Speech reception by listeners with real and simulated hearing impairment: Effects of continuous and interrupted noise

Joseph G. Desloge, Charlotte M. Reed, Louis D. Braida, Zachary D. Perez, and Lorraine A. Delhorne
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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The effects of audibility and age on masking for sentences in continuous and interrupted noise were examined in listeners with real and simulated hearing loss. The absolute thresholds of each of ten listeners with sensorineural hearing loss were simulated in normal-hearing listeners through a combination of spectrally-shaped threshold noise and multi-band expansion for octave bands with center frequencies from 0.25–8 kHz. Each individual hearing loss was simulated in two groups of three normal-hearing listeners (an age-matched and a non-age-matched group). The speech-to-noise ratio (S/N) for 50%-correct identification of hearing in noise test (HINT) sentences was measured in backgrounds of continuous and temporally-modulated (10 Hz square-wave) noise at two overall levels for unprocessed speech and for speech that was amplified with the NAL-RP prescription. The S/N in both continuous and interrupted noise of the hearing-impaired listeners was relatively well-simulated in both groups of normal-hearing listeners. Thus, release from masking (the difference in S/N obtained in continuous versus interrupted noise) appears to be determined primarily by audibility. Minimal age effects were observed in this small sample. Observed values of masking release were compared to predictions derived from intelligibility curves generated using the extended speech intelligibility index (ESII) [Rhebergen *et al.* (2006). J. Acoust. Soc. Am. **120**, 3988–3997]. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3436522]

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I. INTRODUCTION

An improved understanding of the effects of background interference on the perception of speech by hearing-impaired (HI) listeners is significant for the development of improved aids for speech communication. Previous studies of speech perception in noise have demonstrated that the effects of audibility alone can often account for much of the difficulty experienced by listeners with mild-to-moderate hearing impairment in quiet and in continuous background noise (e.g., Zurek and Delhorne, 1987; Humes *et al.*, 1987; Dubno and Schaefer, 1992; Bacon *et al.*, 1998; Takahashi and Bacon, 1992). That is, when the effects of threshold elevation observed in individual HI listeners are simulated in normal-hearing (NH) listeners through the use of additive threshold noise, the speech-reception performance of both groups of listeners is quite similar. Other studies, however, have observed differences in the speech-reception performance of listeners with real and simulated hearing loss even when controlling for audibility. Such a lack of correspondence has been observed in several studies that have compared the speech reception of listeners with real and simulated hearing loss in backgrounds of temporally fluctuating noise (e.g., Eisenberg *et al.*, 1995; Bacon *et al.*, 1998; George *et al.*, 2006).

In NH listeners, the reception of speech is improved when listening in temporally fluctuating noise versus continuous noise of the same long-term root-mean-square (RMS) level. This benefit, referred to as "masking release" (MR), presumably arises from the use of improved speech-to-noise ratios during momentary dips in the level of the fluctuating noise. The magnitude of MR in NH listeners is dependent on various characteristics of the fluctuating noise such as its overall level, rate of interruption, duty cycle, and depth of modulation (e.g., see Gustafsson and Arlinger, 1994; Stuart and Phillips, 1996; Summers and Molis, 2004; Rhebergen *et al.*, 2006; George *et al.*, 2006). Such MR effects have been observed by a number of investigators using sentence materials (e.g., Festen and Plomp, 1990; Arlinger and Gustafsson, 1991; Takahashi and Bacon, 1992; Eisenberg *et al.*, 1995; Peters *et al.*, 1998; Summers and Molis, 2004; George *et al.*, 2006; Rhebergen *et al.*, 2006; Oxenham and Simonson, 2009). The size of MR with NH listeners can be as large as 15 to 25 dB using temporally modulated noises with interruption rates of about 8–20 Hz (e.g., see George *et al.*, 2006; Rhebergen *et al.*, 2006).

Studies conducted in listeners with hearing impairment have generally shown reduced MR effects compared to those observed in NH listeners (Shapiro *et al.*, 1972; Festen and Plomp, 1990; Stuart and Phillips, 1996; Arlinger and Gustafsson, 1991; Gustafsson and Arlinger, 1994; Takahashi and Bacon, 1992; Peters *et al.*, 1998; Summers and Molis, 2004; George *et al.*, 2006; Lorenzi *et al.*, 2006; Jin and Nelson, 2006; Bernstein and Grant, 2009; Strelcyk and Dau, 2009). In a sentence-reception task, for example, Festen and Plomp (1990) measured MR of 4 to 8 dB in NH listeners compared to about 0 dB in HI listeners.

The role of threshold elevation and audibility in the reduction of MR in HI listeners has been examined in several previous studies that have employed additive-noise hearing-loss simulations in NH listeners. Eisenberg *et al.* (1995) observed significantly higher consonant recognition scores in an amplitude-modulated high-pass noise compared to scores in continuous high-pass noise in NH listeners and in NH listeners with noise-masked simulations of hearing loss, but not in HI listeners. Bacon *et al.* (1998) observed that the accuracy of a noise-masked hearing-loss simulation in predicting release from masking varied across individual HI listeners. For nearly half of the HI listeners, the amount of MR was well-matched to that obtained in the noise-masked simulation. For the remaining HI listeners, the amount of MR was less than that observed in their noise-masked counterparts. George *et al.* (2006) examined speech-to-noise ratios (S/N) for reception of sentences in interrupted versus continuous noise in two groups of HI listeners (one group with flat losses and one group with high-frequency sloping losses). The average loss for each of the two groups was simulated using noise-masking in NH listeners. On average, MR for listeners with real and simulated hearing loss was similar and less than that observed in NH listeners for unprocessed speech. When a high-frequency gain was applied to the speech and masking noise, the MR observed in the HI listeners was less than that seen in both the NH and simulated-loss listeners.

In addition to the effects of hearing loss, age may also play a role in a listener's ability to take advantage of a modulated background noise. Dubno *et al.* (2002, 2003) compared the consonant recognition performance of NH young and elderly listeners (whose small differences in thresholds were compensated by the addition of noise to produce equivalent masked thresholds over the range 0.2–6.0 kHz). Their results indicate that the benefits derived from amplitude-modulated maskers were greater for the young compared to the elderly subjects. Thus, even in the absence of a hearing loss, the elderly subjects were less able to take advantage of momentary increases in S/N to improve speech intelligibility. Similarly, Gifford *et al.* (2007) observed higher values of S/N in interrupted noise for older compared to younger NH listeners. Earlier studies (Takahashi and Bacon, 1992; Peters *et al.*, 1998), which tested elderly listeners with hearing loss, were equivocal with respect to this issue. Takahashi and Bacon (1992) found only a weak partial correlation of the release from masking with age when absolute thresholds were taken into account. Peters *et al.* (1998), however, found that age could play a significant role in determining the value of speech-reception threshold in backgrounds with temporal or spectral "dips" when reduced audibility is partially compensated by frequency dependent amplification. Thus, an age-related processing deficit, presumably central to the peripheral auditory system, may be a contributing factor in comparisons of normal and HI listeners that are not balanced for age. In the three previous studies described above (Eisenberg *et al.*, 1995; Bacon *et al.*, 1998; George *et al.*, 2006) comparing MR in listeners with real and simulated hearing loss, age was not controlled and the simulated loss listeners were younger than the HI listeners.

