Informational masking in hearing-impaired and normal-hearing listeners: Sensation level and decision weights[a]

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Informational masking (IM) refers to elevations in signal threshold caused by masker uncertainty. The purpose of this study was to investigate two factors expected to influence IM in hearing-impaired listeners. Masked thresholds for a 2000-Hz signal in the presence of simultaneous multitone maskers were measured in 16 normal-hearing (NH) and 9 hearing-impaired (HI) listeners. The maskers were 70 dB SPL average total power and were comprised of fixed-frequency components between 522 and 8346 Hz that were separated from each other by at least $\frac{1}{3}$ oct and from the signal by at least $\frac{2}{3}$ octs. Masker uncertainty was manipulated by randomly presenting each masker component with probability $p=0.1, 0.2, \ldots, 0.9$, or 1.0 across different trial blocks. Energetic masking was estimated as the amount of masking for $p=1.0$, where masker uncertainty was minimum. IM was estimated as the amount of masking in excess of energetic masking. Decision weights were estimated by a regression of the listener's yes/no responses against the presence or absence of the signal and masker components. The decision weights and sensation levels (SLs) of the stimulus components were incorporated as factors in a model that predicts individual differences in IM based on the level variance (in dB) at the output of independent auditory filters [Lutfi, J. Acoust. Soc. Am. **94**, 748–758 (1993)]. The results showed much individual variability in IM for the NH listeners (over 40 dB), but little IM for most HI listeners. When masker components were presented to a group of NH listeners at SLs similar to the HI listeners, IM was also similar to the HI listeners. IM was also similar for both groups when the level per masker component was 10 dB SL. These results suggest that reduced masker SLs for HI listeners decrease IM by effectively reducing masker variance. Weighting efficiencies, computed by comparing each listener's pattern of weights to that of an ideal analytic listener, were a good predictor of individual differences in IM among the NH listeners. For the HI listeners weighting efficiency and IM were unrelated because of the large variation in masker SLs among individual listeners, the small variance in IM, and perhaps because broadened auditory filters in some listeners increased the covariance in auditory filter outputs. © *2004 Acoustical Society of America.* [DOI: 10.1121/1.1784437]

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I. INTRODUCTION

Informational masking (IM) is the term often used to refer to elevations in signal threshold that cannot be attributed to the energy-based masking at the filters of the auditory periphery. One factor known to produce considerable amounts of IM is uncertainty regarding the spectral properties of the masker. According to this view, IM can be quantified by the difference in masked threshold for maskers whose properties vary unpredictably from trial to trial and maskers with unvarying properties (cf. Watson *et al.*, 1976). Since signal detection for the latter type of masker is limited primarily by energetic masking, IM is equivalent to the residual amount of masking after accounting for the contribution of energetic masking:

$$\mathrm{IM}=\mathrm{TM}-\mathrm{EM}, \tag{1}$$

where TM is the total masking and EM is the energetic masking, all in dB (cf. Lutfi, 1990).

For multitone maskers with random frequencies, pure-tone detection thresholds can be elevated by 50 dB for normal-hearing (NH) adult listeners (Neff and Green, 1987; Neff and Dethlefs, 1995; Oh and Lutfi, 1998) or greater for preschool children (Allen and Wightman, 1995; Oh *et al.*, 2001; Lutfi *et al.*, 2003b; Wightman *et al.*, 2003). Compared to these groups, relatively little is known about the factors that influence IM in hearing-impaired (HI) listeners. To the authors' knowledge, only three other studies (Kidd *et al.*, 2001; Doherty and Lutfi, 1999; Micheyl *et al.*, 2000) have investigated IM for a pure-tone signal in HI listeners.

Kidd *et al.* (2001) adapted the levels of random-frequency multitone maskers in a two-interval, forced-choice procedure to obtain the signal-to-masker ratio at masked threshold in NH and HI listeners. The signal was a sequence of eight contiguous 60-ms tone bursts at 750 or 1000 Hz and was fixed at 20 dB above the signal threshold in quiet. The maskers consisted of two sets of tone bursts, one set below and one set above the signal frequency, and were played synchronously with the eight signal bursts. For the

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‘‘multiple-bursts different’’ (MBD) maskers, the frequencies of the masker bursts varied from burst to burst within each of the two trial intervals. For the ‘‘multiple-burst same’’ (MBS) maskers, the masker bursts were kept at constant frequencies within each interval, like the signal, but were varied across the two intervals in each trial. Kidd *et al.* hypothesized that the signal would perceptually segregate from the MBD maskers since their spectral-temporal properties were different from the signal, thereby lowering detection thresholds. It was found that the signal-to-masker ratio increased for both types of maskers as hearing loss for the signal increased and that this factor accounted for most of the variance in the masked thresholds. The signal-to-masker ratios for the MBS maskers were high even for the NH listeners and increased only slightly as a function of hearing loss. The signal-to-masker ratios for the MBD maskers were much less than they were for the MBS maskers for both groups, but steadily increased with increasing hearing loss so that the difference between the two masker types was minimal for the listeners with the greatest amounts of hearing loss. Kidd *et al.* speculated that the relative increase in signal-to-masker ratios for the MBD maskers with increasing amounts of hearing loss for the signal signified that ‘‘hearing loss adversely affects the ability to *listen analytically*’’ (p. 118).

To listen analytically a listener must attend to a specific target feature of the stimulus (signal) and ignore all other nontarget features (maskers). Analytic listening can be operationally described by decision weights that denote the emphasis or attention that each feature is given in a listener’s decision. This provides a quantitative method for describing and comparing different listening strategies. For a specified stimulus parameter, frequency in this case, decision weights are analogous to an attentional filter; spectral regions given greater weight will tend to have greater influence on a listener’s decision than those given less weight. Decision weights are often estimated by correlation or multivariate regression coefficients that describe the relationship between the listener’s responses and the properties of the stimulus ensemble, assuming a particular decision model (cf. Berg, 1989; Lutfi, 1995; Richards and Zhu, 1994).

In order to describe the association between the masked threshold for a random-frequency masker and decision weights, we adopt a theoretical framework in which the listener is assumed to make decisions about the presence or absence of the signal by forming a weighted sum of the output of independent auditory filters (Lutfi, 1993). Using sensation level, SL (dB above threshold in quiet), as the filter output, the decision variable, D, is

$$D=\sum_{i=1}^{n} w_i \mathrm{SL}_i, \tag{2}$$

where i corresponds to individual signal and masker tones and where w_i represents the decision weights. In this equation, weights and SLs are both linearly related to D so that if a masker component is half the SL of another masker component but is given twice as much weight, then both components will have an equal effect on the magnitude and the variance of D. For a yes/no task it is assumed that the listener responds ‘‘yes’’ if and only if D exceeds some constant internal criterion, C, and responds ‘‘no’’ otherwise. Models of this type have proven quite successful in predicting the amount of IM obtained in conditions like those of the present study (Lutfi, 1992, 1993; Oh and Lutfi, 1998; Lutfi *et al.*, 2003b; Wright and Saberi, 1999; Richards *et al.*, 2002; Tang and Richards, 2002).

One such model is the component relative entropy (CoRE) model (Lutfi, 1993). Oh and Lutfi (1998) develop specific predictions from this model for the case in which the masker is a combination of tones with random frequencies. The prediction is that IM will be proportional to the standard deviation σ in level (dB) at the output of a typical auditory filter,

$$\mathrm{IM}\cong d' \sqrt{n}\,\sigma, \tag{3}$$

where d' is the index of sensitivity and n is a free parameter representing the number of independent auditory filters assumed to be involved in a listener’s decision. In this study, the contribution of independent auditory filters (given by n) is obtained directly from w_i, rather than treated as a free parameter. The standard deviation of filter outputs, moreover, is derived from the SLs of the individual masker components so that the predicted amount of IM is then given by

$$\mathrm{IM}\cong d' \sqrt{\sum w_i^2 \mathrm{SL}_i^2}\,\sigma. \tag{4}$$

From Eq. (4) it is apparent that increasing the weights and/or the SLs of masker components also increases the standard deviation of the decision variable, which increases the amount of IM.

The ability to listen ‘‘analytically’’ in this context can be evaluated by comparing a listener’s decision weights to those of an ideal observer—an observer that would give a weight of one to the signal and zero weight to all masker components. Berg (1990) describes a weighting efficiency measure that represents the degree to which a listener’s weights approaches the ideal weights. In a task in which listeners discriminated the difference in level of a designated signal tone in the presence of level-varying nonsignal tones, Doherty and Lutfi (1999) found that weighting efficiency for listeners with mild to moderate, sloping hearing loss tended to increase as the frequency of the signal and the amount of hearing loss increased. If maskers in a region of hearing loss receive greater weight, as these results indicate, then the amount of IM is expected to be larger.

The influence of SL on IM is inferred from a study by Micheyl *et al.* (2000). Micheyl and colleagues found that under certain circumstances HI listeners had lower masked thresholds for random-frequency multitone maskers than NH listeners. They measured masked threshold for a 1000-Hz signal in listeners with normal hearing and in listeners with symmetric or asymmetric hearing losses (i.e., same or different amounts of hearing loss for the two ears). The signal was gated on and off with four-tone maskers whose frequencies were pseudo-randomly selected from six possible fixed frequencies. For listeners with symmetric hearing loss, the masker levels were set to 40 dB SL. For listeners with asymmetric hearing loss, the masker levels were set to 40 dB SL in the better ear and adjusted for equal loudness in the ear with greater hearing loss. Micheyl *et al.* found that there was not a statistically significant difference in the masked thresholds between the listeners with normal hearing, the listeners with symmetric hearing loss, and the better-hearing ear of those with asymmetric hearing loss. However, in the asymmetric hearing loss group, masked thresholds for the ears with a greater degree of hearing loss were significantly *less* than they were for the better-hearing ears and were significantly less than they were for the NH listeners. Micheyl *et al.* suggested that these differences might be due to the loudness balancing procedure used to adjust the masker levels for the listeners with asymmetrical hearing loss. Because of loudness recruitment, the SLs of the maskers were lower and averaged only 20 dB SL compared to 40 dB SL in the better-hearing ears. These outcomes support the hypothesis that IM is dependent on masker SLs.

