)] at which perceptual fission occurred for alternating tone sequences. Their results were mixed: Listeners with unilateral losses showed no difference between ears in measured ΔERBs; however, one-half of the bilateral-loss listeners did have "abnormally large" ΔERB values. Rose and Moore (1997) suggested that such listeners would have difficulty separating out different auditory objects in multisource environments and attributed the deficit to peripheral coding "distortions."

The two studies reviewed above would support the assertion that many listeners with sensorineural hearing loss also have difficulty with the perceptual organization of sounds: It is more difficult for them to separate auditory objects or focus attention on the desired object. This suggests that such listeners have greater-than-normal difficulty ignoring unwanted sounds (cf. Doherty and Lutfi 1999) and leads to the hypothesis that hearing-impaired listeners would demonstrate greater-than-normal amounts of informational masking. However, there are no studies that we are aware of that have directly measured informational masking in listeners with sensorineural hearing loss. In previous work, we measured informational masking for two maskers that are comprised of tones chosen according to similar statistical rules and thus produce nearly the same amount of peripheral masking but cause very different amounts of informational masking (Kidd et al. 1994). The difference in performance for the two maskers occurs because one masker (multiple-bursts same or MBS; see below) promotes the perceptual fusion of the signal with the masker tones making it difficult to distinguish whether that specific tone is present in either the signal-plus-masker or masker-alone stimuli, while the other masker (multiple-bursts different or MBD) tends to cause the signal to segregate from the masker making it easy to distinguish the stimulus containing the signal. In the present study, we examined whether the same pattern of informational masking occurs in listeners with sensorineural hearing loss.

METHODS

Listeners

A total of 46 listeners participated in these experiments. Thirty-one were patients of the Audiology Clinic at the Boston Veteran's Affairs Healthcare Center. The remaining listeners were participants in a separate study conducted at Boston University. Hearing sensitivity spanned a wide range from normal to moderate-to-severely hearing impaired. There were 35 males and 11 females in the listener group. For those with hearing loss, the only criteria for inclusion in the study were stable sensorineural hearing loss, a sufficient usable range of hearing (based on audiometric configuration), and ability to perform the experimental tasks reliably with brief instruction. All listeners had audiologic evaluations prior to participating in the study. Table 1 summarizes the characteristics of the listener group.

Listener age also varied over a wide range from 31 to 86 years, although the age of the majority of the group was between 70 and 89 years. The average age was 66.6 years (SD = 13.4 years) and the median age was 69.6 years. Pure-tone averages (PTAs) and configurations of losses also varied considerably, with 3-frequency PTAs ranging from 3 to 55 dB and the audiometric slope (threshold at 4 kHz minus the threshold at 1 kHz) ranging from −5 to 70 dB. Approximately one-half of the listeners tested had CID W-22 word recognition scores of 90% correct or higher in quiet and five listeners had scores below 70% correct. The subjects who participated in both experiments are indicated by the asterisks in Table 1.

Stimuli

All sounds were computer-generated at 20 kHz and low-pass filtered at 8 kHz. The signal was a sequence of eight contiguous 1000-Hz tone bursts with each burst having rise/steady-state/decay characteristics of 10/40/10 ms for a total duration of 480 ms. The maskers were also sequences of eight 60-ms bursts gated synchronously with the signal. Three types of maskers were employed: Gaussian noise having a bandwidth from 200 to 5000 Hz and the multiple-bursts same (MBS) and multiple-bursts different (MBD) multitone maskers (Kidd et al. 1994). The MBS and MBD maskers used in this study comprised two equal-level tones, one above the signal frequency and one below the signal frequency, placed outside of a "protected region" centered logarithmically on the signal frequency with a width of 32.4% of the signal frequency. The protected region limits energetic masking by reducing the influence of spread of excitation from the masker tones to the signal. The MBS and MBD masker components were equal in level and were drawn from a maximum frequency range of 200–5000 Hz, excluding the protected region, on every presentation. For listeners with sharply sloping high-frequency hearing loss, the higher end of the masker frequency range was lowered to ensure the audibility of all masker components. The high-frequency limit was lowered to the first frequency above the signal frequency at which threshold was 40 dB or more poorer than the threshold at the signal frequency. The low-frequency limit was often also increased in order to obtain a roughly equal range, on a log scale, of possible masker space on either side of the signal frequency. In eight cases, sharply sloping high-frequency hearing losses also required a lower (750 Hz) signal frequency. For the MBS masker, the two masker tones were chosen at random for the first burst of every sequence of every interval throughout the block of trials. The two masker tones chosen for the first burst were then repeated throughout the sequence for that interval. For the MBD masker, the two masker tones were chosen randomly for *every* burst in each sequence. The maskers plus the signal are illustrated schematically in Figure 1.

For the notched-noise condition (experiment 2), stimuli were generated as described above except that the signal and masker were each a single burst. The signal was 200 ms and the masker 300 ms in duration, each including a 10-ms rise–fall time. The signal frequency for each listener was the same frequency used in experiment 1 and the masker was Gaussian noise that was either symmetrically or asymmetrically notch-filtered around the signal frequency. The five notch widths[1] were 0.0 and 0.0, 0.2 and 0.2, 0.4 and 0.4, 0.2 and 0.4, and 0.4 and 0.2, expressed as the difference

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[1] We chose to test only five notched-noise widths primarily because of the time constraints on collecting the data. However, we also tested five of the listeners on four additional notch widths (nine total) and found that the filter characteristics and processing efficiency estimates were nearly the same as those obtained from the five notched-noise conditions alone. Therefore, the remainder of the listeners were tested using the abbreviated procedure. This issue has been discussed elsewhere (Leeuw and Dreschler 1994; Stone et al. 1992).

