Temporal masking functions for listeners with real and simulated hearing loss

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A functional simulation of hearing loss was evaluated in its ability to reproduce the temporal masking functions for eight listeners with mild to severe sensorineural hearing loss. Each audiometric loss was simulated in a group of age-matched normal-hearing listeners through a combination of spectrally-shaped masking noise and multi-band expansion. Temporal-masking functions were obtained in both groups of listeners using a forward-masking paradigm in which the level of a 110-ms masker required to just mask a 10-ms fixed-level probe (5-10 dB SL) was measured as a function of the time delay between the masker offset and probe onset. At each of four probe frequencies (500, 1000, 2000, and 4000 Hz), temporal-masking functions were obtained using maskers that were 0.55, 1.0, and 1.15 times the probe frequency. The slopes and y-intercepts of the masking functions were not significantly different for listeners with real and simulated hearing loss. The y-intercepts were positively correlated with level of hearing loss while the slopes were negatively correlated. The ratio of the slopes obtained with the low-frequency maskers relative to the on-frequency maskers was similar for both groups of listeners and indicated a smaller compressive effect than that observed in normal-hearing listeners. © 2011 Acoustical Society of America. [DOI: 10.1121/1.3607599]

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I. INTRODUCTION

Functional simulation is an important research tool for elucidating the nature of hearing impairments. A hearing-loss simulation transforms an input stimulus prior to delivery to the ear of a normal-hearing (NH) listener in order to achieve specific changes in auditory abilities that mimic those experienced by listeners with real hearing impairment. A successful simulation should be capable of reproducing with NH listeners the performance of hearing-impaired (HI) listeners on the widest possible range of psychoacoustic tasks.

Previous research has demonstrated that a variety of simulations of hearing loss are capable of reproducing the elevated thresholds, reduction in dynamic range, and loudness recruitment that are the defining characteristics of sensorineural loss (e.g., Zurek and Delhorne, 1987; Dubno and Schaefer, 1992; Florentine *et al.*, 1993; Villchur, 1973, 1974; Moore and Glasberg, 1993; Duchnowski and Zurek, 1995; Lum and Braida, 2000). These simulations have been tested further on tasks ranging from basic detection and discrimination to speech reception in complex backgrounds (in addition to the references above, also see Florentine and Buus, 1984; Milner *et al.*, 1984; Fabry and Van Tassel, 1986; Humes *et al.*, 1987; Humes, 1990; Dubno and Schaefer, 1991; Florentine, 1992; Sommers and Humes, 1993; Needleman and Crandell, 1995; Oxenham *et al.*, 1997; Bacon *et al.*, 1998; Buss *et al.*, 1998; De Gennaro and Braida,

1998; Oxenham and Dau, 2004; Richie *et al.*, 2005; George *et al.*, 2006; Desloge *et al.*, 2010). The current research was concerned with extending the use of hearing-loss simulation to include non-simultaneous forward masking, that is, temporal spread of masking (Elliott, 1962).

Temporal masking in HI listeners is of considerable interest for two reasons. The first concerns its possible role in the release of masking of speech by temporally fluctuating noise, and the second concerns its use in assessing the integrity of the compressive function of the basilar membrane.

The release from masking (MR) for a temporally-interrupted compared to a continuous background noise is often reduced in HI relative to NH listeners (e.g., Shapiro *et al.*, 1972; Festen and Plomp, 1990; Bacon *et al.*, 1998; Peters *et al.*, 1998; Summers and Molis, 2004; Eisenberg *et al.*, 1995; George *et al.*, 2006; Jin and Nelson, 2006; Lorenzi *et al.*, 2006; Bernstein and Grant, 2009; Desloge *et al.*, 2010). One possibility for a reduction of MR in HI compared to NH listeners is a greater susceptibility to temporal masking in HI listeners which would lead to a decreased ability to make use of the improved speech-to-noise ratios that are present during temporal gaps in the noise.

Nelson and colleagues (Nelson and Freyman, 1987; Nelson and Pavlov, 1989; Nelson *et al.*, 2001) introduced the measurement of temporal masking curves to explore the temporal course of forward masking. This procedure employs a forward-masking paradigm in which the masker level required to just mask a brief fixed-level signal is measured as a function of the time delay between the masker and signal. A comparison of the temporal-masking functions obtained with on-frequency and low off-frequency maskers

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can be used to estimate the contribution of cochlear compression to the response growth rate. This is based on the assumption that forward masking obtained using a low-frequency, off-frequency masker is dependent only on recovery from masking at the probe frequency, whereas forward masking obtained with an on-frequency masker depends both on recovery from masking as well as on cochlear compression at the probe frequency. The ratio of the temporal recovery slopes for the low, off-frequency and on-frequency maskers can thus be used to estimate the cochlear compression characterizing the growth of the basilar-membrane input-output function at the characteristic frequency corresponding to the probe frequency (see Nelson *et al.*, 2001; Oxenham and Bacon, 2003; Nelson and Schroder, 2004 for a more detailed explanation of these assumptions).

For NH listeners, the slopes of temporal-masking functions are shallower when measured with low, off-frequency maskers than with on-frequency maskers and indicate compression rates of roughly 0.2 to 0.4 dB/dB over a range of probe frequencies (e.g., Lopez-Poveda *et al.*, 2003; Rosengard *et al.*, 2005). For HI listeners, the slopes of temporal-masking functions are typically shallower than those of NH listeners (e.g., Nelson *et al.*, 2001; Plack *et al.*, 2004; Lopez-Poveda *et al.*, 2005; Rosengard *et al.*, 2005; Stainsby and Moore, 2006). For listeners with mild-to-moderate hearing impairment, the ratio of the slopes obtained with off-frequency and on-frequency maskers is similar to that of NH listeners, thus suggesting a similar amount of compression (Plack *et al.*, 2004). For more severe hearing loss, however, the slopes of the temporal-masking functions tend to be similar for on- and off-frequency maskers and suggest a reduction or even absence of the cochlear compressive function that may arise from outer hair-cell damage. The reduced recovery rates of HI listeners from temporal masking compared to those of NH listeners (likely related to differences in peripheral compression) may contribute to the reduced ability of HI listeners to take advantage of temporal modulations in noise to improve speech reception.

There have been several efforts to understand and model temporal masking. Duifhuis (1973) attempted to account for the time course of backward and forward masking caused by clicks or brief tone pulses. He concluded that whereas backward masking reflected mainly a short-term transient component, extending over 20 ms, due to peripheral interaction between the masker and probe, forward masking also exhibited a longer-term component with a time constant of roughly 75 ms, due presumably to “physiological adaptation.”

Recently, Wojtczak *et al.* (2001) assessed masking period patterns (MPPs) by measuring the threshold of brief tonal probes in the presence of a slowly amplitude-modulated tonal masker. They found that whereas the off-frequency MPPs for NH listeners exhibited deeper and longer valleys compared with the on-frequency MPPs, for HI listeners, the MPPs had similar shapes for on- and off-frequency maskers. They modeled this effect by assuming different cochlear gains for normal versus impaired hearing (i.e., a

reduction or absence of basilar-membrane compressive function) but similar temporal processing characteristics for both groups of listeners.

Two previous studies (Kidd *et al.*, 1983; Gregan *et al.*, 2010) have explored the effects of background noise on the performance of NH listeners in forward-masking paradigms. Kidd *et al.* (1983) used a hearing-loss simulation employing threshold-elevating noise to study the effect of masker duration on forward-masked thresholds. Whereas HI listeners were generally insensitive to the duration of the masker, the listeners with simulated loss experienced greater masking with an increase in masker duration. More recently, Gregan *et al.* (2010) measured growth of forward masking in NH listeners in threshold-elevating noise with a passband of 20–20 000 Hz at levels of 20 to 50 dB sound pressure level (SPL) within the equivalent rectangular bandwidth around 1000 Hz. Measurements were made of the level of a 200-ms forward masker (either 4000 or 1800 Hz) required to just mask a 4-ms, 4000 Hz probe tone with levels in the range 35–85 dB SPL. The delay between masker offset and probe onset was always 0 ms. Estimates of cochlear compression were independent of the level of background masking noise and ranged from 0.23 to 0.31. The authors concluded that, for their experimental paradigm, the use of a masking noise to simulate threshold elevation in hearing loss did not change the compressive function of the basilar membrane.

The current study was undertaken to determine if the temporal-masking functions observed in HI listeners could be reproduced in NH listeners with simulated loss. Temporal-masking functions were obtained in HI listeners at three different masker frequencies for each of four probe frequencies. The hearing loss of each of eight HI listeners was simulated in a corresponding group of age-matched NH listeners, and temporal-masking functions were obtained for these listeners as well. Given the results of forward-masking studies indicating increased susceptibility to forward masking with age (e.g., Dubno *et al.*, 2002; Gifford and Bacon, 2005), the effects of age were controlled in this study through the use of NH listeners who were matched roughly in age to the HI listeners. This study addressed the specific question of whether the slopes of temporal-masking functions for on- and off-frequency maskers observed in HI listeners can be reproduced in the forward-masking results of age-matched NH subjects listening to stimuli processed through a hearing-loss simulation.

