Masking of low-frequency signals by high-frequency, high-level narrow bands of noise^{a)}

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Low-frequency masking by intense high-frequency noise bands, referred to as remote masking (RM), was the first evidence to challenge energy-detection models of signal detection. Its underlying mechanisms remain unknown. RM was measured in five normal-hearing young-adults at 250, 350, 500, and 700 Hz using equal-power, spectrally matched random-phase noise (RPN) and low-noise noise (LNN) narrowband maskers. RM was also measured using equal-power, two-tone complex (TC2) and eight-tone complex (TC8). Maskers were centered at 3000 Hz with one or two equivalent rectangular bandwidths (ERBs). Masker levels varied from 80 to 95 dB sound pressure level in 5 dB steps. LNN produced negligible masking for all conditions. An increase in bandwidth in RPN yielded greater masking over a wider frequency region. Masking for TC2 was limited to 350 and 700 Hz for one ERB but shifted to only 700 Hz for two ERBs. A spread of masking to 500 and 700 Hz was observed for TC8 when the bandwidth was increased from one to two ERBs. Results suggest that high-frequency noise bands at high levels could generate significant low-frequency masking. It is possible that listeners experience significant RM due to the amplification of various competing noises that might have significant implications for speech perception in noise.

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I. INTRODUCTION

The detection of an acoustic signal is often compromised due to the presence of one or more competing maskers. The amount of masking varies significantly depending upon the masker-signal frequency relationship. When the frequency components of the masker are the same or close to those of the signal, the resulting masking is maximal and is referred to as direct masking (DM) or spectral masking. At low masker levels, masking is limited to the vicinity of the masker's frequency components. As the masker level is increased, masking extends beyond the vicinity of the masker's frequency components toward the high-frequency region (Egan and Hake, 1950). Fletcher (1940) proposed a model to describe signal detection in noise and hypothesized that the cochlea functions as a bank of band-pass filters with overlapping passbands. Since then, signal detection in noise has been widely modeled in terms of the relative energy of the signal to that of the noise at the output of the auditory filter centered at the signal frequency. The concept of spectral-energy-based signal detection faced its first challenge when Bilger and Hirsh (1956) reported their observation of "remote masking (RM)," where low-frequency sinusoids were masked by high-level [>80 dB sound pressure level (SPL)], high-frequency noise bands centered more than one and one-half octaves away from the signal frequency. Although RM was first reported

more than 50 years ago, its underlying mechanism is poorly understood even today.

Research in RM is surprisingly limited to the 1960s and 1970s, other than a few papers by Quaranta and colleagues in the 1980s and 1990s (e.g., Cervellera *et al.*, 1978; McFadden *et al.*, 1997), due to at least three factors. First, when RM was discovered, researchers believed that cochlear processing was mostly linear until signal levels were very high (>80 dB SPL). After the discovery of cochlear compressive nonlinearity, the focus of auditory research shifted away from the high-level cochlear saturating nonlinearity to low-level cochlear compressive nonlinearity. Second, RM occurs only in the presence of high-level high-frequency maskers. The dominance of energy-detection models has made the relevance of off-frequency RM less obvious. And third, conversational speech is well below the level needed to generate RM.

The relevance of RM within the hearing-impaired population has largely been ignored. Individuals with hearing loss require high-level signals for daily communication. It is possible that these listeners do experience significant RM due to the amplification of various competing noises (e.g., Rankovic, 1998). There is evidence in the literature suggesting that RM might have significant implications in auditory processing and speech perception (Jerger *et al.*, 1960; Bilger and Matthies, 1985; Henry *et al.*, 1985; Rankovic, 1998) and clinical audiology (e.g., Cervellera *et al.*, 1978). For example, Jerger *et al.* (1960) observed that RM was significantly higher in listeners with sensorineural hearing loss (SNHL) than with normal hearing. Henry *et al.* (1985) reported that very high-frequency noise maskers could interfere with mid-frequency temporal processing. Rankovic (1998) reported that in some listeners with SNHL, significant RM could be observed that could interfere with the audibility of low-frequency speech

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information and, therefore, reduce the benefits of amplification. In a series of studies, Quaranta and colleagues contended that RM reflects the stiffness and integrity of the inner ear. It has even been suggested that RM may be used as a test of cochlear conduction (Cervellera *et al.*, 1978).

Researchers suggest that high-frequency narrowband noise (NBN) and two-tone complex (TC2) maskers at high levels could produce RM (e.g., Bilger, 1958; Cervellera *et al.*, 1978; Karlovich and Osier, 1977; McFadden *et al.*, 1997). The masking growth in RM differs significantly from that in DM at least in three aspects that could not be explained by the existing models for signal detection. First, unlike frequency-dependent DM growth, RM growth for NBN maskers was reported to be relatively independent of signal frequency in the frequency regions where RM occurred. Second, RM for NBN maskers was reported to increase by 2 dB for every 1 dB increase in the masker spectrum level when the masker bandwidth was held constant (e.g., Bilger, 1958). However, the slope of the RM growth functions for very high-frequency TC2s was reported to be less than one (e.g., Karlovich and Osier, 1977). Third, unlike DM, RM was reported to increase by 1 dB for each 1 dB increase in masker bandwidth, even when the masker bandwidth was greater than one equivalent rectangular bandwidth (ERB) (e.g., Bilger, 1958).

Because the masker is more than one and one-half octaves above the signal, the spectral energy of the masker in RM is beyond the auditory filter of interest in signal detection. This warrants a consideration of cues or information other than on-frequency spectral energy in signal detection. Bilger and colleagues hypothesized that random envelope fluctuations in NBN maskers are detected by the cochlea due to its saturating nonlinearity and introduced as a noise that masks low-frequency signals (Bilger, 1958; Bilger and Hirsh, 1956; Bilger and Matthies, 1985). The negative impact of masker envelope fluctuations on signal detection and in on-frequency spectral masking has been well documented (e.g., Hartman and Pumplin, 1988; Kohlrausch *et al.*, 1997). Sensitivity to amplitude modulation (AM) cues has also been established in several psychophysical (e.g., Bacon and Grantham, 1989) and physiological studies (e.g., Eggermont, 1994; Frisina *et al.*, 1990; Nelson and Carney, 2004) and modeled by using either low-pass filters or overlapping modulation filters as a modulation filter bank (MFB; e.g., Dau *et al.*, 1997; Jepsen *et al.*, 2008). However, the masker envelope detection hypothesis (MEDH) proposed by the Bilger group has never been tested to evaluate whether AM plays a role in RM. Although recent research suggests that modulation information in signal detection is primarily processed at a post-cochlear level (e.g., Nelson and Carney, 2004), Stone *et al.* (2008) argued that the reliable coding of stimulus envelope characteristics depends upon the integrity of the inner hair cells (IHCs). If the realization of masker power envelope is the source of RM, the strength of the detected envelope would grow by 1 dB per 1 dB increase in the masker levels. Under such assumptions, the MEDH predicts that the slope of the RM growth as a function of masker level would be one or less than one, which is consistent with some studies (e.g., Karlovich and Osier, 1977) but not others (e.g., Bilger, 1958).

