Inherent envelope fluctuations in forward maskers: Effects of masker-probe delay for listeners with normal and impaired hearing^{a)}

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(Received 30 April 2015; revised 23 December 2015; accepted 2 March 2016; published online 18 March 2016)

Forward-masked thresholds increase as the magnitude of inherent masker envelope fluctuations increase for both normal-hearing (NH) and hearing-impaired (HI) adults for a short masker-probe delay (25 ms). The slope of the recovery from forward masking is shallower for HI than for NH listeners due to reduced cochlear nonlinearities. However, effects of hearing loss on additional masking due to inherent envelope fluctuations across masker-probe delays remain unknown. The current study assessed effects of hearing loss on the slope and amount of recovery from forward maskers that varied in inherent envelope fluctuations. Forward-masked thresholds were measured at 2000 and 4000 Hz, for masker-probe delays of 25, 50, and 75 ms, for NH and HI adults. Four maskers at each center frequency varied in inherent envelope fluctuations: Gaussian noise (GN) or low-fluctuation noise (LFN), with 1 or 1/3 equivalent rectangular bandwidths (ERBs). Results suggested that slopes of recovery from forward masking were shallower for HI than for NH listeners regardless of masker fluctuations. Additional masking due to inherent envelope fluctuations was greater for HI than for NH listeners at longer masker-probe delays, suggesting that inherent envelope fluctuations are more disruptive for HI than for NH listeners for a longer time course

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[EAS]

Pages: 1195–1203

I. INTRODUCTION

A. Effects of masker envelope fluctuations

For listeners with sensorineural hearing loss, reductions in frequency selectivity and cochlear nonlinearities lead to several auditory deficits (Moore, 1996), including reduced speech recognition in the presence of noise (Dubno and Schaefer, 1995). Differences in speech recognition performance between normal-hearing (NH) and hearing-impaired (HI) listeners become exaggerated when the noise is fluctuating in amplitude (e.g., Bacon *et al.*, 1998; Jin and Nelson, 2006). In amplitude-modulated (AM) noise, in which the level of the noise fluctuates over time, NH listeners can take advantage of brief reductions in amplitude between the temporal peaks of the noise, a phenomenon referred to as masking release. Even in cases of mild hearing loss, HI listeners

experience less masking release than NH listeners (e.g., Dubno *et al.*, 2002).

Investigators have been attempting to understand the factors contributing to the reduction in masking release observed for HI listeners. Recently, Stone *et al.* (2012) found that the inherent fluctuations in what had been considered “steady-state” noise may yield more masking than a noise with largely reduced envelope fluctuations, suggesting that traditionally described “masking release” may be primarily a release from the masking effects of these inherent fluctuations, rather than a reduction in the amount of energetic masking yielded by the noise. Savel and Bacon (2003) measured masked thresholds for a 4000 Hz pure-tone signal in the presence of either a narrowband Gaussian noise (GN) or low-fluctuation noise (LFN) simultaneous masker in NH listeners and concluded that fluctuations in the envelope of the GN were likely responsible for its increased masking effectiveness.

Because of conflicting evidence about the effects of inherent masker envelope fluctuations after the offset of a masker (forward masking), Svec *et al.* (2015) measured forward-masked thresholds for narrowband GN and LFN. The authors hypothesized that differences in the effects of

^{a)}A portion of these results were presented at the 38th Annual MidWinter Meeting of the Association for Research in Otolaryngology in Baltimore, MD, February 2015.

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masker envelope fluctuations between NH and HI listeners may partially explain why HI listeners do not “recover” after the offset of a masker, or during the valley of an AM masker, to the same extent as NH listeners.

Results suggested that forward-masked thresholds were higher for maskers with maximal (GN) than minimal (LFN) inherent envelope fluctuations, and masked threshold differences (GN-LFN) were similar for NH and HI adults when measured at 4000 Hz for a single masker-probe delay of 25 ms. The similar pattern observed for NH and HI listeners gave rise to additional questions regarding the mechanisms that may contribute to forward masking differences when considering the effects of inherent envelope fluctuations.

B. Effects of detection cues

When detecting a forward-masked probe, listeners may use a perceived change in the temporal envelope between the offset of the masker and the onset of the probe as a cue to detect the probe. Variability of inherent envelope fluctuations contributes to listener uncertainty by disrupting these envelope-based offset and onset cues. This uncertainty is increased more for narrowband GN than for LFN maskers (Eddins, 2001; Buss *et al.*, 2006). A change in the temporal envelope that is time-locked to the onset or offset of the probe likely leads to robust envelope-based cues for LFN maskers, resulting in lower masked thresholds than for GN maskers.