TABLE 1

A summary of listener characteristics. Listeners are ordered by increasing signal threshold in quiet

Listener[a]	*Age*	*Sex*	*PTA*[b]	*Slope*[c]	*WRS*[d] (%)	*Signal frequency* (Hz)	*Signal* θ[f] (dB SPL)	*Masker range* (Hz)
1	46	M	10	30	100	1000	−1	200–5000
2	69	M	3	30	DNT[e]	1000	−1	200–5000
3*	65	M	7	55	96	1000	3	300–3000
4*	31	M	12	20	96	1000	5	200–5000
5*	72	F	18	35	88	1000	5	200–5000
6	49	M	20	15	96	1000	9	200–5000
7*	61	F	2	0	100	1000	11	200–5000
8	48	M	10	60	96	750	11	200–2500
9	50	M	12	55	92	750	12	200–2500
10*	66	F	7	20	92	1000	12	200–5000
11	71	M	13	20	100	1000	12	200–5000
12*	46	M	17	35	84	1000	15	250–4000
13*	65	M	10	20	92	1000	17	200–5000
14	57	M	15	30	92	1000	17	250–4000
15*	50	F	17	10	100	1000	19	200–5000
16	69	M	17	45	92	1000	19	200–3000
17*	77	F	18	0	96	1000	19	200–5000
18	44	M	27	15	92	1000	19	250–4000
19*	80	M	28	30	88	1000	19	200–5000
20	60	M	27	70	88	750	20	250–2000
21*	72	M	22	35	100	1000	20	300–3000
22*	64	M	25	25	96	1000	20	200–5000
23*	81	F	23	0	100	1000	21	200–5000
24*	82	M	20	60	82	1000	21	250–4000
25	65	M	17	60	88	750	22	200–2500
26*	72	F	25	5	100	1000	22	200–5000
27	44	M	17	30	96	1000	24	300–3000
28	73	M	35	70	68	750	24	200–3000
29*	77	F	27	35	92	1000	24	300–3000
30*	45	M	37	20	96	1000	24	250–4000
31*	69	M	38	40	40	750	28	200–4000
32*	71	M	32	70	84	1000	31	250–4000
33*	83	M	22	50	68	750	31	200–3000
34*	79	F	33	30	88	1000	35	250–4000
35	66	M	33	35	82	1000	37	200–5000
36*	70	M	25	50	80	750	38	200–3000
37*	80	F	32	35	92	1000	40	250–4000
38	84	M	35	15	66	1000	41	200–5000
39*	77	M	45	35	72	1000	42	200–5000
40	74	M	55	20	64	1000	44	200–5000
41*	86	M	40	25	92	1000	45	200–5000
42*	76	F	43	5	88	1000	52	200–5000
43*	82	M	52	−5	74	1000	53	200–5000
44	74	M	53	0	92	1000	53	200–5000
45*	79	M	48	10	80	1000	53	200–5000
46	61	M	40	35	84	1000	55	200–5000

[a] Asterisk indicates listener participated in experiments 1 and 2.
[b] Pure-tone average in dB HL.
[c] Slope is audiometric threshold at 4000 Hz subtracted by audiometric threshold at 1000 Hz.
[d] Word Recognition Score.
[e] Did Not Test.
[f] θ is threshold and Signal θ is in quiet.

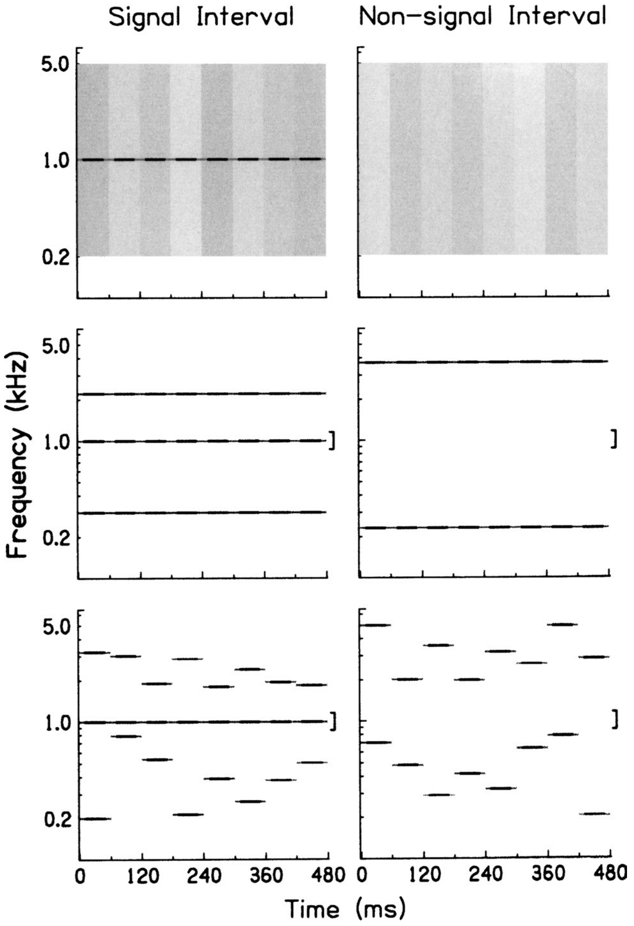

FIG. 1. Schematic spectrograms of the Gaussian noise and MBS and MBD maskers (top to bottom.) The shading for the Gaussian noise case indicates independent bursts with slightly different rms levels. For the informational maskers, the protected region surrounding the signal frequency is indicated by brackets on the right side of the panels. The left panels show typical maskers paired with the 1000-Hz signal, while the right panels show typical masker draws in the nonsignal interval.

between signal frequency and notch edge frequency, divided by signal frequency. The noise had a bandwidth of 400 Hz on either side of the notch.

EXPERIMENT 1

Procedures

The data from experiment 1 were collected in a single 2-hour session for each listener. The measurements obtained from each listener included quiet threshold for the signal tone, tone-in-noise detection, and MBS and MBD masked thresholds. All measurements used a 2-alternative forced-choice adaptive tracking procedure to estimate the level of the variable stimulus producing 70.7% correct detection (Levitt 1971). Response feedback was provided after each trial and the trials were presented in blocks of 50 each. The protocol began with quiet threshold measurement for the signal with two successive adaptive threshold tracks. If the two estimates were more than 3 dB apart, a third estimate was obtained. The arithmetic mean of the estimates was taken as threshold. The level of the signal was then fixed at 20 dB above the quiet threshold [i.e., 20 dB sensation level (SL)], and masked thresholds were obtained by adaptively varying the level of the masker. At the beginning of each run, the masker was set to an inaudible level that subsequently increased as the listener registered correct responses. The step size was initially 6 dB which was reduced to 3 dB on the fourth reversal. In the 2-hour time block, at least 4 estimates of threshold were obtained for each of the 3 maskers. Threshold estimates were included only if a minimum of 6 reversals was obtained. The standard deviations of the measurements obtained during each session, averaged across subjects, were 1.4 dB for quiet threshold, 2.6 dB for broadband noise, 5.7 dB for MBS, and 5.2 dB for MBD. The order of testing the maskers was mixed for each listener.