The masking of low-frequency signals by high-frequency noise bands in RM is an example of an off-frequency masking condition. The suggestion of Bilger and Hirsh (1956) that the envelope fluctuations in a masker could interfere with signal detection has been supported by recent studies (e.g., Gallun and Hafter, 2006; Patra *et al.*, 2009a,b). Gallun and Hafter (2006) showed that off-frequency AM cues could interfere with signal detection, even when the maskers were more than two octaves away. Patra *et al.* (2009b) showed that envelope fluctuations in a 4000-Hz masker could elevate increment detection thresholds for short increments (20 ms) in a longer tone (420 ms) at 500 and 4000 Hz. Electrophysiological studies in animals show that most neurons of the cochlear nucleus and inferior colliculus are selectively tuned to high AM frequencies, the best modulation frequencies ranging from about 50 to 500 Hz (e.g., Frisina *et al.*, 1990; Langner and Schreiner, 1988). As the processing moves from the cochlea to the auditory cortex, the best frequencies for AM tuning decrease and most neurons of the auditory cortex are tuned to low-AM frequencies (e.g., Eggermont, 1994). In addition to envelope coding (Stone *et al.*, 2008), it may be possible that some high-frequency-AM processing starts even at the cochlear level. Deatherage *et al.* (1957) recorded cochlear microphonics (CM) at the first (CM₁) and third (CM₃) turn of the cochlea in guinea pigs for NBN maskers centered at 6950 Hz. When the masker level was above 80 dB SPL, the amplitude of CM₁ did not increase linearly with intensity. At the same time, the amplitude of CM₃ responses increased, although the masker did not contain any low-frequency components. The results were interpreted as an evidence of low-frequency distortion due to the cochlear acoustic overload. Deatherage *et al.* also observed that the action potential (AP) due to 500-Hz tone pips in the presence of the same masker was significantly reduced in size and lacked good synchronization. Whether the introduction of low-frequency distortions due to an intense high-frequency noise band is the result of detection of the masker envelope or some other mechanism remains unclear.

An alternative to MEDH is the quadratic distortion products hypothesis (QDPH), which assumes that the cochlea at high levels generates quadratic distortion products (QDPs), and the resulting QDPs mask low-frequency signals generating RM. The QDPH was originally proposed by Spieth (1957) based on an observation that high-frequency two-tone ($f_1 + f_2$) maskers could mask signals at the difference frequency of the primaries ($f_2 - f_1$). Studies on QDPs suggest that the source of QDPs is presynaptic and possibly the outer hair cells (OHCs) or the hair cell bundles (e.g., Nuttall and Dolan, 1993). However, the modulation distortion components or QDPs have been successfully recorded at post-cochlear levels too (Shofner *et al.*, 1996; Tubach *et al.*, 1996). The QDPH was partially supported by a few studies (e.g., Karlovich and Osier, 1977; Wiegand and Paterson, 1999). This hypothesis cannot predict the effect of masker bandwidth on RM growth. Assuming that the nonlinearity could be explained by classical power-series nonlinearity, the slope of the QDP growth function would be two (Humes, 1980). Under such an assumption, the hypothesis

predicts that the slope of the RM growth function would be two, as reported by Bilger (1958) for NBN maskers. Unfortunately, the QDPH fails to account for a slope of less than one reported for RM growth functions for TC2 maskers (Karlovich and Osier, 1977). If it is assumed that the nonlinearity follows either normalized power-series nonlinearity or half-wave rectified p -law nonlinearity, then the slope of the QDP growth function would be one (Humes, 1980). Therefore, it is difficult to explain the RM growth differences for NBN and TC2 maskers unless additional sources or higher order distortion products are considered.

In the present study, we evaluated two existing hypotheses (MEDH and QDPH) as explanations of RM generation based on data from model simulations and real listeners. Specifically, we conducted two experiments to examine the roles of AM interference and QDPs in producing RM. The first experiment was designed to examine the role of masker envelope fluctuations or off-frequency masker AM in generating RM. We compared RM obtained in two equal-power spectrally matched NBN maskers that differed in envelope fluctuations. These NBN maskers were random-phase noise (RPN) and low-noise noise (LNN) centered at 3000 Hz with either one or two ERBs. LNN is a type of NBN with minimal envelope fluctuations (Pumplin, 1985). The second experiment was designed to examine the role of QDP in generating RM by comparing RM obtained with two equal-power tone-complex (TC) maskers. These TC maskers were either TC2s or eight-tone complexes (TC8). As in the first experiment, one- and two-equivalent rectangular masker bandwidths were used. TC8 maskers may be viewed as intermediate between a narrow band and the simplest TC masker (i.e., TC2). The selection of TC2 was specific to test the QDPH, whereas the selection of TC8 was intended to examine whether the QDPH or MEDH also holds for NBN maskers. According to the MEDH, RM due to the envelope fluctuations of the masker would be expected to occur at low frequencies. Therefore, commonly used low-frequency pure tones in clinical audiology, 250 and 500 Hz, were used as test signals. Assuming that the QDPH might also hold true, RM is expected to occur for TC maskers in frequency regions close to 350 and 700 Hz. Sinusoids of 350 and 700 Hz were, thus, also included as test signals. Methods for both experiments were very similar. To avoid redundancy, general procedures are described first in Sec. II.

II. METHODS

A. Subjects

Five normal-hearing young-adults (two males and three females), aged 18–38 yr (mean = 22.3 yr), with no history of hearing loss or related medical conditions participated in both the experiments. Their pure tone hearing thresholds were less than 20 dB hearing level (HL) (250–8000 Hz) with air-bone gaps no greater than 10 dB. The otoscopic and tympanometric screening findings were within normal limits (Roup *et al.*, 1998).

B. Instrumentation

For RM measurement, all stimuli were generated (sampling frequency = 44 100 Hz) by a laboratory computer with

a multi-channel 24-bit sound-card (Card Deluxe, Digital Audio Labs, Chanhassen, MN) and presented *via* Sennheiser-HD 580 headphones (Sennheiser Electronic Corporation, Old Lyme, CT). Presentation levels were controlled by using two programmable attenuators (System II PA4, Tucker Davis Technologies, Alachua, FL). RM data were collected by using a MATLAB program. Acoustic output was calibrated for maximum SPL, linearity, and harmonic and intermodulation distortions.