Presumably, these envelope detection cues are similarly robust for both NH and HI listeners at a relatively short masker-probe delay (25 ms), given that the masking effectiveness of noises that vary in their inherent envelope fluctuations do not change with hearing loss (Svec *et al.*, 2015). Nonetheless, the slope of the recovery from forward masking is steeper for NH than for HI listeners, due to reduced cochlear nonlinearities with cochlear hearing loss (e.g., Ludvigsen, 1985; Oxenham and Moore, 1997). Oxenham and Moore (1997) and Derleth *et al.* (2001) modeled the effects of hearing loss on recovery from forward masking and showed that changes in forward masking can be predicted solely by introducing a loss of cochlear nonlinearities, affecting the slope of recovery, while keeping the duration of recovery constant. Thus, the time constant of recovery from forward masking, or the time course over which listeners’ forward-masked thresholds return to quiet threshold levels, is not expected to be largely affected by hearing loss (e.g., Oxenham and Bacon, 2003).

When considering the known effects of hearing loss on recovery from forward masking, differences in cochlear nonlinearities cannot explain the similarities in recovery from inherent masker envelope fluctuations for NH and HI listeners observed in Svec *et al.* (2015). However, more information is needed about the slope and time constant of recovery for forward maskers that vary in inherent envelope fluctuations.

C. Effects of forward masker bandwidth

Masker bandwidth may be an important variable for understanding the masking effects of inherent envelope

fluctuations. Although masker bandwidth did not explain differences in forward masking for NH and HI listeners in a previous study (Svec *et al.*, 2015), forward-masked thresholds for maskers with different bandwidths at a range of masker-probe delays may provide additional information related to the theoretical implications posited by Hartmann and Pumphlin (1988). Their results suggested that the temporal envelope of LFN is maximally flat (e.g., minimal fluctuations) when the bandwidth of the masker is within the boundaries of a critical band. As the bandwidth of LFN increases, approaching or exceeding a critical band, fluctuations will likely be introduced to the temporal envelope of the noise by being passed through adjacent auditory filters. Kohlrausch *et al.* (1997) examined the effects of inherent envelope fluctuations by measuring masked thresholds for pure tones in the presence of either GN or LFN simultaneous maskers that varied in bandwidth; they found that GN produced more masking than LFN for a fairly wide range of masker bandwidths at both 1000 and 10 000 Hz. A masker bandwidth of 25–50 Hz produced the greatest difference in masked thresholds between GN and LFN at 1000 Hz, suggesting that a masker bandwidth near one-third an equivalent rectangular bandwidth (ERB; Glasberg and Moore, 1990) may reveal the maximal additional amount of masking yielded by GN as compared to LFN. Generally consistent with these findings for NH listeners, Svec *et al.* (2015) showed that a 1/3 ERB GN forward masker not only produced more masking than a 1/3 ERB LFN forward masker, but that a greater difference (GN > LFN) was observed for the 1/3 ERB maskers compared to the slightly broader bandwidth masker of 1 ERB. However, this effect of masker bandwidth was unexpectedly similar for NH and HI listeners at the short masker-probe delay of 25 ms, inconsistent with the presumed effect of auditory filter bandwidths. Potential bandwidth effects for longer masker-probe delays are one focus of the current study.

D. Research questions

The current study was designed to assess effects of hearing loss on the slopes of recovery and the amount of recovery from four forward maskers in which the amount of inherent envelope fluctuations varied: GN or LFN, with bandwidths of 1 or 1/3 ERB. Previous work (Svec *et al.*, 2015) led to two new research questions: (1) Do slopes of recovery from these variably fluctuating forward maskers differ for NH and HI listeners?, and (2) do differences in additional masking between NH and HI listeners due to inherent envelope fluctuations vary with masker-probe delay? Forward-masked thresholds were measured at 2000 and 4000 Hz, for masker-probe delays of 25, 50, and 75 ms, for NH and HI adults. These conditions were chosen to determine the extent to which (1) these masking effects are consistent at multiple center frequencies; and (2) the differences between NH and HI listeners are dependent on HI listeners’ magnitude of hearing loss at the probe frequency. Slopes of recovery from forward masking for each masker type and bandwidth were estimated by computing the slope of the function relating masked threshold to masker-probe delay.

Additional masking due to inherent envelope fluctuations was estimated by comparing forward-masked thresholds for maskers with maximal fluctuations (GN) to those with minimal fluctuations (LFN).

Based on previous results (e.g., Oxenham and Moore, 1997; Oxenham and Bacon, 2003), we predicted that slopes of recovery from forward masking would be shallower for HI than for NH listeners, and differences in slopes between NH and HI listeners would be larger at 4000 than at 2000 Hz, due to greater hearing loss. Because disruption due to inherent envelope fluctuations may occur for a longer time course for HI than for NH listeners based on previous results from forward-masked modulation detection interference (Koopman *et al.*, 2008), we predicted that the increase in masked thresholds with higher fluctuation maskers would be greater for HI than for NH listeners at longer masker-probe delays.