II. METHODS

A. Hearing-loss simulation techniques

Previous studies have employed two basic approaches to hearing-loss simulation in assessing the psychoacoustic and speech-reception abilities of HI listeners. The first approach involves the use of additive masking noise (e.g., Milner *et al.*, 1984; Zurek and Delhorne, 1987; Florentine *et al.*, 1988; Dubno and Schaefer, 1992; Florentine *et al.*, 1993). The use of additive noise simulates the elevated thresholds, reduction in dynamic range, and loudness recruitment observed in sensorineural hearing loss, and yields signals with equivalent levels expressed both in dB SPL and dB

sensation level (SL) in listeners with real and simulated loss. Because of the levels of required masking noise, however, this simulation technique is limited to losses below roughly 70 dB hearing level (HL). A second approach to simulation of cochlear hearing loss employs multi-band amplitude expansion (Villchur, 1973, 1974; Duchnowski, 1989; Moore and Glasberg, 1993; Duchnowski and Zurek, 1995; Graf, 1997; Lum and Braida, 1997) to provide level-dependent attenuation of the input signal to achieve elevated thresholds and recruitment. This method yields signals with equivalent levels expressed in dB SL (but not dB SPL) in listeners with real and simulated loss and has the advantage of being able to simulate impairments that are more severe than those that can be comfortably simulated using masking noise.

In the current study, the preferred method of hearing loss simulation employed additive threshold noise (TN) that was spectrally shaped to yield the desired threshold shifts. For severe threshold shifts (>60–70 dB HL), however, the required amount of threshold noise could be unacceptably loud (i.e., >80 dB SPL). In these cases, TN was combined with multi-band expansion (MBE) to produce the desired threshold shifts. Each of these methods (TN and TN/MBE) is described briefly below. A more detailed description of the TN and TN/MBE hearing-loss simulation techniques can be found in Desloge *et al.* (2010).

1. Simulation using additive threshold noise (TN)

For this hearing-loss simulation technique, the desired frequency-dependent threshold shifts were used together with the corresponding critical ratio values (Hawkins and Stevens, 1950) to generate spectrally shaped additive TN that elevated the detection thresholds of NH listeners so that they matched those of HI listeners over the frequency range of 80 Hz to 12.5 kHz. This noise was then added to the stimulus signal to yield the hearing-loss-simulated presentation signal (see Fig. 1, top). Because of the matching threshold shift, the test stimuli were presented to HI and simulated-loss NH listeners at the same SPL and SL. Further, because the additive threshold noise produces a growth of loudness similar to that experienced by HI listeners with the same threshold shift (e.g., Steinberg and Gardner, 1937), this method of simulating hearing loss simulated loudness recruitment as well.

The current study used the TN technique to simulate the desired hearing losses whenever possible. In cases of more severe losses, however, the noise was scaled down to a level of 80 dB sound pressure level and then combined with multi-band expansion (MBE) to produce the desired threshold shift.

2. Simulation using additive threshold noise and multi-band expansion (TN/MBE)

Multi-band expansion (MBE) produced threshold shifts by attenuating the stimulus dynamically. This was accomplished by passing the input signal through a multi-band filterbank, monitoring short-time band signal levels, and applying a level-dependent attenuation to each band signal (Duchnowski, 1989; Moore and Glasberg, 1993; Duchnow-

FIG. 1. (top) Block diagram of system used for hearing-loss simulation based on additive threshold noise. (bottom) Block diagram of system used for hearing-loss simulation based on a combination of additive threshold noise and multi-band expansion (MBE) processing. The upper path processes the signal with MBE level-dependent gain while the lower path generates the threshold-shifting noise.

ski and Zurek, 1995; Graf, 1997; Lum and Braida, 1997). The dynamic, level-dependent attenuation for hearing loss simulation was designed to yield the desired threshold shift as well as the loudness growth associated with sensorineural hearing loss within each band. Specifically, MBE within a given band:

- (1) attenuated input signals at levels lower than the desired hearing threshold so that the corresponding outputs were presented at levels below the listener's actual hearing threshold;
- (2) attenuated input signals at levels exactly equal to the desired hearing threshold so that the corresponding outputs were presented at the listener's actual threshold;
- (3) Attenuated input signals at levels between the desired hearing threshold and the full-recruitment level by progressively lower amounts (louder inputs undergo less attenuation) to simulate loudness growth above threshold;
- (4) did not attenuate input signals at levels above the full-recruitment level.

As stated above, in situations where TN simulation alone would have required excessively loud threshold noise, the current study scaled the broadband TN down to the maximum acceptable TN level of 80 dB SPL. Specifically, if the required TN had a broadband level of $(80 + \alpha)$ dB SPL, it was attenuated by α dB. This scaled TN simulated a partial hearing threshold shift of up to α dB lower than desired which was recovered using MBE processing in the combined TN/MBE simulation (see Desloge *et al.*, 2010). The combination of TN and MBE minimized the difference in stimulus level in dB SPL experienced by HI and simulated-loss NH listeners. Specifically, relative to the HI listeners, simulated-loss NH listeners using a TN/MBE simulation experienced

TABLE I. Description of hearing-impaired subjects in terms of sex, audiometric thresholds in dB HL in left and right ears at 6 frequencies, hearing-aid (HA) use, history/etiology, and age in years. For each subject, the test ear employed in the study is denoted by an asterisk and bold lettering. Also provided are the mean ages of the AM-SIM group and the method used to simulate the hearing loss with the α factor (in dB) indicated for the TN/MBE simulations.

Subject	Sex	Ear	Audiometric Thresholds in dB HL specified for frequencies in kHz						HA Use in Test Ear?	Etiology	Age	AM-SIM Group Age	Sim. Method
			.25	.50	1.0	2.0	4.0	8.0					
HI-1	M	* L	15	20	25	35	40	35	No	Hereditary	24	23.0	TN
		R	15	20	15	40	35	25					
HI-2	M	L	30	35	45	55	55	60	Yes	Congenital?	21	20.3	TN
		* R	25	30	45	50	55	60					
HI-3	M	L	25	25	25	30	55	75	No	Unknown/ Adult-onset	64	61.7	TN/MBE ($\alpha = 4$)
		* R	25	35	30	30	40	75					
HI-4	F	* L	10	30	45	60	60	80	Yes	Congenital	59	53.0	TN/MBE ($\alpha = 7$)
		R	20	35	40	60	65	70					
HI-6	F	* L	40	50	55	55	60	45	Yes	Unknown	55	55.3	TN
		R	40	50	55	60	70	90					
HI-7	M	L	65	60	70	80	70	95	Yes	Hereditary/ Congenital	69	61.0	TN/MBE ($\alpha = 13$)
		* R	60	60	75	70	70	85					
HI-8	M	L	55	65	65	65	70	90	Yes	Hereditary	68	64.0	TN/MBE ($\alpha = 10$)
		* R	60	65	65	70	80	70					
HI-10	F	* L	50	35	30	20	15	95	Yes	Congenital	43	43.0	TN/MBE ($\alpha = 30$)
		R	65	50	50	25	20	100					

stimuli at the equivalent SL but at a lower SPL of up to α dB.

As shown in Fig. 1 (bottom), TN and MBE were combined by processing the stimulus signal with MBE processing and then adding the resulting signal to spectrally shaped threshold noise to yield the output signal. The MBE implementation used in this research was based upon the work of Moore and Glasberg (1993).

B. Stimulus generation

Experiments were controlled by a desktop PC equipped with a high-quality, 24-bit PCI sound card (either LynxOne by LynxStudios or E-MU 0404 by Creative Professional). Two-channel stimulus signals (including the hearing-loss simulation, if present) were generated and played out using MatlabTM; passed through a pair of Tucker-Davis (TDT) PA4 programmable attenuators and a TDT HB6 stereo headphone buffer; and presented to the subject in a soundproof booth via a pair of Sennheiser HD580 headphones. The system was calibrated so that precise sound levels could be presented over the HD580 headphones (as measured on a KEMAR manikin). Peak output levels of approximately 118 dB SPL were attainable with this system.

The primary experimental engine used to generate and to adaptively modify the experimental stimuli was the AFC Software Package for MatlabTM provided by Stephan Ewert and developed at the University of Oldenburg, Germany. A monitor, keyboard, and mouse located within the sound-treated booth allowed interaction with the control PC.

