Effects of inherent envelope fluctuations in forward maskers for listeners with normal and impaired hearing^{a)}

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Gaussian noise simultaneous maskers yield higher masked thresholds for pure tones than low-fluctuation noise simultaneous maskers for listeners with normal hearing. This increased masking effectiveness is thought to be due to inherent fluctuations in the temporal envelope of Gaussian noise, but effects of fluctuating forward maskers are unknown. Because differences in forward masking due to age and hearing loss are known, the current study assessed effects of masker envelope fluctuations for forward maskers in younger and older adults with normal hearing and older adults with hearing loss. Detection thresholds were measured in these three participant groups for a pure-tone probe in quiet and in Gaussian and low-fluctuation noise forward maskers with either 1 or 1/3 equivalent rectangular bandwidths. Higher masked thresholds were obtained for forward maskers with greater inherent envelope fluctuations for younger adults with normal hearing. This increased effectiveness of highly fluctuating forward maskers was similar for older adults with normal and impaired hearing. Because differences in recovery from forward masking between listeners with normal and impaired hearing may relate to differences in cochlear nonlinearities, these results suggest that mechanisms other than cochlear nonlinearities may be responsible for recovery from rapid masker envelope fluctuations. © 2015 Acoustical Society of America.

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I. INTRODUCTION

A. Effects of masker fluctuations on recognition and detection

The most commonly reported complaint of listeners with hearing loss is difficulty understanding speech in the presence of background noise. Differences in masked speech recognition in noise between listeners with normal hearing (NH) and listeners with sensorineural hearing loss (HI) are larger when the noise is fluctuating in amplitude (e.g., Bacon *et al.*, 1998; Jin and Nelson, 2006). In amplitude-modulated noise, NH listeners can take advantage of the better signal-to-noise ratio provided by brief reductions in the level of the noise to improve speech understanding compared to that in steady-state Gaussian noise (GN) (Bacon *et al.*, 1998; Dubno *et al.*, 2003; Jin and Nelson, 2006). This improvement, or masking release, is smaller for HI than for NH listeners, even those with mild hearing loss (e.g., Dubno *et al.*,

2002), but the factors that contribute to the reduction in masking release for HI listeners remain unclear.

While amplitude-modulated maskers with relatively low modulation frequencies generally result in improvements in speech recognition relative to that in steady-state maskers, maskers with rapid temporal envelope modulations, or fluctuations, may not improve performance. For example, Stone *et al.* (2012) showed that inherent rapid envelope fluctuations within Gaussian noise can decrease speech recognition for NH listeners as compared to performance in a noise with minimal envelope fluctuations, such as a “low-noise noise” (Pumplin, 1985), referred to here as “low-fluctuation noise” (LFN). The authors concluded that masking release defined in the traditional way is primarily related to a brief cessation of “modulation masking” and less related to reductions in “energetic masking.”

Energetic masking refers primarily to an increase in the energy of an unmodulated masker that falls within the pass-band of the auditory filter(s) that is processing the signal, which yields an increase in masked threshold (e.g., Green and Swets, 1966). In contrast, modulation masking refers to the effect of a masker’s amplitude modulations on detection of an amplitude-modulated signal when the masker and signal are in close spectral proximity or are applied to the same carrier frequency (e.g., Bacon and Grantham, 1989).

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Modulation masking describes any increase in masked threshold observed for modulated masker conditions relative to unmodulated masker conditions.