II. METHODS

A. Participants

For the 4000 Hz conditions, 19 adult listeners (6 males, 13 females) participated in this experiment. For the NH adults ($n = 9$, age 19–35 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 HI adults ($n = 10$, age 60–79 yr), pure-tone thresholds were < 50 dB HL at 250, 500, and 1000 Hz, between 25 and 60 dB HL at 2000 and 4000 Hz, and between 25 and 70 dB HL at 8000 Hz. Based on the absence of age-related differences in forward masking (e.g., Dubno *et al.*, 2003; Svec *et al.*, 2015), we did not include a group of older NH participants in the current study. One NH and two HI listeners that completed the 4000 Hz conditions did not complete the 2000 Hz conditions. 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 sound pressure level (SPL) for the two groups of listeners. For NH listeners, the better ear was chosen as the test ear for all listeners. For the HI listeners, if both ears met the inclusion criteria, the ear with better thresholds at 2000 and 4000 Hz was chosen for testing. If thresholds were identical at 2000 and 4000 Hz, the right ear was chosen for testing. The center and right panels of Fig. 1 contain mean (filled symbols) and individual (open symbols) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 2000-Hz (center), and 4000-Hz (right) probes. Mean probe thresholds at 2000 Hz were 23.2 and 50.1 dB SPL for the NH and HI groups, respectively. At 4000 Hz, mean probe thresholds were 20.4 and 62.2 dB SPL for the NH and HI groups, respectively.

B. Apparatus and stimuli

Each signal was generated at a sampling rate of 44 100 Hz, produced via a MATLAB script file matched with a

FIG. 1. (Color online) Mean (filled symbols) and individual (dashed lines) pure-tone thresholds measured (in dB HL, converted to dB SPL) in the test ear for ~ 250 -ms signals for NH and HI participants (left). Mean (filled) and individual (open) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms probe for two groups at 2000 Hz (middle) and 4000 Hz (right).

Lynx TWO-B soundcard (Lynx Studio Technology, Inc., Costa Mesa, CA) and a Benchmark DAC1 D/A converter (Benchmark Media Systems, Inc., Syracuse, NY) and presented through a Tucker-Davis Technologies (TDT) (Alachua, FL) HB6 headphone buffer driving a Sennheiser (Wedemark Wennebostel, Germany) HD650 circumaural earphone. The duration of both the 2000- and 4000-Hz pure-tone probes was 10 ms, including 5-ms raised cosine onset and offset ramps. Each of eight 400-ms maskers, including 5-ms raised cosine onset and offset ramps, was centered at either 2000 or 4000 Hz: (a) GN with a bandwidth of 1 ERB (241 Hz, or 463 Hz) and cutoff frequencies of 1883 and 2124 Hz, or 3775 and 4238 Hz; (b) GN with a bandwidth of 1/3 ERB (80 Hz or 154 Hz) and cutoff frequencies of 1960 and 2040 Hz, or 3924 and 4078 Hz; and (c) four LFN maskers with bandwidths and cutoff frequencies identical to those of the GN maskers. Both the GN and LFN maskers were generated following a procedure described by Buss *et al.* (2006), originally adapted from the method for creating LFN developed by Kohlrausch *et al.* (1997). A band of GN centered at either 2000 or 4000 Hz for each corresponding bandwidth (1 or 1/3 ERB) was divided by the Hilbert envelope in the time domain and then multiplied by the original spectrum in the frequency domain. For the LFN, the multiplication was repeated ten times, resulting in a temporal envelope with minimal inherent fluctuations.

Crest factors, or the ratios between peak amplitude and the root-mean-square (rms) amplitude within the temporal envelope of the waveform (e.g., Hartmann and Pumplin, 1988), were calculated to provide an estimate of the power in the peaks of the amplitude fluctuations compared to the overall energy of the noise. For our experimental conditions, crest factors were calculated for 100 noise samples generated for each of the 8 maskers; mean crest factors and standard deviations were computed. As expected, mean crest factors for both center frequencies were higher for GN (1 ERB, 11.4; 1/3 ERB, 10.6) than LFN (1 ERB, 4.5; 1/3 ERB, 4.4). In addition, standard deviations were much higher for GN (1

FIG. 2. (Color online) Mean ± 1 standard error (SE) forward-masked thresholds (in dB SPL) for two masker bandwidths (1 ERB, filled; 1/3 ERB, open) and two masker types (GN, squares and triangles; LFN, circles and inverted triangles) for NH (left) and HI (right) listeners.

ERB, 0.77; 1/3 ERB, 0.77) than LFN (1 ERB, 0.12; 1/3 ERB, 0.16).

Initiation of the masker occurred 50 ms after the beginning of the interval. The probe was presented 25, 50, or 75 ms after the offset of the masker. The overall level of the masker was fixed at 80 dB SPL. See Svec *et al.* (2015, Fig. 2) for a schematic of the waveforms for the probe, 1 ERB GN, and 1 ERB LFN. A computer monitor displayed the timing of signal presentations. A touchscreen interface was used to record participant responses inside a double-walled, sound-treated booth.