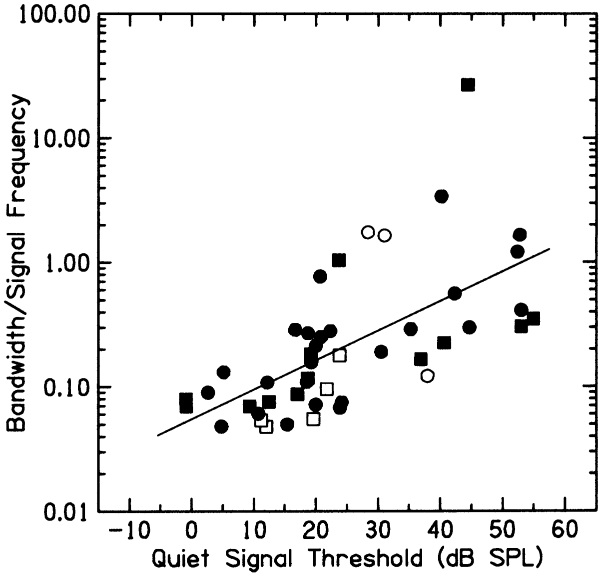

FIG. 2. Thresholds for the signal tone in broadband noise specified as bandwidth divided by signal frequency as estimated by an equal energy/critical ratio hypothesis (see text). The abscissa is threshold for the signal in quiet. Each point represents the threshold for one listener averaged over four estimates. The different symbols represent two groups of listeners and signal frequencies: (1) participated only in experiment 1 and had a 1000-Hz signal frequency (■) or 750-Hz signal frequency (□), and (2) participated in both experiments 1 and 2 and had a 1000-Hz signal frequency (●) or 750-Hz signal frequency (○). The solid line is the least-squares fit to the data.

Results and Discussion

Figure 2 shows the results of the measurements obtained with the Gaussian noise masker. The data are plotted as proportional bandwidth (bandwidth/signal frequency) as a function of quiet threshold at the signal frequency. Bandwidths were estimated indirectly from an equal-energy assumption ($\mathrm{BW} = 10^{(L_s - N_0)/10}$), where BW is the internal bandwidth applied to the noise, L_s is the level of the signal at masked threshold, and N_0 is noise spectrum level in dB) in which it is assumed that, at threshold, the signal-to-masker ratio at the output of the auditory filter centered on the signal frequency is 0 dB. The solid symbols are data collected at a signal frequency of 1000 Hz, while the open symbols are data collected with a 750-Hz signal frequency. The data for subjects who participated in both experiments 1 and 2 are indicated by circles, while the data for those who participated only in experiment 1 are plotted as squares. When quiet signal thresholds were less than about 15 dB SPL, the proportional bandwidths ranged from approximately 0.04 to 0.10, corresponding to critical ratios ($L_s - N_0$) of about 15–20 dB. As quiet signal threshold (i.e., hearing loss) increased, the corresponding proportional bandwidths also increased significantly with a relationship that was reasonably well-fit by a straight line (Pearson product–moment correlation coefficient, $r = 0.63$, $p < 0.001$). The slope of the line indicates that, over the range of values measured, a 13-dB increase in quiet signal threshold results in a doubling of proportional bandwidth. In extreme cases, estimated bandwidths were greater than 1000 Hz. This is a somewhat greater increase in bandwidth with increasing hearing loss than is usually found using more direct bandwidth estimates (cf. Moore 1995).

The results from the MBS and MBD masking conditions are shown in Figure 3. The abscissa is the sound pressure level of the signal at quiet threshold. The ordinate is the sound pressure level per component of the maskers at masked threshold. The MBS masker levels are shown as open symbols and the MBD masker levels are shown as filled symbols. Squares indicate subjects participating in experiment 1 only while circles indicate subjects participating in both experiments. The lines are least-squares fits to the data. The upward-pointing arrows are for listeners who bumped the top of the masker level range for the MBD condition in one or more blocks; their symbols are plotted at the maximum masker level (85 or 95 dB). The data for these five listeners were not included in the line fit. In general, the level of the MBS masker increased as signal threshold increased (slope = 0.56), while the level of the MBD masker was nearly constant over the range of signal thresholds (slope = −0.05). Thus, a markedly different pattern of results was found for the two informational maskers: for MBD, which normally produces little informational masking, the masker levels at masked threshold were unrelated to the amount of hearing loss ($r = 0.05$, $p = 0.74$), while for MBS, the masker levels at masked threshold increased significantly ($r = 0.62$, $p < 0.001$) in proportion to the amount of hearing loss.

