Nonadditivity of forward and simultaneous masking^{a)}

Adam Svec,^{b)} Suyash N. Joshi, and Walt Jesteadt^{c)}

Center for Hearing Research, Boys Town National Research Hospital, 555 N. 30th Street, Omaha, Nebraska 68131

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The current study measured the additional masking obtained for combinations of forward and simultaneous maskers as a function of forward masker bandwidth, signal delay, and simultaneous masker level. The effects of the two individual maskers were equated in all conditions. Additional masking increased with increasing masker level, increasing signal delay, and decreasing masker bandwidth. The portion of the simultaneous masker that made the greater contribution to additional masking was the part that overlapped with the signal, not with the forward masker. The changes in additional masking observed as a function of forward masker bandwidth and the interaction between the effects of forward and simultaneous maskers call into question the use of additional masking as a measure of basilar membrane compression and present problems for the use of simultaneous noise to simulate hearing loss. © 2013 Acoustical Society of America.
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I. INTRODUCTION

The cochlear amplifier provides a significant amount of gain for low-level incoming sounds and less gain as the input level increases, resulting in a wide dynamic range for normal human hearing (Ruggero *et al.*, 1997). At relatively high characteristic frequencies, the active process in the healthy cochlea applies compression at the best frequency of an incoming signal and responds nearly linearly at frequencies that are sufficiently removed from the best frequency (Ruggero *et al.*, 1997). Physiological studies have suggested that sensorineural hearing loss results in a more linear response to incoming signals at all levels and frequencies in the affected region (Ruggero *et al.*, 1997; Robles and Ruggero, 2001). In listeners with hearing impairment, reduction in frequency selectivity and loss of compressive non-linearity are thought to lead to multiple auditory deficits (Moore, 1996), including difficulty understanding speech in the presence of noise (Dubno and Schaefer, 1995). Physiological studies have suggested that moderate-to-high levels of broadband noise also result in a more linear response to incoming signals (Recio-Spinoso and Cooper, 2013; Recio-Spinoso and Lopez-Poveda, 2010). Broadband background noise has often been used to simulate hearing loss in listeners with normal hearing to allow stimuli to be presented at the same physical levels used to test listeners with hearing loss, while maintaining the same degree of audibility (Reed *et al.*, 2009).

Forward masking has been used in a number of ways to obtain behavioral estimates of basilar membrane non-linearity (Oxenham and Plack, 1997; Nelson *et al.*, 2001; Schairer *et al.*, 2003; Plack and O'Hanlon, 2003; Lopez-Poveda *et al.*,

2005). Oxenham and Plack (1997) used growth of masking (GOM) for on- and off-frequency sinusoidal forward maskers to derive a behavioral estimate of basilar membrane compression. They measured the level of 3000 Hz (off-frequency) and 6000 Hz (on-frequency) forward maskers required to mask a 6000 Hz pure tone signal presented at a number of levels. In the on-frequency forward masker condition, the signal and the masker are assumed to be subjected to equivalent amounts of cochlear compression. In the off-frequency forward masker condition, a masker presented more than an octave below the signal frequency is assumed to be processed nearly linearly at the basilar membrane place tuned to the frequency of the signal. By comparing GOM slopes for the on- and off-frequency forward masker conditions, the non-linear response of the basilar membrane to a particular signal frequency can be estimated. Gregan *et al.* (2010) used this paradigm to obtain estimates of cochlear compression in the presence of simultaneous threshold-equalizing noise (TEN) (Moore *et al.*, 2000), for normal hearing listeners. The investigators hypothesized that the simultaneous noise would reduce compression in the noise-masked normal hearing listeners, as well as elevate thresholds, making them more like hearing impaired listeners. Somewhat unexpectedly, estimates of compression exponents were not significantly affected by the simultaneous TEN.

Investigators have also used additivity-of-forward masking (AFM) paradigms to obtain behavioral estimates of basilar membrane compression (Plack and O'Hanlon, 2003; Plack *et al.*, 2008; Gregan *et al.*, 2011). Typically, these experiments contain multiple stages and, instead of utilizing sinusoidal maskers, use temporally non-overlapping octave-band noise (OBN) forward maskers. First, the signal level is fixed at a predetermined sensation level (SL) and the level of a single forward masker (M1) is adaptively varied to find masked threshold. Second, M1 is removed and signal level is held constant at the previous SL while a second forward masker (M2) is varied in level to establish an equated masked threshold between M1 and M2. Finally, M1 and M2 are

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^{b)}Also at: Department of Speech-Language-Hearing Science, University of Minnesota, 164 Pillsbury Drive SE, Minneapolis, MN 55455.

^{c)}Author to whom correspondence should be addressed. Electronic mail: walt.jesteadt@boystown.org

presented together at their equated masker levels while the signal level is adaptively varied (Plack and O'Hanlon, 2003). An energy-summation model predicts that two equated sequential forward maskers add in a linear fashion at low levels and will produce 3 dB more masking than each masker in isolation (Green and Swets, 1966). At moderate and high levels, it is assumed that the effects of the independent equated maskers combine linearly but that the compressive function of the basilar membrane produces non-additive "additional masking" of more than 3 dB (Plack and O'Hanlon, 2003; Plack *et al.*, 2008; Plack and Arifanto, 2010). The additional masking can therefore be used to estimate the amount of compression.

Gregan *et al.* (2011) used the AFM technique with sequential non-overlapping OBN forward maskers in the presence of TEN to obtain an estimate of compression as an alternative to GOM. A linear response, or an absence of compression, was observed for three of the five noise-masked normal hearing listeners. Results suggested that the compression estimates at 4000 Hz were the most affected, or the closest to a linear response, compared to those measured at 500 and 1500 Hz. In a control experiment, the TEN was removed to assess its effect on compression estimates. The authors note that a trend for compressive responses was observed in the absence of TEN at 4000 Hz, but the differences between the two experiments were not statistically significant.