In summary, the literature suggests two different interpretations for the difference in susceptibility of NH and HI listeners to IM. Kidd *et al.* (2001) suggest that HI listeners might have a specific deficit when analytically listening for a signal amongst a group of maskers with similar spectral-temporal characteristics. In terms of decision weights, this suggests that HI listeners might have less efficient weighting strategies when detecting a signal tone in a group of randomly occurring masker tones. The results of Micheyl *et al.* (2000), however, suggest that HI listeners might have lower amounts of IM because the SLs of the masker components will be less in regions of hearing loss, effectively reducing masker uncertainty. We test these interpretations in the following experiments.

II. EXPERIMENT I: EQUAL-SPL MASKER COMPONENTS

A. Method

1. Listeners

Sixteen NH listeners (3 males and 13 females) between the ages of 19 and 24 years, including the first author (NH14), and nine HI listeners (1 male and 8 females) between the ages of 23 and 79 years (median age of 35 years) completed the study.[1] Hearing losses were assumed to be primarily sensorineural since none of the HI listeners had an air-bone gap (i.e., a difference between air conduction and bone conduction thresholds) greater than 10 dB between 500 and 4000 Hz in the test ear. For all HI listeners, the extent of sensorineural hearing loss was about the same for both ears, except for listener HI8 who had a mild sensorineural hearing loss in the nontest ear and a moderate hearing loss in the test ear. Each listener used the right ear for the experiments, except for HI8 who used the left ear.

2. Stimuli

The signal and masker were computer generated with a 40-kHz sampling rate using the MATLAB® programming language (The MathWorks, Inc.) and a 16-bit sound card (Sound Blaster™ audio card; Creative Technology, Ltd.) before being passed through a programmable attenuator (Tucker-Davis Technologies, PA4). All stimuli were presented monaurally through a Sennheiser HD 520 (II) earphone.[2] The signal was a 2000-Hz tone that occurred with a probability of $p=0.5$ on the single interval trial and was gated on and off synchronously with the maskers with 10-ms $\cos^2$ onset/offset ramps for a total duration of 300 ms. On every trial, the phase of the signal and of each masker component was randomly selected from a rectangular distribution ($0\text{–}2\pi$ rad).

The maskers were designed to simplify assumptions about the processing occurring at the auditory periphery. In order to limit the amount of energetic masking, the frequencies of the masker components were remote from the signal frequency and only a small number of components were used. Furthermore, the masker components were separated in frequency from one another so that they would occur in largely independent auditory filters. The masker components were ten randomly occurring, fixed-frequency tones separated by 1/3 oct in the range from 522 to 8346 Hz (522, 657, 828, 1043, 1314, 3312, 4173, 5258, 6624, 8346), excluding the 2/3-oct region on either side of the signal so as to further limit the amount of energetic masking (cf. Neff and Green, 1987; Neff and Callaghan, 1988). Uncertainty or variability in the masker ensemble was created by independently varying the nominal probability of occurrence, $p=0.1,0.2,...,0.9$, or 1.0, of each masker component.[3] Since the masker components were either on or off, the analytical approximation for the standard deviation term in Eq. (4) is given by the standard deviation of the binomial distribution, $\sigma_b=\sqrt{p(1-p)}$.

The level of each masker component was adjusted so that the expected total power of the masker ensemble within the block of trials was always 70 dB SPL:

$$I_i=70-10\log_{10}(10p), \tag{5}$$

where I_i is the intensity level of each masker component in dB SPL and p is the probability of occurrence for each masker component for a given trial. Within a block of trials, both I_i and p were kept constant. Listeners HI1, HI6, and HI7 could not detect the signal above chance with the maskers at these levels. For these three listeners the masker levels were lowered by 10 dB so that average total power of the maskers was 60 dB SPL. Since the number of components in the masker complex and the actual total power varied from trial to trial, neither could be used as a reliable cue for signal detection.

3. Procedure

Listeners ran the experiments individually while seated in a double-walled, sound-attenuated chamber. A single-interval, yes/no procedure with visual feedback was used to estimate masked threshold for the signal in the presence of the multitone maskers. With this procedure, decision weights can be estimated by correlating a listener's yes/no responses with the presence/absence of the tones in the single interval (see the next section). The signal levels were adapted using a two-down, one-up decision rule which estimates the 70.7% point on the psychometric function (Levitt, 1971). The signal level was limited so that the combined total power of the signal and maskers was no greater than 90 dB SPL. When listeners reached this level and responded incorrectly, the

TABLE I. For the test ears of the individual HI listeners, quiet thresholds for the masker components and the 2000-Hz signal in dB SPL are provided along with their age. The mean quiet thresholds and standard deviations for the HI and NH listeners are also listed.

		Frequency (Hz)										
Listener	Age	522	657	828	1043	1314	2000	3312	4173	5258	6624	8346
HI1	21	49.2	50.9	44.5	36.6	31.6	39.3	19.5	20.8	27.2	31.3	35.2
HI2	23	38.2	39.8	39.9	38.0	33.2	41.7	38.3	33.8	31.9	46.2	61.0
HI3	35	18.4	19.6	18.8	9.6	17.7	4.7	10.5	24.8	42.7	62.5	65.6
HI4	46	31.9	44.0	55.4	55.8	50.8	47.2	39.0	33.1	38.5	40.6	41.4
HI5	41	34.1	37.5	38.8	49.6	55.1	50.8	42.1	43.2	47.6	70.8	74.1
HI6	28	39.9	41.8	44.1	50.8	67.0	70.8	60.8	76.5	77.5	76.5	87.0
HI7	76	31.8	35.7	34.4	34.2	34.2	42.1	45.8	51.9	60.8	71.3	85.7
HI8	41	71.8	78.3	71.1	70.6	61.8	47.8	45.6	31.0	22.2	38.8	47.0
HI9	28	52.5	61.7	59.9	66.4	64.1	64.5	48.8	49.5	52.4	59.6	71.1
Mean HI	37.7	40.9	45.5	45.2	45.7	46.2	45.4	39.0	40.5	44.5	55.3	63.1
SD HI	16.8	15.3	16.8	15.3	18.6	17.4	18.6	15.3	17.1	17.4	16.5	18.7
Mean NH	21.6	20.5	22.8	16.2	14.0	14.2	5.6	−0.3	6.3	7.3	15.7	24.4
SD NH	1.6	4.2	4.2	3.2	6.6	7.0	6.6	5.2	4.4	5.8	7.7	8.7

adaptive track remained constant until the listener obtained two consecutive correct responses.[4] Each trial block consisted of 12 reversals in the adaptive track and started with an initial step size of 4 dB that was reduced to 2 dB after the third reversal. Threshold for each block was determined by averaging the levels of the final eight reversals.

The masked threshold for each probability condition was determined by the mean masked threshold for five consecutive blocks of trials. Initial starting levels for each condition were 10 dB above the masked threshold estimated from at least one block of practice trials. Subsequent starting levels were set to 10 dB above the running average of all previous blocks. Each experimental session lasted about 45 min and consisted of one block of trials for each probability condition, the order of which was randomly permutated for each session for each listener. To minimize practice-effects, a block of trials for each probability condition was run as practice and was repeated until the listener could consistently perform above chance. Furthermore, the signal was presented in quiet before the start of every block to remind the listener of the signal characteristics.

Before masked thresholds were estimated, quiet thresholds for one block of trials were estimated for the signal and for each masker tone using the same response-feedback procedure described above. After completion of the IM experiment, quiet threshold estimates for two more trial blocks were obtained. Quiet threshold for each tone was based on the mean across the three trial blocks. Table I shows the quiet thresholds for each of the individual HI listeners along with their age. The mean quiet thresholds and standard deviations for the HI and NH listeners are also provided in Table I. The SLs of the signal and masker components for every trial were computed by subtracting the quiet threshold from the presentation level, which depended on p [cf. Eq. (5)].

4. Analyses

Experimental conditions in which the probability of occurrence for each masker component was less than $p=1.0$ were considered to be the IM conditions because the spectral composition of the masker was uncertain from trial to trial. The amount of IM in these conditions was obtained by subtracting the estimated proportion of masking attributable to energetic masking [cf. Eq. (1)]. One way to estimate the amount of energetic masking in this experiment is to measure signal threshold for each possible masker in isolation without uncertainty. The number of possible maskers makes this approach impractical. We have chosen instead to take the amount of masking for the $p=1.0$ condition as our estimate of energetic masking since the masker composition for this condition was constant from trial to trial. Because the tails of the auditory filters are thought to be relatively flat for frequencies remote from the signal (Patterson and Green, 1978; Patterson *et al.*, 1982) and because the average total power of the masker complex was constant for all the probability conditions, the average amount of masker energy falling in the auditory filter centered on the signal frequency (the amount of energetic masking) is also assumed to be roughly constant for all the probability conditions.

Predictions for IM were based on the analytical expression in Eq. (4) except that the standard deviation term was empirically derived from the actual trial-by-trial standard deviation of the decision variable values [cf. Eq. (2)] for trials in which the signal was absent.[5] Similarly, d' was empirically derived from the difference in a listener's Z-scores for the hit and false-alarm rates across all conditions and blocks.

It is assumed that a listener adopted the same weighting strategy throughout the experiment and that weights were fixed across the probability conditions (Lutfi *et al.*, 2003a). The weights in Eq. (4) were estimated by a logistic regression of a listener's trial-by-trial responses against the SLs of the signal and masker components taken across all conditions except $p=1.0$ (cf. Richards and Zhu, 1994; Lutfi, 1995).[6] Variation in masker SL arises because masker SL was adjusted for each condition to maintain a constant average total power [cf. Eq. (5)]. The variation in signal SLs arises because signal level was varied in the adaptive threshold track. When components were "off" for a given trial, SL was set to 0.