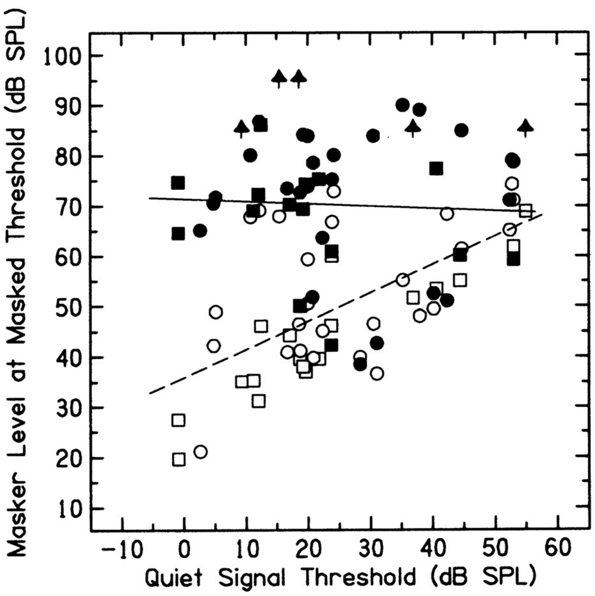

FIG. 3. As in Figure 2, squares indicate listeners in experiment 1 only and circles are for those in both experiments 1 and 2. Open symbol (□,○) are for the MBS masker and closed symbols (■,●,↑) are for the MBD masker. The arrow indicates that the maximum allowable level was reached in one or more adaptive tracks for these listeners. These points were not included in the line fit. Each point is the level per component of the masker at masked threshold for one listener averaged over four estimates. The abscissa is quite signal threshold. The lines are the least-squares fits to the data for MBD (—) and MBS (-----).

Two findings emerged from experiment 1. First, as the hearing loss at the signal frequency increased, the bandwidth estimated by tone-in-noise detection also increased. This finding of an increase in the critical ratio with increasing sensorineural hearing loss is not new and is consistent with a wide range of other studies using a variety of techniques to measure frequency selectivity [for a recent review, see Moore (1995)]. However, as a consequence of the technique used here—detection of a tone in broadband, flat-spectrum noise—these results may have been influenced to an unknown degree by inefficient processing. This point was made by Patterson et al. (1982) in arguing for measurement of auditory filter characteristics *and* processing efficiency rather than critical ratios only. The idea is that two listeners with identical filters could have significantly different thresholds in noise because of a difference in processing efficiency. The reasons for the difference between the two hypothetical listeners is assumed to be due to central factors, but exactly *what* the central factors may be is not well understood. It is particularly important here to determine not only the effects of cochlear pathology on auditory filter

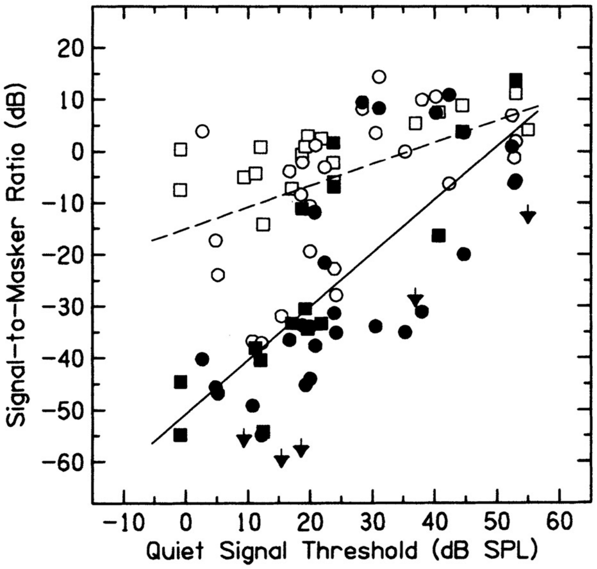

FIG. 4. The data from Figure 3 have been replotted as signal-to-masker ratio at masked threshold. The symbols and line types are the same as in Figure 3.

width, but also to understand the subsequent processing of the output of the filter because informational masking inherently implies inefficient processing of the energy falling in the filter containing the signal. A better understanding of the data shown in Figure 2 could be obtained if the properties of the "auditory filter" around the signal frequency were known and evaluated separately from the processing efficiency of the listener. This is addressed in experiment 2 below. The second finding was that the effect of hearing loss on informational masking was different for the two types of informational maskers. This is a new result and one that requires further consideration.

One way of viewing the informational masking results is to consider the "effectiveness of masking" or signal-to-masker ratio at masked threshold. Because the listeners had different amounts of hearing loss at the signal frequency, the SPL of the fixed sensation-level signal also varied, and thus evaluating the results in terms of the signal-to-masker ratio is a way of relating performance across listeners. Therefore, the results contained in Figure 3 were replotted as signal-to-masker ratio. These values are shown in Figure 4. The abscissa is quiet signal threshold and the ordinate is the signal-to-masker ratio at masked threshold. The symbols are the same as in Figure 3. As signal threshold increased, the signal-to-masker ratio for MBD increased proportionally (slope = 1.03, $r = 0.75$, $p < 0.001$), while for the MBS masker the change in signal-to-masker ratio was less (slope = 0.42, $r = 0.51$, $p < 0.001$). The results plotted in this form suggest that the MBD masker was more effective for the listeners with the greater amounts of hearing loss than for the listeners with lesser amounts of hearing loss. This was not a ceiling effect because the masker levels rarely reached the upper limit of the range of available levels (this occurred in one or more threshold estimates for five listeners; those data points are plotted as upward-pointing arrows in Fig. 3 and downward-pointing arrows in Fig. 4). Thus, these results indicate that the relative effectiveness of the MBD masker increases as hearing loss increases.

Because it is of interest to determine whether factors other than hearing loss could have contributed to the results, a multiple-regression analysis was conducted in which proportional bandwidth, quiet signal threshold, age, speech discrimination score, and audiometric slope were tested as predictor variables for the MBD and MBS signal-to-masker ratios. For MBD, stepwise regression indicated that 66% of the variance ($p < 0.001$) could be accounted for by a model incorporating proportional bandwidth and quiet signal threshold and that none of the other variables significantly increased r^2 ($p > 0.05$). In this model, type II partial r^2 indicated that 19% of the variance was accounted for by proportional bandwidth, controlling for quiet signal threshold ($p < 0.001$). The variance accounted for by quiet signal threshold while controlling for proportional bandwidths was about 7% ($p < 0.01$). For MBS, stepwise regression indicated that quiet signal threshold, speech discrimination score, and audiometric slope were significant predictor variables accounting for about 46% of the variance ($p < 0.001$). Quiet signal threshold accounted for most of the variance (32%; $p < 0.001$), with speech discrimination score and audiometric slope accounting for 8% ($p < 0.05$) and 7% ($p < 0.05$), respectively.