C. Subjects

1. Listeners with hearing impairment

Eight subjects with bilateral sensorineural hearing loss who were native speakers of English participated in the study. Each subject was required to have the report of a recent clinical audiological examination (within 1 year of entry into the laboratory study) to verify that the hearing loss was of cochlear origin on the basis of air- and bone-conduction audiometry, tympanometry, speech-reception thresholds, and word-discrimination scores. On the subject's first visit to the laboratory, informed consent was obtained and an audiogram was readministered for comparison with the subject's most recent evaluation from an outside clinic. In all cases, good correspondence was obtained between these two audiograms.

Information on the eight HI listeners is provided in Table I, with data on sex, audiometric thresholds, history/etiology, hearing-aid use, and age. The subjects (who ranged in age from 21 to 69 yr) were selected to have bilateral losses that were roughly symmetrical. Audiometric thresholds across ears were within 20 dB of each other at each test frequency with the exception of 8000 Hz for HI-6. For each subject, a test ear was selected for monaural listening in the experiments (shown in boldface in Table I). Typically, this was the ear with better average thresholds across test frequencies. Hearing losses ranged from mild/moderate to severe/profound across subjects. The audiometric configurations observed across the hearing losses of these subjects included: (1) sloping high-frequency loss (HI-1, HI-2, HI-3, HI-4), (2) relatively flat loss with no more than a 20-dB difference between adjacent audiometric frequencies (HI-6, HI-

7, HI-8), and (3) inverted “cookie-bite” loss characterized by near-normal thresholds in the mid-frequency range and moderate loss at low and high frequencies (HI-10). All but two of the subjects (HI-1 and HI-3) were regular or occasional hearing-aid users at the time of entry into the study. (All measurements in the current study were obtained without the use of the listener’s hearing aid.)

These eight HI subjects are a subset of the 10 subjects who participated in the speech-reception-in-noise study described by Desloge *et al.* (2010). For continuity with the previous paper, the same subject labels were preserved for the current study.

2. Listeners with normal hearing

Twenty-four NH listeners who were native speakers of English were recruited to participate in the hearing-loss simulation component of the study. Subjects provided informed consent and a clinical audiogram was then obtained to screen for normal hearing in at least one ear, defined as 25 dB HL or better at frequencies in the range of 250 to 4000 Hz and 30 dB HL at 8000 Hz. Subjects ranged in age from 18 to 65 yr. Three NH listeners were selected as age-matched listeners with hearing-loss simulation (AM-SIM) for each of the eight HI listeners. These listeners’ ages were in the range of plus or minus 9 yr relative to that of the given HI listener to whom they were assigned. Only two of the three AM-SIM listeners matched to HI-7 and only one of the three matched to HI-10 were able to complete the testing. The mean ages of the AM-SIM listeners associated with HI-1 through HI-10 who completed the study are provided in Table I. Also provided in Table I is the hearing-loss simulation method (TN or TN/MBE) used to simulate the corresponding HI subject’s loss and, for the TN/MBE simulations, the α term describing the approximate amount of threshold shift simulated by MBE.

For each NH subject, a test ear was selected for conducting the hearing-loss simulation testing. This was typically the same ear as that of the HI subject whose loss was being simulated. In cases where only one ear of a given subject met the audiometric criteria defined above, that ear was selected as the test ear regardless of whether or not it was the same ear as that tested in the HI listener being simulated. Two of these AM-SIM listeners (ages 56 and 62 yr) also participated in the experiment without the use of hearing-loss simulation and are referred to as the NH group. All subjects, both HI and NH, were paid for their participation in the study.

D. Absolute threshold and simulated-loss threshold testing

Absolute detection thresholds were measured in the left and right ears of each HI and NH listener without simulated hearing impairment at frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz. Thresholds at these frequencies were also measured in the NH listeners in the presence of simulated hearing impairment designed to duplicate the threshold shifts evident for the corresponding HI listener. Measurements were obtained for signal durations of 500 and 10 ms.

The 500-ms thresholds obtained in the HI listeners were used to create the hearing-loss simulation. The 10-ms thresholds were used to set the probe signal levels in the forward-masking experiments. It should be noted, however, that for the AM-SIM listeners, the same hearing-loss simulation (based on the 500-ms thresholds) was employed regardless of signal duration.

Threshold measurements were obtained using a three-interval adaptive forced-choice procedure with trial-by-trial correct-answer feedback. Tones were presented with equal *a priori* probability in one of the three intervals and the listener’s task was to identify the interval containing the tone. For 500-ms signals, each interval was cued on the visual display during its 500-ms presentation period with a 500-ms inter-stimulus interval. Subjects were given unlimited time in which to respond. Tones were windowed to have a 500-ms total duration with a 10-ms Hanning-window ramp on and off (yielding a 480-ms steady-state portion). For 10-ms signals, intervals were cued visually for 250 ms with a 500-ms inter-stimulus interval. The signals were windowed to have a 10-ms total duration with a 5-ms Hanning-window on/off ramp (thus, there was no steady-state portion) and then padded to 250 ms total duration to correspond with the visual cue. During all experimental runs, the level of the tone was adjusted adaptively using a one-up, two-down rule to estimate the stimulus level for 70.7% correct (Levitt, 1971). The step size was 8 dB for the first two reversals, 4 dB for the next two reversals, and 2 dB for the remaining six reversals. The final threshold estimate was the mean presentation level of the final six reversals.

When measuring thresholds in NH subjects with simulated hearing loss, each stimulus was processed for hearing loss simulation (using either TN or TN/MBE) immediately preceding each presentation. For both simulation techniques, the threshold-elevating noise was initiated 500 ms before the first stimulus interval and terminated 50 ms after the final interval (for a total noise duration of 3050 ms per trial for the 500-ms signals and 1580 ms per trial for the 10-ms signals).

At each of the two signal durations, thresholds were measured in blocks of 12 runs, with each block consisting of two 6-run sub-blocks (one per ear) where each sub-block measured the 6 test frequencies in random order. The two ears were also tested in random order.

The HI listeners typically completed two blocks of runs measuring thresholds in quiet at each signal duration. Each NH listener completed two blocks of runs measuring thresholds in quiet and another two blocks of runs measuring thresholds under the hearing-loss simulation at each of the two signal durations. Thresholds were averaged across the two runs at each frequency under each type of listening condition (quiet or simulated-loss).

E. Forward masking

Forward masking functions were obtained by measuring the level of a pure-tone masker required to mask a trailing probe signal that was presented at a fixed level above its threshold of detection. The probe signal was a pure-tone

burst with a total duration of 10 ms created using 5-ms Hanning-window on/off ramps (thus, with no steady-state portion) at a frequency of $f_p = 500, 1000, 2000$, or 4000 Hz. For each f_p , three values of masker frequency, f_m , were employed that were 0.55, 1.0, and 1.15 times the value of f_p (i.e., an on-frequency masker and two off-frequency maskers). The total duration of the pure-tone masker was always 110 ms including 5-ms Hanning-window on/off ramps and a steady-state duration of 100 ms. The probe was presented at five different values of time delay between masker offset and probe onset: 0, 10, 20, 60, and 100 ms.

Thresholds were measured using a three-interval adaptive forced-choice procedure with trial-by-trial correct-answer feedback to measure the level of the masker required for 70.7%-correct detection of the probe. The pure-tone masker was presented in all three intervals and the probe was presented in one of these intervals (selected at random on each trial) with the appropriate delay between masker offset and probe onset. The subject's task was to identify which interval contained the probe tone. The intervals were cued visually on a computer screen, and the total duration of each interval was equal to the sum of the durations of the masker, the time delay, and the probe (even when the probe was not present). Each test run was initiated with the masker level at 0 dB SPL. The masker level was then adjusted adaptively using a one-down, two-up rule: masker level was decreased after each incorrectly-identified trial (subject to a restriction that masker level never fall below -10 dB SPL) and increased after two successive correctly identified trials. The adaptive masker-level step size was 8 dB until the first reversal, 4 dB until the second reversal, and then 2 dB for all remaining reversals. The measurement phase commenced when the step size reached 2 dB and lasted for 8 reversals. The threshold was calculated as the average masker level during the measurement phase. For the AM-SIM subjects, all stimuli were processed according to either TN or TN/MBE hearing loss simulation (based upon 500-ms thresholds of the corresponding HI-listener). The TN was initiated 500 ms before the start of each trial, played continuously throughout the three stimulus intervals, and terminated 50 ms after the final interval.

For each HI listener, the initial probe-signal level was set to 5 dB SL with regard to the 10-ms absolute thresholds at the corresponding frequency f_p . For each AM-SIM listener, the initial probe-signal level was set to 5 dB SL relative to their individual 10-ms absolute thresholds at the corresponding frequency f_p in the presence of a simulation designed to reproduce the HI listener's 500-ms threshold shift. If a given HI or AM-SIM listener had difficulty detecting the 5-dB-SL probe in the forward-masking conditions (as evidenced by masker-threshold values that could be attributed to chance performance alone and/or were not affected by time delay for an on-frequency masker) then the level of the probe was increased gradually until masker threshold values showed some dependence on time delay. For any given subject, all data at a given f_p were obtained using the same probe level.