The current study was undertaken to examine the effects of audibility and age on speech reception in continuous and interrupted noise in listeners with real and simulated hearing loss. The individual loss of a given HI individual was simulated in a group of three NH listeners of similar age. To examine the effects of age, these same hearing losses were also simulated in groups of non-age-matched (typically younger) listeners. The S/N ratio required for 50%-correct recognition of HINT sentences (Nilsson *et al.*, 1994) was compared for listening in continuous noise and 10-Hz square-wave interrupted noise at two overall levels (65 and 85 dB SPL) for unprocessed speech and for speech presented with frequency-dependent amplification. Previous research indicates that MR may depend on the overall level or audibility of the background noise. Summers and Molis (2004), for example, observed a decrease in MR as the background noise level was increased from 60 to 90 dB SPL in NH listeners but no such effect on average in a group of HI listeners. Stuart and Phillips (1996), on the other hand, observed higher levels of MR for more adverse values of S/N in both NH and HI listeners when the speech level was held constant at 30 dB relative to SRT in quiet. The role of audibility of the background noise as a factor in determining the size of MR has been noted by de Laat and Plomp (1983), who observed a decrease in MR as the magnitude of the hearing loss increased.

For a given HI listener, S/N values for both continuous and interrupted noise were compared to those obtained in age-matched and non-age-matched groups of NH listeners with simulated loss. The Speech Intelligibility Index (SII) (ANSI, 1997) and an extension of the SII to interrupted noise (ESII, Rhebergen *et al.*, 2006) were used to model the performance of each HI subject under each of the four listening conditions. Values of ESII were obtained for HI and simulated-loss listeners using measurements of S/N for continuous and interrupted noise under each listening condition. Predictions of MR were obtained from these ESII functions and compared to measured values for listeners with real and simulated hearing loss to determine the extent to which audibility is capable of accounting for observed release from masking in individual HI listeners. Comparisons were also made between younger and older listeners with the same simulated hearing loss to examine effects of age.

II. METHODS

A. Hearing-loss simulation techniques

In the current study, hearing loss was simulated whenever possible through the use of 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 specific 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 below.

1. Simulation using additive threshold noise (TN)

Spectrally shaped noise is used to elevate the detection thresholds of NH listeners to those of HI listeners (see left panel of Fig. 1). With this noise, the simulated-loss NH listeners can experience test stimuli at the same overall presen-

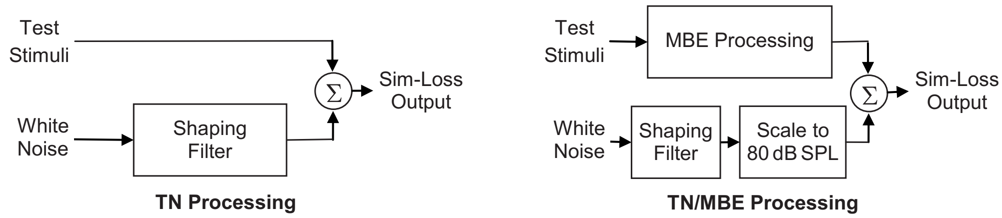

FIG. 1. Panel on left: Block diagram of system used for hearing-loss simulation based on additive threshold noise. Panel on right: Block diagram of system used for hearing-loss simulation based on a combination of additive threshold noise and multi-band expansion (MBE) processing. The upper path processes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

tation levels (SPLs) and sensation levels (SLs), and presumably at roughly equal loudness, as the HI listeners to which they are matched. Although this approach does not completely reproduce all effects of sensorineural hearing impairment (e.g., see Phillips, 1987; Reed *et al.*, 2009, see http://www.ncbi.nlm.nih.gov/pubmed/19074452), it is capable of simulating threshold shifts and loudness recruitment seen in cochlear hearing loss (e.g., Steinberg and Gardner, 1937).

The specific frequency-dependent noise level necessary to simulate a desired hearing loss is derived as follows. First, the desired hearing thresholds are specified in terms of dB SPL at a minimum of six audiometric frequencies including 250, 500, 1000, 2000, 4000, and 8000 Hz. Linear interpolation (in the log-frequency versus dB-SPL domain) is then used to estimate thresholds at the third-octave-band frequencies ranging from 80 Hz to 12,500 Hz. (Threshold values for the lowest and highest measured frequencies are extended to cover third-octave-band frequencies below or above these respective frequencies.) The spectrum level of the desired noise is obtained at each third-octave frequency using the critical ratio (Hawkins and Stevens, 1950), which establishes the minimal signal-to-noise ratio at which a particular tone can be heard. The critical ratio values employed in these computations are 17.75, 16.3, 17.25, 18.5, 19.25, 20.5, 22.5, 25.1, 26, 27 dB at 125, 250, 500, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz, respectively, that are linearly-interpolated (in the log-frequency versus dB domain) to cover the third-octave-band frequencies ranging from 80 to 12 500 Hz.

Specifically, the critical ratio at each third-octave frequency $[\mathrm{CR}(f_{1/3\text{-oct}})]$ is subtracted from the desired threshold in dB SPL $[\mathrm{THR}(f_{1/3\text{-oct}})]$ to determine the necessary spectrum level in dB of the threshold noise at that frequency $[\mathrm{SpecLev}(f_{1/3\text{-oct}})]$:

$$[\mathrm{SpecLev}(f_{1/3\text{-oct}})] = \mathrm{THR}(f_{1/3\text{-oct}}) - \mathrm{CR}(f_{1/3\text{-oct}}).$$

These spectrum levels are then used to generate a filter that, when applied to unit-power white noise, produces the additive threshold noise that yields the threshold shift associated with the simulated loss.

The current study used noise alone to simulate the desired hearing losses whenever possible. For more severe losses (>60–70 dB HL), however, the required noise was in excess of 80 dB SPL overall, which was deemed unacceptably loud for extended listening. In these cases, the noise was scaled down to a level of 80 dB SPL 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) produces threshold shifts by attenuating the stimulus dynamically. The input signal is passed through a multi-band filterbank, monitoring short-time band signal levels, and applying a level-dependent attenuation to each band signal (Duchnowski, 1989; Duchnowski and Zurek, 1995; Graf, 1997; Lum and Braida, 1997; Moore and Glasberg, 1993). The automatic gain control for hearing loss simulation is designed to yield the desired threshold shift as well as the loudness growth associated with sensorineural hearing loss. Specifically, MBE applies band attenuations that translate an input signal at the level of the simulated threshold so that it is presented at the listener's actual hearing threshold. The degree of attenuation then decreases as input level increases above the simulated threshold until full recruitment is reached and the attenuation is equal to 0 dB. For levels above the full recruitment level, no attenuation is used.