As has been done in past studies, the weights are normalized so that their magnitudes sum to unity (cf. Berg,

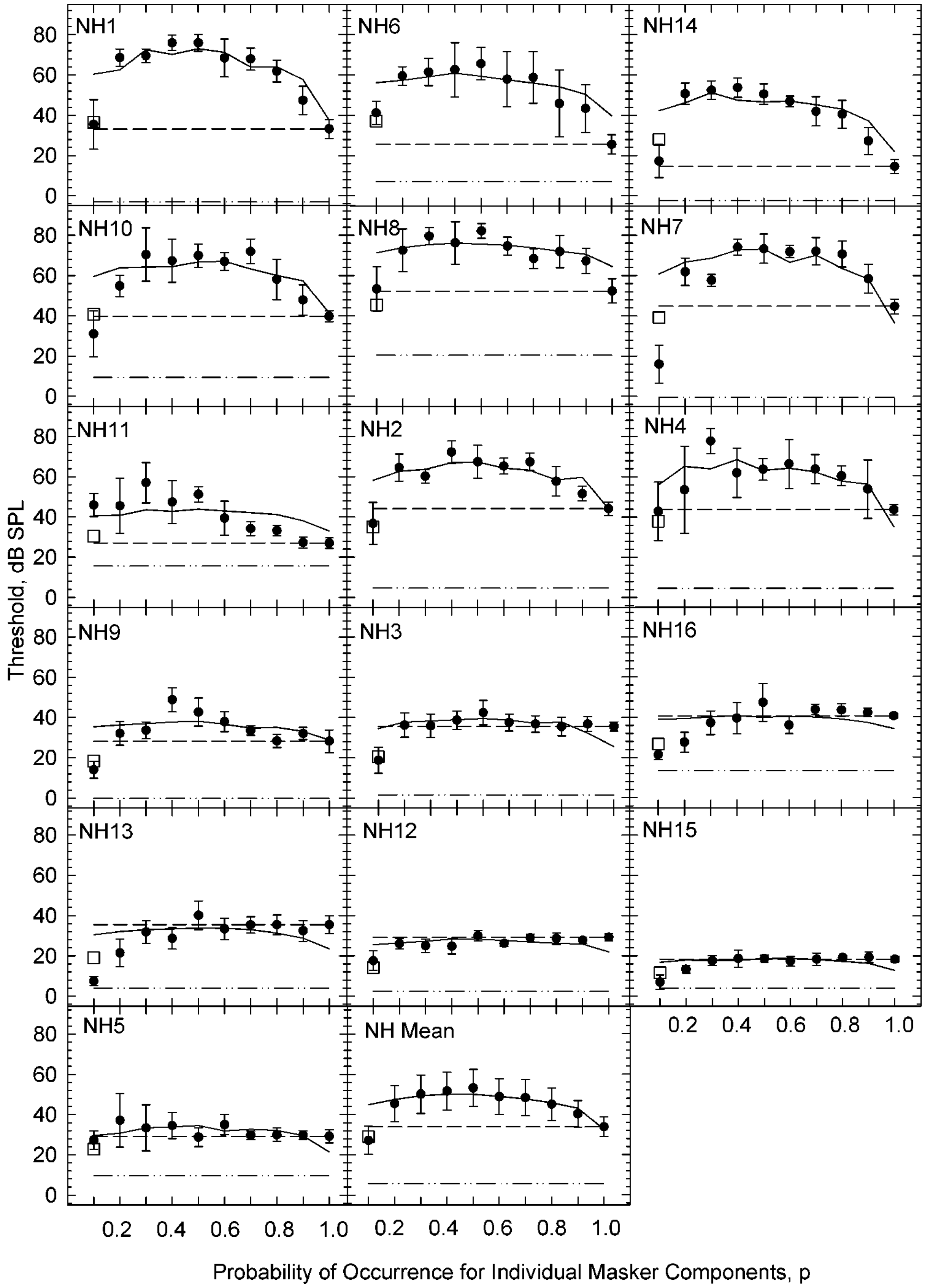

FIG. 1. Masked thresholds for the NH listeners are shown as a function of the probability of occurrence of the individual masker components. Circles represent the mean masked threshold for five trial blocks and the error bars represent the 95% confidence intervals. Listeners are arranged in descending order from left-to-right, top-to-bottom according to the amount of IM at $p=0.5$. The last panel provides the overall group mean and 95% confidence intervals. The amount of masking is represented by the difference between the masked threshold and the quiet threshold for the signal (the dash-dot line). The dashed line represents masked threshold corresponding to energetic masking. The difference between the circles and the energetic masking line is the estimated amount of IM. The solid line is the CoRE model prediction and the open square is the adjusted CoRE model prediction for $p=0.1$ (see footnote 9).

1990; Lutfi, 1992; Doherty and Lutfi, 1996, 1999; Willihnganz *et al.*, 1997; Stellmack *et al.*, 1997). Model predictions are the same for different normalization procedures if the raw regression coefficients for the signal and masker components are all multiplied by the same constant (e.g., normalizing with respect to the signal weight). We chose this particular normalization procedure so that the values can be interpreted as the *proportional* weight that the listeners devote to each component. Weighting efficiency for each listener was determined by computing the root-mean-square (rms) of the difference between the obtained normalized weights and the normalized weights of an ideal analytic listener in which the signal weight is 1 and the masker-component weights are 0 (cf. Dai and Berg, 1992; Willihnganz *et al.*, 1997; Stellmack *et al.*, 1997).[7] We define weighting efficiency as 1–rms so that efficiency ranges from 0 (listener always attends to the wrong auditory filter) to 1 (listener attends only to the signal).

B. Results

1. Information masking

a. Masked thresholds as a function of p. Figures 1 and 2 show the mean masked thresholds (dB SPL) for five blocks of trials as a function of the masker-component probability of occurrence for the NH and HI listeners, respectively. The listeners in each figure are arranged from left-to-right, top-to-bottom in descending order of the amount of IM observed at $p=0.5$, where masker uncertainty is predicted to be greatest. The estimate of energetic masking for all conditions is represented by the amount of masking at $p=1.0$, that is, the masked threshold at $p=1.0$ (the dashed line) minus the quiet

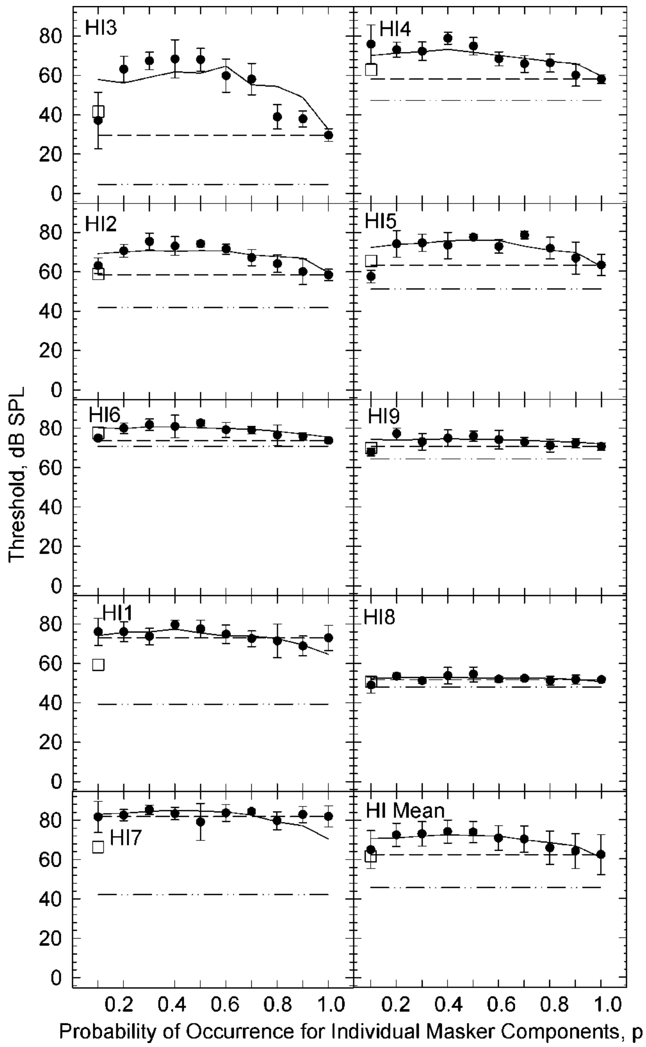

FIG. 2. Masked thresholds for the HI listeners plotted in the same manner as Fig. 1.

threshold for the signal (the dash-dot line). IM for $p<1.0$ is estimated by the difference between the masked thresholds (circles with 95% confidence intervals) and the dashed line for $p=1.0$. The last panel in each figure shows the overall group means with 95% confidence intervals.

For NH listeners masked thresholds for the $p=1.0$ condition ranged from 14.5 to 52.3 dB SPL. Such variability is quite uncharacteristic of what is commonly taken to be energetic masking (cf. Patterson *et al.*, 1982). A possible explanation for the large individual differences is that they reflect a perceptual grouping effect for some listeners in which the pure-tone signal is judged to be absent because it is perceived as belonging to the multitone masker. Such effects have been described in similar conditions by Kidd *et al.* (1994, 2001, 2002). If the masked thresholds for $p=1.0$ do not reflect the exclusive contribution of energetic masking, they still appear to represent a lower limit on masked thresholds for the other masking conditions. Note that the masking functions for $p<1.0$ often collapse on the dashed line representing the masked threshold for $p=1.0$ and, with the exception of the $p=0.1$ condition, individual masked thresholds rarely fall significantly below this line. For this reason we will continue to express the amount of IM relative to the $p=1.0$ condition, recognizing that this may be an underestimate of the amount of IM relative to the amount energetic masking. Some further comments, however, are in order for $p=0.1$ condition. With a few exceptions (NH6, NH11, and HI4), little or no IM was obtained in this condition. This condition is somewhat unusual in that zero or one masker components were present on about 75% of the trials. Seven of the NH and seven of the HI listeners had masked thresholds for $p=0.1$ that were not statistically different from the masked threshold at $p=1.0$ (the minimal uncertainty condition), possibly indicating that masker uncertainty was virtually nonexistent for this condition. (For an alternative explanation, see footnote 9.)