The masking produced by the MBS masker is due primarily to two factors: (1) the presentation-by-presentation uncertainty of the composition of the stimulus in the frequency domain, and (2) the tendency to perceptually group the signal and masker tones together to form a unitary auditory object. The latter is a consequence of the cross-frequency temporal synchrony of the bursts of signal and masker throughout each presentation. Cues that help segregate the signal from the masker, such as dichotic presentation, temporal asynchrony or a difference in amplitude modulation, can help the listener hear out the signal component and reduce the informational masking (Kidd et al. 1994; Neff 1995). Relative level is also a potential cue: If the signal is high enough in level relative to the masker tones, the listener can detect its presence either by making a judgement based on overall loudness of the complex or by hearing out the signal tone as a spectral prominence (e.g., "profile analysis." Green 1988). However, the lack of a constant spectral reference across intervals and trials would make judgments based on profile analysis extremely difficult (Kidd et al. 1986). From the line fit, listeners with near-normal hearing at the signal frequency detected the signal when the signal-to-masker ratio was between −20 and −10 dB (noting the modest goodness of fit for the line and the large individual differences observed). As hearing loss increased, signal-to-masker ratio increased gradually until the listeners with more severe hearing losses required a signal level which was the same as or greater than the level of each component of the MBS masker. The levels of the masker components were constant within a trial so that the possibility cannot be ruled out that listeners used the cue of overall level to determine the signal interval. For example, if we assume that a 1 dB increase in overall level was sufficient to produce a reliable loudness cue, then loudness could be the basis for discrimination when the signal-to-masker ratio was −3 dB or greater. It is likely, though, that the majority of listeners were able to use some cue other than loudness to detect the signal.

For the MBD masker, the interpretation is quite different. Normally, very little masking is produced because the signal "stream" is the only coherent auditory object in an otherwise unrelated set of tones. The stimulus configuration may be thought of as promoting "analytic listening" in that the listener tends to hear out a specific component of the complex sound. For the listeners with the least amount of hearing loss at the signal frequency, the signal-to-masker ratio was in the range from −60 to −40 dB, while the listeners with the greater amounts of hearing loss required a signal-to-masker ratio from approximately −20 to 10 dB. Thus, the difference in signal-to-masker ratio at masked threshold between MBS and MBD maskers can be enormous for the listeners with near-normal hearing at the signal frequency but diminishes as hearing loss increases. These signal-to-masker ratios for the listeners with little hearing loss at the signal frequency are very similar to those that we have found for normal-hearing young-adult college students tested using an identical procedure (Kidd et al. 2000).

The increase in signal-to-masker ratio for the MBD masker as hearing loss increases could be due to at least two factors: first, the excitation patterns of the masker tones could broaden with increasing hearing loss to the point that the masking was energetic in nature. If the auditory filter containing the signal were sufficiently wide (e.g., encompassing the entire frequency range of the masker tones), we would not expect a difference in energetic masking between MBS and MBD maskers because the masker energy in the filter for the two maskers would be the same. The difference in performance we normally expect depends on perceiving the differences in the spectrotemporal patterns of the masker tones presumably falling in different auditory filters. Although such an extreme case of reduced frequency selectivity seems implausible (excepting for the possibility of cochlear "dead regions" as discussed below), nonetheless some of the equal-energy bandwidths measured were extraordinarily large (Fig. 2). Seven of them, in fact, were greater than 1000 Hz, significantly overlapping the frequency range from which the maskers were drawn. A second possibility is that the capability for auditory stream formation or sound segregation has been adversely affected by the hearing loss. This argument assumes that the signal is not energetically masked—and thus presumably is available in the peripheral neural representation of the stimulus—but that one or more of the subsequent steps in processing the peripheral stimulus necessary to perceptually segregate the signal from the masker has been affected. In that case, the advantage normally found for the MBD masker would be lost and the two informational maskers might well prove to be equally effective.

Thus, two aspects of the interpretation of experiment 1 depend on an accurate estimate of the frequency selectivity of the listeners. First, understanding the reason for the increase in the critical ratios found with increasing hearing loss requires an estimate of the width of the auditory filter separate from the processing efficiency of the listener. Second, an accurate estimate of the width of the auditory filter permits evaluation of the hypothesis that the reduction in the difference between MBS and MBD masked thresholds was simply due to increased energetic masking. Experiment 2 was undertaken next in an attempt to examine these issues.

EXPERIMENT 2

Procedures

Following collection of the data obtained in experiment 1, 28 of the 46 listeners returned for additional measurements to estimate the characteristics of their auditory filters and processing efficiencies. These measurements were also completed during a single 2-hour block. Detection thresholds for tones in the notched-filtered noise were measured by a 2-alternative forced-choice adaptive detection procedure, as in experiment 1. The signal was temporally centered within the noise on the signal intervals. Quiet threshold was (re)measured for the signal frequency. The signal level was then fixed at 10 dB above this threshold, and the level of the widest notched-noise was adaptively varied to estimate masked threshold. The value of the noise spectrum level obtained from this threshold estimate was fixed for all of the subsequent notched-noise measurements in which signal thresholds were measured using an adaptive signal level procedure. The filter that was estimated from these data