If compression estimates using these two forward masking techniques (GOM, AFM) are affected differently by the presence of simultaneous TEN, then perhaps some interaction between the forward maskers and the TEN contributes to the reduction in additional masking in the AFM paradigm. Additional masking has been observed for combinations of a single forward masker and simultaneous noise. Jesteadt *et al.* (1996) examined effects of bandwidth on additional masking for forward and simultaneous masker combinations. Masked threshold for a 20-ms, 1000 Hz pure tone signal was measured in the presence of a 400-ms, broadband simultaneous masker (10 000 Hz low pass noise) presented at 55 dB sound pressure level (SPL). Masked threshold for the same pure tone signal was also measured for a 300-ms, 1000 Hz sinusoidal forward masker presented at 45, 60, 75, or 90 dB SPL. The two maskers were then combined and the signal level was adaptively varied to find masked threshold. In the combined condition, 14 dB of additional masking was observed when the independent maskers were equated, but a large effect occurred across a range of forward masker levels. In a second experiment, the sinusoidal forward masker and the sinusoidal signal were replaced with broadband noise. The simultaneous masker was shortened to 20 ms and temporally aligned with the signal. In this condition, where the simultaneous masker, forward masker, and signal were all broadband noise, little or no additional masking was observed. Increasing the bandwidth of each stimulus component reduced the combined effects to those predicted by linear summation.

Studies using two temporally non-overlapping maskers have shown that additional masking increases as the amount of masking provided by each individual masker increases (e.g., Penner and Shiffrin, 1980; Oxenham and Moore, 1994,

1995; Plack and O'Hanlon, 2003). However, effects of masker level and bandwidth on additional masking for combinations of simultaneous and forward maskers have not previously been reported in the literature in a systematic fashion.

In light of the unexpected results in the presence of a simultaneous masker obtained by Gregan *et al.* (2010, 2011), and because few studies have examined the effect of masker bandwidth in additivity-of-masking paradigms, the first two experiments examined the effects of masker bandwidth and level for forward maskers in the presence of an equated simultaneous broadband noise. The experiments differed only in the use of an additional notched-noise masker to restrict off-frequency listening in the forward-masker alone conditions. Based on the results obtained by Jesteadt *et al.* (1996), we hypothesized that additional masking in the combined-masker conditions would be affected by forward masker bandwidth, with significantly more additional masking when the forward masker was a sinusoid than when it was a broadband noise.

II. EXPERIMENT 1: EFFECTS OF LEVEL AND FORWARD MASKER BANDWIDTH ON ADDITIONAL MASKING

A. Listeners

The listeners in all experiments had pure tone thresholds of 20 dB hearing level (HL) or better at octave frequencies between 250 and 8000 Hz (ANSI, 2004). Each listener was compensated for their participation in the study, except the first author. The experimental procedures were approved by the Institutional Review Board at the Boys Town National Research Hospital.

Seven adult listeners (4 males, 3 females) participated in experiment 1. Listener age ranged from 21 to 32 yr.

B. Methods

The stimuli were generated digitally in MATLAB at a sampling rate of 44 100 Hz and were presented to subjects via 24-bit digital-to-analog convertors (Digital Audio Labs, CardDeluxe). All stimuli were presented to the left ear of the listener through a headphone buffer (PreSonus HP4) and Sennheiser HD25-1 II professional headphones in a double-walled sound-attenuated booth (Industrial Acoustics). The same equipment was used in all experiments.

Quiet thresholds for a 6-ms (2-ms onset and offset raised-cosine ramps and 2-ms steady state portion), 4000-Hz pure tone signal were measured using a two-interval forced choice (2IFC) two-up, one-down adaptive procedure tracking 70.7% correct on the psychometric function (Levitt, 1971). Each block contained 50 trials. Each trial contained a warning interval of 300 ms and two 300-ms observation intervals separated by 500 ms. The listeners did not receive feedback. The stimulus starting level was 55 dB SPL. The initial step size was 8 dB, changing to 4 dB after the first two reversals, and to 2 dB after the next four reversals. Thresholds were calculated as the mean level in dB SPL for all reversals after the sixth. Mean thresholds for each condition were based on four blocks. Each experiment listed below utilized this same

procedure to find masked threshold of a signal by either adaptively varying the signal level in the presence of a fixed-level masker or adaptively varying the masker level in the presence of a fixed-level signal.

In the simultaneous-masker alone (SM-alone) conditions, a 4000-Hz sinusoidal signal was adaptively varied in level to find masked threshold in the presence of a 20–20 000 Hz broadband noise (BBN) simultaneous masker (SM). The 300-ms BBN SM, including 5-ms onset and offset raised-cosine ramps, filled the entire observation interval. The signal was presented 256 ms after the BBN SM onset. The signal starting level was 20 dB above the overall noise level. In the forward-masker alone (FM-alone) conditions, the SM was removed, the signal level was fixed at masked threshold measured in the SM-alone condition, and a 200-ms forward masker (FM), including 2-ms onset and offset raised-cosine ramps, was adaptively varied to find the level at which the FM just masked the signal. FM starting level was 15 dB below the signal level. The FM offset occurred 6 ms before the signal onset. After finding equated masked thresholds for the same signal level using SM and FM individually, the two maskers were combined (SM+FM) and fixed at their equated levels. The SM onset preceded the FM onset by 50 ms. The SM offset occurred 38 ms after the signal offset, as in the SM-alone condition. In the SM+FM condition, the signal level was adaptively varied to find masked threshold. The signal starting level was 20 dB above masked threshold in the SM-alone condition. In the FM-alone and the SM+FM conditions, a contralateral masker made up of a $\frac{2}{3}$ -octave noise band (3175–5040 Hz) centered at 4000 Hz was presented to the right ear (non-test ear) at 40 dB below the signal presentation level to mask crosstalk, or detection of the signal in the contralateral ear. The contralateral noise was gated with the onset and offset of the entire interval (300 ms, 5-ms raised-cosine ramps), as in the *Gregan et al.* studies.