Two threshold measurements were obtained at each of the 60 experimental conditions ($4 f_p \times 3 f_m \times 5$ delays). For

each of two replications of the experiment, the conditions were presented in random order as follows. First, the order of the four probe frequencies was randomized, then the order of the three masker frequencies for each f_p , and finally, for each f_m , the order of the five time delays. For each of the 60 conditions, a third measurement was obtained if the first two thresholds differed by more than 10 dB, and the outlier measurement was discarded.

Due to both hardware limitations and safety concerns, the maximum output level of the experimental hardware was capped at known values ranging from 104 to 118 dB SPL depending upon the subject. These caps resulted in situations where the masker could never be presented at a level sufficiently loud to completely mask the probe signal. In these cases, "masking" threshold values were still obtained, but these values were heavily influenced by the output-level cap. Such trials were flagged and were handled with special care in the data analyses as described in detail below.

III. RESULTS

A. Absolute thresholds and simulation thresholds

The threshold measurements for each of the eight HI-listeners and for the AM-SIM group associated with each listener are shown in Fig. 2 (for 500-ms signals) and in Fig. 3 (for 10-ms signals). In each figure, the HI-listener data points are the average of two measurements, while the AM-SIM group points are the average of six measurements (two measurements for each of the three subjects within a group) for all subjects with the exceptions of HI-7 (four measurements) and HI-10 (two measurements). In addition to these two sets of data points, each panel also shows the average thresholds for each AM-SIM group without simulated loss. As with the simulated-loss data points, these data points are the average of six measurements for all subjects except for HI-7 (four measurements) and HI-10 (two measurements).

For the 500-ms signals (Fig. 2), the simulated-loss thresholds of the AM-SIM group are generally within 5 dB (and, in the majority of cases, within 2 dB) of the desired, HI-listener thresholds. The one exception to this behavior involves the thresholds for HI-10 at 4000 Hz. In this case the single AM-SIM subject has thresholds that are approximately 10–12 dB higher than those of the HI subject. This discrepancy resulted from the steep increase (over 80 dB) in hearing threshold between 4000 and 8000 Hz. The energy of the TN in the frequency region around 8000 Hz likely led to masking at 4000 Hz.

Results obtained with 10-ms signals are shown in Fig. 3. Using the same hearing-loss simulation that produced a good match to the performance of the HI listeners for 500-ms signals, the 10-ms thresholds of the AM-SIM groups tend to be higher than those of their corresponding HI listeners. This result is consistent with the previously reported observation of a decreased effect of duration on threshold for HI compared to noise-masked NH listeners (e.g., see Florentine *et al.*, 1988). The difference in thresholds in dB SPL between the 10-ms and 500-ms signals is plotted as a function of test frequency in Fig. 4 for each HI-listener and for

FIG. 2. Threshold in dB SPL as a function of frequency for 500-ms tone stimuli. In each subplot, absolute thresholds are shown for a given HI listener (filled squares). For each HI listener, simulated-loss thresholds are averaged across the NH listeners in the AM-SIM group (filled circles). Also shown are average quiet (without simulated loss) thresholds for the AM-SIM group (unfilled circles).

the corresponding AM-SIM group both with and without hearing-loss simulation. The improvement in thresholds with an increase in signal duration is similar in the AM-SIM listeners whether listening without simulation or under simulated-loss conditions and is generally greater than that observed for the HI listeners (similar to results of Gengel (1972) and Florentine *et al.* (1988)).

In conducting the forward-masking tests with AM-SIM listeners, the decision was made to employ the simulation conditions that led to the desired threshold elevations of the HI listeners for 500-ms stimuli. Under these conditions, the AM-SIM listeners demonstrated a tendency for higher thresholds for 10-ms signals than those of the HI listeners (see Fig. 3). As stated in Sec. II E, the initial levels of the 10-ms probe tones employed in forward-masking tests were set to 5 dB SL for each listener at the corresponding probe frequency. Probe-tone levels for the HI subjects and average probe-tone levels for the corresponding AM-SIM groups can be determined by adding 5 dB to the 10 ms

FIG. 3. Threshold in dB SPL as a function of frequency for 10-ms tone stimuli. In each subplot, absolute thresholds are shown for a given HI listener (filled squares). For each HI listener, simulated-loss thresholds are averaged across the NH listeners in the AM-SIM group (filled circles). Also shown are average quiet (without simulated loss) thresholds for the AM-SIM group (unfilled circles).

threshold values at 500, 1000, 2000, and 4000 Hz shown in Fig. 3. On average, the 5-dB SL 10-ms probe-tone levels were 7.2 dB higher for the AM-SIM subjects than for the HI subjects.

B. Forward-masking

Temporal-masking functions were obtained by plotting the levels of the forward masker (referred to as the forward-masking threshold) versus the time delay between masker offset and probe onset (in ms) for each of the 12 probe/masker conditions. Plots of the data for each HI listener and for the individual AM-SIM listeners associated with that particular HI listener are provided in Fig. 5 (HI-1 and HI-2), Fig. 6 (HI-3 and HI-4), Fig. 7 (HI-6 and HI-7), and Fig. 8 (HI-8 and HI-10). Open symbols indicate data that were determined to be limited by the maximum presentation level. As such, these points represent a lower bound on the forward-masking threshold. Filled symbols indicate forward-

FIG. 4. The difference in threshold in dB as a function of stimulus duration (10-ms threshold minus 500-ms threshold) as a function of signal frequency. In each subplot, threshold-difference values are shown for a given HI listener (filled squares). For each HI listener, simulated-loss threshold-difference values are averaged across the NH listeners in the AM-SIM group (filled circles). Also shown are average quiet (without simulated loss) threshold-difference values for the AM-SIM group (unfilled circles).

masking thresholds that were not limited by the maximum presentation level. Also indicated are the standard deviations averaged across the 60 experimental conditions for each HI listener and AM-SIM group. Average standard deviations ranged from 1.3 (HI-8) to 3.1 (HI-4) dB across the 8 HI listeners and averaged 2.4 dB. For individual AM-SIM listeners, average standard deviations ranged from 1.5 to 8.2 dB with a mean of 3.1 dB. Examination of the AM-SIM data for a given HI listener reveals cases of substantial variability among subjects, a result that is not unexpected given the demonstration of variations in performance among NH listeners on forward masking tasks (e.g., [Lopez-Poveda et al., 2003](#); [Nelson and Schroder, 2004](#)). The standard deviations across the AM-SIM groups ranged from 3.5 to 8.2 dB and averaged 6.1 dB.

The HI data and the AM-SIM data for each probe/masker condition were independently fit with two line seg-

FIG. 5. (left) Low-frequency, (middle) on-frequency, and (right) high-frequency masker forward masking threshold values in dB SPL as a function of delay between masker offset and probe-tone onset for subjects HI-1 (upper half of figure) and HI-2 (lower half of figure). For each subject, different rows show results for different probe frequencies (500, 1000, 2000, and 4000 Hz proceeding from top to bottom). Thresholds for the HI listeners are shown by squares and thresholds for the individual AM-SIM listeners associated with a given HI listener are shown by triangles in three different orientations. Open data points correspond to measurements that included “equipment-limited” data that were influenced by the maximum presentation-level of the experimental hardware and as such indicate lower-bounds on forward masking threshold. Also indicated are two-segment, linear-regression fits to the data for the HI listener (solid lines) and for the mean AM-SIM data (dashed lines). Average standard deviations across all 60 experimental conditions are indicated for each HI subject and corresponding AM-SIM group.

FIG. 6. As in Fig. 5 except for subjects HI-3 and HI-4.

FIG. 7. As in Fig. 5 except for subjects HI-6 and HI-7.

ments that met at a knee-point with the slope of the segment fitting the higher probe-delay data points constrained to equal zero. This two-line regression was completely described by the slope of the linear segment fitting the lower probe-delay data points and the knee-point location, which was specified by two values as (probe-delay, masker-level). The reason for this particular two-segment regression with a flat fit for higher probe delays lies in the flattening of forward masking thresholds at these delays observed in several of the plots: the flat portion of the two-segment linear regression represents this high-probe-delay region of the data. The observed behavior arose either due to performance saturation

on the part of the test subject (indicated by filled symbols) or due to equipment limitations on maximum masker output level (indicated by open symbols). The optimal two-segment linear regression fit was determined by varying all three parameters freely to find those that yielded the minimum root mean square (RMS) masker-level error between the data and the fit. The equipment-limited measurements (open symbols) were included in this fitting procedure, since each of these data points provided useful information in the form of a lower bound on forward masking threshold. They were, however, treated with special care in computing the RMS error that was minimized during the two-segment,

FIG. 8. As in Fig. 5 except for subjects HI-8 and HI-10.

linear-regression fitting process. Specifically, each of these equipment-limited, lower-bound measurements contributed to the error only when the fit was below the measurement value and not when the fit exceeded the measurement value. In other words, an equipment-limited measurement was treated as a “valid” data point when located above the two-segment fit and ignored otherwise.