MBE operation and the process for combining TN and MBE to produce a desired threshold shift band is illustrated in Fig. 2. The first step of TN/MBE simulation involves attenuating the noise by a factor of

$$\alpha = \mathrm{TN}_{\mathrm{lev}} - 80 \ \ \mathrm{dB}$$

to yield noise with a wideband level of exactly 80 dB SPL. Given that the unscaled TN is designed to produce the de-

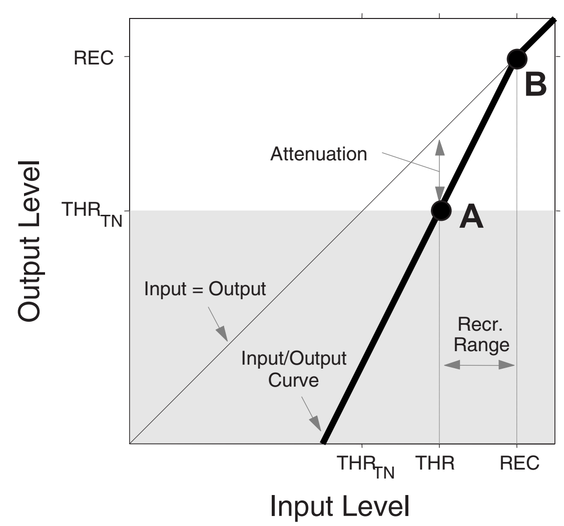

FIG. 2. Input-to-output level MBE mapping curve that produces a threshold shift of THR when combined with additive threshold noise that yields a threshold shift of $\mathrm{THR}_{\mathrm{TN}}$. Full recruitment is reached at REC. The attenuation produced by the expander decreases over the recruitment range.

sired threshold shifts of THR(f), the attenuated noise then yields reduced threshold shifts of:

$$\mathrm{THR_{TN}(f)} = \max\{0, \mathrm{THR(f)} - \alpha\} \text{ dB SL}.$$

The resulting $\mathrm{THR_{TN}(f)}$ is always less than THR(f), since α is greater than 0 dB, and is always greater than or equal to 0 dB SL, since the simulated thresholds are assumed to be no better than the normal-hearing thresholds. The purpose of the MBE in the combined TN/MBE processing is to produce the remaining THR-$\mathrm{THR_{TN}}$ dB of threshold shift that is lost when the TN is scaled down to 80 dB SPL.

Figure 2 describes this process for a single MBE frequency band. Given that this illustrative example is limited to a single frequency band, the explicit frequency dependence is suppressed in the figure and the following description. The key element is the MBE input-to-output mapping curve, shown in bold, that provides the desired threshold shift of THR when combined with the scaled noise. MBE attenuation is equal to the difference between the MBE input/output mapping curve and the input-equals-output curve shown in the plot. The two most relevant features of the MBE mapping curve are points **A** and **B**. As shown at point **A**, the MBE mapping attenuates inputs at THR so that the corresponding output level is exactly equal to $\mathrm{THR_{TN}}$ = the hearing threshold in the presence of the threshold noise. MBE attenuation then decreases as input level increases until the level of full recruitment (REC) is reached at point **B** and no MBE attenuation occurs. In this way, MBE attenuates input sound levels that are below THR into output sound levels that are below $\mathrm{THR_{TN}}$ and that are inaudible in the presence of the scaled-down threshold noise. MBE output levels corresponding to input levels above REC are not attenuated. For the current research, the full-recruitment level REC is always fixed at 100 dB HL.

The specific MBE implementation used in this research is based upon the work of Moore and Glasberg (1993):

1. It divides the input into 13 frequency bands using a fourth-order gammatone filterbank with center frequencies ranging from 100 to 5837 Hz and bandwidths in the range of 106.5 to 1964 Hz. It time-aligns the bandpass filter impulse responses so that all impulse response peaks are coincident.
2. It uses the Hilbert Transform to separate each band signal into an envelope (Hilbert-Transform-magnitude lowpass filtered at 100 Hz) and fine-structure (Hilbert Transform divided by envelope) components.
3. It converts the input envelopes into output envelopes via the MBE input-to-output mapping described above.
4. It combines the output envelopes with the input fine-structure and applies the inverse Hilbert Transform to obtain output band signals.
5. It sums the output band signals to form the final output signal.

A block diagram of the system used for hearing-loss simulation employing the TN/MBE system is shown in the right panel of Fig. 1. The input signal (upper path) is modified via MBE processing and added to spectrally-shaped noise (lower path), which is scaled to a level of 80 dB SPL, for presentation to the listener. Note that TN/MBE processing only occurs in the current study for threshold shifts that would require excessively loud levels of additive noise (>80 dB SPL) in threshold-noise-only simulations.

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 in Matlab™ and played through the sound card with 24-bit precision using the SoundMex toolbox for Matlab™. The audio output was then passed through a pair of Tucker-Davis (TDT) PA4 programmable attenuators and a TDT HB6 stereo headphone buffer before being sent into a sound-treated booth for presentation to the subject 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) for any given setting of PA4 attenuation and HB6 gain. Specifically, sounds were generated in Matlab™ at SPL-calibrated levels and, immediately prior to sound presentation, they were passed through a compensation filter that ensured level-accurate presentation to the eardrums. Peak output levels of approximately 117 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 Matlab™ 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

Ten subjects with bilateral sensorineural hearing loss who were native speakers of American English participated in the study. Each subject was required to have a copy of a recent clinical audiological examination (within one 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 ten 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 years) 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 in all but two subjects. This definition of symmetry was violated at one frequency (8000 Hz) for HI-6. For subject HI-9, her severe-to-profound hearing loss was roughly 30–35 dB worse across measurable test frequencies

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 and NAM-SIM groups for each hearing-impaired listener and the simulation method used.

			Audiometric thresholds (dB HL) Specified for frequencies (kHz)											
Subject	Sex	Ear	0.25	0.50	1.0	2.0	4.0	8.0	HA use in test ear?	Etiology	Age	AM-SIM group age	NAM-SIM group age	Sim. method
HI-1	M	***L**	**15**	**20**	**25**	**35**	**40**	**35**	No	Hereditary	24	23.0	19.7	TN
		R	15	20	15	40	35	25						
HI-2	M	L	30	35	45	55	55	60	Yes	Congenital?	21	20.3	28.7	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	18.3	TN/MBE
		***R**	**25**	**35**	**30**	**30**	**40**	**75**						
HI-4	F	***L**	**10**	**30**	**45**	**60**	**60**	**80**	Yes	Congenital	59	53.0	23.3	TN/MBE
		R	20	35	40	60	65	70						
HI-5	F	***L**	**15**	**15**	**5**	**60**	**65**	**65**	Yes	Early-childhood/measles	48	45.7	19.7	TN
		R	15	10	30	60	65	55						
HI-6	F	***L**	**40**	**50**	**55**	**55**	**60**	**45**	Yes	Unknown	55	55.3	20.0	TN
		R	40	50	55	60	70	90						
HI-7	M	L	65	60	70	80	70	95	Yes	Hereditary/congenital	69	61.3	21.0	TN/MBE
		***R**	**60**	**60**	**75**	**70**	**70**	**85**						
HI-8	M	L	55	65	65	65	70	90	Yes	Hereditary	68	64.0	23.0	TN/MBE
		***R**	**60**	**65**	**65**	**70**	**80**	**70**						
HI-9	F	L	85	95	110	110	110+	110+	Yes	Congenital	21	22.0	31.7	TN/MBE
		***R**	**50**	**65**	**75**	**75**	**100**	**95**						
HI-10	F	***L**	**50**	**35**	**30**	**20**	**15**	**95**	Yes	Congenital	43	45.7	21.3	TN/MBE
		R	65	50	50	25	20	100						

in her left compared to right ear. 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: (i) sloping high-frequency loss (HI-1, HI-2, HI-3, HI-4, and HI-5), (ii) relatively flat loss with no more than a 20-dB difference between adjacent audiometric frequencies (HI-6, HI-7, HI-8), (iii) severe low-frequency loss advancing to profound high-frequency loss (HI-9), and (iv) 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.