In experiment 1, FM bandwidth and SM level were manipulated as the independent variables. In the SM-alone conditions, masked thresholds were found for four SM levels; 30, 40, 50, and 60 dB SPL. In the FM-alone conditions, four FM bandwidths were used; broadband noise (BBN; 20–20 000 Hz), octave-band noise (OBN; 2828–5657 Hz), $\frac{1}{12}$ -octave narrow-band noise (NBN; 3886–4117 Hz), and a sinusoid (SIN; 4000 Hz pure tone). The OBN and NBN FMs were geometrically centered at 4000 Hz. Because the ipsilateral notched-noise used in the *Gregan et al.* (2010) study could have operated as a simultaneous masker in the FM-alone condition, this notched-noise was omitted for experiment 1.

C. Results

As expected, mean masked thresholds across the seven listeners in the SM-alone conditions increased by about 10 dB for each 10-dB increase in the level of the masker. The slope of the masking function was 1.02 dB/dB. Mean FM spectrum levels at masked threshold across the seven listeners as a function of FM bandwidth¹ for the FM-alone conditions at the four signal levels are shown by the filled

FIG. 1. (Color online) Mean FM spectrum levels required to just mask a 4000 Hz pure tone signal presented at four signal levels across the listeners in experiment 1 and experiment 2 as a function of FM bandwidth in the FM-alone conditions. The filled symbols represent FM spectrum levels from experiment 1, and the solid lines connect the data points. The open symbols represent FM spectrum levels from experiment 2, and the dotted lines connect the data points from this experiment. The values next to the corresponding symbols show masked threshold in the SM-alone conditions in experiments 1 and 2.

symbols and solid lines in Fig. 1. Throughout this paper, error bars show ± 1 standard error across listeners. The values next to the symbols show masked threshold in the SM-alone conditions, which were subsequently used as the signal presentation levels for the FM conditions. As FM bandwidth increased, FM spectrum level required to mask a fixed-level signal decreased, as would be expected given the equivalent rectangular bandwidth of the auditory filter of approximately 460 Hz at 4000 Hz (*Glasberg and Moore, 1990*). A three-way within-subjects analysis of variance (ANOVA) showed significant main effects of both SM level [$F(3, 20.6) = 130.27, p < 0.001$] and FM bandwidth [$F(3, 11.9) = 101.40, p < 0.001$] on FM spectrum level. A significant interaction was observed between SM level and FM bandwidth [$F(9, 27.4) = 3.85, p = 0.003$]. At each SM level, significant differences in FM spectrum level were observed between the SIN FM-alone conditions and all other bandwidth conditions ($p < 0.001$).

Figure 2 shows the mean additional masking across the seven listeners as a function of FM bandwidth for the SM+FM conditions (filled symbols). The values next to the filled symbols in the key represent masked threshold in the SM-alone conditions for experiment 1. Additional masking in the combined conditions (i.e., masked threshold in SM+FM—masked threshold in SM alone) increased as a function of increased masker level and decreased as a function of masker bandwidth. At the lowest presentation levels (25.1 dB SPL conditions) of broadband masker combinations (BBN SM + BBN FM), additional masking of 2.7 dB was consistent with linear energy summation. At the highest presentation levels (55.6 dB SPL conditions), the BBN SM +

FIG. 2. (Color online) Mean amounts of additional masking as a function of FM bandwidth for the SM+FM conditions in experiments 1 (filled symbols) and 2 (open symbols). The values next to the symbols represent masked threshold in the SM-alone conditions. Regression lines represent the best linear fit to the data points for corresponding conditions as a function of bandwidth. The error bars represent standard error across listeners.

BBN FM produced additional masking of 6.1 dB. At the lowest presentation levels, a broadband simultaneous masker combined with a sinusoidal forward masker (BBN SM + SIN FM) produced additional masking consistent with energy summation, 3.5 dB, while at the highest presentation levels, this combination produced 17.1 dB of additional masking. The sinusoidal FM was not a special case. The OBN and NBN FMs in combination with the BBN SM produced additional masking that fell on a regression line that was linear with log bandwidth. An analysis of variance (ANOVA) showed significant main effects of SM level [$F(3, 20.3) = 15.75, p < 0.001$] and FM bandwidth [$F(3, 10.7) = 18.75, p < 0.001$].² Additionally, a significant interaction between SM level and FM bandwidth was observed [$F(9, 27.7) = 6.34, p < 0.001$]. At the two lowest SM levels, 30 and 40 dB SPL, no significant differences in additional masking were observed across bandwidths. At the 50 dB SPL SM level, significant differences in additional masking were observed between the SIN FM+BBN SM combined conditions and each other FM bandwidth (BBN, $p < 0.001$; OBN, $p < 0.001$; NBN $p = 0.001$). At the 60 dB SPL SM level, significant differences in additional masking were observed between the SIN FM+BBN SM combined conditions and each other FM bandwidth (BBN, $p < 0.001$; OBN, $p < 0.001$; NBN $p = 0.009$), as well as between the BBN FM+BBN SM and NBN FM+BBN SM conditions ($p = 0.009$).