The two-segment linear-regression fits to the data are shown as a solid line (for the HI data) and a dashed line (for the average AM-SIM data) in Figs. 5–8. The RMS difference between the fits and the observed data was less than 5 dB for 96% of the functions obtained in the HI listeners and aver-

aged 1.6 dB. For the mean AM-SIM results, fitting errors were somewhat larger (averaging 4.9 dB) due to inter-subject variability. The results of the linear fits are described below in terms of their slopes and y-intercepts.

Table II summarizes the slopes in dB/ms of the lower-delay portion of the linear-regression fits to the data for the 8 HI subjects and corresponding AM-SIM groups across all test conditions. The final column of Table II contains the slopes of the lower-delay linear-regression fits for the mean NH data. The table also provides information regarding the probe-delay corresponding to the linear-regression knee-point. This knee-point probe delay describes the extent of the sloping region of the regression fit. Table III summarizes the y-intercepts of the linear fits in dB SPL for the 12 functions obtained for each HI listener and the corresponding AM-SIM group, as well as for the NH group.

As a means of comparing the simulation results to the data of the HI listeners, the RMS error was computed between each of the 12 masking functions obtained for a given HI listener and the corresponding average AM-SIM masking functions. The RMS error between these functions was calculated using only data from probe delays where neither the HI nor any of the AM-SIM subjects experienced equipment-related limitations on maximum masker presentation level. Out of 96 possible RMS-error calculations (8 HI subjects and 12 masking functions), 11 were eliminated on the basis of this criterion. Figure 9 shows a histogram of the RMS errors for the remaining 85 calculations. Of these, 61 (72%) had RMS error within the range of 0–10 dB. (For reference, the errors of measurement in the data were 2.4 dB averaged over the 8 HI listeners and 6.1 dB over the 8 AM-SIM groups.) Mean RMS errors were lowest for HI-1, HI-3, HI-6, and HI-8 (who had 0–2 functions each with RMS error greater than 10 dB) and intermediate for HI-2 and HI-7 (both with 4 functions in this range). Twelve of the twenty-four functions with RMS error greater than 10 dB arose from the data of HI-4 and HI-10. The larger RMS-error cases were roughly equally distributed among the three maskers and the four probe frequencies.

Visual inspection of the data indicates atypical temporal masking patterns for subject HI-6 and for the single AM-SIM subject matched to HI-10. In the case of HI-6, for f_p of 1000 Hz and above, the masking functions saturate at relatively low probe delays and masker levels. At these frequencies, HI-6 shows very little sensitivity to increases in probe delay despite repeated practice on the task and more typical performance at $f_p = 500$ Hz. In the case of the AM-SIM match to HI-10, the masking functions exhibit high measurement variability and atypically low forward masking thresholds at high probe delays. The peculiar properties of the inverted cookie-bite loss of HI-10 (and the poor hearing-loss simulation at 4000 Hz, see Fig. 2) may contribute to this behavior. It is also possible for both subjects that the probe-tone levels were not sufficiently high to allow for a high rate of detection (either in quiet for HI-6 or in the simulation noise for the AM-SIM listener). However, higher probe levels of up to 10 dB SL were investigated with these two listeners and did not lead to an increase in the performance saturation level. Masker-probe confusion (Neff, 1986) is

TABLE II. Slopes (in dB/ms) of the lower-probe-delay portion of the two-segment linear-regression fit to the temporal-masking data shown for the 8 HI subjects and their corresponding AM-SIM groups. Also shown are slopes for the NH subject group. Regression fits without footnotes (the most common cases) had knee-points ranging from 20–40 ms. Slopes marked with an asterisk indicate the presence of equipment-limited measurements in the data for the experimental condition. As described in the text, equipment-limited data were treated as lower bounds on performance in the slope calculation.

f_p	f_m	Group	Subject								
			HI-1	HI-2	HI-3	HI-4	HI-6	HI-7	HI-8	HI-10	NH
500 Hz	0.55* f_p	HI	0.63	0.74*	0.65	1.01*	0.37*	0.58*	0.54	0.55 ^{a*}	0.42 ^a
		AM-SIM	0.78	0.78	0.63*	0.51 ^{a*}	0.88 ^b	0.82	0.02 ^c	0.23 ^c	
	1.0* f_p	HI	0.64 ^{a*}	0.56 ^{a*}	0.95	1.15*	0.57*	0.37 ^{c*}	0.48	0.66 ^{a*}	0.84 ^a
		AM-SIM	1.42	1.96	0.87*	0.55 ^{a*}	0.73	0.92	0.76	0.22 ^{a*}	
	1.15* f_p	HI	0.52 ^{a*}	0.41 ^{a*}	1.01	0.51*	0.45*	0.37 ^{c*}	0.41	0.65 ^{a*}	1.54*
		AM-SIM	1.47	1.28	1.04	1.02	1.07	0.66	0.95	0.30 ^{a*}	
1000 Hz	0.55* f_p	HI	0.71	0.41 ^a	0.36 ^{a*}	0.63*	0.14 ^{c*}	0.39 ^a	0.29 ^a	0.52 ^a	0.54 ^a
		AM-SIM	0.84	0.82	0.36 ^{a*}	1.01*	0.34	0.86	0.16 ^a	1.70 ^b	
	1.0* f_p	HI	0.79 ^a	0.82	0.75 ^{a*}	1.37*	0.19 ^{c*}	0.46 ^a	0.26 ^c	0.58 ^{c*}	0.95 ^{a*}
		AM-SIM	1.29	1.11	0.54 ^{a*}	0.46	0.56 ^a	0.41	0.57	0.26 ^{c*}	
	1.15* f_p	HI	1.19	0.49	0.68	1.17 ^{b*}	0.17 ^{c*}	0.23 ^{a*}	0.34	0.69 ^{a*}	1.03
		AM-SIM	1.48	0.69	0.54 ^a	0.65	0.44	-0.07	0.62	0.45 ^{c*}	
2000 Hz	0.55* f_p	HI	0.58	0.26 ^c	0.45 ^{a*}	0.69*	0.41	0.72	0.31	0.49 ^{a*}	0.78
		AM-SIM	0.56	0.31	0.43 ^a	0.52	1.17 ^b	0.18 ^c	0.56 ^b	0.13 ^{c*}	
	1.0* f_p	HI	0.80	0.64	0.82 ^a	1.01	-0.01 ^b	0.65	0.32	1.17 ^a	0.99 ^a
		AM-SIM	0.83	0.96	0.56 ^a	0.54 ^b	0.94	0.38 ^a	0.37	0.22 ^{c*}	
	1.15* f_p	HI	0.51 ^b	0.22	1.11	1.50 ^b	0.15 ^c	0.59	0.31	0.71	1.31
		AM-SIM	0.87	0.78	1.04	0.50 ^b	0.44	0.47	0.43	0.27 ^{c*}	
4000 Hz	0.55* f_p	HI	0.50 ^b	0.13 ^a	0.35 ^{a*}	0.32	0.08*	0.38 ^a	0.26	0.39 ^{a*}	0.36
		AM-SIM	0.58	1.15 ^b	0.47 ^a	0.19	0.76 ^b	0.12 ^a	0.20 ^b	0.21 ^a	
	1.0* f_p	HI	0.65	0.52	0.42 ^{c*}	0.43 ^a	0.22 ^{b*}	0.37 ^a	0.25	0.66 ^{a*}	0.62 ^c
		AM-SIM	1.04	0.54 ^b	1.54 ^b	0.10 ^{c*}	0.81	0.49 ^b	0.62 ^b	0.65 ^b	
	1.15* f_p	HI	0.38 ^b	1.45 ^b	1.18 ^b	0.36 ^a	-0.05 ^{c*}	0.26 ^a	0.21	0.46	0.91 ^a
		AM-SIM	0.65	0.61	0.71 ^b	0.31*	1.46 ^b	0.31 ^a	0.34	1.02	

^aRegression fits with knee-points ranging from 40–60 ms.

^bRegression fits with knee-points ranging from 10–20 ms.

^cRegression fits with knee-points ranging from 60–100 ms.

another possibility that may account for these results, particularly for short delays with an on-frequency masker. Neff (1986), however, observed that confusion effects were minimal for sinusoidal maskers and signals of the durations employed here. Additionally, Wojtczak and Oxenham (2010) concluded that masker-probe confusion in a forward masking task was likely absent in HI listeners based on the similarity of the recovery-of-masking functions observed for 150-ms sinusoidal on-and off-frequency maskers of a 10-ms tone.