Although the term modulation masking is typically reserved for situations in which both the signal and the masker are amplitude modulated, rapid masker envelope fluctuations have also been shown to affect detection of unmodulated pure-tone signals. Savel and Bacon (2003) measured masked detection thresholds for a 4000-Hz pure tone (10 or 200 ms) in the presence of three simultaneous maskers: Gaussian noise, low-fluctuation noise (Kohlrausch *et al.*, 1997), or a pure tone. The bandwidth of each noise masker was 500 Hz, and each masker was placed either lower or higher in frequency than the signal (e.g., 3053–3553 or 4500–5000 Hz); the pure-tone masker was either 3553 or 4500 Hz. Gaussian noise produced substantially more masking than low-fluctuation noise or pure-tone maskers, and low-fluctuation noise and pure tones produced comparable amounts of masking. Similar to the conclusions of Stone *et al.* (2012) related to modulation masking, Savel and Bacon (2003) proposed that the rapid fluctuations in the temporal envelope within the Gaussian noise were responsible for its increased masking effectiveness. For fluctuating maskers, the amount of fluctuation can be quantified by the crest factor or the ratio between peak amplitude and the root-mean-square (rms) amplitude within the temporal envelope of the waveform (e.g., Hartmann and Pumplin, 1988). Crest factors provide an estimate of the relationship between the power in the peaks of the amplitude fluctuations compared to the overall energy of the noise. In the current study, noises described as having “maximal” fluctuations have relatively high crest factors, whereas noises described as having “minimal” fluctuations have relatively low crest factors.

Hartmann and Pumplin (1988) suggested that for masker bandwidths exceeding a critical band, the envelope of a low-fluctuation noise masker will no longer be flat, and its masking properties will mirror those of Gaussian noise. To test this notion, Kohlrausch *et al.* (1997) measured masked detection thresholds for pure-tone probes centered at 1000 and 10 000 Hz in the presence of either Gaussian noise or low-fluctuation noise simultaneous maskers with a range of bandwidths. The results were consistent with the views of Hartmann and Pumplin (1988) in that differences in masked thresholds between Gaussian noise and low-fluctuation noise were maximal (GN > LFN) when the bandwidth of the two maskers was 25–50 Hz, which is approximately one-third of an equivalent rectangular bandwidth (ERB, Glasberg and Moore, 1990), an estimate of auditory filter width that is comparable to the notion of a critical band. Wider and narrower masker bandwidths yielded smaller masked threshold differences between Gaussian noise and low-fluctuation noise. As such, differences between rapid masker envelope fluctuations are expected to be maximal (GN > LFN) when the bandwidth of the two maskers is $\sim 1/3$ ERB or sufficiently within the bandpass of an auditory filter.

B. Effects of fluctuations in forward maskers

Recovery from forward masking refers to the ability to detect a signal at some time point after the offset of a

steady-state masker or the offset of an amplitude peak within a modulated masker. In the current study, a “recovery function” refers to the decrease in masked threshold as a function of the increase in duration between the offset of the masker and the onset of the signal (or masker-signal delay); the rate of change in masked threshold is determined by the slope of the function and the function’s time constant refers to the briefest masker-signal delay that results in a return to the signal’s quiet threshold. The time constant for the recovery function is assumed to depend on neural mechanisms, such as integration and/or adaptation (Oxenham, 2001), whereas the slope of the function is largely driven by intact (NH) or reduced (HI) cochlear nonlinearities (Oxenham and Moore, 1997; Oxenham and Bacon, 2003). In NH listeners, the time constant using a relatively short-duration signal is ~ 200 ms (e.g., Jesteadt *et al.*, 1982; Ludvigsen, 1985). Following the offset of a high-level masker, the slope of the recovery function is relatively steep in NH listeners, but shallower in HI listeners (e.g., Oxenham and Moore, 1997). This decrease in slope with hearing loss is assumed to be due to the reduced dynamic range in HI listeners, which is a consequence of reduced cochlear nonlinearities (Oxenham and Bacon, 2003).

C. Effects of fluctuations in modulated forward maskers

An effect described as analogous to forward masking of audio frequencies has been observed in the modulation masking domain when an amplitude-modulated masker preceded an amplitude-modulated signal applied to the same broadband carrier (Wojtczak and Viemeister, 2005). Extending the findings of Wojtczak and Viemeister (2005) to HI listeners, Koopman *et al.* (2008) presented NH and HI listeners with a 1000-Hz signal carrier and a 2000-Hz masker carrier, both sinusoidally amplitude modulated (SAM) at 8 Hz, including variable masker-signal delays. Results revealed more modulation detection interference for HI than NH listeners when measured at comparable sound pressure levels [dB sound pressure level (SPL)], even when the masker preceded the signal in time (e.g., forward masking). Similar to modulation masking, modulation detection interference describes the disruption of a listener’s ability to detect amplitude modulation of a signal in the presence of an amplitude-modulated masker. In contrast to modulation masking, the term modulation detection interference is used when the maskers and signals are imposed upon separate carriers and are spectrally distant from each other (e.g., Yost and Sheft, 1989).