C. Procedures

Detection thresholds for the 10-ms probe at either 2000 or 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, indicated by lights corresponding to the duration of the interval, separated by a 500-ms inter-stimulus interval. Only one of the three intervals contained the probe. Participants received feedback for whether or not they chose the correct interval on a given trial. The probe starting level was 50 dB SPL for NH listeners and 80 dB SPL for HI listeners. Initial step size was 5 dB and changed to 2 dB after the first two reversals. Thresholds were calculated as mean probe level (dB SPL) for the final eight reversals following completion of a given block. Mean thresholds for each condition were based on at least three blocks. If the standard deviation of a given block exceeded 5 dB, a fourth block was obtained, and the mean of all four threshold estimates

became the final probe threshold. A very similar procedure, aside from probe starting levels, was used to measure masked thresholds by holding the masker level constant at 80 dB SPL and varying the probe level adaptively.

A training session was completed before data collection commenced to familiarize listeners with the 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. Training for a given condition ceased once the participant's performance reached a standard deviation of < 5 dB within a block. Once forward masking data collection began, starting levels for the probe were set to 20 dB SL re: masked threshold determined during training.

The testing conditions were blocked by masker bandwidth (1 ERB or 1/3 ERB), masker type (GN or LFN), and masker-probe delay (25, 50, or 75 ms), and randomized by a number assigned to each of the 24 conditions. Over multiple visits, testing did not exceed 10 h, including informed consent, audiometry, training, and data collection. Frequent breaks were offered to participants.

A repeated-measures analysis of variance (ANOVA) was used to assess the within-subject effects of masker type (GN, LFN), bandwidth (1/3 ERB, 1 ERB), and masker-probe delay (25, 50, 75 ms), as well as the between-subject effects of participant group (NH, HI) on forward-masked thresholds. Separate ANOVAs were completed for 2000 and 4000 Hz. Differences were considered significant with $p < 0.05$. The hypotheses predicted significant main effects for all three within-subject factors, and significant interactions of participant group with masker type and masker-probe delay. Because masker bandwidth did not play a substantial role in explaining differences between NH and HI listeners in a previous study (Svec *et al.*, 2015), an interaction of participant group with masker bandwidth was not anticipated. Regression slopes and masked threshold differences for NH and HI listeners were analyzed using the Welch two sample t -tests with unequal variance assumed (Welch, 1947). The association between slopes of recovery from LFN or GN maskers and magnitude of hearing loss (threshold for the probe in quiet) were assessed using correlational analyses.

III. RESULTS

A. Quiet thresholds

For Fig. 1, quiet thresholds for the 10-ms pure-tone probe at 2000 and 4000 Hz (center and right panels, respectively) were not significantly different for NH listeners ($p > 0.05$), but thresholds were significantly higher at 4000 than at 2000 Hz for HI listeners ($p < 0.05$). In addition, quiet thresholds for the 10-ms pure-tone probe were significantly higher for HI than for NH listeners at both 2000 ($p < 0.001$) and 4000 Hz ($p < 0.001$).

B. Masked thresholds

For Fig. 2, masked thresholds are plotted against masker-probe delay for NH (left panels) and HI (right panels) listeners for the 1 ERB (filled symbols) and 1/3 ERB (open symbols) masker bandwidths, for both GN (squares

and triangles) and LFN (circles and inverted triangles) masker types, and for center frequencies of 2000 (top panels) and 4000 (bottom panels) Hz. For most conditions, masked thresholds improve as masker-probe delay is increased across masker types, as expected. Masked thresholds for all maskers at all masker-probe delays were significantly higher for HI than for NH listeners for both 4000 Hz [$F(1,17) = 123.2$, $p < 0.001$] and 2000 Hz [$F(1,14) = 54.4$, $p < 0.001$] (see Fig. 2).

For the 4000-Hz conditions, significant main effects of masker type [$F(1,17) = 66.5$, $p < 0.001$] and masker-probe delay [$F(2,34) = 83.4$, $p < 0.001$] were observed. A significant two-way interaction of listener group and masker-probe delay [$F(2,34) = 31.87$, $p < 0.001$], as well as a three-way interaction of listener group, masker-probe delay, and masker type [$F(2,34) = 3.82$, $p < 0.05$], suggested that masked thresholds and differences between GN and LFN reduced as masker-probe delay increased for both groups of listeners. The pattern of results at 4000 Hz did not change significantly with masker bandwidth.

In contrast to the results for the 4000-Hz conditions, bandwidth played a significant role for 2000 Hz, resulting in greater threshold differences between GN and LFN for the wider bandwidth (1 ERB) maskers than for narrower bandwidth (1/3 ERB) maskers at the shortest masker-probe delays. These differences became smaller in both groups of listeners at longer masker-probe delays. For the 2000-Hz probe frequency, significant main effects of masker type [$F(1,14) = 51.3$, $p < 0.001$], masker-probe delay [$F(2,28) = 54.6$, $p < 0.001$], and masker bandwidth [$F(1,14) = 29.5$, $p < 0.001$] were observed. A significant two-way interaction of masker-probe delay and listener group [$F(2,28) = 3.941$, $p < 0.05$], as well as a three-way interaction of masker type, masker bandwidth, and masker-probe delay [$F(2,28) = 0.355$, $p < 0.05$], indicated that masked thresholds, differences between GN and LFN, and differences between narrower and wider masker bandwidths reduced as masker-probe delay increased for both groups of listeners. However, as predicted, no significant interaction between masker bandwidth and listener group was observed. Similar to the findings at 4000 Hz, these results suggest that masked thresholds were higher for HI than for NH listeners for both masker types at the shortest masker-probe delays, and the differences between masked thresholds for both HI and NH listeners increased at longer masker-probe delays. Implications for masker bandwidth effects at different center frequencies will be given further consideration in Sec. IV.