2. Listeners with normal hearing

Sixty NH listeners who were native speakers of American 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 years. Thirty of these sixty subjects were selected as age-matched controls to each of the ten HI listeners. These listeners' ages were in the range of plus or minus 9 years relative to that of the given HI listener to whom they were assigned. The remaining thirty NH individuals (three assigned to each HI listener) were selected without regard to age. These listeners were typically college-age students and were younger than the HI listeners in most cases (with the exceptions of the three youngest HI listeners, HI-1, HI-2, and HI-9). The mean ages of the three age-matched (AM-SIM) and three non-age-matched (NAM-SIM) hearing-loss simulation subjects associated with each HI listener are provided in Table I.

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

TABLE II. Mean audiometric thresholds in dB HL in the test ear for normal-hearing listeners who participated in the age-matched (AM-SIM) and non-age-matched (NAM-SIM) simulation groups. Subjects are grouped into five age categories.

Age range (years)	No. of subjects			Mean audiometric HL (dB) (test ear) frequency (kHz)					
	AM-SIM	NAM-SIM	Total	0.25	0.50	1.0	2.0	4.0	8.0
18–30	9	26	35	4.6	12.4	3.6	3.3	1.7	4.4
31–40	0	4	4	5.0	6.2	5.0	2.5	2.5	11.3
41–50	6	0	6	10.0	5.8	0.8	3.3	7.5	15.0
51–60	8	0	8	5.6	4.4	4.4	5.6	7.5	11.9
61–70	7	0	7	12.1	10.7	10.7	12.1	17.9	20.0

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 whether or not it was the same ear as that tested in the HI listener being simulated. Mean audiometric results for the test ears of the NH subjects are provided as a function of age in Table II. Subjects are grouped into five age categories (18–30, 31–40, 41–50, 51–60, and 61–70 years). Audiometric thresholds in dB HL at the six frequencies in the range of 250 to 8000 Hz were averaged across the subjects in each age group. Mean audiometric thresholds for the youngest group were within the range of 1.7 to 4.4 dB HL across the six frequencies; for the oldest group, thresholds ranged from 10.7 to 20.0 dB HL across frequencies.

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 (in dB SPL) 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.

The simulated hearing impairment used TN processing whenever possible, which was for subjects HI-1, HI-2, HI-5, and HI-6. The remaining HI subjects had losses that required levels of threshold-shifting noise in excess of 80 dB SPL, and so simulations of these losses used TN/MBE processing. The degree of TN/MBE processing depended upon the amount by which the noise level required for TN-only simulation exceeded the 80 dB SPL threshold. Subjects HI-3 and HI-4 required 80–90 dB SPL of threshold noise for TN-only simulation, and so TN/MBE was used to simulate up to 10 dB of threshold shift. Subjects HI-7 and HI-8 required 90–100 dB SPL of masking noise for TN-only simulation, and so TN/MBE was used to simulate up to 20 dB of threshold shift. Subjects HI-9 and HI-10 both required approximately 110 dB SPL of masking noise for TN-only simulation, and so TN/MBE was used to simulate up to 30 dB of threshold shift.

Threshold measurements were obtained using a three-interval, three-alternative, 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. Each interval was cued on the visual display during its 500-ms presentation period with a 500-ms inter-stimulus interval. Tones were windowed to have a 500-ms total duration with a 10-ms Hanning-window (yielding a 480-ms steady-state portion). During the experimental run, 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. Subjects had unlimited response time and were provided with visual trial-by-trial feedback following each response.

When measuring thresholds in NH subjects with simulated hearing loss, each stimulus was processed for hearing loss simulation (using either TN or TN/MBE as described in Sec. II A) immediately preceding each presentation. In both cases, 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-onset time of 3050 ms per trial).

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. 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. Thresholds were averaged across the two runs at each frequency under each type of listening condition (quiet or simulated-loss).

E. Speech testing

Sentence intelligibility was measured using the hearing in noise test (HINT) (Nilsson *et al.*, 1994) made up of 26 phonetically balanced lists of 10 sentences each that were recorded by a single male talker at the House Ear Institute. The HINT test employs an adaptive procedure to measure the speech-reception threshold (SRT) in a speech-shaped noise which is matched to the long-term spectrum of these same recorded sentences. Both the HINT sentences and HINT noise were digitized at 16-bit resolution and a sampling rate of 24 kHz. We further processed the HINT Noise in five different ways, described below in Sec. II E 2, to yield five separate noise conditions.

1. Hint procedure

For each given noise condition, the SRT for 50%-correct sentence reception was measured using an adaptive procedure. The first sentence of a given list was repeated on consecutive trials with increasing level (in 8 dB steps) until the subject was able to repeat it correctly. The nine remaining sentences in a given list were presented once each, with the presentation level either increased for an 'incorrect' previous response or decreased for a 'correct' previous response. The step size was 4 dB until the first reversal and 2 dB thereafter. The SRT for 50%-correct sentence reception was obtained by averaging the presentation levels of the final six sentences in the list. During HINT testing, an experimenter was present in the sound-treated booth with the subject. The subject was asked to provide a word-for-word oral response to each stimulus. The experimenter scored each response as either 'correct' if the subject identified all words correctly (with the minor exceptions such as a/the and is/was) or 'incorrect' otherwise.

2. Experimental conditions for speech testing

SRTs were measured for listeners with real and simulated hearing impairment in noise backgrounds that were derived from the continuous speech-shaped noise provided with the HINT test. Five different noise conditions were studied in conjunction with two hearing-aid configurations.[1]

The five noise conditions were: (1) continuous HINT noise presented at 30 dB SPL RMS, (2) continuous HINT noise presented at 65 dB SPL RMS, (3) interrupted HINT noise presented at 65 dB SPL RMS, (4) continuous HINT noise presented at 80 dB SPL RMS, and (5) interrupted HINT noise presented at 80 dB SPL RMS. For the two interrupted noise conditions, the HINT noise was modulated with a 10 Hz square wave at a modulation depth that yielded a 30 dB SPL noise level in the troughs.