Taken together, these results suggest that inherent rapid envelope fluctuations within otherwise “steady-state” maskers yield more masking than noises with flatter envelopes, at least in NH listeners, especially when masker bandwidths are less than a critical band (Hartmann and Pumplin, 1985) or an ERB (Kohlrausch *et al.*, 1997). Moreover, if the increased effect of modulated forward maskers observed in HI listeners (Koopman *et al.*, 2008) is relevant for detecting pure-tone signals, HI listeners may be more susceptible to the effects of rapid envelope fluctuations in forward maskers

than NH listeners. If forward maskers with minimal inherent envelope fluctuations result in elevated masked thresholds for HI listeners, relative to NH listeners, then differences in masked thresholds between NH and HI listeners for forward maskers with maximal inherent envelope fluctuations may define recovery from inherent envelope fluctuations that exceed recovery from forward masking.

D. Research questions

To assess sensitivity to inherent masker envelope fluctuations, the current study measured forward-masked detection thresholds for a 4000 Hz pure-tone signal (probe) in narrower and wider bandwidth noises with maximal or minimal inherent envelope fluctuations. To assess effects of age and hearing loss, participants were younger and older adults with normal hearing and older adults with hearing loss. Forward-masked thresholds were measured for four maskers: (1) 1/3 ERB LFN—inherent masker fluctuations are reduced, flattest temporal envelope; (2) 1 ERB LFN—inherent masker fluctuations are reduced, but minor temporal envelope fluctuations are likely created as signals are processed through multiple auditory filters; (3) 1 ERB GN—inherent masker fluctuations are intact, but flatter temporal envelope due to wider masker bandwidth; and (4) 1/3 ERB GN—inherent masker envelope fluctuations are intact and greater due to narrower masker bandwidth.

The experiment was designed to answer two primary research questions. The first question focused on the relationship between inherent masker envelope fluctuations and forward-masked thresholds for younger NH adults. Based on results with simultaneous maskers (Savel and Bacon, 2003; Kohlrausch *et al.*, 1997), we predicted that forward-masked thresholds would be highest in 1/3 ERB GN with maximal inherent masker envelope fluctuations and lowest in 1/3 ERB LFN with minimal inherent masker envelope fluctuations. We further predicted that forward-masked thresholds for the wider bandwidth maskers (1 ERB GN vs LFN) would differ less due to their more similar temporal envelopes.

The second research question focused on the contribution of hearing loss and age on the effectiveness of forward maskers with inherent envelope fluctuations. Based on previous findings related to modulation detection interference with hearing impairment (Koopman *et al.*, 2008), we predicted that threshold differences for the narrower bandwidth maskers (1/3 ERB GN vs LFN) would be larger for HI than for NH listeners. In contrast, based on the absence of age-related differences in forward masking (e.g., Dubno *et al.*, 2003), we predicted no age-related differences in effectiveness of inherent masker envelope fluctuations.

II. METHODS

A. Participants

Twenty-five adult listeners (7 males, 18 females) participated in this experiment. For the younger adults with NH (YNH, $n = 8$, age: 22–30 yr), pure-tone thresholds in the test ear were ≤ 20 dB hearing level (HL) at audiometric frequencies from 250 to 8000 Hz (ANSI, 2004). For the older adults

with NH (ONH, $n = 8$, age: 62–66 yr), pure-tone thresholds in the test ear were ≤ 20 dB HL at audiometric frequencies from 250 to 4000 Hz and ≤ 25 dB HL at audiometric frequencies from 6000 to 8000 Hz. For older adults with HI (OHI, $n = 9$, age: 60–89 yr), pure-tone thresholds were < 50 dB HL at 250, 500, and 1000 Hz, between 25 and 55 dB HL at 2000 and 4000 Hz, and between 25 and 70 dB HL at 8000 Hz. HI listeners with conductive or mixed hearing losses were not eligible for participation. Listeners were compensated for their participation.