Two three-way analysis of variances (one on slopes and the other on y-intercepts) were conducted using the main factors of probe frequency, masker type (low-frequency, on-frequency, and high-frequency), and hearing status (HI, AM-SIM, and NH) and tested for significance at the 0.01 level. For the slope analysis, significant effects were found for masker frequency ($F = 6.00$, $df = 2$, 180 , $p = 0.003$) and hearing status ($F = 5.62$, $df = 2$, 180 , $p = 0.004$) but not for probe frequency ($F = 1.72$, $df = 3$, 180 , $p = 0.157$). No significance was observed for any of the two-way interactions. A *post hoc* Scheffe test on the masker effect indicated that the masker frequency of $0.55*f_p$ produced significantly shallower slopes than the masker frequency of $1.15*f_p$. The on-frequency masker slopes were intermediate between those of the low- and high-frequency maskers and were not significantly different from either. A *post hoc* Scheffe test on hear-

ing status indicated that the slopes observed in the NH data were significantly steeper than those of the HI data, and that the AM-SIM slope values were intermediate between the HI and NH values and not significantly different from either. The analysis of variance on y-intercepts also indicated significant effects for masker frequency ($F = 14.27$, $df = 2$, 180 , $p < 0.0001$) and hearing status ($F = 19.71$, $df = 2$, 180 , $p < 0.0001$) but not for probe frequency ($F = 3.14$, $df = 3$, 180 , $p = .027$). None of the two-way interactions reached significance. The *post hoc* Scheffe analyses showed that the on-frequency masker produced lower y-intercepts than the other two maskers (which were equivalent) and that the y-intercepts for the NH group were significantly lower than those for the HI and AM-SIM groups (which were equivalent).

The ratio of the HI slope (S_{HI}) to the AM-SIM slope (S_{AM-SIM}) was calculated for each of the 12 masking functions for each of the 8 HI listeners. A histogram of the base-10 logarithm of these ratios is provided in Fig. 10.¹ Values of $\log_{10}(S_{AM-SIM}/S_{HI})$ greater than 0 indicate steeper S_{AM-SIM} compared to S_{HI} , and values less than 0, shallower S_{AM-SIM} compared to S_{HI} . The two bins with the highest frequency of occurrence were centered at values of 0 (indicating equivalence of S_{AM-SIM} and S_{HI}) and 0.25 (representing cases of steeper S_{AM-SIM} compared to S_{HI}).

TABLE III. The y-intercepts in dB SPL of the straight-line fits to the temporal-masking functions for each HI listener and the corresponding AM-SIM group. Results from the NH group are shown in the final column.

f_p	f_m	Group	Subject								
			HI-1	HI-2	HI-3	HI-4	HI-6	HI-7	HI-8	HI-10	NH
500 Hz	$0.55^* f_p$	HI	66.50	75.52	75.11	64.94	86.67	74.02	101.90	70.24	68.02
		AM-SIM	66.77	79.98	77.32	55.39	101.19	87.02	108.92	77.73	
	$1.0^* f_p$	HI	49.04	61.43	53.36	54.36	82.75	68.49	90.92	55.70	38.17
		AM-SIM	40.69	56.27	61.03	50.44	81.77	86.84	96.09	61.58	
	$1.15^* f_p$	HI	58.27	71.15	65.15	66.94	84.36	68.45	92.17	53.17	35.57
		AM-SIM	47.08	70.29	64.75	49.96	86.85	90.11	95.27	60.22	
1000 Hz	$0.55^* f_p$	HI	71.81	82.40	70.85	71.45	87.42	85.65	93.60	70.38	66.14
		AM-SIM	74.46	93.71	66.24	64.40	105.67	85.24	103.07	68.58	
	$1.0^* f_p$	HI	47.83	69.76	42.06	61.81	82.97	81.91	86.01	41.50	33.90
		AM-SIM	42.65	65.87	50.84	86.51	79.15	102.96	89.23	66.22	
	$1.15^* f_p$	HI	66.56	86.41	60.06	89.83	87.44	88.38	91.18	42.83	50.04
		AM-SIM	67.51	93.56	59.91	88.35	92.48	109.43	94.91	52.65	
2000 Hz	$0.55^* f_p$	HI	79.10	82.43	75.36	76.79	86.29	92.88	95.46	67.93	73.26
		AM-SIM	88.60	96.96	73.82	90.57	101.36	91.95	103.14	67.02	
	$1.0^* f_p$	HI	65.29	73.10	50.33	81.67	89.17	92.58	96.40	34.41	32.32
		AM-SIM	59.65	69.52	60.58	107.71	86.50	89.04	99.02	51.39	
	$1.15^* f_p$	HI	97.17	105.83	78.10	86.83	86.92	92.23	99.79	81.60	56.19
		AM-SIM	83.81	93.70	76.20	107.24	104.41	89.13	102.84	56.21	
4000 Hz	$0.55^* f_p$	HI	91.58	97.93	84.58	92.67	79.37	87.69	102.35	70.83	85.38
		AM-SIM	92.09	91.49	80.51	88.34	104.24	96.72	110.09	89.11	
	$1.0^* f_p$	HI	67.79	81.63	66.80	78.64	77.46	88.35	104.21	33.99	35.11
		AM-SIM	55.98	74.12	85.25	77.40	81.08	82.74	103.73	57.96	
	$1.15^* f_p$	HI	98.50	92.33	96.21	84.90	81.91	90.12	103.54	81.06	50.47
		AM-SIM	84.28	89.33	96.21	84.22	84.99	89.25	104.72	86.40	

The slopes obtained in the off-frequency masking conditions ($S_{\text{Off-Freq}}$) were compared to those obtained with on-frequency maskers ($S_{\text{On-Freq}}$). For each HI listener and corresponding AM-SIM group, the ratio of the slope of the low-frequency masker to the slope of the on-frequency masker and the ratio of the slope of the high-frequency masker to the slope of the on-frequency masker was calculated at each of the four probe frequencies. A histogram of the logarithm of these ratios at each of the four probe frequencies is shown in Fig. 11 for HI and AM-SIM listeners. A χ^2 goodness-of-fit contingency analysis was conducted to compare the distribu-

tions observed between the two groups of listeners at each frequency. The χ^2 values and degrees of freedom at each probe frequency and ratio type are provided in the panels of Fig. 11. None of these values achieved significance at the 0.05 level to indicate independence in the behavior of the two subject groups. For the results shown in the left-hand panels of Fig. 11, a clear tendency is seen in both groups for logarithmic values of the ratios to lie in the range below 0, indicating that shallower slopes were observed with the low-frequency compared to the on-frequency maskers. In the right-hand panels, however, the histograms tend to be

FIG. 9. Histogram of RMS error values between the HI and AM-SIM forward masking thresholds (excluding cases where either the HI or AM-SIM listeners experienced equipment-limited masker presentation levels).

FIG. 10. Histogram of the $\log_{10}$ ratio of the AM-SIM slopes ($S_{\text{AM-SIM}}$) to HI slopes (S_{HI}) of the temporal-masking function (as determined by the two-segment, linear-regression fits to the data).

FIG. 11. Histograms of the $\log_{10}$ ratio of off-frequency-masker slopes ($S_{\text{Off-Freq}}$) to on-frequency-masker slopes ($S_{\text{On-Freq}}$) of the temporal-masking function (as determined by the two-segment, linear-regression fits to the data) for the HI (black bars) and AM-SIM (gray bars) subjects. The left column of panels shows histograms for the low-frequency maskers at each of the four probe-tone frequencies and the right column of panels shows histograms for the high-frequency maskers at each of the four probe-tone frequencies.

centered about 0, indicating a tendency for similar slopes with high-frequency and on-frequency maskers. Grouped over the four probe frequencies, the logarithmic ratio of the low-frequency masker slope to the on-frequency masker slope was -0.12 and -0.10 for the HI and AM-SIM groups, respectively. For the corresponding high-frequency to on-frequency slope ratios, the means were -0.02 and -0.00 for the two groups respectively. The logarithmic ratios of low-frequency-to-on-frequency and high-frequency-to-on-frequency masker slopes were -0.22 and 0.15 , respectively, for the NH group.