Compared to the NH listeners, the HI listeners in Fig. 2 appear to have lower amounts of IM. At $p=0.5$, NH listeners on average have about 8 dB more IM (M=19.3 dB, SD =14.8) than HI listeners (M=11.5 dB, SD=12.0), however, this difference is not statistically significant, $t(23)=1.34$, $p=0.19$. Notice that the masking function for HI3 is similar to the masking functions of the NH listeners who show moderate to large amounts of IM. This is also the only HI listener whose hearing loss was confined to regions above 2000 Hz, with normal hearing for the 2000-Hz signal and all the masker components below it. When the listeners with normal hearing for the signal frequency, including HI3, are compared to those with a hearing loss for the signal frequency, then the means are 20.4 dB (SD=15.0) and 8.2 dB (SD =7.0), respectively. Listeners who have a hearing loss for the signal frequency have significantly less IM (12.2 dB) than those who have normal hearing for the signal frequency, $t(23)=2.18$, $p=0.04$.

The amount of IM is quite variable among listeners in both groups, ranging from −0.5 to 42.8 dB at $p=0.5$ for the NH group and from −2.9 to 38.3 for the HI group.[8] This range of individual differences is comparable to that of other IM studies (Neff and Green, 1987; Neff and Dethlefs, 1995; Oh and Lutfi, 1998). Although individual differences in IM are more appropriately described by a continuous function (Lutfi *et al.*, 2003b), it is often convenient to describe listeners who show little or no IM as "analytic" or "low-threshold" listeners and those who are susceptible to IM as "holistic" or "high-threshold" listeners (Neff *et al.*, 1993). Listeners who show either high or low amounts of IM were distinguished by using an arbitrary criterion of 10 dB of IM at $p=0.5$. The mean masked thresholds for the high- and low-threshold listeners are shown in Fig. 3 for both the NH and HI listeners.

For the NH listeners ($n=10$) and HI listeners ($n=4$) who show high amounts of IM, panels (a) and (b) of Fig. 3, the masked thresholds depend on p. For these listeners, there is a broad maximum of IM between $p=0.3$ and 0.5, the points where variance in the masker ensemble (predicted masker uncertainty) are greatest. In addition, IM is greater for lower probability conditions than for higher probability conditions even though the standard deviation of the binomial distribution on which the predictions are based is symmetric. One likely reason for this is that the level per masker component (SL) increased as the probability of occurrence decreased in order to keep the expected total power

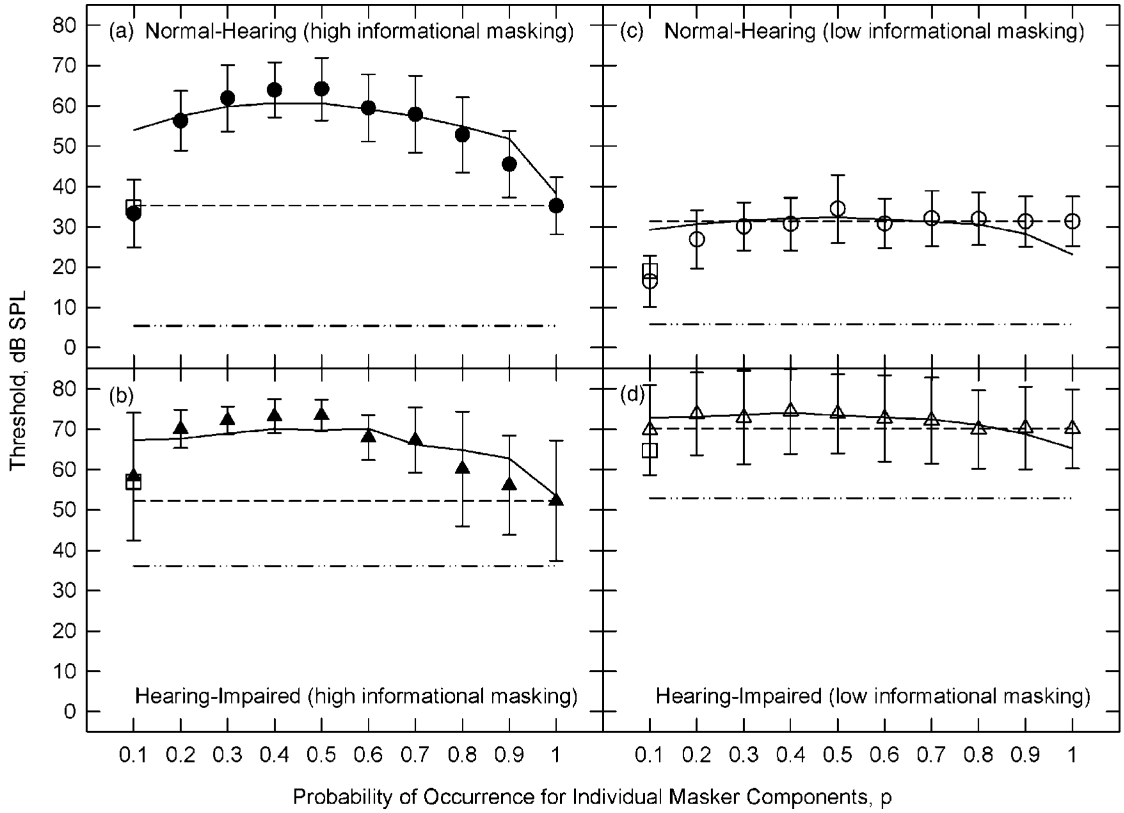

FIG. 3. Mean masked thresholds for the NH (circles) and HI listeners (triangles) plotted separately for listeners who had high (filled symbols) and low (open symbols) amounts of IM. Thresholds are plotted in a similar manner as Figs. 1 and 2 with error bars representing the 95% confidence intervals of the mean masked thresholds.

of the masker ensemble constant [cf. Eq. (5)]. An additional reason might be that as the probability of masker occurrence increased, the outputs of auditory filters became less independent of one another. This would reduce the unshared masker variance at the output of the auditory filters, and so would reduce the amount of IM as p increased.

Six of the 16 NH listeners (NH3, NH16, NH13, NH12, NH15, and NH5), about $\frac{1}{3}$, show little or no IM. This proportion is comparable to other studies (Neff and Green, 1987; Neff and Dethlefs, 1995; Oh and Lutfi, 1998). Five of the nine HI listeners (HI6, HI9, HI1, HI8, and HI7) also show little or no IM. For these listeners the masked thresholds in panels (c) and (d) of Fig. 3 are essentially equal to the masked threshold at $p=1.0$. This result is consistent with the assumption that the masked threshold for $p=1.0$ represents at least a lower bound on masked thresholds in these conditions, if not the exclusive effect of energetic masking. The two groups of NH listeners in panels (a) and (c) of Fig. 3 have similar mean thresholds for the signal in quiet and for $p=1.0$. However, the HI listeners who show little or no IM in panel (d) generally have higher thresholds for the signal in quiet and for $p=1.0$ than their counterparts in panel (b). Even after partialing out the effects of the signal quiet threshold, the amount of IM for the HI listeners is significantly correlated with the masked threshold for $p=1.0$, $r(6)=-0.71$, $p=0.049$. There is no such relationship for the NH listeners, $r(13)=0.14$, $p=0.61$. This pattern of results suggests that different factors might contribute to reduced amounts of IM in NH and HI listeners.

As will be shown in the next section, NH listeners with low amounts of IM have weighting functions that more closely approximate those of an ideal listener, whereas the same is not necessarily true for the HI listeners with low amounts of IM. One explanation is that ‘‘low-threshold’’ HI listeners, excluding HI8, could have used overall intensity level or loudness for the decision variable. Note, in particular, that masked thresholds for all probability conditions including $p=1.0$ are greater than the average total power of the masker ensemble. The signal levels corresponding to these thresholds are great enough to shift the overall intensity level of the signal+masker trials several jnd's above the overall intensity level for a majority of the masker-only trials, thus making it a reliable cue for signal detection. However, as noted earlier, where the signal levels adapted to lower thresholds as with the ‘‘high-threshold’’ HI listeners, loudness cannot reliably distinguish signal+masker trials from masker-only trials because the number of masker components, hence the overall intensity level, varied randomly from trial to trial. In addition, if overall loudness on each trial was the decision variable instead of the weighted sum of masker and signal SLs, then it might be expected that the variance of the decision variable, hence IM, would be greater than predicted because of the rapid change in loudness associated with loudness recruitment.

b. Practice effects. An effect of practice would be indicated by a decrease in IM across the five trial blocks. A least-squares linear regression analysis revealed that the amount of IM on average decreased by less than 1 dB for the

NH listeners ($b=-0.97$, SE=0.42) and by even less for HI listeners ($b=-0.26$, SE=0.36). Given the large variation in the amount of IM between listeners and the size of the observed effects, this rate of improvement does not alter the interpretation of the data.

c. Predicted amounts of informational masking. Model predictions are shown by the continuous lines in Figs. 1–3. The predicted amount of IM as function of p was first generated using the trial-by-trial standard deviation of the decision variable [Eq. (4)]. Then, the predicted IM function was fit to the data by selecting the intercept that yielded the least-squares error between $p=0.2$ and 0.9. The point at $p=0.1$ was not included in this prediction since, as earlier noted, zero or one masker components were present on about 75% of the trials for this condition.[9] The intercept of the fitted masking function can be taken as the model prediction for energetic masking and should approximately equal the estimated threshold at $p=1.0$. As indicated by the predictions for the individual listeners in Figs. 1 and 2, the model does an adequate job of predicting masked thresholds. The mean difference between the masking at $p=1.0$ and the predicted masking (model intercept) is 1.2 dB for the NH listeners (see last panel in Fig. 1) and 1.4 dB for the HI listeners (see last panel in Fig. 2).