D. Discussion

The debate about which mechanisms contribute to additional masking when two or more maskers are combined began decades ago (e.g., Bilger, 1959), before cochlear

compression had been observed. Notably, as proposed by Green (1967), disruption of parallel spectral and temporal cues may explain some of the additional masking that occurs when maskers are combined. In the BBN SM-alone conditions, a listener's detection cues may include a within-filter increase in energy at the place of the signal frequency (Green, 1967), across-channel comparisons of intensity, typically referred to as "spectral profile" (Green, 1983), or subtle changes in the temporal properties of the stimulus (Berg, 2004; Moore, 1975; Richards and Nekrich, 1993). Masking in the FM-alone conditions is assumed to occur as a result of masker persistence or neural adaptation (Oxenham, 2001). Both forward masking mechanisms are frequency selective, and off-frequency listening (Leshowitz and Wightman, 1972; O'Loughlin and Moore, 1981) can impact results. Off-frequency listening refers to the use of cues that are not at the place of the signal frequency, as a result of spread of excitation along the basilar membrane that increases with presentation level. Off-frequency listening can distort the results observed in studies of additivity of masking by playing a bigger role in FM-alone conditions than when both the simultaneous and forward masker are present.

O'Loughlin and Moore (1981) found an effect of off-frequency listening in the presence of a forward masker when measuring psychophysical tuning curves (PTCs). Subsequently, to limit off-frequency listening in forward masker paradigms a notched noise has been presented in adjacent frequency regions above and below the signal frequency (Oxenham and Plack, 1997; Grogan *et al.*, 2010). Experiment 2 implemented a notched noise identical to that used by Grogan *et al.* (2010) to examine the effects of off-frequency listening on forward masker level. Any contribution to the forward masker level needed to just mask the signal that was likely a direct result of off-frequency listening was determined by comparing the results for experiments 1 and 2. Additionally, indirect contributions of off-frequency listening to additional masking were assessed by examining differences in forward masker level between the two experiments that resulted in changes of additional masking.

III. EXPERIMENT 2: EFFECTS OF OFF-FREQUENCY LISTENING ON FORWARD MASKER SPECTRUM LEVEL AND ADDITIONAL MASKING

A. Listeners

Seven adult listeners (3 males, 4 females) participated in experiment 2. Listener age ranged from 21 to 32 yr. Four of the seven listeners had participated in experiment 1.

B. Methods

Experiment 2 examined the effect of a notched noise (NN) on masked threshold in the FM-alone conditions. A notched noise, high-pass filtered from 4468 to 20 000 Hz and low-pass filtered from 3532 to 20 Hz, including 5-ms onset and offset raised-cosine ramps, was presented to the test ear at a level 25 dB below the signal presentation level during the entire 300-ms interval in the NN+FM-alone conditions. Other than the addition of the notched noise in the NN+FM-

alone conditions, the procedure for experiment 2 was identical to that for experiment 1.

C. Results

As in experiment 1, mean masked thresholds across the seven listeners in the SM-alone conditions increased by about 10 dB for each 10-dB increase in masker level. The slope of the masking function was 1.11 dB/dB. Since the SM-alone conditions were not repeated for the four listeners who participated in experiment 1, the slight increase in the slope of the function can be attributed to the data from the three listeners who were not identical between the two experiments. Figure 1 compares mean FM spectrum levels resulting in masked threshold across the seven listeners as a function of FM bandwidth for the FM-alone conditions at the four signal levels in experiment 1 (filled symbols) and experiment 2 (open symbols). An ANOVA using repeated measures to examine effects of level and bandwidth on FM spectrum level in experiments 1 and 2 showed no significant main effect of presence vs absence of Notched Noise ($p=0.287$). Significant main effects of SM level [$F(3, 140)=489.88, p<0.001$] and FM bandwidth [$F(3, 140)=248.14, p<0.001$] were observed, as well as significant interactions between Notched Noise condition and SM level [$F(3, 82)=11.03, p<0.001$] and Notched Noise condition and FM bandwidth [$F(3, 82)=2.77, p=0.047$]. Significant differences between Notched Noise conditions at a given SM level were only observed at the highest SM level, 60 dB SPL [$F(1, 17.6)=16.25, p<0.001$].

Figure 2 shows the mean amount of additional masking across the seven listeners as a function of FM bandwidth for the SM+FM conditions in experiments 1 (filled symbols) and 2 (open symbols). Across experiments 1 and 2, significant main effects of both SM level [$F(3, 133)=22.39, p<0.001$] and FM bandwidth [$F(3, 131)=24.28, p<0.001$] were observed. Additionally, significant interactions between SM level and both Notched Noise condition [$F(3, 103)=11.97, p<0.001$] and FM bandwidth [$F(9, 131)=2.81, p=0.005$] were observed. At the highest presentation levels (55.6 dB SPL condition from experiment 1 and 58.4 dB SPL condition from experiment 2), the inclusion of a notched noise significantly reduced the amount of additional masking for all four FM bandwidths ($p<0.001$). No significant reductions in additional masking were observed for any of the lower presentation levels. An ANOVA assessing additional masking in experiment 2 alone showed a significant main effect of FM bandwidth [$F(3, 11.1)=12.22, p<0.001$]; however, no significant main effect of SM level was observed [$F(3, 20.5)=2.24, p=0.1139$]. Additionally, no significant interaction between SM level and FM bandwidth was observed [$F(9, 27)=1.76, p=0.1242$]. At the two lowest SM levels, 30 and 40 dB SPL, no significant differences in additional masking were observed across bandwidths. At the 50 dB SPL SM level, significant differences in additional masking were observed between the SIN FM+BBN SM combined conditions and the OBN FM+BBN SM combined conditions ($p=0.021$). At the 60 dB SPL SM level, significant differences in additional masking were observed between the SIN

FM+BBN SM combined conditions and both the OBN FM+BBN SM ($p<0.001$) and NBN FM+BBN SM ($p=0.029$) combined conditions.