C. Procedures

Both unmasked and masked thresholds were measured using the “single interval adjustment matrix” (SIAM) procedure (Kaernbach, 1990). A run for a threshold estimation consisted of 52 trials. Initially, the target sound was presented with *a priori* probability of 0.75 with an attenuation step size of 8 dB. After the first reversal, the target sound was presented with *a priori* probability of 0.5, and the attenuation step size was changed to 4 dB. The attenuation step size was further changed to 2 and 1 dB after four and six reversals. A trial began with the warning light (200 ms), followed by a presentation of either the target or the alternative stimulus. For unmasked threshold estimation, the target was a 490-ms signal, and the alternative was a 490-ms zero-matrix or silence. For masked threshold estimation, the target was a 490-ms masker plus a 490-ms signal, aligned temporally without any time-delay. The alternative sound was only the masker of 490 ms. All stimuli were gated with cosine squared envelopes with 25-ms rise/fall time. The listener indicated if a given trial contained the target sound by selecting on one of the two boxes labeled “YES” or “NO.” Visual feedback was provided. Presentation levels were adjusted adaptively to arrive at the signal level that corresponded to 75% correct detection. Listeners were provided with frequent breaks to counter the potential effects of temporary threshold shifts, fatigue, and boredom. Threshold was calculated as the mean of the reversal levels after the fourth reversal. The means of three threshold values were averaged to estimate the mean threshold for a given test condition. RM was measured at 250, 350, 500, and 700 Hz using two types of NBN (RPN and LNN) and two types of TC (TC2 and TC8) maskers with one- and two-equivalent rectangular masker bandwidths.

III. MODEL

Based on the two existing hypotheses in the literature, two versions of a cochlear saturating nonlinearity model, the masker envelope detection model (MEDM) and the quadratic distortion product model (QDPM) have been tested in this study. The MEDM assumes that the distortion is introduced due to the detection of the masker envelope, whereas the QDPM assumes that the distortion is introduced due to a quadratic process. The masking process and the end result are essentially the same in both cases and may be considered as two versions of only one model. The essentials of the model are shown in Fig. 1. In the presence of a high-level masker, a normal cochlea generates distortions due to its saturating nonlinearity either *via* an amplitude demodulation or

FIG. 1. The proposed model for RM. The asterisk indicates that the distortion is introduced only at high levels, and the source is assumed to be primarily cochlear, although unknown.

a quadratic process. A level-dependent feedback loop is assumed to exist that introduces saturating nonlinear distortions to the cochlea. The source of the distortion is assumed primarily to be cochlear; however, any retro-cochlear contribution could not be ruled out. Irrespective of the source of the distortion, the distortion is realized either *via* masker envelope extraction using Hilbert transform or a square device. This distortion, along with the signal and the masker, is processed *via* a cochlear filterbank at the signal frequency for optimal signal-to-noise ratio, as in the power spectrum model. A γ -tone filterbank with one critical band (CB) bandwidth parameter has been used to realize this stage of the model. During the next stage of processing, the signal-to-noise ratio of the output is computed and a normally distributed decision noise is added to it to arrive at a decision variable. The listener would detect a signal if the decision variable is greater than zero and would fail otherwise.

When a NBN masker is generated, as in the present study, by adding one sinusoid per hertz with any arbitrary phase beginning at frequency f , the frequency of the last component of this masker would be $(f + n)$, where n is the bandwidth of this NBN. According to the QDPM, the cochlea would then generate QDPs composed of several difference tones. The mixture of possible difference tones would contain a maximum total of $n(n + 1)/2$ sinusoids ranging from $(n + 1)$ sinusoids with frequencies of 1 Hz to only one sinusoid of the highest possible frequency n . The distortion products due to difference tones would not contain any components with frequencies higher than n . RM is therefore expected to be test frequency dependent. The MEDM also predicts the spectral components of the distortion. The primary difference between these two versions of the model is the growth of distortion products rather than the spectral component of the distortion products. In the present study, RM was tested at 250, 350, 500, and 700 Hz. For NBN type

of maskers, the maximum RM would be expected at 250 Hz and would decrease from 250 to 700 Hz. In addition, upward spread of masking would also be the maximum at 250 Hz. The current model has no mechanism to account for an upward spread of masking. Therefore, to offset any upward spread of masking, an additional 5 dB masking at 250 Hz was assumed while implementing the model. Wenner (1968) reported that TC2 maskers produced 5–10 dB greater masking in the vicinity of 800 Hz, when compared to masking at frequencies either above or below 800 Hz. Wenner contended that higher masking in the 800-Hz region was a result of cochlear resonance. As per Wenner's observation, an additional masking of approximately 5 dB would be expected at 700 Hz for the present study. Accordingly, an additional 5 dB masking at 700 Hz was assumed while implementing the model. The predicted RM data were computed using the above version of the model implemented in MATLAB. The average RM values of 3 repetitions of 52-trial runs on a virtual listener were computed for the model evaluation. These simulated data are presented and discussed separately for each experiment below.

IV. EXPERIMENT I

The first experiment was designed to investigate how envelope fluctuations of off-frequency maskers influence RM and, thereby, to examine the validity of the MEDH. Two types of equal-power and spectrally matched NBN, namely RPN and LNN, centered at 3000 Hz, were used as maskers. The kurtosis values were 1.3–1.6 for LNN and 3.0–4.0 for RPN maskers. The crest factor values were 1.5–1.7 for LNN and 3.0–4.0 for RPN maskers. Masker bandwidths of 349 and 698 Hz (i.e., one and two ERBs) were used. RM was measured at 250, 350, 500, and 700 Hz as a function of masker level for maskers from 80 to 95 dB overall SPL.

A. Results

The comparison of the observed and model-predicted RM patterns for NBN maskers with one- and two-equivalent rectangular masker bandwidth conditions are shown in Figs. 2 and 3, respectively. The ordinate represents RM in decibels, and the abscissa represents signal frequency in hertz. The observed, QDPM-, and MEDM-predicted data are shown in the bottom, middle, and top panels, respectively. Predictions by both, the MEDM and QDPM, were fairly similar for many test conditions. First, the amount of observed RM would depend upon the masker level. When present, RM would always be expected to be greater in RPN than LNN maskers. Second, RM would be expected to vary according to masker bandwidth. When present, RM would most likely increase as the bandwidth of the masker is increased from one to two ERBs. Third, RM will most likely vary according to signal frequency. In general, the trend in the observed data was captured better with the MEDM than the QDPM. For example, only the MEDM was successful in predicting the observed RM growth and patterns for one-ERB-wide RPN maskers at 90 dB SPL. When two-ERB-wide RPN maskers were presented at 95 dB SPL, the MEDM over-predicted RM at 500 Hz. By contrast, the QDPM systematically over-predicted RM

FIG. 2. The observed RM patterns (bottom panels) are compared with predicted RM patterns for MEDM (top panels) and QDPM (middle panels) as a function of signal frequency for one-ERB-wide RPN (left panels) and LNN (right panels) maskers. Error bars indicate ± 1 SD of the mean across listeners. Masker level is the parameter.

at 350 and 500 Hz. Consequently, the QDPM predicted a concave RM pattern; however, the observed RM pattern was sloping. RM due to LNN maskers was minimal for all test conditions, and both versions of the model predicted the results quite successfully.