2. Decision weights

a. The independence of weights and SLs. Doherty and Lutfi (1996) found that HI listeners tend to place relatively more weight on stimulus frequencies where hearing loss is greatest (where SLs are generally lowest). To examine whether there was a relationship between the relative weight and the relative SL of the masker components, masker weights and SLs were normalized for each listener so that the sum of their magnitudes equaled unity. No relationship was found between the two variables for the NH listeners, $R^2=0.006$, $F(1,158)=1.0$, $p>0.05$ and for the HI listeners, $R^2=0.01$, $F(1,62)=6.44$ $p=0.014$. These results indicate that SLs and decision weights can be treated as independent factors for both groups. The likely reason that these results fail to replicate the findings of Doherty and Lutfi (1996) is that, unlike the present study, their study involved intensity discrimination in which all the components were potential signals. A fairer comparison is to the companion study of Doherty and Lutfi (1999) in which the signal was a single tone. The results of that study are consistent with those reported here.

b. Weighting functions. Figures 4 and 5 show the individual weighting functions for the NH and HI listeners arranged in the same order as Figs. 1 and 2, respectively (from most to least amount of IM at $p=0.5$). Mean weighting functions for the two groups of listeners are also shown in the last panel of each figure. As the amount of IM decreases for the NH listeners, more weight is placed on the 2000-Hz signal and less weight on the masker frequencies. As noted earlier, listeners who do well on IM experiments have often been termed "analytic listeners," meaning that the SL of the signal is a very strong predictor of a listener's "yes/no" responses. It is clear from the weighting functions in Fig. 4 that this term aptly applies to the six NH listeners in Fig. 1 who have little or no IM (NH3, NH16, NH13, NH12, NH15, and NH5). The weighting functions of these listeners are closer to the ideal weighting function with a mean weighting efficiency of 0.88 (SD=0.03) compared to the remainder of the NH listeners who have a mean weighting efficiency of 0.80 (SD=0.03), $t(14)=4.48$, $p\leqslant 0.001$.

The weighting functions for the HI listeners in Fig. 5 should be interpreted with caution because some masker components were presented at levels below quiet threshold (SL$\leqslant$0 dB) and were assigned a weight of zero. These cases are indicated by the open circles in Fig. 5. The scatterplot in Fig. 6 shows the amount of IM at $p=0.5$ as a function of the weighting efficiency for each listener. As can be seen by open circles in the scatterplot, there is no relationship between weighting efficiency and the amount of IM for the HI listeners, $R^2=0.05$, $F(1,7)<1.0$, $p>0.05$. It follows that the HI listeners with little or no IM in Fig. 2 (HI6, HI9, HI1, HI8, and HI7) have a mean weighting efficiency of 0.81 (SD=0.08) that is not significantly higher than the mean weighting efficiency of 0.77 (SD=0.02) from the rest of the HI listeners, $t(7)=1.10$, $p>0.05$.

The scatterplot in Fig. 6 for the NH listeners (filled circles) shows that there is a negative linear relationship between listeners' weighting efficiencies and the amount of IM, $R^2=0.65$, $F(1,14)=25.5$, $p\leqslant 0.001$. This relationship suggests that factors associated with analytic listening or attention are largely responsible for differences in the amount of IM for NH listeners. This conclusion is also consistent with the findings of Lutfi *et al.* (2003b) who preformed a principal components analysis on IM functions from 38 NH children and 46 NH adults and found that one factor was able to account for about 83% of the variance in masked thresholds within and across the age groups. This factor was highly correlated with the estimated number of monitored auditory filters, just as lower weighting efficiencies in this study correspond to the degree to which a listener attends to or monitors the output of nonsignal auditory filters instead of the auditory filter centered on the signal frequency.

C. Experiment I discussion

Results for the equal-SPL maskers in experiment I are summarized in Table II. The listeners are listed by group in descending order according to the amount of IM at $p=0.5$ (fourth column), the same ordering used for Figs. 1 and 2. The table provides the quiet threshold for the signal (dB SPL), the mean SL of the ten masker components that were presented in experiment I when $p=0.5$ along with their range, and the listener's weighting efficiency. It is apparent from Table II that the mean SL of the masker components was the primary difference between the NH listeners (M=48.9 dB SL, SD=3.0) and the HI listeners (M=16.0 dB SL, SD=9.4), $t(23)=13.1$, $p<0.001$. In contrast, there was a fair amount of overlap in the weighting efficiencies between the NH listeners (M=0.83, SD=0.05) and the HI listeners (M=0.80, SD=0.06), $t(23)=1.63$, $p=0.12$. This indicates that the difference in IM between NH and HI listeners is not likely explained by differences in weighting strategies.

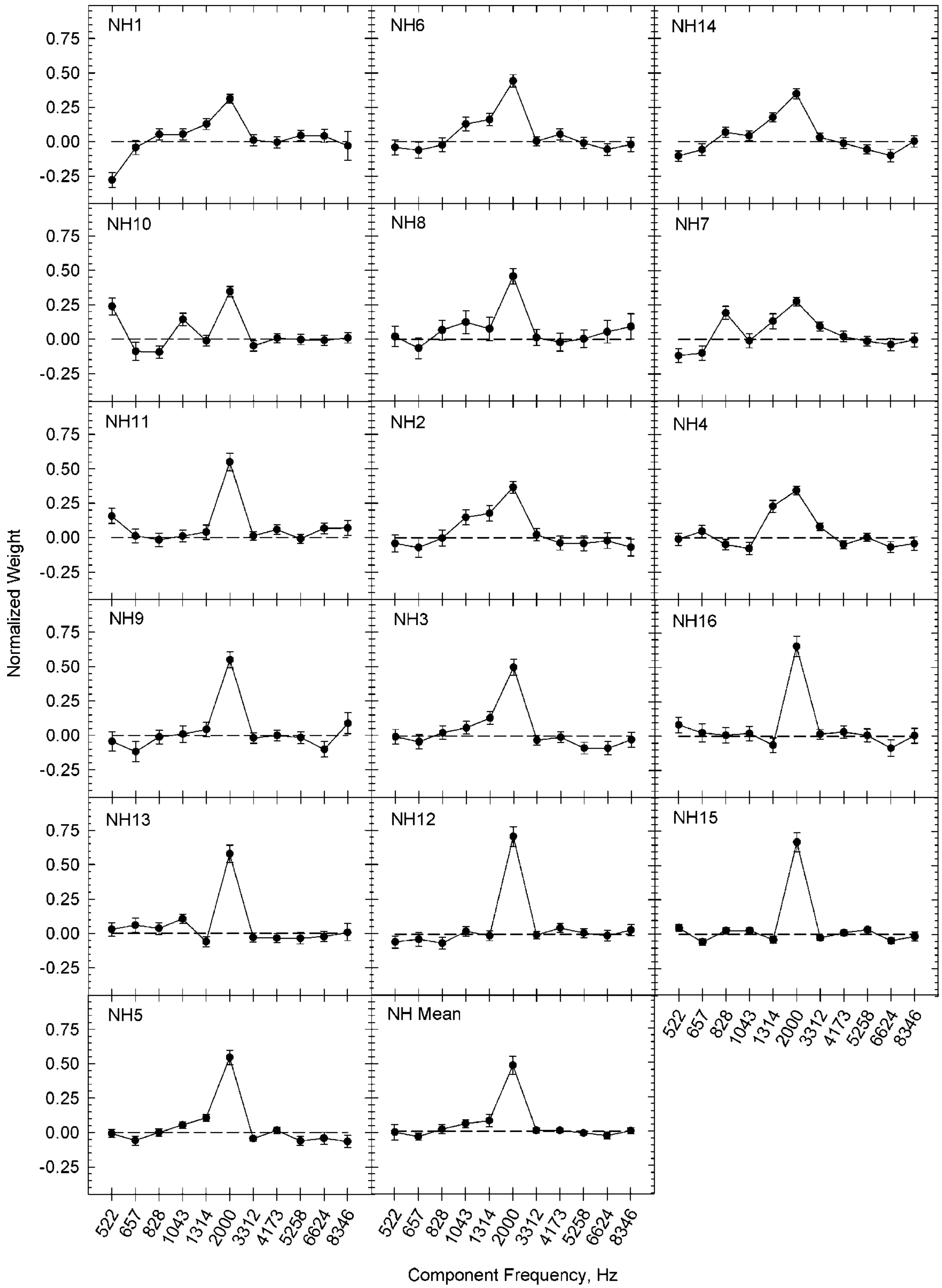

FIG. 4. Decision weights (filled circles) as a function of the 2000-Hz signal and of the masker components for the NH listeners plotted in the same order as Fig. 1, with error bars representing the 95% confidence intervals.

According to Eq. (4), the reduced masker-component SLs associated with hearing loss effectively reduce the trial-by-trial variance of the masker at the output of the auditory filters. That is, even though masker components were either on or off, the difference in the output level in the auditory filters between the on and off states was smaller for the HI listeners than for NH listeners. IM is the result of an interaction and requires that large weights be placed on masker components with relatively high SLs. Thus, two listeners can have similar weighting functions, but if the SLs of the masker components are greater for one listener than for another, then there can be a large difference in the amount of IM between the two. For example, the weighting functions for listeners NH14 and HI5 in Figs. 4 and 5 are somewhat