C. Masked threshold differences (GN-LFN)

For Fig. 3, masked threshold differences (GN-LFN) are plotted against masker-probe delay for NH (left panels) and HI (right panels) listeners for the 1 ERB (squares) and 1/3 ERB (circles) masker bandwidths for both 2000 (top panels) and 4000 (bottom panels) Hz. For the 4000-Hz conditions, additional masking for the GN, relative to the LFN maskers, was significantly larger for HI than for NH listeners for both masker bandwidths at the 50- and 75-ms masker-probe delays ($p < 0.05$ and $p < 0.001$, respectively). However, no

FIG. 3. (Color online) Mean (± 1 SE) masked threshold differences (in dB) for two masker bandwidths (1 ERB, squares; 1/3 ERB, circles) for NH listeners (left) and HI listeners (right).

significant masked threshold differences between NH and HI listeners were observed for the 25-ms delay ($p > 0.05$), consistent with previous results (Svec *et al.*, 2015). For the 2000-Hz conditions, masked threshold differences (GN-LFN) did not differ significantly for NH and HI listeners ($p > 0.05$), although a trend was observed suggesting larger differences for HI than for NH listeners at the longest masker-probe delay ($p = 0.05$).

Because masked threshold differences between GN and LFN maskers were observed for HI listeners at the longest masker-probe delays for the 4000-Hz conditions, these findings suggest that the masking effects from inherent envelope fluctuations are larger and persist for a longer time course for HI listeners in regions with greater hearing loss than for NH listeners. These findings also suggest that the additional masking due to inherent masker envelope fluctuations for HI listeners is not significantly different from NH listeners in regions with better hearing, namely, 2000 Hz.

D. Associations between recovery slopes and hearing loss

For Fig. 4, slopes of recovery (see Table I) are plotted against quiet probe threshold (dB SPL) for NH (squares) and HI (triangles) listeners for the 1 ERB (filled symbols) and 1/3 ERB (open symbols) masker bandwidths, both GN (left panels) and LFN (right panels) masker types, and center frequencies of 2000 (top panels) and 4000 (bottom panels) Hz. For all LFN maskers at both 2000 and 4000 Hz, slopes of recovery were significantly shallower for HI than for NH listeners ($p < 0.001$), consistent with previous findings (e.g., Oxenham and Bacon, 2003). Similar to LFN, for all GN maskers at both 2000 and 4000 Hz, slopes of recovery

FIG. 4. (Color online) Slopes (dB/ms) of recovery functions plotted against quiet probe thresholds (in dB SPL) for two masker bandwidths (1 ERB, filled; 1/3 ERB, open) and two masker types (GN, left; LFN, right) at 2000 Hz (top) and 4000 Hz (bottom) for NH (squares) and HI (triangles) listeners.

were significantly shallower for HI than for NH listeners (1 ERB GN, $p < 0.05$; all other GN maskers, $p < 0.001$; see Table I).

For NH listeners, slopes of recovery were not significantly correlated with probe thresholds in quiet for any masker ($p > 0.05$; see Table II). This is expected due to the narrow range of quiet thresholds for the NH participants. For HI listeners, slopes of recovery were positively correlated with probe thresholds for narrower bandwidth (1/3 ERB) maskers for 4000 (GN, $r = 0.71$, $p < 0.05$) and 2000 (GN, $r = 0.81$, $p < 0.05$ and LFN, $r = 0.78$, $p < 0.05$) Hz. Therefore, as hearing loss at the probe frequency increased for HI listeners, slopes of recovery functions became shallower, primarily for maskers with maximal inherent envelope fluctuations (e.g., 1/3 ERB GN).

TABLE I. Mean (± 1 SE) slopes of recovery, calculated from forward-masked thresholds at 2000 and 4000 Hz probes for GN and LFN maskers at three masker-probe delays (25, 50, 75 ms) for NH and HI listeners.

Frequency	Bandwidth	Type	NH		HI	
			Mean	SE	Mean	SE
2000 Hz	1 ERB	GN	-0.46	0.05	-0.32	0.04
		LFN	-0.30	0.03	-0.22	0.03
	1/3 ERB	GN	-0.36	0.03	-0.18	0.03
		LFN	-0.28	0.03	-0.18	0.03
4000 Hz	1 ERB	GN	-0.48	0.08	-0.12	0.02
		LFN	-0.42	0.05	-0.08	0.02
	1/3 ERB	GN	-0.56	0.08	-0.16	0.02
		LFN	-0.36	0.05	-0.10	0.03

TABLE II. Correlations between recovery slope and quiet probe threshold for each bandwidth (1 ERB, 1/3 ERB) of GN and LFN for center frequencies of 2000 Hz (top) and 4000 Hz (bottom) Hz.