The observed RM due to RPN maskers was primarily limited to 250 Hz when the masker bandwidth was one ERB, except at 95 dB SPL where there was a spread of RM to 350 Hz. When the RPN masker bandwidth was increased to two ERBs, there was a spread of RM from 250 to 700 Hz, especially at high masker levels. The masker level interacted with other independent variables (such as masker type, masker

bandwidth, and signal frequency), which might conceal the effects of these independent variables. Therefore, the data were analyzed using separate three-way repeated-measures analysis of variances (ANOVAs) at each level. Appropriate follow-up analyses were conducted using two-way and one-way repeated-measures ANOVAs and paired-samples *t*-test *post hoc* procedures. An *a priori* α -level of .05 was set for statistical analyses. To improve readability, *p* values are not separately reported in the following text. The partial η -squared (η_p^2) values were computed to estimate the corresponding effect size. The observed effect size for significant results discussed below was more than 0.5 (large). Similar to

FIG. 3. The observed RM patterns (bottom panels) are compared with predicted RM patterns for MEDM (top panels) and QDPM (middle panels) as a function of signal frequency for two-ERB-wide RPN (left panels) and LNN (right panels) maskers. Error bars indicate ± 1 SD of the mean across listeners. Masker level is the parameter.

p values, η_p^2 values are also not individually reported in the text to improve readability. There were frequent interactions among the independent variables that warranted further follow-up analyses. Statistical analyses and results that are only directly relevant to the model predictions and model evaluations are briefly discussed below.

Results were consistent with the first prediction that RPN maskers produced more RM than LNN maskers. At the lowest masker level, 80 dB SPL, the main effect for the masker type was significant [$F(1,4) = 19.4$] indicating that significantly greater RM was produced due to RPN than LNN maskers. The main effect for the masker type was also significant above 80 dB SPL [e.g., at 85 dB SPL, $F(1,4) = 14.3$]. When the maskers were at 85 dB SPL, a significant interaction was present between the bandwidth and the masker type [$F(1,4) = 17.4$]. Follow-up analyses revealed that RM was significantly greater in RPN than in LNN maskers for masker bandwidths of one ERB [$F(1,4) = 9.61$] and two ERBs [$F(1,4) = 15.7$], respectively. When the masker level was 90 dB SPL, there were significant interactions among the bandwidth, masker type, and signal frequency [$F(3,12) = 5.01$], between the bandwidth and masker type [$F(3,12) = 29.6$] and also between the masker type and signal frequency [$F(3,12) = 7.52$]. Further analyses showed that RPN produced significantly greater RM than LNN for one-ERB conditions at 250 Hz [$F(1,4) = 14.1$] and 350 Hz [$F(1,4) = 15.2$]. As the bandwidth was increased to two ERBs, RPN maskers produced significantly greater RM than LNN maskers across all signal frequencies. Finally, when the maskers were at 95 dB SPL, there were significant interactions among the bandwidth, masker type, and signal frequency [$F(3,12) = 6.75$] between the bandwidth and masker type [$F(3,12) = 202$] and also between the masker type and signal frequency [$F(3,12) = 7.55$]. Follow-up analyses revealed that RPN with one ERB at 95 dB SPL produced significantly greater RM than LNN maskers at 250 and 350 Hz. As the bandwidth was increased to two ERBs, RPN maskers produced significantly greater RM than LNN across all signal frequencies.

Results were also in general agreement with the second prediction that RM increases as the bandwidth of the masker is increased from one to two ERBs. Significant main effects of masker bandwidth effect were present only if the masker level was above 80 dB SPL [e.g., at 85 dB SPL, $F(1,4) = 10.0$]. There were significant interactions between the bandwidth and masker type at 85 dB SPL [$F(1,4) = 17.4$]. Follow-up analyses revealed that the bandwidth effect was significant only in RPN maskers [$F(1,4) = 13.7$]. When the masker level was 90 dB SPL or above, there were multiple interactions among the masker bandwidth, masker type, and signal frequency [e.g., at 90 dB SPL: $F(3,12) = 5.01$], as mentioned earlier. Further analyses revealed that RPN maskers produced significantly greater RM across 350–700-Hz probe frequencies, as the bandwidth was increased from one to two ERBs. When the masker was 95 dB SPL, RM in LNN maskers also increased significantly as the masker bandwidth was increased from one to two ERBs [$F(1,4) = 7.94$].

Finally, the results also broadly supported the third prediction that RM would decrease as the signal frequency was

increased (from 250 to 700 Hz). In general, the frequency effect decreased as the masker bandwidth and level were increased. At lower levels (80 and 85 dB SPL), RM in RPN was primarily limited to 250 Hz. Since the observed RM in LNN was minimal, effects of signal frequency were not significant at all levels. The main effect for signal frequency was significant only when the masker level was 95 dB SPL [$F(3,12) = 5.68$]. There were multiple interactions between the signal frequency and other independent variables at 90 dB SPL masker levels. Upon follow-up analyses, RM in RPN with one ERB decreased significantly as the signal frequency increased [$F(3,12) = 5.14$]. As the masker bandwidth for RPN increased from one to two ERBs, there was a spread in RM across all signal frequencies, and there were no longer any significant differences in RM due to signal frequency [$F(3,12) = 2.48$]. At 95 dB SPL masker levels, RM in RPN maskers with one ERB decreased significantly as the signal frequency increased from 250 to 700 Hz [$F(3,12) = 7.84$]. RM at 250 Hz for RPN maskers with one ERB was significantly greater than RM at any other signal frequency. As the masker bandwidth was increased from one to two ERBs, RM spread beyond 250–700 Hz. Further analyses indicated that RM only at 250 Hz was significantly greater than that at 700 Hz [$t(4) = 4.93$], and there were no significant differences in RM across any other frequencies.

RM growth at 250 Hz is plotted as a function of the masker level for NBN maskers for one- and two- ERBs conditions in the left and right panels of Fig. 4, respectively. Other frequencies are not considered as the RM values obtained at other frequencies were small. The observed, MEDM-, and QDPM-predicted data are shown in filled triangles, open squares, and open circles, respectively. Error bars indicate ± 1 standard deviation (SD) of the mean across the five listeners. A reference dotted line with a unit slope is shown in each panel for comparison. As the masker bandwidth was increased, RM for RPN grew rapidly. The slope of the RM growth function for RPN maskers with one ERB was approximately 0.6. As the masker bandwidth was increased to two ERBs, the slope increased close to unity. RM growth for LNN, however, was negligible irrespective of the masker bandwidth. While the observed data were in general agreement with both versions of the model, the observed RM growth and data in general were in better agreement with the MEDH than the QDPH.