D. Discussion

At high signal levels, off-frequency listening may have increased forward masker spectrum levels in the FM-alone conditions. This could lead to an increase in the amount of additional masking because off-frequency listening would not be available in the combined masker condition. The differences were small, however, and only occurred at high levels. Additional masking still exceeded predictions of linear summation when the FM-alone conditions included a notched noise. As observed in experiment 1, additional masking in the combined conditions increased as a function of increased masker level and decreased as a function of masker bandwidth among the three lowest presentation levels. Surprisingly, however, the amount of additional masking did not increase from the third to the fourth masker level at any of the masker bandwidths. The basilar membrane is assumed to be maximally compressive between input levels of 40–80 dB SPL (Ruggero *et al.*, 1997). The two highest signal presentation levels (46.6, 58.8 dB SPL) would have entered this compressive region of the input-output function, while the two lowest presentation levels (25.3, 35.4 dB SPL) would have likely been processed more linearly. The fact that the additional masking in this combined condition was the same at the two highest presentation levels, even though both simultaneous and forward masker levels were approximately 10 dB higher in the 60 dB SPL SM condition, suggests that there is a link between compression and additional masking.

Both a power law (Lutfi, 1983) and modified power law (MPL) (Humes *et al.*, 1988; Humes and Jesteadt, 1989) non-linearity predict additional masking in combined masker conditions. Humes and Jesteadt (1989) applied the MPL in conditions where the stimulus components overlapped in time and frequency. Oxenham and Moore (1994, 1995) argued that stimuli would need to be processed independently before their effects were combined for compression to result in additional masking, ruling out most situations involving simultaneous maskers. When the signal and maskers are entirely sequential with no temporal overlap, representations of each stimulus component may be independently compressed before combining with the representations of other components. When stimulus components occur simultaneously and in the same spectral domain, it is difficult to see how they would undergo separation and independent compression before they are once again combined. The same problem exists when portions of the stimulus components occur sequentially and portions occur simultaneously (e.g., combination of a simultaneous masker, forward masker, and a signal). Compression of the forward masker could occur independently of the simultaneous masker, but the simultaneous masker and the signal could not be processed independently. Even if that problem could be resolved, it is difficult to see how the Oxenham and Moore (1994) model could account for the effects of bandwidth on the

amount of additional masking observed in the first two experiments.

The increase in both forward masker spectrum level and additional masking as a function of decreased bandwidth in experiments 1 and 2 suggests that the forward masker level is important and needs to be isolated as a variable when assessing additional masking. One way to examine the effects of forward masker level while holding the amount of masking constant is to keep the signal level constant while increasing the temporal gap between the offset of the forward masker and the onset of the signal in the FM-alone conditions. In this way, increased forward masker levels are necessary to just mask a constant-level signal. In the theoretical framework used to estimate compression from the additional masking produced by sequential forward maskers, it is signal level rather than forward masker level that determines the amount of additional masking observed in the combined conditions.

To further examine the effects of signal delay and consequent forward masker level in these combined conditions, experiment 3 held the initial amount of masking constant and measured additional masking as a function of signal delay and masker bandwidth. In this case, the contribution of increased forward masker level to additional masking was examined while the simultaneous masker level was held constant at 40 dB SPL. Because preliminary analysis of experiments 1 and 2 did not reveal a significant effect of including a notched noise at the three lower presentation levels (30, 40, 50 dB SPL SM conditions), we omitted the notched noise for experiment 3 to avoid any additional simultaneous masking effects that the notched noise may have contributed.

IV. EXPERIMENT 3: EFFECTS OF SIGNAL DELAY AND FORWARD MASKER BANDWIDTH ON ADDITIONAL MASKING

A. Listeners

Seven adult listeners (3 males, 4 females) participated in experiment 3. Four of the seven participated in experiments 1 and 2.

B. Methods

In the SM-alone condition, masked thresholds were found in the presence of a BBN SM fixed at 40 dB SPL. FM levels required to mask the fixed-level signal were determined for each FM bandwidth used in the two previous experiments at signal delays of 3, 6, 12, and 24 ms. The procedures for finding equated masker levels of FM and SM and for measuring masked threshold in the combined conditions were identical to those for experiment 1.

C. Results

In experiment 3, the amount of simultaneous masking was constant in all conditions, but the amount of additional masking increased as FM bandwidth decreased and as signal delay and FM level increased. Figure 3 shows FM spectrum level as a function of FM bandwidth. An expected increase in masker spectrum level was observed for an increase in signal delay beyond 6 ms for all four FM bandwidths. As

FIG. 3. (Color online) Mean FM spectrum levels required to just mask a 4000 Hz pure tone signal presented at 35.1 dB SPL and at four different signal delays (24, 12, 6, and 3 ms) across the seven listeners as a function of FM bandwidth in the FM-alone conditions (experiment 3).

observed in experiments 1 and 2, FM spectrum level was significantly higher for the SIN FM-alone conditions than for the other bandwidths at all signal delays ($p < 0.001$ for all comparisons except OBN vs SIN at the 24-ms delay, where $p = 0.004$). An ANOVA showed significant main effects of signal delay [$F(3, 8.10) = 15.66, p = 0.001$] and FM bandwidth [$F(3, 8.09) = 106.13, p < 0.001$], but no significant interaction ($p = 0.118$).