The left panel of Fig. 1 contains mean (filled symbols) and individual (dashed lines) pure-tone thresholds in the test ear measured in dB HL (ANSI, 2004) and converted to dB SPL for the three groups of listeners. The test ear was the better ear for all listeners in the YNH and ONH groups. For the OHI listeners, if both ears met the inclusion criteria, the ear with a better threshold at 4000 Hz was chosen for testing. If thresholds were identical at 4000 Hz, the right ear was chosen for testing. The right panel of Fig. 1 contains mean (filled symbols) and individual (open symbols) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 4000-Hz probe. Mean thresholds were 19.7, 25.6, and 59.2 dB SPL for the YNH, ONH, and OHI groups, respectively.

B. Apparatus and stimuli

Each signal was generated at a sampling rate of 44 100 Hz and produced via a MATLAB script file matched with a Lynx TWO-B soundcard, including an A/D and D/A type 24-bit, multi-level delta-sigma converter, and a built-in antialiasing filter with a cutoff frequency of 21 300 Hz. Signals were presented through a Tucker-Davis Technologies (TDT) HB5 headphone buffer driving an ER-5A Etymotic insert earphone. No earphone was placed in the non-test ear. The duration of the 4000-Hz pure-tone probe was 10 ms, including 5-ms raised cosine onset and offset ramps. Each of four 400-ms maskers, including 5-ms raised cosine onset and offset ramps, was centered at 4000 Hz: (a)

FIG. 1. (Color online) Mean (filled symbols) and individual (dashed lines) pure-tone thresholds measured (in dB HL and converted to dB SPL) in the test ear for ~ 250 -ms signals for three groups (left panel). Mean (filled) and individual (open) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 4000-Hz probe for three groups (right panel).

GN with a bandwidth of 463 Hz (1 ERB) and cutoff frequencies of 3775 and 4238 Hz; (b) GN with a bandwidth of 154 Hz (1/3 ERB) and cutoff frequencies of 3924 and 4078 Hz, and (c) two LFNs with bandwidths and cutoff frequencies identical to those of the GNs. Both the GNs and LFNs were generated following a procedure described by Buss *et al.* (2006) that had been adapted from the method for generating LFN developed by Kohlrausch *et al.* (1997). A band of GN centered at 4000 Hz for each bandwidth (463 and 154 Hz) was divided in the time domain by the Hilbert envelope and then multiplied by the original spectral region (463 and 154 Hz wide bands) in the frequency domain. For the LFN, the multiplication was repeated 10 times, resulting in a temporal envelope with minimal inherent fluctuations. To quantify masker fluctuation, peak-to-rms ratios (crest factors, in dB) were calculated for 100 noise samples generated for each of the four maskers; mean crest factors and standard deviations were computed. As expected, mean crest factors were higher for GN than LFN. In addition, standard deviations were much higher for GN than LFN.

Initiation of the masker occurred 50 ms after the beginning of the interval. The probe was presented 25 ms after the offset of the masker. The overall level of the masker was fixed at 80 dB SPL. See Fig. 2 for a schematic of the waveforms for the probe, 1 ERB GN (top), and 1 ERB LFN (bottom). Inside the double-walled, sound-treated booth, a computer monitor displayed the timing of signal presentations; a touchscreen interface was used to record participant responses.

C. Procedures

Detection thresholds for the 10-ms probe at 4000 Hz were measured in quiet using a three-interval forced choice (3IFC) two-up, one-down adaptive psychophysical procedure tracking 70.7% correct on the psychometric function (Levitt, 1971). Each block ceased after 12 reversals. Each trial contained three 600-ms observation intervals, one of which contained the probe, separated by a 500-ms inter-stimulus

interval. Participants received feedback for correct and incorrect responses. The starting level for the probe was 50 dB SPL for NH listeners and 80 dB SPL for HI listeners. Initial step size was 5 dB, changing to 2 dB after the first two reversals. Thresholds were calculated as the mean probe level in dB SPL for the final eight reversals. Mean thresholds for each condition were based on at least three blocks. If the standard deviation of a block exceeded 5 dB, a fourth block was obtained. In these cases, the mean of all four threshold estimates was the final probe threshold. The right panel of Fig. 1 displays probe thresholds measured in quiet. A very similar procedure, with the exception of probe starting levels, was used to determine masked thresholds by keeping the masker level constant at 80 dB SPL and adaptively varying the probe level.