V. EXPERIMENT II

The second experiment was specifically designed to test QDPH using TC maskers as the expected RM is easily predictable and testable. Two equal-power TC maskers arithmetically centered at 3000 Hz, one with two primaries (TC2) and the other with eight primaries (TC8), were used as maskers in the second experiment. As in the first experiment, one- and two-equivalent rectangular masker bandwidths were used. The primaries for TC2 maskers were separated by 349 and 698 Hz for one- and two-ERB conditions, respectively. The primaries for one-ERB-wide TC8 maskers were linearly spaced at 50-Hz intervals with the exception of the last two components, which were separated by 49 Hz. The

FIG. 4. The observed and model-predicted RM growth at 250 Hz are compared as a function of the masker level for RPN (top panels) and LNN (bottom panels) maskers with one-ERB (left panels) and two-ERB (right panels) bandwidth conditions, respectively. The observed, MEDM-, and QDPM-predicted data are shown in filled triangles, open squares, and open circles, respectively. Error bars indicate ± 1 SD of the mean across listeners. A reference dotted line with a unit slope is shown in each panel for comparison.

primaries for two-ERB-wide TC8 maskers were linearly spaced at 100-Hz intervals with the exception of the last two components, which were separated by 98 Hz. The phases of the component frequencies were changed randomly with each presentation. As in the first experiment, masker levels were varied from 80 to 95 dB overall SPL in 5-dB steps, and RM was measured at 250, 350, 500, and 700 Hz.

A. Results

The comparison of the observed and model-predicted RM patterns for TC maskers with one- and two-equivalent

rectangular masker bandwidth conditions are shown in Figs. 5 and 6, respectively. The observed, QDPM-, and MEDM-predicted data are shown in the bottom, middle, and top panels, respectively. The simulated data for QDPM and MEDM differ significantly in at least two aspects. First, the slope of the RM growth as a function of masker level is expected to be close to two as per QDPM, but only close to one as per MEDM. Second, only MEDM predicted any significant RM at 700 Hz for a one-ERB wide TC2 masker. Similar to the NBN masker conditions, many predictions from both versions of the model were similar and efficient for many test

FIG. 5. The observed RM patterns (bottom panels) are compared with predicted RM patterns for MEDM (top panels) and QDPM (middle panels) as a function of signal frequency for one-ERB-wide TC2 (left panels) and TC8 (right panels) maskers. Error bars indicate ± 1 SD of the mean across listeners. Masker level is the parameter.

FIG. 6. The observed RM patterns (bottom panels) are compared with predicted RM patterns for MEDM (top panels) and QDPM (middle panels) as a function of signal frequency for two-ERB-wide TC2 (left panels) and TC8 (right panels) maskers. Error bars indicate ± 1 SD of the mean across listeners. Masker level is the parameter.

conditions and are described as follows. First, while keeping the overall level constant if the number of components of the TC maskers is increased, RM observed at any frequency would decrease due to a decrease in the masker spectrum level. Specifically, the highest RM observed by TC8 maskers would be less than that by TC2 maskers. Second, an increase in the masker bandwidth would not result in an increase in RM, as observed in NBN maskers, since QDP levels depend upon the masker spectrum level. An increase in the TC-masker bandwidth resulted in an increase in frequency separation among primaries. The frequency at which RM might occur would be expected to vary. Therefore, a significant bandwidth effect is expected on the frequency at which RM would occur. Finally, the third prediction explicitly specifies the expected frequency region where RM may be expected. RM would be observed at signal frequencies corresponding to the difference tones of the TC primaries. Specifically, RM would be expected to occur at 350 Hz for TC2 maskers with one-ERB. For TC2 maskers with two-ERBs, significant RM would mainly be observed at 700 Hz. Nonsignificant or no RM would be expected at any other frequencies. In contrast, RM in TC8 maskers would primarily be observed at 250 and 350 Hz for one-equivalent rectangular masker bandwidth and at 500 and 700 Hz for two-equivalent rectangular masker bandwidths conditions, respectively.

Similar to the analyses for NBN maskers, data for TC maskers were analyzed at each masker level. There were significant effects on RM due to interactions among the bandwidth, masker type, and signal frequency at all masker levels [at 80 dB SPL, $F(3,12) = 10.0$; at 85 dB SPL, $F(3,12) = 6.63$; at 90 dB SPL, $F(3,12) = 11.3$, and at 95 dB SPL, $F(3,12) = 13.8$]. Results were consistent with the first prediction that the expected RM would differ due to masker type. Specifically, the results showed that RM was significantly greater for TC2 than TC8 maskers at 350 and 700 Hz

when the bandwidth was one ERB. When the bandwidth was two ERBs, RM for TC2 maskers was significantly greater than for TC8 maskers at 700 Hz. The main effect for the masker type was significant at all masker levels [e.g., at 80 dB SPL, $F(1,4) = 24.3$, and at 85 dB SPL, $F(1,4) = 32.59$]. Upon follow-up analyses, RM was significantly greater in TC2 than in TC8 maskers at 350 Hz [$F(1,4) = 7.70$] and also at 700 Hz [$F(1,4) = 60.9$], when the masker bandwidth was one ERB and the masker level was 80 dB SPL. This observation was also true at other masker levels from 85 to 95 dB SPL. Irrespective of masker bandwidth, RM at 700 Hz was always significantly greater in TC2 maskers than in TC8 maskers [e.g., at 85 dB SPL, $F(1,4) = 104$].

The results show a significant bandwidth effect on the frequency at which RM occurred. The main effect for the masker bandwidth was significant at all masker levels [e.g., at 80 dB SPL, $F(1,4) = 15.7$]. Follow-up analyses revealed a significant bandwidth effect at 700 Hz for TC2 maskers [e.g., at 80 dB SPL, $F(1,4) = 21.7$] as well as for TC8 maskers [e.g., at 80 dB SPL, $F(1,4) = 6.36$] at all masker levels. An increase in the masker bandwidth from one to two ERBs resulted in a decrease in RM at 350 Hz for TC2 maskers at masker levels of 90 dB SPL and above [e.g., at 90 dB SPL, $F(1,4) = 15.2$]. An increase in the masker bandwidth from one to two ERBs at and above 90 dB SPL also resulted in an increase in RM at 500 Hz for both, TC2 and TC8 maskers [e.g., at 90 dB SPL, $F(1,4) = 70.7$, and at 700 Hz [$F(1,4) = 82.3$]. There was a significant relation between bandwidth and the frequency at which maximum RM occurred. The finding was consistent with the second prediction. However, RM did not remain unchanged when masker bandwidth was changed from one to two ERBs, as predicted.