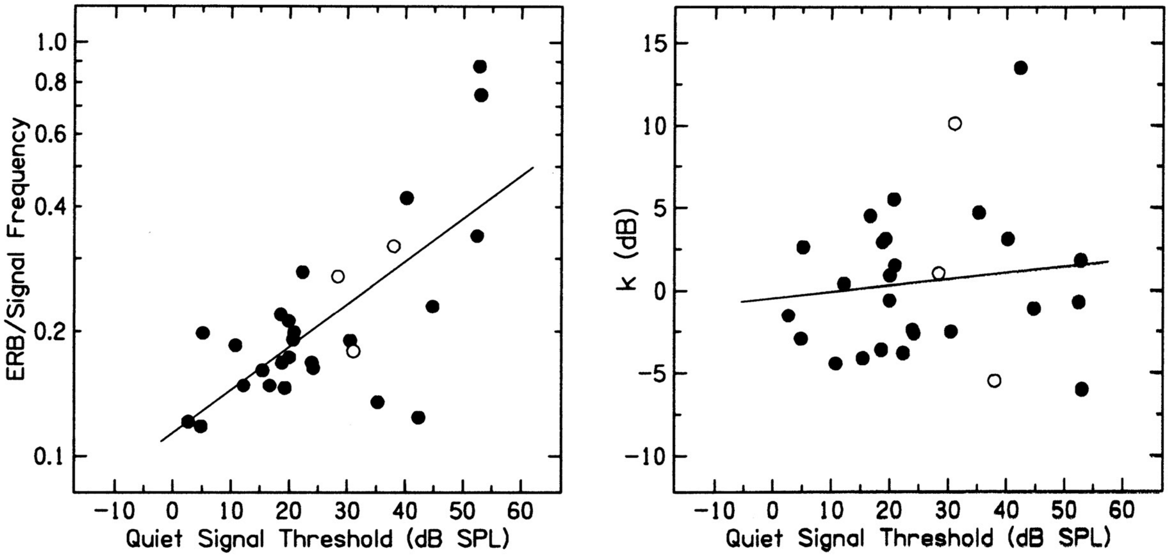

FIG. 5. ERB divided by signal frequency in the left panel and processing efficiency (*k*) in dB in the right panel as a function of quiet signal threshold for listeners tested at 1000 Hz (●) or 750 Hz (○). ERB and *k* values were derived from fits to the tone in notched-noise thresholds from experiment 2. The lines are the least-squares fits to the data.

was the 2-parameter roex version[2,3] of the model originally proposed by Patterson et al. (1982). This version of the filter, as implemented, allowed the estimation of the dynamic range of the filter as well as separate estimates of the upper and lower slopes (Rosen and Baker 1994). Threshold estimates were counted toward the average only if at least six reversals were obtained. The order of testing the notch widths was mixed and randomized for each listener. Two to three threshold estimates were obtained at each notch width.

Results and Discussion

The results are plotted in Figure 5 and the calculated filter values and estimates of processing efficiency *k* (in decibels) are given in Table 2. The left panel of Figure 5 shows the estimated proportional equivalent rectangular bandwidth (ERB/signal frequency) for each listener as a function of quiet signal threshold, while the right panel shows the estimated value of *k* (in dB) also plotted as a function of quiet signal threshold. The open symbols in both panels are for the listeners tested at a signal frequency of 750 Hz. The slopes of the lines indicate that the proportional ERB will double for every 30.1 dB increase in quiet signal threshold, while *k* increases 0.04 dB for every 1 dB increase in threshold. Separating bandwidth from *k* thus decreases the slope of the hearing loss-bandwidth function (see experiment 1 and Fig. 2). With respect to the issue raised in the first experiment regarding the reason for the variation in proportional bandwidth with increasing hearing loss, the Pearson product–moment correlation between proportional ERB and quiet signal threshold ($r = 0.70$) was statistically significant ($p < 0.001$), while the correlation between *k* and quiet signal threshold was not significant ($r = 0.12$, $p = 0.55$). Proportional ERB and *k* were not significantly correlated ($r = -0.25$, $p = 0.20$). The ERBs found for the listeners with near-normal hearing at the signal frequency are in the normal range and are consistent with earlier work from our laboratory using identical procedures with normal-hearing young-adult college students serving as subjects (Kidd et al. 2000). Comparable findings of an increase in ERBs with increasing sensorineural hearing loss have been reported in other studies (Glasberg and Moore 1986; Lutman et al. 1991; Leek and Summers 1993; also Moore, 1995, pp. 57–59, 81–84). Eliminating the two

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[2] Filter parameters were initially estimated from the notched-noise thresholds by both the 1-parameter (upper slope and lower slope computed separately) and 2-parameter (upper slope and lower slope computed separately but dynamic range the same) versions of the roex model. The differences between the predicted filters were usually trivial, so we arbitrarily chose the 2-parameter model. However, for one listener, the 2-parameter version yielded values that we considered to be implausible based on our own experience and other reports in the literature, so for that subject the 1-parameter model was used. The software used to implement the model fits (Glasberg and Moore 1990) is available at the Auditory Perception Group, University of Cambridge, website (http://hearing.psychol.cam.ac.uk/Demos/demos.html).

[3] The rounded exponential, or roex, filter estimated in this study is defined by the equation:

$$W(g) = (1 - r)(1 + pg)e^{pg} + r$$

where g is normalized distance from the center of the filter f_c ($|g| = f - f_c/f_0$), and p and r are the parameters determining the slopes and the dynamic range of the filter, respectively (Patterson et al. 1982).

TABLE 2

A summary of filter parameters from the fits to the notched-noise data. Listener numbers are the same as in Table 1

Listener	*Signal Frequency (Hz)*	*Noise level*[a]	*ERB (Hz)*	p_l	p_u	*k (dB)*	*r (dB)*	*Sum of squared residuals*
3	1000	24	121.1	34.8	31.5	−1.5	−41.5	0.1
4	1000	26	118.1	40.0	29.5	−2.9	−37.3	2.3
5	1000	9	197.7	18.9	23.3	2.6	−25.0	0.1
7	1000	37	184.6	28.2	17.6	−4.4	−38.9	8.2
10	1000	24	147.8	32.3	23.4	0.4	−36.4	0.0
12	1000	31	160.8	23.6	26.4	−4.1	−36.2	0.2
13	1000	32	148.5	26.5	27.5	4.5	−35.5	16.0
15	1000	26	220.0	22.9	15.5	−3.6	−27.5	0.2
17	1000	36	168.4	29.0	20.2	2.9	−43.3	16.6
19	1000	19	145.9	38.1	22.8	3.1	−25.3	5.2
21	1000	30	212.1	29.5	13.9	−0.6	−34.5	1.0
22	1000	31	173.0	21.9	24.7	0.9	−34.0	12.7
23	1000	19	191.4	21.8	21.0	5.5	−26.1	0.2
24	1000	31	199.1	16.1	28.7	1.5	−25.4	3.2
26	1000	32	277.9	14.6	14.3	−3.8	−31.9	0.6
29	1000	38	167.6	21.9	26.9	−2.4	−29.9	2.4
30	1000	42	163.1	23.3	25.8	−2.6	−77.8	38.1
31	750	27	203.5	12.3	18.5	1.0	−37.5	5.8
32	1000	47	189.7	15.9	31.4	−2.5	−34.8	0.1
33	750	26	134.3	24.0	21.3	10.1	−29.7	0.4
34	1000	50	134.6	22.2	45.0	4.7	−40.5	0.3
36	750	50	241.0	20.8	8.9	−5.5	−60.3	68.7
37	1000	20	419.9	50.0	6.4	3.1	−13.9	2.6
39	1000	44	123.6	28.9	37.3	13.5	−34.6	0.8
41	1000	48	230.3	17.8	18.2	−1.1	−23.5	0.0
42	1000	56	340.4	11.4	12.1	−0.7	−66.8	2.5
43	1000	35	876.4	2.7	14.3	1.8	n/a	9.7
45	1000	49	747.0	7.1	4.0	−6.0	−56.5	10.8