For measuring forward-masked thresholds, a training session was completed before data collection to familiarize listeners with various maskers, using the 1 ERB GN and LFN maskers. During training, the starting level for the probe was 80 dB SPL for the NH listeners and 95 dB SPL for the HI listeners. Once the participant's performance reached a standard deviation of <5 dB within a block, training for that condition ceased. Once data collection for measuring masked thresholds commenced, starting levels for the probe were 20 dB SL re: masked threshold determined during training.

The testing conditions were blocked by masker bandwidth (1 ERB or 1/3 ERB) and masker type (GN or LFN) and randomized by a number assigned to each of the four maskers. Testing did not exceed 4 hr over multiple visits, including informed consent, measurement of audiometric thresholds, training, and data collection. Frequent breaks were offered to participants as needed.

Effects of masker type (LFN, GN) and bandwidth (1/3 ERB, 1 ERB) on forward-masked thresholds were assessed with a repeated-measures analysis of variance (ANOVA) with one grouping variable (YNH, ONH, OHI). Relationships between masked and quiet probe thresholds were evaluated using correlational analyses. Effects were considered significant with $p < 0.05$. The hypotheses predicted main effects for all three factors and an interaction among masker type, masker bandwidth, and participant group. The hypotheses also predicted significant correlations between masked and quiet probe thresholds for all listener groups. However, weaker associations were predicted for maskers with maximal inherent envelope fluctuations than for maskers with minimal inherent envelope fluctuations and for HI listeners due to larger individual differences in masked thresholds using stimuli with fluctuating temporal envelopes (e.g., Eddins, 2001) and among HI listeners (e.g., Jin and Nelson, 2006).

III. RESULTS

As hypothesized, rapid inherent masker envelope fluctuations had a significant effect on forward-masked pure-tone detection. GN yielded significantly higher masked thresholds than LFN for all participant groups [$F(1, 22) = 48.04$, $p < 0.001$] (Fig. 3). Masker bandwidth had a significant

FIG. 2. (Color online) Waveforms showing 400-ms maskers (left) and 10-ms probe (right), for Gaussian noise (GN) (top) and low-fluctuation noise (LFN) (bottom).

FIG. 3. (Color online) Mean (± 1 SE) forward-masked thresholds (in dB SPL) for two forward maskers (GN, filled; LFN, striped) and two masker bandwidths (1/3 ERB and 1 ERB) for three groups.

effect as well. Masked threshold differences between GN and LFN were significantly larger for narrower bandwidth maskers (1/3 ERB GN $\gg$ 1/3 ERB LFN) than for wider bandwidth maskers (1 ERB GN > 1 ERB LFN) [$F(1, 22) = 15.97$, $p < 0.05$], and the effect of bandwidth was greater for LFN than GN across listener groups [$F(1, 22) = 146.06$, $p < 0.05$]. For the 1 ERB bandwidth, mean masked thresholds were 59.5 (YNH), 66.2 (ONH), and 81.5 (OHI) dB SPL for the GN masker and 53.5 (YNH), 59.3 (ONH), and 74.8 (OHI) dB SPL for the LFN masker. Similarly, for the 1/3 ERB bandwidth, mean masked thresholds were 57.6 (YNH), 65.8 (ONH), and 81.9 (OHI) dB SPL for the GN masker and 47.3 (YNH), 51.9 (ONH), and 72.3 (OHI) dB SPL for the LFN masker.

There was no significant effect of listener age. As predicted for the ONH group, pairwise comparisons of the between subjects factor showed that masked thresholds (Fig. 3) and mean differences in masked thresholds (Fig. 4) were not significantly different from those for the YNH group ($p > 0.05$). In contrast, there was a significant effect of hearing loss. Masked thresholds for the OHI group were significantly higher than for the other two groups ($p < 0.001$), which is at least partially due to their elevated probe thresholds. However, contrary to predictions, mean differences in masked thresholds between GN and LFN maskers for OHI

listeners (1 ERB = 6 dB, 1/3 ERB = 10.4 dB) were not significantly different from those for the YNH (1 ERB = 6.6 dB, 1/3 ERB = 9.7 dB) or the ONH (1 ERB = 6.9 dB, 1/3 ERB = 13.9 dB) listeners ($p > 0.05$).