Figure 4 shows additional masking in the combined conditions as a function of bandwidth. For the BBN and OBN FM combinations with BBN SM, additional masking ranged

FIG. 4. (Color online) Mean amount of additional masking at four different signal delays (24, 12, 6, and 3 ms) across the seven listeners as a function of FM bandwidth for the SM+FM conditions (experiment 3). Regression lines represent the best linear fit to the data points for corresponding conditions as a function of bandwidth.

from 2.9 to 5.6 dB across signal delays. For the NBN and SIN FM combinations with BBN SM, additional masking ranged from 4.6 to 7.7 dB for the 3 ms delay and 7.6 to 10.7 dB for the 24 ms delay. An ANOVA showed significant main effects of signal delay [$F(3, 11.2) = 4.06, p < 0.035$] and FM bandwidth [$F(3, 19.6) = 12.54, p < 0.001$]; however, no significant interaction was observed ($p = 0.424$). Additional masking for the 3-ms delay was significantly different than for the 24-ms conditions across FM bandwidths ($p = 0.039$). Across signal delays, additional masking for SIN FM+BBN SM combined conditions was significantly different from that for the other combined conditions (BBN, $p < 0.001$; OBN, $p < 0.001$; NBN, $p = 0.025$); however, differences among the other bandwidths (BBN vs OBN vs NBN) were not significant.

D. Discussion

The differences in additional masking as a function of signal delay and forward masker bandwidth suggest that forward masker level influences the amount of additional masking independent of any change in signal level or in the amount of masking produced by individual maskers. Current mechanistic models (e.g., Oxenham and Moore, 1994, 1995) predict that additional masking will vary with signal level at masked threshold but will not be influenced by the level of the maskers. Compression is not a possible contributor to this additional masking when the signal and/or one or more maskers overlap in time and in frequency because they are processed by the peripheral auditory system at the same time and place, and therefore, cannot be compressed independently. Lutfi (1990) has proposed a model of the additivity of masking that assumes that the effects of individual maskers are a result of both energetic and informational masking and that these effects add differently when maskers are combined. Energetic masking is assumed to add as energy, and informational masking is assumed to add in dB units approximating amounts of masking. The proportions of informational and energetic masking determine the observed amount of additional masking. Compression of one or both maskers might also play a role, but this model does not require an assumption of independent processing to account for additional masking. To account for the current data in terms of such a model, it would be necessary to assume a higher proportion of informational masking for forward maskers with narrower bandwidths and longer signal delays. It is not clear why that would be the case. In the FM-alone conditions, signal delay and forward masker bandwidth interacted to determine the spectrum level required to mask the signal, but in the combined masker conditions, the lack of a significant interaction between bandwidth and delay suggests that they functioned independently in determining the amount of additional masking.

Differences in additional masking have been observed previously when the temporal relationship between a forward masker, a signal, and a backward masker were varied. When measuring thresholds for a 4000 Hz sinusoid in the presence of white noise forward and backward maskers in isolation and in combination, Oxenham and Moore (1995)

observed an increase in additional masking with increasing delay between the offset of the forward masker and the onset of the signal. The authors had previously developed a model that predicted signal thresholds for the combined conditions using a weighting function that was subjected to a non-linearity before integration (Oxenham and Moore, 1994). This weighting function was applied to a temporal window (e.g., Moore *et al.*, 1988) that was determined by estimates of the slopes and time constants for recovery from both backward and forward masking. Their results suggested that the growth of additional masking was more rapid when the temporal gap between the forward masker and the signal was 25 ms, than when it was 10 ms or 5 ms, an effect similar to that observed here. They accounted for this result in terms of the properties of the temporal window and concluded that the effect of signal delay was consistent with the compressive transfer function of the normal cochlea.

As noted by Humes and Jesteadt (1989), when using multiple temporally overlapping maskers, it is important to determine effects of suppression between the maskers (inter-masker suppression) when determining masked threshold. Additionally, because the Oxenham and Moore model suggested that differences in additional masking are directly influenced by whether or not the stimulus components are processed independently or in combination, it is worth exploring whether the BBN simultaneous masker contributes to additional masking by interacting with the forward masker during the presentation of the forward masker or by interacting with the signal. To examine this question of masker interaction, experiment 4 presented a BBN masker that temporally overlapped with either the forward masker or the signal. Only the sinusoidal forward masker was used because the greatest additional masking was observed for the sinusoidal forward masker in the earlier experiments.

V. EXPERIMENT 4: EFFECTS OF VARYING THE TEMPORAL POSITION OF THE SIMULTANEOUS MASKER

A. Listeners

Five adult listeners (3 males, 2 females) participated in experiment 4. Listener age ranged from 23 to 32 yr. One listener (the first author) participated in all of the previous experiments. Three listeners participated in experiment 1, and one of those participated in experiment 2.

B. Methods

To examine the effect of the BBN SM on forward masking, a control experiment was designed so that the broadband “simultaneous masker” was temporally aligned with either the signal alone (BBN_{sig}) or the sinusoidal forward masker alone (BBN_{fm}). The BBN_{sig} masker was 50 ms in duration, including 5 ms onset and offset raised-cosine ramps, and offset from the beginning of the test interval by 250 ms. The BBN_{fm} was 250 ms in duration, including 5 ms onset and offset raised-cosine ramps, and began at the initiation of the test interval. In the combined BBN_{fm}+SIN FM conditions, the BBN masker became a second forward masker.