Frequency	Bandwidth	Type	NH	HI	Overall
2000 Hz	1 ERB	GN	0.103	0.452	0.567 ^a
		LFN	0.118	0.324	0.772 ^b
	1/3 ERB	GN	-0.181	0.806 ^a	0.726 ^b
		LFN	-0.215	0.778 ^a	0.801 ^b
4000 Hz	1 ERB	GN	0.471	0.262	0.800 ^b
		LFN	0.532	0.218	0.826 ^b
	1/3 ERB	GN	0.533	0.705 ^a	0.915 ^b
		LFN	0.617	0.366	0.846 ^b

^aCorrelation is significant at the 0.05 level (two-tailed).

^bCorrelation is significant at the 0.01 level (two-tailed).

IV. DISCUSSION

A. Primary findings

The current study revealed two primary differences between NH and HI listeners for recovery from forward maskers that varied in inherent envelope fluctuations. First, as predicted and as previously observed, slopes of recovery from forward masking were shallower for HI than for NH listeners. In addition, this relationship between slopes and listener group was observed regardless of masker fluctuations and degree of hearing loss at the probe frequency. Because slopes of recovery from both GN and LFN at 2000 Hz, a region in which HI listeners had better hearing, were still significantly shallower for HI than for NH listeners, we infer that even mild cochlear hearing loss affects slopes of recovery from forward masking for both masker types.

Second, at 4000 Hz, additional masking attributed to inherent masker envelope fluctuations, or masked thresholds differences between GN and LFN, was significantly larger for HI than for NH listeners at the two longer masker-probe delays. At the shortest masker-probe delay, no significant differences in additional masking were observed between NH and HI listeners, which is in good agreement with the results from Svec *et al.* (2015). At 2000 Hz, no significant differences in additional masking were observed between NH and HI listeners at any masker-probe delay, although at the longest delay a trend for group differences ($p = 0.05$) was observed, as seen in Fig. 3. Overall, results suggest that recovery from inherent envelope fluctuations may be more similar in the 2000-Hz region where hearing thresholds were more similar for NH and HI listeners than in the 4000-Hz region. Consequently, the persistence of masking effects from inherent envelope fluctuations at a longer time course may increase with increasing hearing loss in a particular cochlear region.

B. Implications of masking due to envelope fluctuations and slopes of recovery

At 4000 Hz, a significant difference for HI listeners between masked thresholds for GN and LFN conditions at the longest masker-probe delay suggests that these listeners

have not fully recovered from additional masking attributable to the inherent envelope fluctuations of the GN. Although shallower slopes of recovery from forward masking in HI listeners are predicted by reductions in cochlear nonlinearities, as stated previously, the time constant of recovery from forward masking is not expected to be largely affected by hearing loss. Given the similarities in the presumed effect of inherent envelope fluctuations for NH and HI listeners at a short masker-probe delay and the differences in this effect between NH and HI listeners at a longer masker-probe delay, a mechanism other than loss of cochlear nonlinearities may be responsible for the change in the time course of recovery from inherent fluctuations for HI listeners.

Ludvigsen (1985) developed a model of recovery from forward masking for NH and HI listeners for both low- and high-level maskers that may have implications for the results from the current study. While the model is based on a fairly broad assumption that forward-masked thresholds return to quiet probe thresholds by a masker-probe delay of 200 ms regardless of the fixed masker level and degree of hearing loss, it provides a framework for describing forward masking effects as a function of masker level and masker-probe delay in NH and HI listeners. In the model, masked thresholds at a masker-probe delay of 3 ms (masker offset) for the low- and high-level maskers are set to be equivalent for NH and HI listeners, and recovery from both masker levels is assumed to be complete at a masker-probe delay of 200 ms. Slopes of recovery from both maskers are steeper for NH than for HI listeners. At any masker-probe delay before convergence, there is a greater difference between the low- and high-level maskers for the HI than for the NH listeners; however, masked thresholds for the low- and high-level maskers converge at the same masker-probe delay in both sets of listeners.

According to the model proposed by Ludvigsen (1985), if the magnitude of masking attributed to inherent fluctuations were simply an increase in effective masker level leading to greater forward masking in the current study, functions defining recovery from GN and LFN for the NH and HI listeners would have converged at the same masker-probe delay. However, in contrast to model predictions, GN and LFN functions converged relatively quickly (~ 50 ms) for NH listeners, whereas for HI listeners, functions had not converged with a masker-probe delay of 75 ms. Therefore, the masked threshold differences observed for GN and LFN in the current study suggest that a mechanism in addition to forward masking may also be contributing.

One limitation of the current study is that the actual time constants of recovery, the duration over which listeners' forward-masked thresholds return to quiet threshold levels, were not measured. Consequently, differences in time constants between NH and HI listeners for recovery from inherent fluctuations cannot be directly compared.