Across all listeners, masked thresholds were highly correlated with quiet probe thresholds (see Fig. 5) ($r = 0.76$ – 0.93 , $p < 0.05$); however, when evaluated within listener groups, these relationships for each masker condition were no longer significant in the OHI group ($p > 0.05$). For both the YNH and ONH groups, small increases in quiet probe thresholds resulted in large increases in masked thresholds especially for the GN maskers. In contrast, masked thresholds remained relatively constant with increases in quiet probe thresholds for listeners with hearing loss, suggesting that the dependence on quiet probe thresholds may be limited for listeners with reduced dynamic ranges at the probe frequency.

IV. DISCUSSION

Results of the current study demonstrate that forward maskers with greater inherent envelope fluctuations (Gaussian noise) yielded higher thresholds than those with reduced inherent envelope fluctuations (low-fluctuation noise) for younger and older normal hearing listeners and older hearing-impaired listeners. These results suggest that the effects of inherent masker envelope fluctuations previously observed in simultaneous masking for pure tones (Kohlrausch *et al.*, 1997; Savel and Bacon, 2003) and speech recognition (Stone *et al.*, 2012) also occur in forward masking. The precise mechanisms responsible for this increased masking are not clear, but they may be explained, in part, by differences in detection cues and modulation masking attributes of Gaussian noise and low-fluctuation noise. Because differences between masked thresholds with maximal and minimal inherent envelope fluctuations obtained from listeners with normal and impaired hearing were similar, cochlear impairment may not affect recovery from masker envelope fluctuations after controlling for recovery from forward masking.

A. Detection cues

To detect a short-duration pure-tone probe in the presence of a simultaneous noise masker, a listener relies on different cues depending on the bandwidth and temporal properties of the masker. In a narrowband noise masker, a listener may be attending to the onset and offset of the probe

FIG. 4. (Color online) Mean (± 1 SE) differences in masked thresholds (in dB) between GN and LFN for each masker bandwidth (1/3 ERB and 1 ERB) for three groups.

FIG. 5. (Color online) Forward-masked thresholds (in dB SPL) for each masker (GN and LFN) and masker bandwidth (1/3 ERB and 1 ERB) plotted against probe thresholds for YNH (squares), ONH (circles), and OHI (triangles) listeners. The lines represent the linear relationship between forward-masked threshold and probe threshold for the corresponding color (online) and listener group (YNH, ONH, OHI, respectively). Within-group correlations are shown next to the corresponding symbols in each panel.

or a change in the temporal envelope to detect the signal (Oxenham, 1998). Variability of inherent fluctuations in the temporal envelope of the stimuli disrupts these envelope-based cues and increases listener uncertainty more for a Gaussian noise than for a low-fluctuation noise masker (Buss *et al.*, 2006; Eddins, 2001).

In forward masking, the reduction in temporal envelope fluctuations associated with a low-fluctuation noise masker may increase the change in the overall temporal envelope that is time-locked to the onset of the probe, providing more robust envelope-based cues for detecting the probe and resulting in lower masked thresholds. In the current study, for the condition with the narrowest bandwidth noise with minimal inherent envelope fluctuations (1/3 ERB LFN), listeners may have perceived a clear change in the temporal envelope that occurred between the offset of the masker and the onset of the probe, a robust envelope-based detection cue. Whereas in the two masker conditions with maximum masker envelope fluctuations (1 ERB GN and 1/3 ERB GN), the temporal envelope-based detection cue was maximally disrupted, resulting in higher masked thresholds. In the wider bandwidth noise with reduced inherent envelope fluctuations (1 ERB LFN), exceeding a critical band likely introduced minor fluctuations in the masker envelope, which may have somewhat disrupted the temporal envelope-based cue, resulting in slightly elevated masked thresholds relative to the masker envelope with the least amount of inherent fluctuations (1/3 ERB LFN). In this way, rapid inherent envelope

fluctuations in a forward masker can result in higher masked thresholds for a short-duration probe by varying the amount of disruption to the envelope-based cue used for detecting the probe.