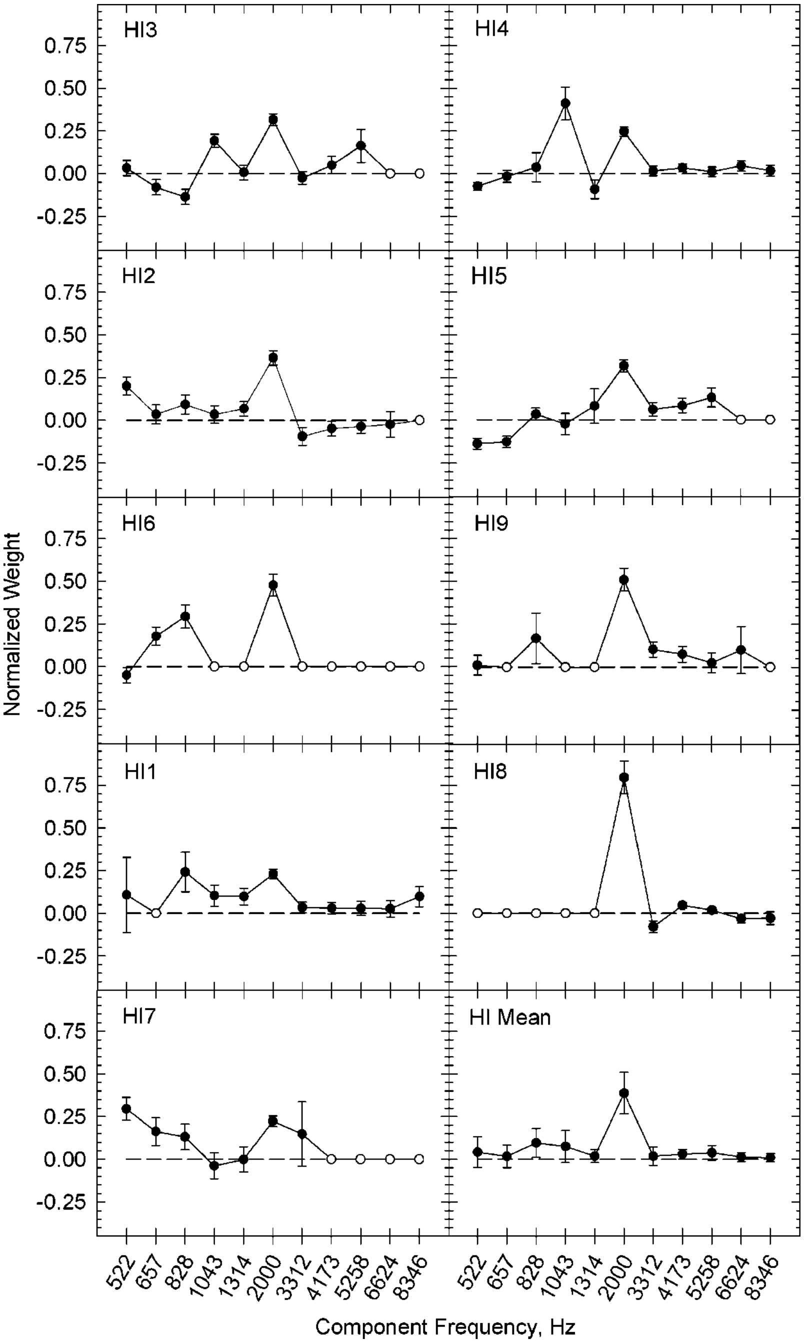

FIG. 5. Decision weights (filled circles) as a function of the 2000-Hz signal and of the masker components for the HI listeners plotted in the same order as Fig. 2, with error bars representing the 95% confidence intervals. Open circles indicate weights that were set to 0 because the masker components were presented at levels lower than their thresholds in quiet.

similar, but due to the differences in the mean SL of the masker components, 49.1 vs. 15.6 dB SL, NH14 has much more IM at $p=0.5$, 36.0 dB, than HI5 who has only 14.1 dB. Figure 6 shows that when two listeners, one from each group, have equally poor weighting efficiencies (about 0.80 or less) that the NH listener will usually have a greater amount of IM than the HI listener. The one exception is HI3 (the lone open circle in the upper-left hand corner of Fig. 6) who has as much IM as the NH listeners. This is likely because there were a sufficient number of masker components with high SLs for this listener who had normal hearing for the 2000-Hz signal and below.

Unlike for the NH listeners, weighting efficiency and IM are not strongly correlated among the HI listeners. One reason for this might be that there is more variability in the mean masker-component SLs for the HI listeners (SD=9.4 dB) than there is for the NH listeners (SD=3.0 dB). Because IM depends on both SLs and weights, when the SLs of the masker components are relatively homogenous among listeners as they are for the NH listeners, individual differences in the amount of IM will be more directly influenced by weighting efficiency. However, when the SLs of the masker components are relatively heterogeneous, as they are for the HI listeners, the amount of IM will be less directly influenced by weighting efficiency.

The results of this study suggest that when masker SL differs substantially between or within groups of listeners that it will be the dominant factor determining IM. One way to confirm this hypothesis would be to show substantial IM in HI listeners when masker SLs are the same as for the NH listeners. This is not practical in the present study since masked threshold for $p=1.0$ in many HI listeners was close

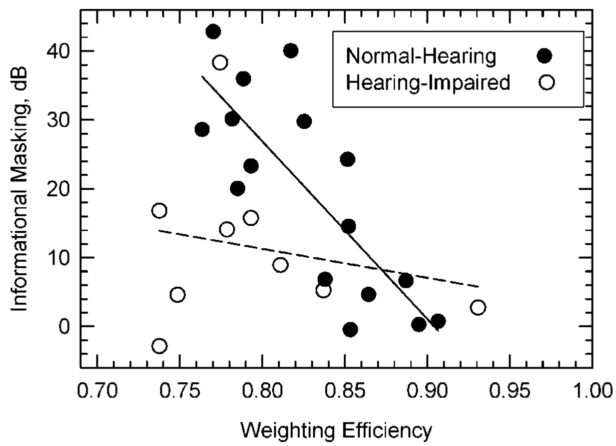

FIG. 6. IM at $p=0.5$ as a function of the weighting efficiency for the NH listeners (filled circles) and the HI listeners (open circles). The solid and dashed lines represent the least-squares linear regression fit for the NH and HI listeners, respectively.

to the maximum allowable signal level. Instead, two types of control experiments were conducted in which masker SLs were equated for NH and HI listeners.

III. EXPERIMENT II: SIMULATION OF REDUCED SL'S IN NORMAL-HEARING LISTENERS

A. Method

Four NH listeners who showed large amounts of IM in experiment I (NH1, NH4, NH7, and NH14) repeated the experiment with the masker levels adjusted to roughly equal the average masker SLs of the HI listeners. Masker levels were determined by subtracting the average hearing loss of the HI listeners from the otherwise equal-SPL masker levels.[10] The average total power of the maskers across all conditions was reduced by about 20 dB to a little more than 50 dB SPL. In order from lowest to highest frequency, the mean masker-component SLs for the four listeners were 26.2, 22.5, 20.6, 16.4, 17.8, 25.8, 21.4, 22.9, 7.0, and 3.7 dB. The mean masker SL per component was reduced from 47.7 to 18.4 dB, which was close to the mean for HI listeners, 16.0 dB.

B. Results

Weighting efficiency for NH1, NH4, NH7, and NH14 was 0.76, 0.81, 0.79, and 0.85, respectively and IM was 16.3, 13.3, 11.7, and 12.0 dB, respectively. Mean weighting efficiency was not much different in this experiment, 0.80, compared to experiment I, 0.78, $t(3)=1.73$, $p>0.05$. Figure 7 shows that when the SL of the masker components are adjusted to simulate the average hearing loss of the HI listeners in experiment I that IM as a function of p is reduced. At $p=0.5$ the mean amount of IM decreased from 31.9 dB in experiment I to 13.3 dB in experiment II, $t(3)=4.20$, $p=0.025$. The amount of IM for the NH listeners in this experiment was similar to the 11.5 dB of IM for the HI listeners in experiment I and indirectly supports the conclusion that reduced masker-component SLs were mostly responsible for the lower amounts of IM in the HI listeners.

IV. EXPERIMENT III: EQUAL-SL MASKER COMPONENTS

A. Method

This experiment addressed how equating the SLs of the masker components affects the difference in the amount of IM and weighting efficiency between 12 NH and 6 HI listeners from experiment I (the listeners are those in Table II with entries under the heading "Equal-SL"). The signal and maskers were the same as in experiments I and II. Only the minimum ($p=1.0$) and maximum ($p=0.5$) uncertainty conditions were tested. For the $p=0.5$ condition, each masker component was played at 10 dB SL based on the estimates of quiet threshold obtained earlier. As before, the level per masker component in the $p=1.0$ condition was 3 dB less so that the average total power of the masker ensemble would be the same for both conditions. A constant 10 dB SL was used because higher masker levels would have prevented some HI listeners from detecting the signal above chance even at the most intense levels tested (about 90 dB SPL). For HI6 and HI7 the SL of the 8346-Hz masker component was set to 0 dB SL because setting it at 10 dB SL would have exceeded 90 dB SPL.

B. Results and discussion

For the equal-SL maskers in this experiment, Table II provides the masked thresholds for $p=0.5$ and $p=1.0$, the amount of IM (i.e., the difference between the two masked thresholds), and the weighting efficiency. IM for the NH listeners was significantly less in this experiment (M=5.0 dB, SD=3.7) compared to experiment I (M=18.8, SD=16.2), $t(11)=26.2$, $p<0.001$. This decrease was likely due to the difference in the masker SLs rather than weighting efficiency because weighting efficiency was significantly less in this experiment (M=0.78, SD=0.05) compared to experiment I (M=0.83, SD=0.05), $t(11)=3.16$, $p\leqslant 0.01$, which would otherwise be associated with greater IM. As with experiment I, weighting efficiency and IM in NH listeners were significantly correlated, $R^2=0.35$, $F(1,10)=5.38$, $p=0.04$. The relationship is smaller in this experiment compared to experiment I where masker-component SLs varied within and between listeners probably because there is less variance in the amount of IM.

IM for the HI listeners in this experiment (M=9.4 dB, SD=7.8) was not significantly different from experiment I (M=7.5 dB, SD=7.3) where the mean masker SL was 11.4 dB, $t(5)=1.10$, $p>0.05$. The results of this experiment also indicate that when masker-component SLs were equal for NH and HI listeners that IM and weighting efficiency were not significantly different between the two groups, $t(16)=1.68$, $p=0.11$, and $t(16)=1.82$, $p=0.09$, respectively. As with the NH listeners, weighting efficiency for the HI listeners was significantly less in this experiment, 0.74 (SD=0.03), compared to experiment I, 0.81 (SD=0.07), $t(11)=3.54$, $p=0.02$. This seems to indicate that equating SL across masker components makes masker components more difficult to ignore for both groups of listeners.