The two hearing-aid configurations were: (1) unprocessed speech (i.e., no hearing aid) and (2) linear hearing aid with the NAL-RP prescription (Byrne *et al.*, 1990; Dillon, 2001). For the NAL-RP aid, the processing was customized to the particular loss of each HI listener. The NAL-RP aid processed the combined speech and noise input signals with a 513-tap FIR linear filter designed to produce the prescribed frequency-dependent gain according to the prescription.

Figure 3 depicts the process for generating the stimuli for use in these speech tests. First, the HINT Noise was transformed into one of the five noise conditions described above. This was then added to a HINT sentence, which had been scaled to the appropriate level and padded with 100 ms of silence at the beginning and end, and the combined signal was processed according to one of the two hearing-aid processing options (No Aid and NAL-RP). The resulting signal was then either sent to the listener (for the HI subjects) or processed for simulated hearing impairment (see Fig. 1) and sent to the listener (for simulated-loss, NH subjects). For

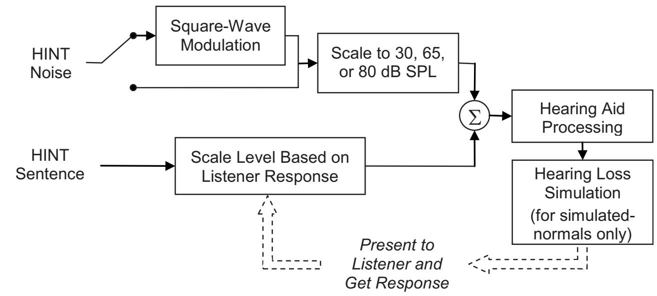

FIG. 3. Block diagram of system used for HINT sentence testing.

simulated hearing-impairment, the threshold-shifting noise, required by both TN and TN/MBE simulation, played throughout the duration of the stimulus.

Two measurements of SRT (based on one HINT list per measurement) were obtained at each of the 10 conditions (5 noise conditions for two hearing-aid conditions). For the first repetition of the experiment, the hearing-aid conditions were tested in the order No-Aid and NAL-RP. Within each hearing-aid condition, the noises were presented in the order (1), (2), (3), (4), and (5) as defined above. For the second repetition of the experiment, the hearing-aid conditions were presented in a random order and the noises were presented in the same order described above. Signals were presented monaurally to the test ear of each subject.

The SRT obtained on each experimental run was converted into the corresponding S/N using the RMS levels of the speech and noise signals. For each subject, mean S/N values were obtained for the 10 test conditions by averaging the results from the two runs conducted for the individual conditions. For the NH subjects with simulated hearing loss, the data were further condensed by averaging the results for each condition across the 3 subjects in the AM-SIM group and the 3 subjects in the NAM-SIM group for each HI listener. This yielded a set of three S/N values for each HI subject under each condition: their own S/N and the average S/Ns across that HI listener's AM-SIM and NAM-SIM groups.

III. RESULTS

A. Absolute thresholds and simulation thresholds

The measured HI-listener and simulated-normal thresholds are shown in Fig. 4 The HI-listener data points are the average of two measurements, while the AM-SIM and NAM-SIM group points are the average of six measurements (two measurements for each of the three subjects within a group). In addition to these three sets of data points, each panel also shows the average thresholds for each AM and NAM group without simulated loss. As with the simulated-loss data points, these data points are the average of six measurements (two per subject).

In general, the simulated-loss subjects show elevated thresholds that are 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 4 kHz. In this case, both the AM-SIM and NAM-SIM groups have thresholds that are approximately 10–12 dB

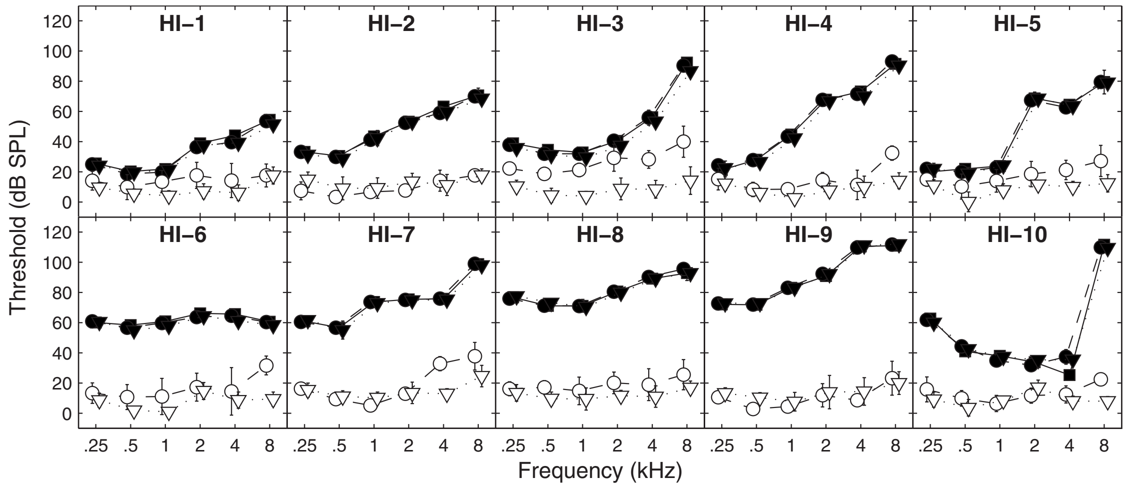

FIG. 4. Threshold in dB SPL as a function of frequency. In each subplot, absolute thresholds are shown for a given HI listener (solid squares). For each HI listener, simulated-loss thresholds are averaged across the three NH listeners in the AM-SIM group (filled circles) and the NAM-SIM group (filled inverted triangles). Also shown are thresholds without simulated loss for the AM-SIM group (unfilled circles) and NAM-SIM group (unfilled inverted triangles).

higher than those of the HI subject. This discrepancy resulted from the steep increase (over 80 dB) in hearing threshold between 4 and 8 kHz. The intensity of the hearing-loss-simulation noise needed to raise threshold at 8 kHz appears to have been sufficient to produce downward spread of masking at 4 kHz.

B. HINT results

The mean dB SPL measurements for 50%-correct HINT-sentence reception in noise condition 1, 30 dB SPL continuous noise, are shown in Fig. 5. The mean S/N measurements on 50%-correct HINT-sentence reception for the remaining four noise conditions (2: 65 dB SPL continuous noise, 3: 65 dB SPL interrupted noise, 4: 80 dB SPL continuous noise, and 5: 80 dB SPL interrupted noise) are shown in Fig. 6. Results are shown for the 10 HI listeners and their corresponding AM-SIM and NAM-SIM matches under unaided conditions in the upper row of panels and under NAL-RP conditions in the lower row of panels. Each HI-listener data point is based on an average of two measurements and each AM-SIM or NAM-SIM data point is based on an average of six measurements (two obtained from each of three subjects within a group).