The main effect for the signal frequency was significant at all masker levels [e.g., at 80 dB SPL, $F(1,4) = 30.6$]. When the masker bandwidth was one ERB, RM due to TC2

FIG. 7. The observed and model-predicted RM growth are compared as a function of the masker level for one-ERB-wide TC2 maskers at 350 Hz (top left panel), two-ERB-wide TC2 maskers at 700 Hz (top right panel), one-ERB-wide TC8 maskers at 250 Hz (bottom left panel), and two-ERB-wide TC8 maskers at 700 Hz (bottom right panel), respectively. The observed, MEDM-, and QDPM-predicted data are shown in filled triangles, open squares, and open circles, respectively. Error bars indicate ± 1 SD of the mean listeners. A reference dotted line with a unit slope is shown in each panel for comparison.

maskers was primarily present at 350 and 700 Hz. As the TC2 masker bandwidth was increased to two ERBs, RM at 350 Hz became negligible but RM at 700 Hz increased. In addition, there was a spread of RM to 500 Hz, especially at high masker levels. Considering significant interactions among all independent variables, several follow-up analyses were required. When the masker bandwidth was two ERBs, TC2 maskers for all tested masker levels generated significantly greater RM at 700 Hz than any other test frequencies [e.g., at 80 dB SPL masker level, for 250 Hz, $t(4) = 7.29$; for 350 Hz, $t(4) = 7.27$; and for 500 Hz, $t(4) = 5.97$]. When the masker bandwidth was one ERB, RM due to TC2 maskers was observed at 350 and 700 Hz. RM in one-ERB-wide TC2 maskers was significantly greater at 350 Hz than at 250 Hz [e.g., at 80 dB SPL, $t(4) = 3.65$] and 500 Hz [e.g., at 80 dB SPL, $t(4) = 3.42$] at all masker levels. The observed RM at 350 and 700 Hz was similar and not significantly different even when the masker level was 95 dB SPL [$t(4) = 0.216$]. In summary, the presence of significant RM at 350 and 700 Hz in TC2 maskers with one- and two-ERB conditions, respectively, was consistent with the third prediction. However, the presence of significant RM at 700 Hz in one-ERB-wide TC2 maskers was not consistent with the QDPH.

RM was observed at 250 and 350 Hz when the TC8 masker bandwidth was one ERB. RM in one-ERB-wide TC8 maskers was significantly greater at 250 Hz than at 500 Hz [e.g., at 80 dB SPL, $t(4) = 4.88$] or 700 Hz [e.g., at 80 dB SPL, $t(4) = 4.66$] at all masker levels, and also than at 350 Hz at masker levels of 85 dB SPL [$t(4) = 4.94$] and above. RM at 350 Hz was also significantly greater than that at 500 Hz at masker levels of 85 dB SPL [$t(4) = 3.24$] and 700 Hz [$t(4) = 6.40$] or above. When the masker bandwidth was increased to two ERBs, the frequency region at which RM was observed due to TC8 maskers shifted to 500 and 700 Hz from 250 and 350 Hz. RM at 500 and 700 Hz was similar at all masker levels as evidenced from the nonsignificant difference in RM measures at

these two frequencies even at 95 dB SPL [$t(4) = -1.94$]. RM in two-ERB-wide TC8 maskers was significantly greater at 500 Hz than at 350 Hz at masker levels of 85 dB SPL [$t(4) = 5.67$] or above. RM at 500 Hz due to TC8 maskers with two ERBs was significantly greater than that at 350 Hz [$t(4) = 5.69$] and also at 250 Hz [$t(4) = 5.01$] only when the masker level was increased to 85 and 90 dB SPL, respectively. When the masker level was increased to 90 dB SPL and above, RM at 700 Hz was also significantly greater than that at 250 Hz [$t(4) = 2.69$] and 350 Hz [$t(4) = 3.86$] test frequencies. All findings for TC8 maskers were consistent with the third prediction.

Figure 7 compares the observed and model-predicted RM growth as a function of the masker level for one-ERB-wide TC2 maskers at 350 Hz (top left panel), two-ERB-wide TC2 maskers at 700 Hz (top right panel), one-ERB-wide TC8 maskers at 250 Hz (bottom left panel), and two-ERB-wide TC8 maskers at 700 Hz (bottom right panel), respectively. The observed, MEDM-, and QDPM-predicted data are shown in filled triangles, open squares, and open circles, respectively. Error bars indicate ± 1 SD of the mean across the five listeners. A reference dotted line with a unit slope is shown in each panel for comparison. The slope of the RM growth function at these frequencies was greater than one (close to 1.2). The slope of the RM growth function for TC8 maskers was close to one. As the masker bandwidth increased, the RM growth rate for TC2 maskers increased slightly. Unlike the slope of the RM growth function for RPN and LNN maskers, the slope for TC2 maskers increased from 1.2 to above 1.5, as the masker bandwidth or frequency separation increased from one to two ERBs. Although the general trend of the observed RM data is in good agreement with both versions of the model, the RM growth and also the RM patterns in the observed data are in better agreement with the MEDM. However, both models fail to completely account for RM growth for TC maskers.

VI. DISCUSSION

The masker center frequency in this study was 3000 Hz. Signal frequencies were 250, 350, 500, and 700 Hz. RM was observed only at the frequency region numerically equal to or less than the masker's bandwidth in hertz. RM observed in this study cannot be explained by the traditional power spectrum model since the maskers were more than one and one-half to two octaves above the signal, and the spectral energy of the maskers were beyond the auditory filters of interest in signal detection. The partial loudness model (PLM) of masking (Moore *et al.*, 1997), a variation of the energy-detection model, is frequently used to account for masking data. One of the salient features of PLM is that it takes the spread of excitation to other frequencies into account in computation. Despite this feature, RM data cannot be explained by this model since there would be no overlap of the area of spread of excitation for the low-frequency, low-level signal and high-frequency, high-level maskers. Moreover, the frequency effect on RM in the present study was non-monotonic. Specifically, RM in one-ERB-wide TC2 maskers was present at 350 and 700 Hz and not at 250 and 500 Hz. The frequencies at which RM occurred in TC8 maskers shifted from the 250–350-Hz region to the 500–700-Hz region. RM in NBN maskers decreased as the signal frequency increased. The non-monotonic frequency effect was not consistent with the masking effect due to the spread of excitation.