In experiment I the lack of a significant relationship between weighting efficiency and IM was attributed to unequal

TABLE II. Summary data for experiment I (equal-SPL maskers) and experiment III (equal-SL maskers) for normal-hearing (NH) and hearing-impaired listeners (HI) is shown. Listeners are listed in descending order according to the amount of IM at $p=0.5$ for the equal-SPL maskers (fourth column), the same ordering used for Figs. 1 and 2. Shown for each listener are the quiet threshold for the signal (dB SPL), the mean and range of the SLs for the ten masker components that were presented when $p=0.5$ for the equal-SPL maskers, and the weighting efficiency (see text). For the equal-SL maskers, the masked threshold when $p=0.5$ and when $p=1.0$ are given along with the amount of IM (i.e., the difference between the two) and the weighting efficiency.

Masker type		Equal-SPL			Equal-SL			
Listener	Signal quiet threshold (dB SPL)	Mean masker SL at $p=0.5$ (range)	IM at $p=0.5$	Weight efficiency	Masked threshold at $p=0.5$	Masked threshold at $p=1.0$	IM	Weight efficiency
NH1	−3.1	50.3(21.3–59.6)	42.8	0.77	17.52	12.33	5.2	0.72
NH6	7.1	52.0(40.6–69.3)	40.1	0.82	15.18	8.02	7.2	0.76
NH14	−2.5	49.1(39.7–58.2)	36.0	0.79	4.54	−2.25	6.8	0.80
NH10	9.4	50.7(31.8–63.1)	30.2	0.78				
NH8	20.3	44.2(35.3–56.3)	29.8	0.83	30.41	21.91	8.5	0.76
NH7	−0.6	49.9(41.1–65.6)	28.6	0.76	16.95	13.75	3.2	0.75
NH11	15.7	47.0(35.4–65.3)	24.3	0.85				
NH2	4.7	50.5(40.6–61.2)	23.3	0.79				
NH4	3.9	49.5(36.6–69.6)	20.1	0.79	16.12	8.91	7.2	0.72
NH9	−0.2	43.6(29.3–61.1)	14.6	0.85	13.59	1.96	11.6	0.76
NH3	1.5	50.6(42.7–64.6)	6.9	0.84	8.49	6.87	1.6	0.81
NH16	13.3	45.3(35.1–65.4)	6.6	0.89	22.32	16.87	5.5	0.77
NH13	4.0	49.1(30.5–63.7)	4.7	0.86				
NH12	2.3	55.1(42.1–72.7)	0.8	0.91	18.42	14.45	4.0	0.75
NH15	4.0	49.1(32.0–61.2)	0.3	0.90	4.58	5.98	−1.4	0.82
NH5	9.7	47.0(29.2–68.3)	−0.5	0.85	9.30	9.11	0.2	0.92
HI3	4.7	34.2(0.0–53.4)	38.3	0.77				
HI4	47.2	20.0(7.2–31.1)	16.8	0.74	68.68	48.18	20.5	0.73
HI2	41.7	23.0(2.0–31.1)	15.8	0.79				
HI5	50.8	15.7(0.0–28.9)	14.1	0.78	68.97	58.71	10.3	0.73
HI6	70.8	3.5(0.0–13.1)	8.9	0.81	89.88	82.19	7.7	0.73
HI9	64.5	5.7(0.0–14.2)	5.2	0.84	82.49	68.69	13.8	0.74
HI1	39.3	18.4(2.1–33.5)	4.6	0.75				
HI8	47.8	13.2(0.0–40.8)	2.7	0.93	56.99	49.67	7.3	0.78
HI7	42.1	10.3(0.0–21.2)	−2.9	0.74	88.58	91.58	−3.0	0.70

masker-component SLs within and across listeners. However, even though masker-component SLs were equated in this experiment, weighting efficiency alone did not reliably predict IM in HI listeners, $R^2=0.09$, $F(1,4)<1.0$. One possible reason for this weakened relationship is that the auditory-filter bandwidths for some HI listeners might be broad enough to increase the correlation between the auditory filter outputs, which would effectively reduce the masker variance. As we have noted, some correlation is likely, particularly at high values of p. Another reason, however, is that there is less variance in the amount of IM for HI listeners.

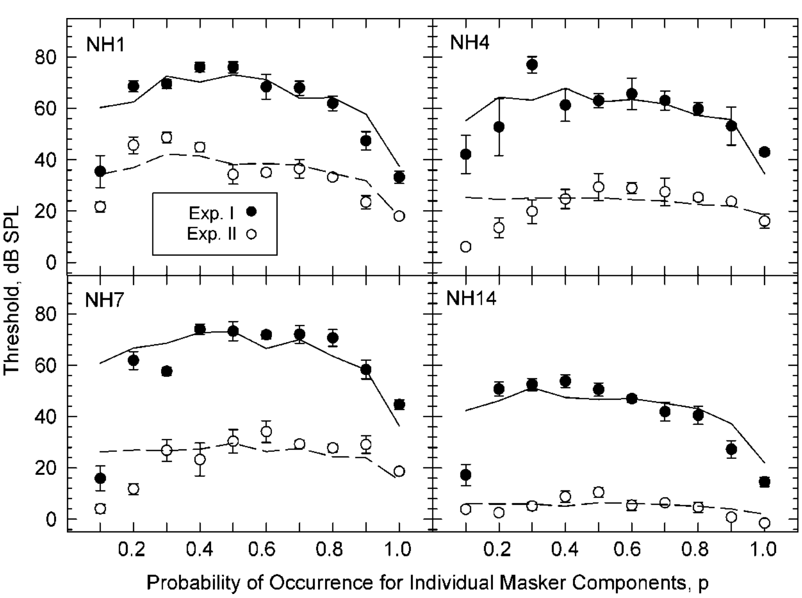

FIG. 7. Open circles indicate masked thresholds with 95% confidence intervals for the four NH listeners in experiment II where the level per masker component was adjusted to simulate the reduced SLs associated with hearing loss. For comparison, the experiment I results for these listeners are replotted from Fig. 1 (filled circles).

V. SUMMARY AND CONCLUSIONS

Interpreting the results of this study within the framework of a specific decision model [Eq. (4)] allows us to evaluate how IM is affected by a hearing loss in terms of lower masker SLs and in terms of perceptual differences in how the stimulus components are weighted. According to the model, differences in the amount of IM between and within NH and HI listeners is dependent on how decision weights are distributed across masker components with different SLs, with the greatest amounts of IM occurring when large weights are combined with high SLs. For the experiments in this study, it seems that the SLs and weights of the masker components are independent factors because a notable relationship between them is lacking for both groups.

The results of the experiments in this study are in general agreement with the findings of Micheyl *et al.* (2000). As in that study, differences in the amount of IM between our NH and HI listeners seem to be strongly affected by differences in the SLs of the masker components. When the signal was in a region of hearing loss, the amount of IM for the equal-SPL maskers never reached a level as high as that obtained by a majority of NH listeners. Because the dB SPL per masker component was equal for the NH and HI listeners, masker SLs were much lower for the HI listeners than for the NH listeners. The observed results are thus interpreted in terms of the resulting reduction in the variance of the assumed decision variable. The significant decrease in IM for the NH listeners when the masker SLs were reduced in experiments II and III confirm that the differences in masker SLs between the NH and HI listeners in experiment I was likely a major contributing factor to the differences in the amounts of IM. Further confirmation is provided by the results of experiment III where no significant differences in IM were found when masker-component SLs were equated within and across the two groups of listeners.

Although HI listeners generally had lower weighting efficiencies than the NH listeners in experiments I and III, our results do not lend strong support to the speculation by Kidd *et al.* (2001) that HI listeners use a less analytic listening (weighting) strategy than NH listeners. However, unlike for NH listeners, the relationship between weighting efficiency and IM was not significant for HI listeners even in experiment III where the effect of masker-component SLs was virtually eliminated. We suggest that in addition to reduced masker SLs, broadened auditory filters accompanying sensorineural hearing loss might also reduce IM by increasing the covariance between auditory filter outputs, thereby decreasing the masker ensemble variance.

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[1]While the HI listeners were generally older than the NH listeners, observed differences between the two groups are unlikely related to the age difference because four of the nine HI listeners were of the same approximate age (<30 years) as the NH listeners.

[2]The Sennheiser earphone (test earphone) was calibrated with a TDH-50 earphone (standard earphone) using continuous tones and a binaural loudness balancing procedure (ANSI, 1996). Calibration at the octave frequencies between 250 and 8000 Hz was carried out by two normal-hearing experimenters. The output levels of tones played through the standard earphone were set to 60 dB SPL, then the test earphone was balanced using the method of adjustment and a programmable attenuator (TDT, PA4). Median RMS voltages across several independent adjustments of the output levels from the test earphone for each ear of the experimenters were taken as the matching values. The RMS voltage for the 1000-Hz tone was used as the reference for the Sennheiser earphone.

[3]When rounded to the nearest one-hundredth, actual masker probabilities averaged across all listeners were equal to the nominal probabilities except at $p=0.5$ where the actual probability was 0.51. The standard deviations of the actual probabilities across all listeners was 0.003 for $p=0.3$, 0.5, and 0.6 and was 0.002 for the other conditions.

[4]This occurred on 0.39% of the trials used in the computation of masked threshold for the NH listeners and on 1.82% of these trials for the HI listeners, excluding HI7 (34.2%) who had difficulty even at the reduced masker levels.

[5]The analytic expression in Eq. (4) yields almost identical predictions as the empirical estimate.

[6]Data were fit to a generalized linear model and a binomial distribution using the "glmfit" function in Matlab® to obtain the weights. Note that Eq. (4) assumes that the weights are normalized with respect to the signal weight, w_s, which is 1 in this instance. When the weights are instead normalized to sum to 1 as they are for this report, the right-hand side of Eq. (4) must be divided by w_s.