The HI results in the 30 dB SPL noise condition (Fig. 5) were used to determine the effectiveness of the 65 and 80 dB SPL maskers. Specifically, the results of Plomp (1986) suggest that an effective noise masker must have a level at least 15 dB in excess of the 50%-correct speech reception level in

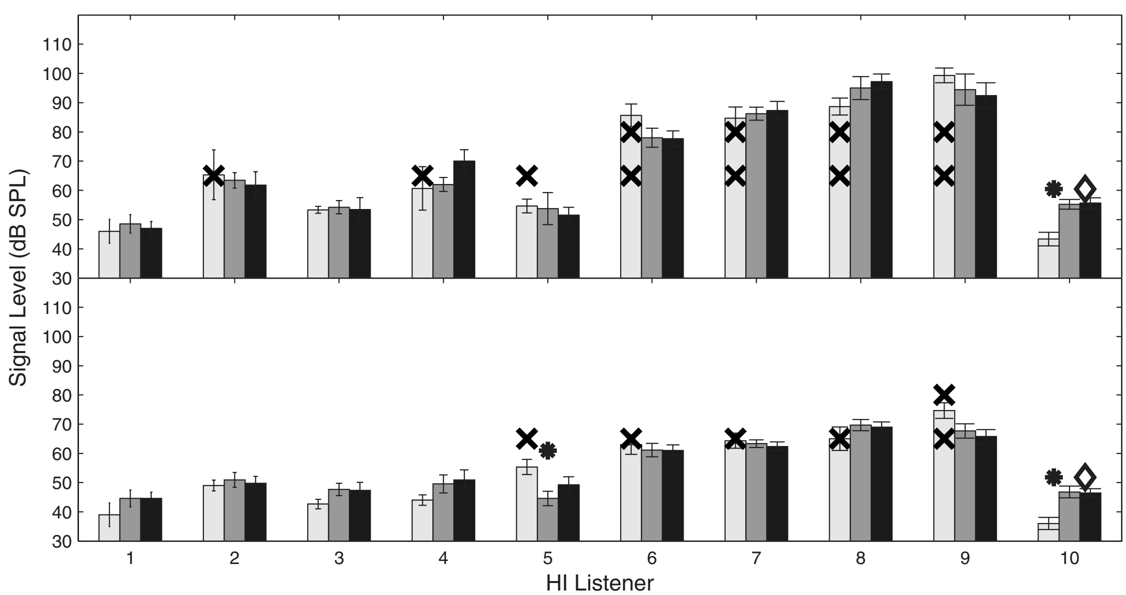

FIG. 5. Measurements of masked speech-reception thresholds (dB SPL) in 30 dB SPL continuous background noise types for unaided and NAL-RP conditions. In each panel, the dB SPL threshold is plotted for the 10 HI listeners and for the corresponding AM-SIM and NAM-SIM groups. Asterisks indicate a significant difference between the HI and AM-SIM groups and diamonds indicate a significant difference between HI and NAM-SIM groups. Also plotted are lines indicating the 65 and 80 dB SPL noise conditions used to measure masking release. These louder noises were deemed to be effective maskers for a particular HI-listener hearing loss when the noise level exceeded the HI-listener continuous-noise, 30 dB SPL threshold by at least 10 dB. The 'X' symbols indicate situations where the 65 and 80 dB noises did not meet this criterion and were not effective as maskers.

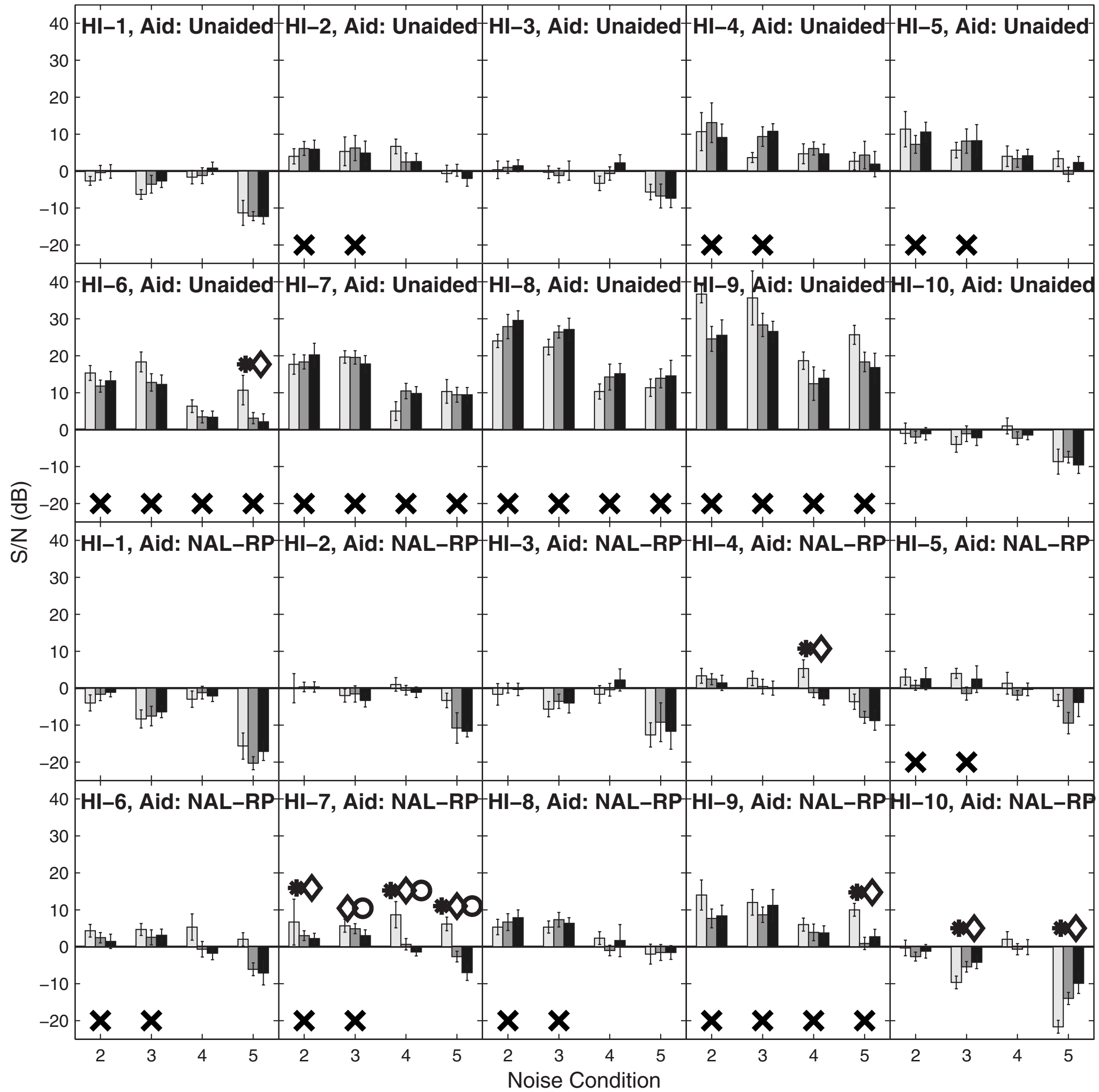

FIG. 6. Measurements of masked speech-reception thresholds (S/N) in four different background noise types for unaided and NAL-RP conditions. In each panel, S/N is plotted for a given HI listener and for the corresponding AM-SIM and NAM-SIM groups. The noise conditions are 2: 65 dB SPL continuous noise, 3: 65 dB SPL interrupted noise, 4: 80 dB SPL continuous noise, and 5: 80 dB SPL interrupted noise. The 'X' symbols indicate conditions for which the noise was not an effective masker for the HI-listener. Other symbols indicate differences between listener groups. Asterisks indicate a significant difference between the HI and AM-SIM, diamonds between HI and NAM-SIM, and circles between AM-SIM and NAM-SIM.