In the BBN_{sig} -alone conditions, a 4000 Hz sinusoidal signal was adaptively varied in level to find masked threshold in the presence of the BBN_{sig} masker fixed at 40 dB SPL. Signal starting level was 20 dB above the overall noise level. In the FM-alone conditions, the procedure for finding masked threshold in the presence of the SIN FM was identical to the procedure used in experiment 1. After finding equated masked thresholds for the same signal level using the BBN_{sig} and the SIN FM, masked threshold was measured in the combined condition with an identical procedure to the one used in experiment 1 (e.g., $\text{BBN}_{\text{SM}} + \text{SIN FM}$). Because the goal in the BBN_{fm} conditions was to assess the effect of the BBN “simultaneous masker” on the forward masker, masker levels used in the BBN_{fm} condition were the same as those used in the $\text{BBN}_{\text{sig}} + \text{SIN FM}$ condition. Masked threshold was measured in the $\text{BBN}_{\text{fm}} + \text{SIN FM}$ condition using identical procedures to those for the previous combined condition.

Again, in the FM-alone and the $\text{BBN} + \text{FM}$ conditions, a contralateral masker made up of a $\frac{2}{3}$ -octave noise band (3175–5040 Hz) centered at 4000 Hz was presented to the right ear (non-test ear) at 40 dB below the signal presentation level to mask possible crosstalk.

C. Results and discussion

Approximately 8.8 dB of additional masking was observed in the $\text{BBN}_{\text{sig}} + \text{SIN FM}$ combined conditions; whereas 3.6 dB of additional masking was observed in the $\text{BBN}_{\text{fm}} + \text{SIN FM}$ combined conditions. Additional masking of 7.7, 7.5, and 6.6 dB was found in the analogous conditions in experiments 1, 2, and 3, respectively. While the simultaneous and forward maskers may interact throughout the interval, the portion of the simultaneous masker that makes the greater contribution to additional masking is the part that overlaps with the signal. Any suppression of either masker by the other should have reduced the amount additional masking observed in experiments 1, 2, and 3 compared to that of the $\text{BBN}_{\text{sig}} + \text{SIN FM}$ combined conditions in experiment 4. A reduction in additional masking was not observed, supporting the argument that “stimulus independence” is most important when considering the effects of both maskers at the time of the signal presentation, in this instance. That is, the amount of additional masking does not change depending on whether or not the BBN simultaneous masker and the forward masker overlap in time. However, the overall amount of additional masking is substantially reduced when the BBN masker and the signal do not overlap in time.

The 3.6 dB of additional masking observed in the $\text{BBN}_{\text{fm}} + \text{SIN FM}$ condition is similar to that obtained by [Neff and Jesteadt \(1983\)](#) for equated NBN and SIN forward maskers, although the BBN_{fm} masker was presented at the level of the BBN_{sig} masker and was thus less effective than the SIN FM. The use of unequated maskers should have resulted in less additional masking. The effect is small, however, and it would be difficult to investigate it further.

VI. GENERAL DISCUSSION

As discussed previously, in addition to off-frequency listening, disruption of parallel spectral and temporal cues

may explain some of the additional masking from the current study. In the presence of a broadband forward masker, a listener may have access to similar cues as in the SM-alone conditions, leading to little additional masking in combined conditions due to few differences in detection cues. However, as bandwidth of the forward masker decreases, across channel comparisons of phase or spectral profile cues that were useful in the presence of a broadband noise may become disrupted and less available to a listener, requiring use of other cues in the forward masking task. In the combined conditions, the simultaneous masker may make those cues less effective. This is a variation on the original account of non-additivity proposed by [Green \(1967\)](#). [Lutfi's \(1990\)](#) model provides an alternative account of additional masking but requires assumptions about changes in the proportion of informational masking across conditions that are difficult to justify.

Differences in the effectiveness of forward maskers as a function of bandwidth are sometimes attributed to confusion effects, where the signal is above threshold but is perceived as a continuation of the forward masker ([Neff, 1986](#)). This confusion occurs most often with NBN forward maskers at relatively short signal delays. [Neff and Jesteadt \(1983\)](#) found that an NBN forward masker (60-Hz BW centered on 1000 Hz, 70 dB SPL total power) produced 20 dB more masking than a 1000 Hz sinusoidal forward masker of equal power, but the difference was reduced to 4 dB when a noise was presented to the contralateral ear and temporally aligned with the forward masker. Approximately 3 dB of additional masking was observed for equated NBN and SIN forward maskers in the presence of the cue, but no additional masking was observed in the absence of the cue, presumably because the maskers were not truly equated in that condition. It seems unlikely that confusion effects contributed to the pattern of additional masking observed here, where additional masking varied systematically with both bandwidth and signal delay. To test for the presence of a confusion effect, three subjects who had been tested in one or more of the four experiments were retested in a condition with a 40 dB SPL simultaneous masker, a 6-ms signal delay, and no notched noise surrounding the signal. The forward masker was either BBN or NBN, presented binaurally. If confusion effects were present in the original NBN conditions, forward masker levels at threshold in the FM-alone conditions should have been lower for NBN, but presumably not for BBN . Comparing the binaural results to those of experiment 1, the mean forward masker levels at threshold for the three subjects were 31.2 dB in the NBN binaural condition, compared to 32.0 dB for the same subjects from the monaural condition. The corresponding values for the BBN forward masker were 50.6 dB for binaural and 47.3 dB for monaural. In the NBN conditions, 7.0 dB of additional masking was observed in the monaural condition, and 7.8 dB of additional masking was observed in the binaural condition. Mean additional masking of 4.8 dB was observed for these three listeners in both the BBN monaural and binaural conditions. Since release from masking was not observed for the binaural forward masker relative to the monaural forward masker, confusion effects were not likely substantially contributing to

masked threshold in either the FM-alone or the combined conditions in the four experiments discussed here.