B. Effects of hearing loss and forward masking

Contrary to predictions, the relative masking effectiveness of noises that vary in their inherent envelope fluctuations did not change with hearing loss, at least for the 25-ms masker-probe delay included in the current study. If recovery from forward masking is dependent on neural mechanisms that determine the time constant (e.g., Oxenham, 2001), in combination with peripheral mechanisms (cochlear compression) that contribute to the slope of recovery (e.g., Oxenham and Moore, 1997), sensorineural hearing loss of cochlear origin should affect the slope of recovery due to changes in cochlear nonlinearities but should leave the time constant relatively intact (e.g., Oxenham and Bacon, 2003). Because the results of the current study suggest that “recovery” from the inherent envelope fluctuations of Gaussian noise relative to low-fluctuation noise is similar for NH and HI listeners at this masker-probe delay (see Fig. 4), recovery from rapid envelope fluctuations may be unaffected by differences in cochlear nonlinearities between NH and HI listeners and a portion of this recovery may occur beyond the cochlea. Thus our unexpected finding of similar recovery from rapid envelope fluctuations for NH and HI listeners suggests that this

recovery and recovery from forward masking may arise from somewhat distinct mechanisms.

C. Effects of hearing loss and modulation masking

As discussed, listeners may have perceived a change in the temporal envelope that occurred between the offset of the masker and the onset of the probe and used this cue to detect the probe. When this temporal envelope-based cue was disrupted due to inherent fluctuations in the masker envelope, a less robust cue for probe detection resulted in higher masked thresholds. If changes in the temporal envelope of the masker affect a listener's ability to take advantage of envelope-based detection cues related to the onset of the probe, these effects may be comparable to the effects of modulation masking. For example, forward masking in conjunction with modulation masking may partially explain increased modulation detection interference in HI, relative to NH listeners (Koopman *et al.*, 2008).

Although the use of an unmodulated pure-tone probe calls into question the role of modulation masking in the current experiment, our results nevertheless suggest that maskers with rapid inherent envelope fluctuations result in more masking than maskers with reduced inherent fluctuations. The effectiveness of maskers that vary in their inherent envelope fluctuations did not differ between NH and HI listeners at a relatively short (25-ms) masker-probe delay. However, effects of hearing loss on masker effectiveness for various fluctuating forward maskers for longer masker-probe delays remains unknown.

D. Future directions

Measuring masked thresholds under conditions in which maskers and probes are separated in time and frequency may reveal differences in slopes and time constants of recovery from these masking mechanisms. Using longer masker-probe delays will provide a better test of the hypothesis that energetic and modulation masking interact differently for NH and HI listeners across time due to differences in slopes of recovery from forward masking. In addition, measuring analogous conditions at lower frequencies (such as 2000 Hz) will allow masked thresholds to be measured in HI listeners in regions with wider dynamic ranges.

Similarly, changes in masker effectiveness as the masker and probe are separated in frequency may isolate the effects of hearing loss related to the upward spread of forward masking and minimize confusion effects (Neff, 1986); this may contribute to elevated on-frequency forward-masked thresholds in narrowband maskers.

V. CONCLUSIONS

(1) As predicted, forward-masked thresholds were higher for maskers with greater inherent envelope fluctuations than for less fluctuating maskers for younger adults with normal hearing. Increases in inherent masker fluctuations may have disrupted detection of the temporal envelope-based cue between the masker offset and probe onset, resulting in elevated masked thresholds.

(2) As predicted, no significant effect of listener age on forward-masked thresholds was observed. However, contrary to predictions, mean differences in forward-masked thresholds between Gaussian and low-fluctuation maskers for older adults with hearing loss were similar to those for younger and older adults with normal hearing. Results suggest that recovery from inherent masker envelope fluctuations and recovery from forward masking may arise from different mechanisms. Given the similarities in the recovery from inherent masker envelope fluctuations for listeners with normal and impaired hearing, a portion of this recovery may occur beyond the cochlea.

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