RPN maskers generated significantly greater RM than LNN maskers. One might argue that RM resulted from the uncertainty and stimulus variability in the RPN waveforms, as in informational masking. This is clearly not the case. An increase in masker bandwidth decreases both the uncertainty and stimulus variability, and therefore, one would expect a reduction in masking as the masker bandwidth is increased. RM was greater, however, in two- than one-equivalent rectangular masker bandwidth conditions. This finding is also in direct opposition to energy-detection models. An increase in the masker bandwidth, while keeping the overall level constant, results in a decrease in the spectrum level. Energy-detection models predict that the contribution of the maskers' spectral energy beyond one ERB would decrease generating any masking as in the case of DM. In a recent study on increment detection in noise, Patra *et al.* (2009b) also reported a bandwidth effect similar to that observed in this study. Patra *et al.* measured increment detection thresholds at 500 and 4000 Hz in on- and off-frequency RPN and LNN maskers, where they varied the masker bandwidth from one to two ERBs while keeping the overall level constant. The results of the study showed that the increment detection thresholds of sinusoids increased with increasing masker bandwidths and envelope fluctuations.

The results of the present study demonstrated the possibility of significant low-frequency masking due to masker envelope fluctuations, even with an off-frequency masker situated more than one-octave away from the signal frequency. There is evidence from psychophysical (e.g., Bacon and Grantham, 1989) and physiological studies (e.g., Frisina *et al.*, 1990; Langner and Schreiner, 1988;

Nelson and Carney, 2004) that the auditory system is sensitive to AM cues. The importance of AM cues for speech perception also has been established (e.g., Shannon *et al.*, 1995). It may be assumed that the detection of AM cues is a necessary feature inherent to the auditory system for complex signal processing such as speech. The reliable coding of stimulus envelope characteristics most likely begins at the level of the cochlea (Stone *et al.*, 2008), and further processing of modulation information continues at various post-cochlear levels (e.g., Eggermont, 1994; Frisina *et al.*, 1990; Nelson and Carney, 2004). Continuous speech contains low-frequency AM in its temporal envelope, and most of these speech related AM cues are less than 20 Hz, below the human auditory frequency range. This inherent natural design probably ensures the robustness in speech perception with minimal interference with low-frequency noise. As a consequence of the reliance on AM cues, signal detection may suffer in some cases due to the presence of randomness in the masker envelope. For example, DM effects on detection of sinusoids are reported to be larger in RPN than in equal-power spectrally matched LNN maskers (Hartman and Pumplin, 1988; Kohlrausch *et al.*, 1997). Due to the differences in envelope fluctuations in LNN and RPN, the interference is greater in RPN than LNN. RM might be a special case of modulation detection interference, where the detection of off-frequency masker envelopes interferes with the detection of low-frequency signals.

Contrary to the observation in the present study, the QDPM does not predict any RM at 700 Hz for one-ERB-wide TC2 maskers. On the other hand, the MEDM was fairly successful in predicting such an observation. According to the MEDM, significant masking may be expected at frequencies corresponding to the difference tones ($f_2 - f_1$) as well as at their harmonics [i.e., multiples of ($f_2 - f_1$)], which is in agreement with an observation by Spieth (1957). Based on an observation on generation of best beats, Spieth reported that TC2 maskers at high levels would produce difference tones ($f_2 - f_1$) as well as their harmonics [i.e., multiples of ($f_2 - f_1$)]. Therefore, the observed result was not necessarily an anomaly or unexpected. Researchers have demonstrated significant roles of both energy and modulation cues in the detection of tones in noise (e.g., Hartman and Pumplin, 1988; Kohlrausch *et al.*, 1997; Richards, 2002) and also in the detection of signals in general (e.g., Dau *et al.*, 1997; Jepsen *et al.*, 2008). Poorer performance was reported due to the presence of on- and off-frequency masker fluctuations in intensity resolution (Gallun and Hafter, 2006; Patra *et al.*, 2009b). The results of the study suggested that interference due to masker envelope fluctuations is not limited to only intensity resolution conditions or on-frequency masking. The presence of high-level masker envelope fluctuations may result in a significant low-frequency masking even when the masker is more than one-octave away from the signal.

The observed slopes of the RM growth as a function of masker level in this study were close to zero for LNN and one for RPN and TC maskers. This observation was more or less in agreement with the MEDH. However, the slope of two for RM growth for NBN as reported by Bilger (1958)

could be explained only if an additional nonlinearity in the distortion growth (i.e., the detection and introduction of the masker power envelope as the noise) as a function of masker level is assumed. The QDPM mostly failed to account for observed slopes in this study. In addition, the QDPM could not account for any RM at 700 Hz for one-ERB-wide TC2 maskers. However, the roles of QDP or higher-order distortion products may not be ruled out. Humes (1980) reported success in describing a large set of data by incorporating two-level-dependent nonlinearities, a half-wave rectified p -law device and the classical power-series nonlinearity. Some combination of nonlinearities might be operating within the cochlea that plays significant roles in RM generation. The present study did not evaluate the existence of such nonlinearities and further studies are warranted.

VII. CONCLUSIONS

The general trends in the observed data were consistent with predictions by both versions of the cochlear saturating nonlinearity model. The MEDM seems to capture the general trends in the observed data better than the QDPM. The observed data suggest that high-frequency noise bands with envelope fluctuations at high levels most likely would generate significant low-frequency masking that might have some implications for low-frequency signal detection and speech perception in noise. The observations made from this study may be summarized as below:

- (1) RM depends upon the envelope fluctuations, bandwidth, and presentation level of the masker. An increase in the envelope fluctuations, bandwidth, or level of the masker, individually or in combination, tends to increase masking of the signal.
- (2) RM by TC maskers depends upon the number of primaries, bandwidth or frequency separation, and presentation level of the masker. An increase in the envelope fluctuations or level of the masker, individually or in combination, tends to increase RM.
- (3) RM occurs in the frequency region that corresponds to the spectral components of the masker envelope, which is equivalent to various combinations of the difference frequencies of the masker primaries.
- (4) RM cannot be explained by existing energy-detection models. It is unlikely that RM is generated by a purely quadratic process. A model based on masker envelope detection was fairly successful in accounting for the observed data in this study.