C. Effects of forward masker bandwidth

As noted in Sec. III for 2000 Hz, the wider bandwidth (1 ERB) GN yielded more masking than the narrower bandwidth (1/3 ERB) GN for both NH and HI listeners (see Fig.

3). This result was unexpected due to previous findings at different center frequencies, suggesting that narrower bandwidth GN maskers primarily yield more masking than wider bandwidth GN maskers (e.g., Kohlrausch *et al.*, 1997; Svec *et al.*, 2015). However, a careful consideration of the particular bandwidths chosen for the current study suggests that small changes in masker bandwidth may not result in consistent changes across center frequencies. As noted, the crest factors for both bandwidths of GN were very similar for 2000 and 4000 Hz, as were the crest factors for LFN. Because the results of Kohlrausch *et al.* (1997) suggested that GN yields more masking than LFN for a fairly wide range of masker bandwidths, it is possible that the observed masking relationship between 1 and 1/3 ERB is not constant across center frequencies. At bandwidths narrower than 25 Hz, Kohlrausch *et al.* (1997) found reduced differences between GN and LFN, similar to broader bandwidth maskers, suggesting some intermediate bandwidth (25–50 Hz) may yield the largest difference between the two masker types. Thus, at 2000 Hz, 1/3 ERB may not be an optimal bandwidth for yielding the largest difference between GN and LFN. However, without a continuum of masker bandwidths, it is difficult to fully assess the effect of bandwidth on the contribution of inherent envelope fluctuations observed here.

D. Effects of detection cues

Considered in similar domains as “confusion effects” (Neff, 1986), the term “masker uncertainty” is often invoked when describing sources of masking associated with across-trial statistical variations of masker waveforms, leading to what we will call “listener uncertainty.” As mentioned, listener uncertainty is greater for GN than for LFN maskers due to variability of inherent fluctuations in the temporal envelope of the stimuli (Eddins, 2001; Buss *et al.*, 2006). Lutfi (1990) quantified this uncertainty and estimated that up to 22% of the amount of masking for tone-in-noise experiments (simultaneous and forward masking) may be due to listener uncertainty. Although there was little reason to assume that the masker-probe delays used in the current study would elicit conventionally described “confusion effects,” we hypothesized that listener uncertainty due to inherent masker fluctuations may be reduced by presenting the listener with a robust diotic cue for the masker offset.

To determine the extent to which a diotic temporal cue would affect listener uncertainty in conditions where a substantial difference was observed between GN and LFN maskers, a subset of listeners were presented with binaural masking conditions that were designed to optimize detection of the probe. Diotic forward maskers (1/3 and 1 ERB, GN and LFN) centered at 4000 Hz were presented binaurally in conjunction with the identical monaural probe used in the previous experiment at a masker-probe delay of 25 ms to three of the NH listeners and three of the HI listeners who had participated in the previous portion of the current study. In addition, these same diotic forward maskers were presented to these HI listeners at a masker-probe delay of 75 ms, because substantial differences in masked thresholds

between GN and LFN were still observed for HI listeners at the longest masker-probe delay.

Overall, the diotic maskers reduced binaural masked thresholds relative to monaural masked thresholds by 13.5 to 15.1 dB for GN and by 6.7 to 11.0 dB for LFN for the NH listeners. For HI listeners, binaural relative to monaural masked thresholds were reduced by 5.9 to 6.9 dB for GN and by 1.5 to 1.8 dB for LFN at a masker-probe delay of 25 ms, and by 0.6 to 5.4 dB for GN and by -2.0 to 0.6 dB for LFN at a masker-probe delay of 75 ms.

For Fig. 5, masked threshold differences (GN-LFN) for 4000 Hz are plotted for the monaural (solid bars) and diotic (striped bars) conditions at masker-probe delays of 25 (left panels) and 75 (right panels) ms for NH (top panels) and HI (bottom panels) listeners, respectively. As predicted, the binaural cue reduced additional masking, or masked threshold differences (GN-LFN), by 8.3 dB for 1/3 ERB and by 2.5 dB for 1 ERB for NH listeners. For HI listeners, the binaural cue reduced masked threshold differences (GN-LFN) by 4.1 dB for 1/3 ERB and by 5.4 dB for 1 ERB at a masker-probe delay of 25 ms, as well as by 2.3 dB for 1/3 ERB and by 2.2 dB for 1 ERB at a masker-probe delay of 75 ms. These results suggest that the envelope-based cue was likely disrupted by the greater inherent masker envelope fluctuations of GN than by LFN in the monaural conditions.

While the listener uncertainty effect mirrors some of the attributes of confusion effects, it seems unlikely that a listener is confusing a masker and probe that are separated by 75 ms. More aptly, we are describing this effect as the “persistence of listener uncertainty,” suggesting that the disruption due to inherent masker envelope fluctuations persists in HI listeners for a longer time than in NH listeners. Questions remain regarding effective and efficient ways to

measure listener uncertainty with methods more suitable than a control for traditional confusion effects. If, for instance, a combination of non-simultaneous modulation masking and listener uncertainty are yielding masked thresholds, measuring the effects of each will help isolate the contributions of both.