To examine the effects of hearing loss on temporal masking functions, the slopes and y-intercepts of the masking functions were plotted in Fig. 12 as a function of the 500-ms threshold at the probe frequency for individual HI listeners (Fig. 12, left) and for mean data across subjects in each of the corresponding 8 AM-SIM groups (Fig. 12, right). Linear least-squares fits to the data are shown for each of the three masker types. For correlations with slope (Fig. 12, top), a trend is seen for a decrease in slope values with an increase in hearing loss with each masker type and both groups of listeners. For the HI data, the correlation between

FIG. 12. (top) Plots of temporal-masking function slopes and (bottom) y-intercepts as a function of 500-ms-tone threshold for (left) HI and (right) AM-SIM subjects for low-frequency (filled-circle), on-frequency (gray-triangle), and high-frequency (open-square) maskers across all probe-tone frequencies. Also shown are straight-line fits to these data.

slope and hearing loss reached significance for the low-frequency ($\rho = -0.50$, $p = 0.004$) and on-frequency ($\rho = -0.59$, $p = 0.0004$) maskers but not for the high-frequency masker ($\rho = -0.31$, $p = 0.09$). For the AM-SIM results, the correlations with slope reached significance for the on-frequency ($\rho = -0.38$, $p = 0.03$) and high-frequency ($\rho = -0.55$, $p = 0.001$) maskers but not for the low-frequency masker ($\rho = -0.27$, $p = 0.13$). For correlations of y-intercept with 500-ms hearing thresholds (Fig. 12, bottom), a high degree of positive correlation was observed for all masker types for both HI and AM-SIM listeners (ρ in the range of 0.63 to 0.92 and $p < 0.0001$ for HI listeners and ρ in the range of 0.76 to 0.91 and $p < 0.0001$ for AM-SIM listeners).

IV. DISCUSSION

A. Comparison with other studies of forward masking in HI listeners

The temporal masking functions obtained here with HI and NH listeners are generally consistent with those obtained in previous studies in terms of (a) shallower forward masking slopes for HI compared to NH listeners; (b) a greater similarity between on- and off-frequency masking slopes for HI compared to NH listeners; and (c) a tendency for slopes to decrease with degree of hearing loss.

Rosengard *et al.* (2005) measured temporal masking functions in 5 NH and 5 HI listeners (with 40–70 dB HL at the probe frequencies) using low- and on-frequency-masker stimulus conditions and methods similar to those employed

in the present study. Using the two-segment fitting procedure that was applied to the current data (see Sec. III B), we derived slope values for their temporal-masking functions for NH and HI listeners (using the data shown in Figs. 2 and 7 of Rosengard *et al.*, 2005) and compared these slope values to our results shown in Table II. For the low-frequency masking condition (where $f_m = 0.55 f_p$) at each of three probe frequencies (1000, 2000, and 4000 Hz), the mean slopes in dB/ms of the Rosengard *et al.* data were 0.64, 0.56, and 0.48 for NH listeners and 0.32, 0.24, and 0.33 across HI listeners. In the current data, mean slopes for the low-frequency masker condition at 1000, 2000, and 4000 Hz probe frequencies, respectively, were 0.54, 0.78, and 0.36 for NH listeners and 0.43, 0.49, and 0.30 for HI listeners. Thus, both sets of data indicate shallower low-frequency masker slopes for HI compared to NH listeners. Decreasing slopes of the functions for low-frequency maskers with an increase in probe frequency were observed in the data of Rosengard *et al.* as well as in other previous studies (e.g., Stainsby and Moore, 2006; Lopez-Poveda *et al.*, 2003, 2005). Presumably, this observation reflects a relatively wider region of compressive responses at lower center frequencies of the probe. Although such a tendency was observed for both the NH and HI listeners in the present study, the effect did not reach statistical significance.

Stainsby and Moore (2006) measured temporal masking curves for three HI listeners with audiometric loss of 45 to 60 dB HL at five probe frequencies in the range of 500 to 6000 Hz. For each probe frequency, temporal-masking functions were obtained using the on-frequency masker and four off-frequency maskers (including two maskers higher and two lower than the probe frequency). The slopes of the masking functions for a given subject were similar across maskers at a given probe frequency. Across subjects, mean slopes in dB/ms were 0.31, 0.29, 0.18, and 0.17 at probe frequencies of 500, 1000, 2000, and 4000 Hz. Slope estimates of this magnitude for HI listeners in the current study tended to be associated with higher levels of hearing loss (roughly 60 dB SPL and greater—see Fig. 12). The 20-ms thresholds of the HI listeners of Stainsby and Moore (averaging roughly 66.3 dB SPL across the four probe frequencies in the range of 500 to 4000 Hz) are roughly consistent with a 500-ms threshold of 60 dB SPL.

The effects of hearing loss observed in the current data (shown in Fig. 12) indicate a trend for a decrease in slope with an increase in 500-ms hearing threshold level for all three masker types for both HI and AM-SIM listeners. Similar effects of hearing loss on slopes of temporal-masking functions have been observed previously. Rosengard *et al.* (2005) noted that the off-frequency masking slopes of a listener with 40 dB HL were roughly 2–3 times greater than the slopes of listeners with greater loss (in the range of 45–65 dB HL) and were similar to the slopes obtained with NH listeners. Plack *et al.* (2004) plotted the slope of the masking function obtained with a 2200-Hz masker and a 4000-Hz probe as a function of the absolute threshold of the 8-ms signal and observed a decrease in slope as threshold increased over the range of roughly 5 to 60 dB SPL.

B. Comparison of HI and AM-SIM results

1. Threshold simulations

The hearing-loss simulations, which were tailored to reproduce the 500-ms thresholds of the HI listeners, yielded simulated 500-ms thresholds that were generally within 5 dB of the target loss. These same hearing-loss simulations, however, yielded 10-ms thresholds that were higher than those of the corresponding HI listeners. The AM-SIM listeners experienced a greater increase in threshold with a shortening in stimulus duration from 500 to 10 ms than did the HI listeners.

These results are consistent with previous studies that have shown reduced effects of duration on threshold for HI compared to NH listeners (e.g., Gengel and Watson, 1971; Tyler *et al.*, 1980; Chung, 1981; Oxenham *et al.*, 1997) and no change in this effect for NH listeners in quiet and in the presence of a background noise (e.g., Gengel, 1972; Florentine *et al.*, 1988). Reduced threshold difference for different durations in HI listeners compared to noise-masked listeners was also observed by Kidd *et al.* (1983) in a study of the effect of the duration of a 3000-Hz forward masker on the threshold of a 20-ms 3000-Hz probe whose onset was delayed by 10 ms from the masker offset. Whereas both NH listeners and NH listeners in the presence of a threshold-elevating background noise had forward masked thresholds that were larger in the presence of a 300-ms compared to a 35-ms masker, HI listeners had similar masked thresholds at both masker durations. The insensitivity to masker duration observed only in the HI listeners is likely related to the decreased effects of signal duration on threshold observed in HI compared to NH and noise-masked NH listeners (Florentine *et al.*, 1988; also see Fig. 4 of the current paper). Because HI absolute thresholds are relatively insensitive to duration, changing the duration of a forward masker is not likely to alter its underlying sensory representation in these listeners and thus will be less likely to affect its temporal course of masking than for NH listeners.

2. Temporal-masking simulations

The ability of the hearing-loss simulation employed here to reproduce the temporal masking functions of the HI listeners was evaluated by comparing results obtained for a given HI listener and the corresponding AM-SIM group. The simulations were assessed through: (1) comparison of masker levels for a given combination of masker and probe frequency; (2) comparison of the slopes and y-intercepts calculated from the linear-regression fits to the masking functions; and (3) comparison of off-frequency slopes relative to on-frequency slopes.

The masker-level RMS error between the HI listeners and their corresponding AM-SIM groups (excluding conditions where either the HI listener or AM-SIM group experienced equipment-related limitations on maximum masker presentation level) were in the range 0–10 dB in 71.8% of the conditions and greater than that in the remaining conditions (see Fig. 9). Differences in masker levels between HI and AM-SIM listeners are not entirely unexpected due to

differences in probe-signal presentation levels that resulted from differences in HI and AM-SIM 10-ms tone thresholds.

The slopes of the masking functions were significantly shallower for the HI listeners compared to the NH listeners. The slopes for the AM-SIM listeners were intermediate between those of the NH and HI listeners but not significantly different from either. A tendency was observed in both the HI and AM-SIM data, however, for a decrease in slope with an increase in hearing threshold. The y-intercepts of the masking functions, which were highly positively correlated with hearing threshold, were equivalent for the HI and AM-SIM groups and significantly higher than those of the NH group.

Recently, Wojtczak and Oxenham (2009, 2010) have postulated that high-level low-frequency maskers may lead to the activation of efferent feedback mechanisms (i.e., the middle-ear muscle reflex or the medial olivocochlear reflex) in NH but not in HI listeners. These reflexes would operate to decrease the recovery time from masking. It is possible that these mechanisms may play a role in the results obtained with the AM-SIM listeners based on the relatively high masker levels observed in their temporal-masking functions and their shallower slope values on average compared to the NH listeners. In the cases of greater hearing loss, however, the simulation employs multi-band expansion in addition to masking noise, thus effectively lowering the stimulus levels to which the AM-SIM listeners were exposed. Although the reflexes would operate to attenuate the low-frequency masker and reduce the slope of the masking function in the AM-SIM listeners, they would also be expected to exhibit greater compression than the HI listeners. Thus, the resulting slopes of the masking functions could be similar for both listener groups. Without explicit measurements of these reflexes in our listeners, it is unclear whether differences in feedback mechanisms between the HI and AM-SIM listeners may have played a significant role in the results of the current study.