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- Bacon, S. P., and Grantham, D. W. (1989). "Modulation masking: Effects of modulation frequency, depth, and phase," *J. Acoust. Soc. Am.* **85**, 2575–2580.
- Bilger, R. C. (1958). "Intensive determinants of remote masking," *J. Acoust. Soc. Am.* **30**, 817–824.
- Bilger, R. C., and Hirsh, I. J. (1956). "Masking of tones by bands of noise," *J. Acoust. Soc. Am.* **28**, 623–630.
- Bilger, R. C., and Matthies, M. L. (1985). "Oto-acoustic emissions and remote masking," *J. Acoust. Soc. Am.* **77**, S95–S95.
- Cervellera, G., Quaranta, A., and Cassano, P. (1978). "Le «remote masking»: un test de surdit de transmission cochleaire (Remote masking as a test of cochlear conductive hearing losses)," *Audiol.* **17**, 317–323.
- Dau, T., Kollmeier, B., and Kohlrausch, A. (1997). "Modeling auditory processing of amplitude modulation. I. Detection and masking with narrow-band carriers," *J. Acoust. Soc. Am.* **102**, 2892–2905.
- Deatherage, B. H., Davis, H., and Eldredge, D. H. (1957). "Physiological evidence of the masking of low frequencies by high frequencies," *J. Acoust. Soc. Am.* **29**, 132–137.
- Egan, J. P., and Hake, H. W. (1950). "On the masking pattern of a simple auditory stimulus," *J. Acoust. Soc. Am.* **22**, 622–630.
- Eggermont, J. J. (1994). "Temporal modulation transfer functions for AM and FM stimuli in cat auditory cortex: Effects of carrier type, modulating waveform and intensity," *Hear. Res.* **74**, 51–66.
- Fletcher, H. (1940). "Auditory patterns," *Rev. Mod. Phys.* **12**, 47–65.
- Frisina, R. D., Smith, R. L., and Chamberlain, S. C. (1990). "Encoding of amplitude modulation in the gerbil cochlear nucleus: I. A hierarchy of enhancement," *Hear. Res.* **44**, 99–122.
- Gallun, F. J., and Hafter, E. R. (2006). "Amplitude modulation sensitivity as a mechanism for increment detection," *J. Acoust. Soc. Am.* **119**, 3919–3930.
- Hartmann, W. M., and Pumphlin, J. (1988). "Noise power fluctuations and the masking of sine signals," *J. Acoust. Soc. Am.* **83**, 2277–2289.
- Henry, K. R., Ayars, N. M., Paolinelli, M. C., and Nguyen, H. H. (1985). "Extra-high-frequency noise remotely masks and alters temporal integration at lower frequencies," *Int. J. Audiol.* **24**, 309–318.
- Humes, L. E. (1980). "On the nature of two-tone aural nonlinearity," *J. Acoust. Soc. Am.* **67**, 2073–2083.
- Jepsen, M. L., Ewert, S. D., and Dau, T. (2008). "A computational model of human auditory signal processing and perception," *J. Acoust. Soc. Am.* **124**, 422–438.
- Jerger, J. F., Tilmann, T. W., and Petersen, I. L. (1960). "Masking by octave bands of noise in normal and impaired ears," *J. Acoust. Soc. Am.* **32**, 385–390.
- Kaernbach, C. (1990). "A single-interval adjustment-matrix (SIAM) procedure for unbiased adaptive testing," *J. Acoust. Soc. Am.* **88**, 2645–2655.
- Karlovich, R. S., and Osier, H. A. (1977). "Remote masking generated by high-frequency two-tone complexes," *Int. J. Audiol.* **16**, 507–521.
- Kohlrausch, A., Fassel, R., van der Heijden, M., Kortekaas, R., van de Par, S., Oxenham, A. J., and Puschel, D. (1997). "Detection of tones in low-noise noise: Further evidence for the role of envelope fluctuations," *Acta Acust.* **83**, 659–669.
- Langner, G., and Schreiner, C. E. (1988). "Periodicity coding in the inferior colliculus of the cat. I. Neuronal mechanisms," *J. Neurophysiol.* **60**, 1799–1822.
- McFadden, S. L., Henderson, D., and Quaranta, A. (1997). "Remote masking in normal and noise-exposed chinchillas," *Audiol. Neuro-Otol.* **2**, 128–138.
- Moore, B. C. J., Glasberg, B. R., and Baer, T. (1997). "A model for the prediction of thresholds, loudness, and partial loudness," *J. Audio Eng. Soc.* **45**, 224–240.
- Nelson, P. C., and Carney, L. H. (2004). "A phenomenological model of peripheral and central neural responses to amplitude-modulated tones," *J. Acoust. Soc. Am.* **116**, 2173–2186.
- Nuttall, A. L., and Dolan, D. F. (1993). "Intermodulation distortion (F_2 – F_1) in inner hair cell and basilar membrane responses," *J. Acoust. Soc. Am.* **93**, 2061–2068.
- Patra, H., Feth, L. L., and Roup, C. M. (2009a). "Modeling the masking of low frequency signals by high frequency, high level narrow bands of noise (A)," *Assoc. Res. Otolaryngol. Abstr.* **32**, 302.
- Patra, H., Messersmith, J., and Jesteadt, W. (2009b). "The relative weighting of energy and envelope-modulation cues in increment detection (A)," *J. Acoust. Soc. Am.* **125**, 2524–2524.
- Pumphlin, J. (1985). "Low-noise noise," *J. Acoust. Soc. Am.* **78**, 100–104.
- Rankovic, C. M. (1998). "Factors governing speech reception benefits of adaptive linear filtering for listeners with sensorineural hearing loss," *J. Acoust. Soc. Am.* **103**, 1043–1057.

- Richards, V. M. (2002). "Varying feedback to evaluate detection strategies: The detection of a tone added to noise," *J. Assoc. Res. Otolaryngol.* **3**, 209–221.
- Roup, C. M., Wiley, T. L., Safady, S. H., and Stoppenbach, D. T. (1998). "Tympanometric screening norms for adults," *Am. J. Audiol.* **7**, 1–6.
- Shannon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., and Ekelid, M. (1995). "Speech recognition with primarily temporal cues," *Science* **270**, 303–304.
- Shofner, W. P., Sheft, S., and Guzman, S. J. (1996). "Responses of ventral cochlear nucleus units in the chinchilla to amplitude modulation by low-frequency, two-tone complexes," *J. Acoust. Soc. Am.* **99**, 3592–3605.
- Spieth, W. (1957). "Downward spread of masking," *J. Acoust. Soc. Am.* **29**, 502–505.
- Stone, M. A., Moore, B. C. J., and Greenish, H. (2008). "Discrimination of envelope statistics reveals evidence of sub-clinical hearing damage in a noise-exposed population with 'normal' hearing thresholds," *Int. J. Audiol.* **47**, 737–750.
- Tubach, M., McGee, J. A., and Walsh, E. J. (1996). "Distortion generated by the ear: Its emergence and evolution during development," *Laryngoscope* **106**, 822–830.
- Wenner, C. H. (1968). "Frequency dependency of aural difference tones," *J. Acoust. Soc. Am.* **43**, 780–784.
- Wiegand, L., and Patterson, R. D. (1999). "Quantifying the distortion products generated by amplitude modulated noise," *J. Acoust. Soc. Am.* **106**, 2709–2718.