[a] Noise level is in dB spectrum level.

subjects with the extremely large proportional ERBs (>0.7) did not change the conclusions regarding the relationship between ERB and hearing loss and had minor effects on the straight-line fit (slope decreased such that a 50.2 dB increase in quiet threshold resulted in a doubling of ERB; $r = 0.54$, $p < 0.01$).

Multiple-regression analysis was undertaken using the factors of quiet signal threshold, age, speech recognition score, and audiometric slope to predict the variation in proportional ERB and *k*. With respect to proportional ERB, stepwise regression revealed that only the variable of quiet signal threshold was significant, accounting for 47% of the variance ($p < 0.001$). With respect to the variation in *k* only age was significant, accounting for about 22% of the variance ($p < 0.05$).

Figure 6 plots the signal-to-masker ratios at masked threshold for the MBS and MBD maskers as a function of proportional ERB and *k*. The left panel plots signal-to-masker ratio in dB as a function of proportional ERB and the right panel plots signal-to-masker ratio in dB as a function of *k*. In the left panel, the lines describing the change in signal-to-masker ratio as a function of proportional ERB increase at the rate of 8 dB per doubling of ERB for MBS ($r = 0.39$, $p < 0.05$) and 14 dB for MBD ($r = 0.50$, $p < 0.01$). Eliminating the two extreme values (above 0.7) changed the line fits only slightly. For MBS, the slope increased to 14 dB per doubling ($r = 0.44$, $p < 0.05$) and, for MBD, the slope increased to 15 dB per doubling ($r = 0.47$, $p = 0.02$). In the right panel, the lines relating signal-to-masker ratio as a function of *k* have slopes of 0.75 dB ($r = 0.22$, $p = 0.23$) for MBS and 1.8 dB ($r = 0.40$, $p = 0.04$) for MBD. Eliminating the two extreme values here (different subjects than left panel; see Table 1) decreased the slope for MBS slightly to 0.62 ($r = 0.14$, $p = 0.49$) but affected MBD much more (slope decreased to 0.34, $r = 0.06$, $p = 0.78$).

A multiple-regression analysis was conducted to determine which factors could account for the variation in MBS and MBD signal-to-masker ratios. The same factors were tested as were used in experiment 1, except that proportional ERB and *k* were substituted for proportional bandwidth (critical ratio). The results indicated that 71% of the variance of MBD was explained by quiet signal threshold, *k*, and speech discrimination score ($p < 0.001$). Type II partial r^2 revealed that quiet signal threshold, controlling for

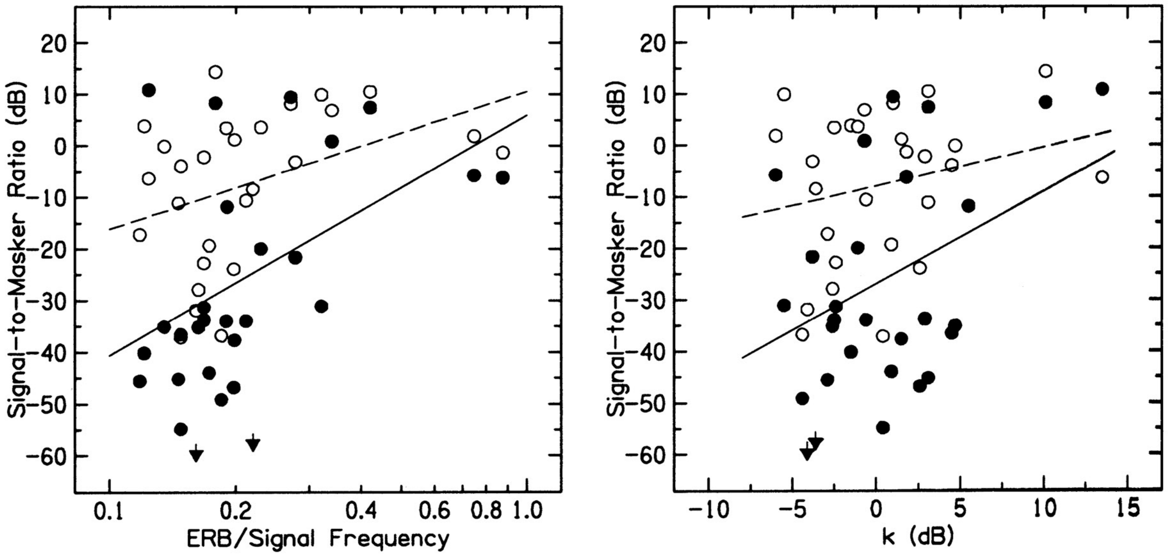

FIG. 6. Signal-to-masker ratio in dB at masked threshold for the MBS (○) and MBD (●) maskers as a function of proportional ERB (left panel) and *k* in dB (right panel) obtained from experiment 2. Arrows are MBD measures that exceeded the limit. The lines are least-squares fits to the data for MBD (—) and MBS (-----).

the other variables, explained the largest proportion of the variance ($r^2 = 0.47$, $p < 0.001$). The factors *k* and speech discrimination score accounted for 12% ($p < 0.01$) and 5% ($p < 0.05$) of the remaining variance, respectively. For MBS, 50% of the variance was accounted for by quiet signal threshold and speech discrimination score ($p < 0.001$). Type II partial r^2 indicated that 35% of the variance was explained by quiet signal threshold ($p < 0.001$) and 18% of the variance was attributable to speech discrimination score ($p < 0.01$).