E. Mechanisms of forward masking in the audio and modulation frequency domains

Although the mechanism in the auditory system that is responsible for the time constant of recovery from forward masking remains unclear, investigators have recently focused on a few possibilities. [Nelson *et al.* \(2009\)](#) recorded single-fiber responses in neurons of the inferior colliculus (IC) in marmosets to assess whether or not forward masking could be accounted for at the level of the mid-brain. Many individual cells exhibited suppression comparable to the phenomenon of forward masking, leading the investigators to assert that the auditory mechanism responsible for the time constant of recovery presumably precedes the IC in the afferent auditory pathway. While this is consistent with the assumption that the time constant for recovery is dependent on some combination of neural integration and adaptation occurring shortly after cochlear processing in the audio-frequency domain ([Oxenham, 2001](#)), the results of [Wojtczak *et al.* \(2011\)](#) suggest that this may not be the case when considering forward masking in the modulation frequency domain. They compared AM forward masking for behavioral results in human participants and physiological results in the IC neurons of rabbits. For the behavioral experiment in humans, they measured AM forward masking using pure-tone carriers, including a 40-Hz AM masker (150 ms) that was followed by a 40-Hz AM signal (50 ms). Behavioral results were in good agreement with those from [Wojtczak and Viemeister \(2005\)](#), which used broadband noise carriers instead of pure tones, suggesting that an AM forward masker can significantly elevate masked modulation detection thresholds for NH listeners with masker-signal delays as long as 210 ms. Very similar conditions measured in the IC neurons of rabbits revealed that, unlike forward masking in the audio-frequency domain, suppression at the level of the IC could not reasonably account for AM forward masking, suggesting that the mechanisms for recovery from the sequential modulation masking may arise from mechanisms central to the IC.

As previously mentioned, changes in the temporal envelope of the masker, such as those related to inherent envelope fluctuations, affect a listener’s ability to take advantage of envelope-based detection cues related to the onset or offset of the probe, which may be comparable to effects of modulation masking. The magnitude and time course of recovery from inherent envelope fluctuations that are related to recovery from AM forward masking, in contrast to forward masking in the audio-frequency domain, would explain some of the results for our NH listeners. However, the time course and magnitude of recovery from AM forward masking for HI listeners remains unknown.

FIG. 5. (Color online) Mean (± 1 SE) masked threshold differences (in dB) for the monaural (solid) and diotic (striped) conditions for two masker bandwidths (within each panel: 1/3 ERB, left; 1 ERB, right) for NH listeners (top) at a masker-probe delay of 25 ms (left) and HI listeners (bottom) at masker-probe delays of 25 (left) and 75 (right) ms.

F. Implications and future directions

Because inherent envelope fluctuations of a forward masker yielded relatively more masking at longer masker-probe delays for HI than for NH listeners, the contribution of AM forward masking may be relevant. This persistence of the effect of inherent envelope fluctuations may also differentially affect the detection of signals other than pure tones, such as detecting modulation within a signal after the offset of the masker. By using GN and LFN AM forward maskers in a frequency-specific place, questions related to AM forward masking observed for NH listeners (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011) and for listeners with hearing loss can continue to be explored. For example, it is not known if AM forward masking at longer masker-signal delays will be larger for HI than for NH listeners. If so, the contribution of AM forward masking and effects of inherent envelope fluctuations may be relevant for interpreting differences between NH and HI listeners for speech recognition presented in AM noise.

V. CONCLUSIONS

- (1) As predicted, slopes of recovery from forward masking were shallower for HI than for NH listeners, regardless of masker fluctuations and degree of hearing loss at the probe frequency.
- (2) Additional masking at 4000 Hz attributed to inherent envelope fluctuations was significantly larger for HI than for NH listeners at the two longer masker-probe delays, suggesting that some persistence of the masking effects from inherent envelope fluctuations occurs for a longer time course in a region of greater hearing loss.
- (3) No significant differences in additional masking between NH and HI listeners were observed at any masker-probe delay for 2000 Hz, suggesting that recovery from inherent envelope fluctuations is more similar for the two groups in this region where quiet thresholds were also more similar.
- (4) A binaural cue associated with a diotic forward masker elicited a reduction in the differences between GN and LFN masked thresholds for a subset of listeners, suggesting that listener uncertainty persists over a longer time course after the offset of a masker for HI than for NH listeners.

ACKNOWLEDGMENTS

This work was supported by the Bryng Bryngelson Research Fund in the Department of Speech-Language-Hearing Sciences at the University of Minnesota, the Charles E. Speaks Fellowship, and National Institutes of Health/National Institute on Deafness and Other Communication Disorders (NIH/NIDCD; R01 DC000184, J.R.D.). Thanks to Dr. Edward Carney for providing assistance with experimental design and software. Thank you to the two anonymous reviewers for their helpful suggestions for improving the manuscript.

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