The relative slope ratio of the low-frequency to the on-frequency maskers has been used by previous investigators to make inferences regarding the compressive function of the basilar membrane (see Nelson *et al.*, 2001; Oxenham and Bacon, 2003; Nelson and Schroder, 2004). When considering off-frequency slopes relative to on-frequency slopes in the current study, similar patterns were observed in the HI and AM-SIM listeners. The distributions of relative slope values (in the form of the logarithm of the off-frequency-to-on-frequency slope ratios shown in Fig. 10) were not significantly different for the two groups of listeners at any probe frequency. These ratios indicated a general trend of shallower slopes for low-frequency compared to on-frequency maskers and of similar slopes for high-frequency and on-frequency maskers. The mean ratio of low-frequency to on-frequency slopes across the four probe frequencies was highly similar for the HI (0.75) and AM-SIM (0.71) groups and higher than that for the NH listeners (0.61). These results are in agreement with some previous studies that have shown greater compressive effects for NH compared to HI listeners (Lopez-Poveda *et al.*, 2005; Rosengard *et al.*, 2005) in listeners with moderate-to-severe

hearing loss. Plack *et al.* (2004), however, using listeners with mild-to-moderate hearing loss, found that compression exponents were similar for their HI and NH listeners even though the slopes of the temporal-masking functions themselves tended to be shallower for the HI listeners. Our conclusion of similar compressive effects estimated from temporal-masking functions for listeners with real and simulated hearing loss also appears to differ from that of Gregan *et al.* (2010) who found no change in estimates of cochlear compression in NH listeners with an increase in the level of a threshold-elevating background noise to simulate flat hearing loss.

C. Relation between temporal masking and speech reception in interrupted noise

Several studies have been conducted to determine if the reduced masking release (MR) observed in HI listeners can be reproduced in NH listeners with simulated hearing loss (e.g., Eisenberg *et al.*, 1995; Bacon *et al.*, 1998; George *et al.*, 2006; Desloge *et al.*, 2010). The ability of a hearing-loss simulation to reproduce the MR results of HI listeners has varied from study to study. For example, Bacon *et al.* (1998) found that a hearing-loss simulation based on additive noise was capable of reproducing the MR of some HI listeners but resulted in greater MR than that observed in other HI listeners. George *et al.* (2006) obtained good matches of MR for HI and simulated-loss NH listeners for unprocessed speech but found less MR in HI listeners for speech processed with high-frequency emphasis. Desloge *et al.* (2010), using a simulation that combined masking noise and multiband expansion, have reproduced many of the effects observed in HI listeners for the reception of speech in continuous and temporally modulated noise over a variety of audiometric configurations and for unprocessed speech as well as speech with high-frequency emphasis.

To assess the role of temporal masking in the MR for speech reception in temporally modulated noise versus continuous noise, the slopes and y-intercepts of the forward masking functions of the HI and AM-SIM listeners were compared to MR measurements obtained by Desloge *et al.* (2010) for these same listeners. The MR values used in the regression analyses were derived from the 80-dB SPL noise condition with speech processed for high-frequency emphasis using the NAL-RP prescription (Dillon, 2001, pp. 239–242). Correlations (Pearson coefficient) between MR and the slopes and y-intercepts of the temporal masking functions were examined for each of the 12 masker/probe combinations. Significant correlations of MR with slope were observed in only two of these conditions: $f_p = 1000$ Hz/ $f_m = 1150$ Hz ($\rho = 0.6$, $p = 0.013$) and $f_p = 2000$ Hz/ $f_m = 2000$ Hz ($\rho = 0.57$, $p = 0.022$), both indicating an increase in MR with slope. Correlations of MR with y-intercept, however, were significant in 11 of the 12 conditions (in these cases ρ values varied between -0.5 and -0.91 with $p < 0.05$) and indicated an increase in MR with a decrease in y-intercept. The one case of insignificant correlation with y-intercept was for $f_p = 4000$ Hz/ $f_m = 4600$ Hz ($\rho = -0.4$, $p = 0.13$).

These results corroborate those reported by [Dubno *et al.* \(2003\)](#) in a study of temporal masking and speech reception in younger and older listeners with normal hearing. Forward masking was measured using a 200-ms speech-shaped noise masker and 20-ms probes (500 and 4000 Hz) at four delays between masker offset and probe onset. Consonant recognition was measured in speech-shaped noise at four rates of temporal interruption (2, 10, 25, and 50 Hz). When the speech-recognition scores were compared to the temporal-masking results, no correlations were observed with the slopes of the functions, but strong negative correlations were observed with the y-intercept (as well as with the forward-masked thresholds at each delay). [Dubno *et al.* \(2002\)](#) also found a negative correlation between the forward-masked threshold and consonant recognition in temporally interrupted noise in young and older listeners with normal hearing, but only for probe frequencies greater than 2000 Hz. [Gifford *et al.* \(2007\)](#) showed a similar trend in a small sample of young and elderly NH listeners who were matched for audiometric thresholds. One older listener with an elevated S/N for sentence identification in temporally interrupted noise compared to his younger match had higher forward masked thresholds than two younger listeners; another older listener had both S/N and forward masked thresholds that were similar to one of his younger matches. [Jin and Nelson \(2006\)](#) observed that masking release for syllable identification for HI listeners in 8-Hz and 16-Hz interrupted noise was positively correlated with the amount of forward masking at 2000 Hz but not with quiet thresholds, forward masked thresholds, or slopes of the forward-masking functions. Masking release for identification of keywords in sentences showed a negative correlation with low-frequency hearing sensitivity and with the forward-masked threshold at 2000 Hz.

The analysis in the current study shows that in agreement with [Dubno *et al.* \(2002, 2003\)](#) and [Jin and Nelson \(2006\)](#) for sentences, MR decreased with an increase in the y-intercept of the temporal-masking function. The correlation of MR with the y-intercept and not with the slope of the temporal masking functions suggests that the magnitude of MR may be more closely related to hearing threshold (and the stimulus levels needed to achieve audibility) than to properties of temporal masking itself.

V. SUMMARY AND CONCLUSIONS

The TN/MBE hearing-loss simulation employed here is capable of reproducing certain effects of hearing impairment to a greater extent than others. The simulation is capable of reproducing the hearing-threshold levels of HI listeners with a wide range of audiometric configurations; however, the reduced effect of duration on threshold observed in HI listeners is not reproduced by the simulation. The simulation has been shown to be generally effective for reproducing the speech-reception performance of HI listeners in terms of S/N required for 50%-correct intelligibility of sentences in backgrounds of continuous and temporally modulated noise and in terms of release from masking ([Desloge *et al.*, 2010](#)). The simulation was less successful in reproducing the temporal modulation transfer functions of hearing-impaired listeners

in that the simulations resulted in lower sensitivity and higher cut-off frequencies than observed in the HI listeners ([Desloge *et al.*, 2011](#)). The results of the current paper indicate that the TN/MBE hearing-loss simulation yielded slopes and y-intercepts of the masking functions that were not significantly different from those of listeners with real hearing impairment and was capable of reproducing the ratios of slope values for low-frequency to on-frequency maskers.

Our measurements of temporal-masking functions in listeners with normal hearing, hearing impairment, and NH under a simulation of hearing loss lead to the following conclusions.

- (1) Slopes of the masking functions were significantly shallower for HI than for NH listeners without the hearing-loss simulation. The AM-SIM slopes were intermediate between those of the other two groups but not significantly different from either. For all three groups of listeners, the slopes obtained with the low-frequency maskers were significantly shallower than slopes obtained with the on-frequency and high-frequency maskers (which were equivalent).
- (2) The y-intercepts of the masking functions were equivalent for the HI and AM-SIM listeners and significantly higher than those of the NH listeners. For all three groups, the y-intercepts were lower for the on-frequency maskers than for the two off-frequency masker types.
- (3) The slopes of the masking functions for a given probe frequency tended to decrease with an increase in the 500-ms hearing-threshold level, while y-intercept was strongly positively correlated with threshold. Masking release for speech reception in fluctuating noise was more highly correlated with y-intercept than with slope.
- (4) The distribution of the ratio of off-frequency-masker to on-frequency-masker slopes was similar for HI and AM-SIM listeners and suggests that compressive effects may be similar for the two groups. These results suggest that the reduced compression in HI compared to NH listeners, thought to arise from outer-hair cell loss, is generally reproduced through the hearing-loss simulation techniques of TN and TN/MBE employed here in a temporal-masking paradigm.

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¹Figure 10 includes 93 of the total 96 ratios. The three missing values result from cases of negative slope for which the log10 could not be calculated. Two of these values are for HI-6 and one for AM-SIM for HI-7 (see Table II).

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