In the statistical analyses above, quiet signal threshold was the dominant factor in predicting the variation in proportional ERB and the MBS and MBD signal-to-masker ratios. For *k,* the only significant predictor variable was age which was significant at the 0.05 level. Thus, it appears that the increase in the critical ratio as a function of hearing loss reported in experiment 1 was primarily due to increasing filter width rather than to processing efficiency. It is interesting to note that both processing efficiency and speech discrimination score did contribute significantly to the variation in MBD signal-to-masker ratio even though each factor accounted for relatively small proportions of the variance. As noted above, the relationship between MBD and *k* was strongly influenced by the two subjects with extremely large values of *k*. Subject age, which varied over a wide range but was skewed toward the later decades was a significant factor only for predicting the variation in *k* but even then it accounted for only about 22% of the variance. This finding should be viewed with some caution because of other studies showing no significant increase in *k* with age (Patterson et al. 1982; Lutman et al. 1991; Sommers and Humes 1993). Audiometric slope, which influenced the audibility and loudness of the higher-frequency masker component as it adapted in MBS and MBD, was not a significant factor in predicting the variation in MBS signal-to-masker ratio in the analysis using ERB and *k* instead of proportional bandwidth.

With respect to the second issue raised after experiment 1 concerning the possibility that all of the masked thresholds in the informational masker were due to energetic masking, the ERBs for all but four of the listeners were narrower than the protected region surrounding the signal, and for two of those four listeners, the ERBs were only slightly wider than the protected region. Further, for the listeners having the greater amounts of hearing loss, the levels of the masker tones at masked threshold were near the level of the signal so that the masker energy would be attenuated by the filter skirts to the point that spread of masking would be negligible. Thus, the explanation that the decreasing difference in the effectiveness of the MBS and MBD maskers with increasing hearing loss was due to energetic masking does not appear to be supported for 26 of the 28 listeners. The statistical analysis described above is consistent with the minor role of filter width in predicting the MBD results. For the two listeners with extremely wide ERBs (750–900 Hz), it is possible that masker energy fell in the signal's auditory filter resulting in a diminished difference between MBS and MBD maskers; these listeners did indeed have small (less than 8 dB) differences in performance between the two maskers. It is also possible that there are other factors that influenced the estimates of the filter. For example, Moore et al. (2000, 2001), have found evidence for tonotopically limited "dead regions" in the cochlea. If our listeners had such regions located at the signal frequency, it would likely cause elevations in the signal thresholds and wider bandwidth estimates. However, even if the signal frequency fell in a dead region, maskers remote in frequency would still be expected to produce large amounts of informational masking.

If the results discussed above cannot be attributed to energetic masking, then is seems likely that they must be due to informational masking. The main finding of our study is that the MBD signal-to-masker ratio increases in proportion to the amount of hearing loss. Because the MBD condition promotes "analytic listening," i.e., the hearing out of part of a complex sound, then it follows that hearing loss adversely affects the ability to listen analytically. It should be pointed out that low signal-to-masker ratios in the MBS condition may also be due to superior analytic listening ability. However, the MBS masker is intended to promote synthetic listening and, in this study at least, most listeners demonstrated large amounts of masking. Our explanations for why analytic listening abilities may be compromised by sensorineural hearing loss are, at this point, entirely speculative. One possibility is a change in the weight given to grouping and segregation cues as hearing loss increases. The multiple-bursts paradigm exploits a strong grouping cue by use of synchronous gating of the signal and masker tones throughout the burst sequence. Synchronous gating of the rapid burst sequence, which may be thought of as a form of amplitude modulation across frequencies, tends to cause the listener to perceptually group the elements of the sound together to form a single auditory object. In MBD, however, the random variation in the frequencies of the masker tones throughout the burst sequence opposes the grouping cue of coherent amplitude modulation causing the masker tones to sound unrelated. The increase in the effectiveness of the MBD masker with increasing hearing loss could thus be due to a greater-than-normal weighting of coherent, cross-frequency amplitude modulation in the grouping and segregation process. Another possibility is that the broader than normal internal representation in frequency of the individual elements of the MBD masker (as implied by the wider auditory filter estimates) would result in more common areas of excitation (overlap of same tonotopic frequency regions) throughout the burst sequence, perhaps causing the MBD masker to be perceived more like the MBS masker. The finding of Rose and Moore (1997) that some hearing-impaired listeners require wider frequency separations of successive tones for stream segregation is consistent with that argument. However, proportional ERB did not account for a significant proportion of the variance in MBD signal-to-masker ratio. Another possibility is that hearing-impaired listeners in general are less able to form streams and thus the frequency coherence of the signal over time in the MBD masker is inadequate to cause it to segregate from the masker. The current experiments were not sufficient to test these speculations and further work is needed to determine if any of these explanations is viable.

SUMMARY

To summarize the results obtained in the two experiments described above: First, for the entire pool of 46 listeners, proportional bandwidths (critical ratios) increased as the amount of hearing loss at the signal frequency increased. Second, for a subset of 28 of the listeners, auditory filter measurements indicated that the relationship between hearing loss and critical ratio was due more to the broadening of the auditory filters than to decreased processing efficiency. Third, an abnormal pattern of informational masking was found that was related to the degree of hearing loss at the signal frequency. As hearing loss increased, the difference in the effectiveness of two different types of informational maskers decreased with the normally less effective MBD masker increasing in effectiveness until, for the listeners with the greatest amounts of loss, it was nearly as effective as the MBS masker. Because the "hearing out" of an audible component of a complex sound—normally the basis for the MBD advantage over MBS—is generally considered to be a form of "analytic listening," our conclusion is that cochlear hearing loss adversely affects the ability to perform tasks requiring analytic listening.

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