[7]Note that this method of quantifying efficiency or η is different from the method outlined by Berg (1990) and Tanner and Birdsall (1958) in which the obtained d' (squared) is divided by the d' (squared) from an ideal observer:

$$\eta_{obt}=\eta_{wgt}\times\eta_{noise}\Leftrightarrow\frac{(d'_{obt})^2}{(d'_{ideal})^2}=\frac{(d'_{wgt})^2}{(d'_{ideal})^2}\times\frac{(d'_{obt})^2}{(d'_{wgt})^2},$$

where η_{obt} represents the degree to which a listener's obtained sensitivity matches that of an ideal observer, where η_{wgt} represents the degree to which the sensitivity from a hypothetical listener who utilizes the measured weights matches the sensitivity of an ideal observer, and where η_{noise} represents the degree to which a listener's obtained sensitivity matches that of a hypothetical listener who utilizes the measured weights. This computation is not meaningful in the present study because an ideal observer is equivalent to a filter matched to the signal frequency and would therefore commit no errors; that is, the denominator d' ideal is infinite.

[8]"Negative" amounts of IM are possible because IM is operationally defined as the difference between two estimates of masked threshold, one for $p<1.0$ and another for $p=1.0$. Because of variability or errors in the estimates, predictions for negative IM are inevitable. These values were left uncorrected (i.e., were not set equal to zero) so as not to artificially deflate the variability in the estimates, especially for the purposes of statistical analysis.

[9]Since the total amount of masking is predicted to be the dB sum of energetic and informational masking, the failure of the model to predict the masked threshold at $p=0.1$ must be attributed to one or both of these factors. If the predicted amounts of IM were incorrect, this would imply that the listeners used a different, more analytic, weighting strategy for this condition. However, it is also reasonable to consider that the prediction for energetic masking must be inaccurate to some extent because for some listeners in Figs. 1 and 2 the estimated thresholds for $p=0.1$ are lower than the $p=1.0$ estimate of energetic masking. One parsimonious solution for this discrepancy is to assume that energetic masking at $p=0.1$ is some constant proportion, k, of the CoRE model prediction for energetic masking at $p=1.0$ (in dB). As shown by the open squares plotted at $p=0.1$ in Figs. 1–3, arbitrarily choosing $k=0.4$ yields accurate predictions for most listeners. This adjustment dramatically improves the model predictions by decreasing the mean discrepancy between the estimated and the predicted thresholds at $p=0.1$ to only -1.9 dB for the NH listeners and to 3.4 dB for the HI listeners.

[10]The amount of hearing loss was determined by subtracting the mean quiet thresholds of the HI listeners from laboratory norms for the frequencies used in the experiments. Norms were obtained from the 10 NH listeners

who had hearing levels no greater than 10 dB HL for all the octave frequencies during a routine audiologic evaluation. So that the computed average hearing loss would more closely reflect the actual masker-component SLs, quiet thresholds that were greater than the presentation level for a masker component were substituted with the level that corresponded to 0 dB SL (i.e., the presentation level). Note that the effect of restricting the amounts of hearing loss that entered into the total was to make the average hearing loss appear more similar across frequency, especially in the high-frequency regions.

Allen, P., and Wightman, F. L. (**1995**). ''Effects of signal and masker uncertainty on children's detection,'' J. Speech Hear. Res. **38**, 503–511.

ANSI (**1996**). ANSI S3.6-1996, ''American National Standards specification for audiometers'' (American National Standards Institute, New York).

Berg, B. G. (**1989**). ''Analysis of weights in multiple observation tasks,'' J. Acoust. Soc. Am. **86**, 1743–1746.

Berg, B. G. (**1990**). ''Observer efficiency and weights in a multiple observation task,'' J. Acoust. Soc. Am. **88**, 149–158.

Dai, H. and Berg, B. G. (**1992**). ''Spectral and temporal weights in spectral-shape discrimination,'' J. Acoust. Soc. Am. **92**, 1346–1355.

Doherty, K. A., and Lutfi, R. A. (**1996**). ''Spectral weights for overall level discrimination in listeners with sensorineural hearing loss,'' J. Acoust. Soc. Am. **99**, 1053–1057.

Doherty, K. A., and Lutfi, R. A. (**1999**). ''Level discrimination of single tones in a multitone complex by normal-hearing and hearing-impaired listeners,'' J. Acoust. Soc. Am. **105**, 1831–1840.

Kidd, Jr., G., Mason, C. R., and Arbogast, T. L. (**2002**). ''Similarity, uncertainty, and masking in the identification of nonspeech auditory patterns,'' J. Acoust. Soc. Am. **111**, 1367–1376.

Kidd, Jr., G., Arbogast, T. L., Mason, C. R., and Walsh, M. (**2001**). ''Informational masking in listeners with sensorineural hearing loss,'' J. Assoc. Res. Otolaryngol. **3**, 107–119.

Kidd, Jr., G., Mason, C. R., Deliwala, P. S., Woods, W. S., and Colburn, H. S. (**1994**). ''Reducing informational masking by sound segregation,'' J. Acoust. Soc. Am. **95**, 3475–3480.

Levitt, H. (**1971**). ''Transformed up-down methods in psychoacoustics,'' J. Acoust. Soc. Am. **49**, 467–477.

Lutfi, R. A. (**1990**). ''How much masking is informational masking?'' J. Acoust. Soc. Am. **88**, 2607–2610.

Lutfi, R. A. (**1992**). ''Informational processing of complex sound. III. Interference,'' J. Acoust. Soc. Am. **91**, 3391–3401.

Lutfi, R. A. (**1993**). ''A model of auditory pattern analysis based on component-relative-entropy,'' J. Acoust. Soc. Am. **94**, 748–758.

Lutfi, R. A. (**1995**). ''Correlation coefficients and correlation ratios as estimates of observer weights in multiple-observation tasks,'' J. Acoust. Soc. Am. **97**, 1333–1334.

Lutfi, R. A., Kistler, D. J., Callahan, M. R., and Wightman, F. L. (**2003a**). ''Psychometric functions for informational masking,'' J. Acoust. Soc. Am. **114**, 3273–3282.

Lutfi, R. A., Kistler, D. J., Oh, E. L., Wightman, F. L., and Callahan, M. R. (**2003b**). ''One factor underlies individual differences in auditory informational masking within and across age groups,'' Percept. Psychophys. **65**, 396–406.

Micheyl, C., Arthaud, P., Reinhart, C., and Collet, L. (**2000**). ''Informational masking in normal-hearing and hearing-impaired listeners,'' Acta Oto-Laryngol. **120**, 242–246.

Neff, D. L., and Callaghan, B. P. (**1988**). ''Effective properties of multicomponent simultaneous maskers under conditions of uncertainty,'' J. Acoust. Soc. Am. **83**, 1833–1838.

Neff, D. L., and Dethlefs, T. M. (**1995**). ''Individual differences in simultaneous masking with random-frequency, multicomponent maskers,'' J. Acoust. Soc. Am. **98**, 125–134.

Neff, D. L., and Green, D. M. (**1987**). ''Masking produced by spectral uncertainty with multicomponent maskers,'' Percept. Psychophys. **41**, 409–415.

Neff, D. L., Dethlefs, T. M., and Jesteadt, W. (**1993**). ''Informational masking for multicomponent maskers with spectral gaps,'' J. Acoust. Soc. Am. **94**, 3112–3126.

Oh, E. L., and Lutfi, R. A. (**1998**). ''Nonmonotonicity of informational masking,'' J. Acoust. Soc. Am. **104**, 3489–3499.

Oh, E. L., Wightman, F. L., and Lutfi, R. A. (**2001**). ''Children's detection of pure-tone signals with random multitone maskers,'' J. Acoust. Soc. Am. **109**, 2888–2895.

Patterson, R. D., and Green, D. M. (**1978**). ''Auditory masking,'' in *Handbook of Perception, Volume IV*, edited by E. Carterette and M. Friedman (Academic, New York), pp. 337–361.

Patterson, R. D., Nimmo-Smith, I., Weber, D. L., and Milroy, R. (**1982**). ''The deterioration of hearing with age: Frequency selectivity, the critical ratio, the audiogram, and speech threshold,'' J. Acoust. Soc. Am. **72**, 1788–1803.

Richards, V. M., and Zhu, S. (**1994**). ''Relative estimates of combination weights, decision criteria, and internal noise based on correlation coefficients,'' J. Acoust. Soc. Am. **95**, 423–434.

Richards, V. M., Tang, Z., and Kidd, Jr., G. (**2002**). ''Informational masking with small set sizes,'' J. Acoust. Soc. Am. **111**, 1359–1366.

Stellmack, M. A., Willihnganz, M. S., Wightman, F. L., and Lutfi, R. A. (**1997**). ''Spectral weights in level discrimination by preschool children: Analytic listening conditions,'' J. Acoust. Soc. Am. **101**, 2811–2821.

Tang, Z., and Richards, V. M. (**2002**). ''Internal noise invariance across two informational masking tasks,'' J. Acoust. Soc. Am. **111**, 2470.

Tanner, W. P., and Birdsall, T. G. (**1958**). ''Definitions of d' and η as psychological measures,'' J. Acoust. Soc. Am. **30**, 922–928.

Watson, C. S., Kelly, W. J., and Wroton, H. W. (**1976**). ''Factors in the discrimination of tonal patterns. II. Selective attention and learning under various levels of stimulus uncertainty,'' J. Acoust. Soc. Am. **60**, 1176–1186.

Wightman, F. L., Callahan, M. R., Lutfi, R. A., Kistler, D. J., and Oh, E. (**2003**). ''Children's detection of pure-tone signals: Informational masking with contralateral maskers,'' J. Acoust. Soc. Am. **113**, 3297–3305.

Willihnganz, M. S., Stellmack, M. A., Lutfi, R. A., and Wightman, F. L. (**1997**). ''Spectral weights in level discrimination by preschool children: Synthetic listening conditions,'' J. Acoust. Soc. Am. **101**, 2803–2810.

Wright, B. A., and Saberi, K. (**1999**). ''Strategies used to detect auditory signals in small sets of random maskers,'' J. Acoust. Soc. Am. **105**, 1765–1775.