quiet. In the current study, which measured 50%-correct sentence reception in 30 dB SPL continuous noise as opposed to quiet, an effective noise masker was defined as one with a level that is at least 10 dB in excess of the 50%-correct speech reception level in 30 dB SPL continuous noise. When a noise masker exceeds this threshold for a particular listener, the measured 50%-correct speech reception level is likely to be determined primarily by the noise masker. On the other hand, when a noise masker level fails to exceed this threshold, the measured 50%-correct speech reception level is likely to be determined (at least partially and perhaps even completely) by the subject's own hearing threshold. Regardless of masker effectiveness, the HI-subject performance can nonetheless be compared to that of the corresponding AM-SIM and NAM-SIM subjects.

Figure 6 shows S/N results obtained with the 65 and 80 dB SPL noise levels and indicates, with an 'X' symbol, the cases where a given noise level was an ineffective masker for a particular HI listener. Another means of assessing whether speech reception is dominated by hearing threshold or by the masking noise lies in the difference between S/N for 65 and 80 dB SPL noise levels for a given aided condition. If hearing threshold dominates, then the S/N for 80 dB SPL noise should be roughly 15 dB lower than that for 65 dB SPL noise since the absolute signal level for 50%-correct reception has minimal dependence upon noise level; if masking noise dominates, then the two S/N values should be roughly similar. For the most part, this measurement is consistent with the method described above for assessing masker effectiveness (shown in Fig. 5). There are some cases of inconsistency, however, between these two methods of judging masker effectiveness (e.g., HI-6 and HI-7, unaided conditions and HI-9, NAL-RP conditions). These cases most likely represent partial contributions from the masking noise and from hearing threshold.

For the unaided amplification conditions, the 65 dB SPL maskers are ineffective for HI listeners 2, 4, 5, 6, 7, 8, and 9, and the 80 dB SPL maskers are ineffective for HI listeners 6, 7, 8, and 9. For the NAL-RP amplification conditions, the 65 dB SPL masker is ineffective for HI listeners 5, 6, 7, 8, and 9, and the 80 dB SPL masker is ineffective only for HI-9.

For each HI listener, a separate two-way ANOVA was performed on the 14 data values (two repetitions each for one HI, three AM-SIM, and three NAM-SIM subjects) obtained for each of the 10 listening conditions (two amplifications times five noise conditions) to examine the main effects of Group (HI, AM-SIM, and NAM-SIM) and Repetition. Significance was defined at the level of $p \leq 0.01$ (with $F \geq 8.65$, df=2,8 for Group and $F \geq 11.26$, df=1,8 for Repetition). In cases where a significant effect of Group was found, the *post hoc* Scheffe test ($p \leq 0.05$) was used to determine inter-group significant differences. In Figs. 5 and 6, asterisks indicate a significant Group difference between HI and AM-SIM, diamonds between HI and NAM-SIM, and circles between AM-SIM and NAM-SIM. A main effect of Repetition was observed in only four cases: for HI-7 under noise conditions 2 and 3 with NAL-RP amplification and for HI-10 under noise conditions 1 and 5 with unaided amplification. A single significant interaction effect was observed for HI-7 under noise condition 2 with NAL-RP amplification.

For the unaided conditions, significant Group effects were observed in 2 HI listeners: Subject HI-6 required a significantly higher S/N than either of the two simulated-loss groups for noise condition 5 and HI-10 required a lower S/N in noise condition 1 than either of the two simulated-loss groups.

For the NAL-RP conditions, significant Group effects were observed in 10 instances from 5 HI listeners. Four of these five HI listeners required significantly higher S/N values compared to either or both the AM-SIM and NAM-SIM groups: HI-4 in noise condition 4; HI-5 in noise condition 1; HI-7 in noise conditions 2 through 5; and HI-9 in noise condition 5. Subject HI-10, on the other hand, required significantly lower S/N values compared to the two simulated-loss groups in noise condition 1 as well as noise conditions 3 and 5. Further significant differences were observed between the HI-7 AM-SIM and NAM-SIM groups for noise conditions 3, 4 and 5.

The effects of the NAL-RP amplification are most evident in comparing NAL-RP to unaided results in the presence of 30-dB continuous noise (Fig. 5). Across subjects, the NAL-RP S/N values are 5–25 dB lower than the corresponding unaided S/N values, with larger improvements in S/N associated with more severe hearing losses. This observation reflects the fact that the 30-dB noise was either near or below threshold for all listeners, in which case the unaided S/N value was more heavily influenced by the hearing threshold than by the noise level and the presence of NAL-RP amplification yielded a lower S/N even for the same noise type. As the noise presentation level increased to 65 and 80 dB SPL, the noise became more audible, and the differences between same-noise-type unaided and NAL-RP S/N values decreased. Even at higher noise presentation levels, however, the unaided noise was still partially below threshold for subjects with more severe losses (Subjects HI-6 through HI-9), which is evident in the fact that unaided-versus-NAL-RP differences remain greater for these subjects than for those with milder losses (Subjects HI-1 through HI-5 and HI-10).

Masking release (MR) is plotted in Fig. 7 as a function of noise level for each HI listener and the corresponding AM-SIM and NAM-SIM groups. MR is defined as S/N in dB in continuous noise minus the S/N in dB in interrupted noise for a given RMS noise level. Conditions with ineffective maskers are marked by 'X' symbols. Similarly to the S/N plots, the two upper rows of panels show values for the unaided conditions while the two lower rows of panels show values for the NAL-RP conditions. For both types of amplification, MR values are shown for both the 65-dB and 80-dB noise levels. Each HI-listener data point is based on an average of two MR values (one obtained from each of the two separate experimental runs) and each AM-SIM or NAM-SIM data point is based on an average of six MR values (two obtained from each of three subjects within a group). The 'X' symbols indicate situations where the noise maskers were determined to be ineffective for a particular HI listener as described above and as shown in Fig. 5.

For each HI listener, a two-way ANOVA was performed on the MR results for each condition plotted in Fig. 7 (with the same factors, significance levels, F-values, and *post hoc* testing as described previously for the dB SPL and S/N results in Figs. 5 and 6). Only two instances of significant Group differences in MR were observed. For HI-7 at 80-dB noise in unaided listening, the MR was significantly lower than that obtained in either the AM-SIM or NAM-SIM group. For HI-10 at 80-dB noise in NAL-RP processing, the MR was significantly different for all three pairs of groups in the order HI-10 > AM-SIM > NAM-SIM. Subject HI-10 is the only HI listener who consistently shows higher levels of masking release than the corresponding AM-SIM and NAM-SIM groups for all four test conditions. The source of these higher levels arises from the lower S/N values obtained by this subject in the interrupted noise (see Fig. 6). Only one Repetition effect was observed (for HI-7 at 65-dB noise with NAL amplification) and one interaction effect (for HI-1 at 65 dB noise under unaided listening).