To more closely assess similarities between the results from the current study, and the results from [Gregan *et al.* \(2010, 2011\)](#), data points were examined from the [Gregan *et al.*](#) studies that represented threshold measurements in the presence of one or two forward maskers and either the presence or absence of TEN. When adaptively varying the level of an on-frequency sinusoidal forward masker to find masked threshold of a signal fixed at 44.9 dB SPL, [Gregan *et al.* \(2010\)](#) found that the presence of TEN with a level of 20 dB SPL within the equivalent rectangular bandwidth of an auditory filter (ERB_N) centered around 1000 Hz ([Moore *et al.*, 2000](#)) required a forward masker to be 7.1 dB less intense (36.6 dB SPL) than a forward masker in quiet (43.7 dB SPL) to achieve masked threshold. Similarly, achieving masked threshold at a fixed signal level of 54.8 dB SPL required a forward masker to be 5.2 dB less intense (45.2 dB SPL) in the presence of 30 dB TEN than a forward masker in quiet (50.4 dB SPL). These comparisons are for conditions where the signal level at threshold was held constant and the level of the forward masker required to mask the signal was varied. The results are consistent with the current study and can be considered as the equivalent of additional masking in that a lower level of the forward masker was required in the presence of the TEN. As in the present study, this additional masking suggests that the presence of the TEN is either shifting the amount of masking provided by the forward masker or that the forward masker is altering the effect of the TEN. In [Gregan *et al.* \(2011\)](#), removing the TEN in their experiment 2 (high level) reduced masked thresholds in the presence of the same spectrum level of M1 (200-ms, octave-band Gaussian noise) by 1.7–5.5 dB and by 1.6–7.0 dB for M2 (6-ms, octave-band Gaussian noise). In the absence of TEN, additional masking observed for combinations of M1 and M2 increased by as much as 5.0 dB. Although the differences in compression estimates obtained with and without TEN were not statistically significant, the effect of TEN on M1 and M2 masked thresholds was consistent with effects reported here.

Although [Gregan *et al.* \(2010\)](#) asserted that behavioral estimates of basilar membrane compression using the GOM technique were not significantly affected by simultaneous TEN, the non-additive effects of the combined maskers in their data may have been partially accounted for by masker interactions while using sinusoidal forward maskers in conjunction with simultaneous presentation of TEN. The reduction in compression estimates seen in [Gregan *et al.* \(2011\)](#) while using OBN sequential forward maskers may have been partially due to the increased bandwidth of the forward maskers, compared to the sinusoidal forward maskers used in the GOM technique ([Gregan *et al.*, 2010](#)).

Regardless of the mechanisms underlying the increase in additional masking, the results of the current study suggest that forward masker bandwidth may have significant effects in a combined masker experiment using simultaneous broadband noise in the presence of one or more forward maskers, and that these maskers interact at the time of the signal. As bandwidth of the forward maskers increased,

additional masking in these combined conditions decreased. While further efforts to compare estimates of basilar membrane non-linearity in noise-masked normal hearing and hearing impaired listeners are clearly important, this bandwidth effect may limit the efficacy and the validity of using broadband noise in normal hearing listeners when making measurements of this kind. Namely, if a BBN simultaneous masker combines linearly with a BBN forward masker but combines nonlinearly with a NBN or SIN forward masker, the interaction of the forward masker with this simultaneous noise will likely contaminate any extrapolated compression estimates when using different behavioral methods (e.g., GOM vs AFM).

The current results pose a more significant problem for use of the AFM paradigm to estimate compression from observed additional masking in that the model proposed by [Oxenham and Moore \(1994, 1995\)](#) cannot be applied to these masker combinations. The highly systematic results are difficult to account for with a combination of cues, as proposed by [Green \(1967\)](#), and suggest that forward masker level is an important variable independent of the signal level. It is possible, of course, to assume that additional masking observed in the AFM paradigm reflects compression while the additional masking observed here reflects other processes.

VII. CONCLUSIONS

- (1) The results of the current study, [Gregan *et al.* \(2010, 2011\)](#), and [Jesteadt *et al.* \(1996\)](#) suggest that forward masker bandwidth has significant effects in a combined masker experiment using simultaneous broadband noise in the presence of one or more forward maskers, and that the portion of the simultaneous masker that makes the greater contribution to additional masking is the part that overlaps with the signal.
- (2) Although off-frequency listening and confusion effects often play a role in signal detection when measuring masked thresholds for narrowband forward maskers, the conditions controlling for these cues in the current study suggest that some other mechanisms were contributing to masked threshold in all of the experiments discussed.
- (3) Comparing estimates of basilar membrane non-linearity in normal hearing and hearing impaired listeners remains important; however, the observed bandwidth effect may seriously confound efforts using broadband noise to simulate a hearing loss in normal hearing listeners while using forward maskers to obtain estimates of compression.

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¹The 200-ms sinusoid was assumed to have a bandwidth of 5 Hz for purposes of specifying masker spectrum level. An FFT of the waveform including onset and offset ramps resulted in an equivalent rectangular bandwidth of 5.04 Hz.

²The degrees-of-freedom calculations in this paper are detailed by Kenward and Roger (1997). The Kenward–Rogers option in SAS Proc Mixed is specifically intended to be used in conjunction with any repeated measures ANOVA model having correlated observations (e.g., repeated measures), with the same or different number of observations per subject.

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