The magnitude of MR, as expected, was greater for the effective compared to the ineffective masking conditions. Averaged across all cases of ineffective maskers (including both noise levels and both types of amplification), MR averaged −0.65, −0.26, and 0.18 dB for the HI, AM-SIM, and NAM-SIM groups, respectively. The mean MR for effective masker conditions rose to 5.86, 5.48, and 5.90 dB for the three listener groups, respectively. Thus, on average, the hearing-loss simulations were effective in reproducing the MR results obtained in the HI listeners.

C. ESII modeling and MR prediction

Further comparisons of the performance of the HI listeners to NH listeners with simulated hearing loss were conducted using the Extended Speech Intelligibility Index (ESII) as calculated by the procedure described in Rhebergen *et al.* (2006). The ESII is a modification to the SII (ANSI, 1997)

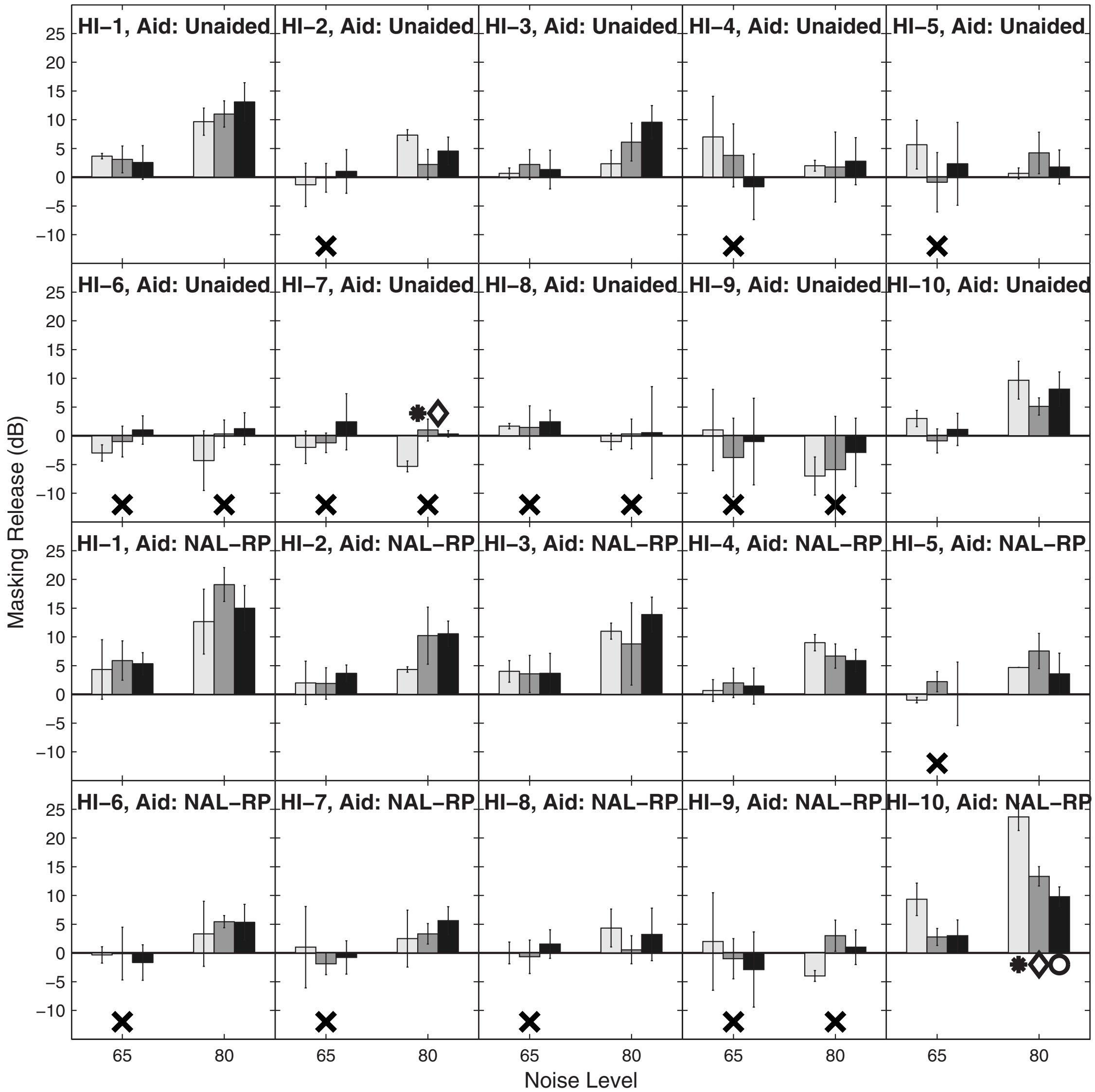

FIG. 7. Masking release (MR) as a function of noise level in unaided and in NAL-RP conditions. In each panel, MR is plotted for a given HI listener and for the corresponding AM-SIM and NAM-SIM groups. The 'X' symbols indicate conditions for which the noise was not an effective masker for the HI-listener. Other symbols indicate differences between listener groups. Asterisks indicate a significant difference between the HI and AM-SIM, diamonds between HI and NAM-SIM, and circles between AM-SIM and NAM-SIM.

that is capable of modeling speech-reception performance in interrupted noise incorporates a function to account for forward-masking models in the calculations.

ESII functions for each test condition as a function of S/N were computed based upon (1) the specific hearing thresholds (using the 70.7%-correct thresholds obtained in the 3AFC testing with 33%-correct performance expected on the basis of chance alone), (2) the noise spectrum associated with the test condition, (3) the speech spectrum as determined by the noise spectrum and S/N value, and (4) the amplification used in the test condition. This procedure yields ESII functions that are identical to the SII functions obtained using the ANSI standard for continuous noise (ESII-C), but extends the model to handle interrupted noise (ESII-I). The predicted MR is the difference between S/N values corresponding to a specified value of ESII. Assuming that the ESII reflects speech intelligibility as it is affected by audibility, the degree to which predicted MR values match the actual MR values for each subject will indicate the extent to which audibility can account for observed masking release in HI individuals.

Figure 8 shows an example of two ESII functions computed for subject HI-10 for the 80 dB SPL noise condition under NAL-RP amplification. These functions were derived using the measured values of S/N corresponding to 50%-correct sentence reception to calculate the psychometric curves for continuous noise (ESII-C) and interrupted noise (ESII-I). Predictions of masking release were then obtained from the ESII-C and ESII-I curves using an ESII value of 0.33. This ESII value represents the audibility for NH listeners in continuous noise reported by Rhebergen *et al.* (2006). For each of the two functions (ESII-C and ESII-I), the S/N corresponding to a value of 0.33 was estimated from the curves. The ESII-predicted value of MR was then defined as the estimated S/N for continuous noise minus the estimated S/N for interrupted noise.

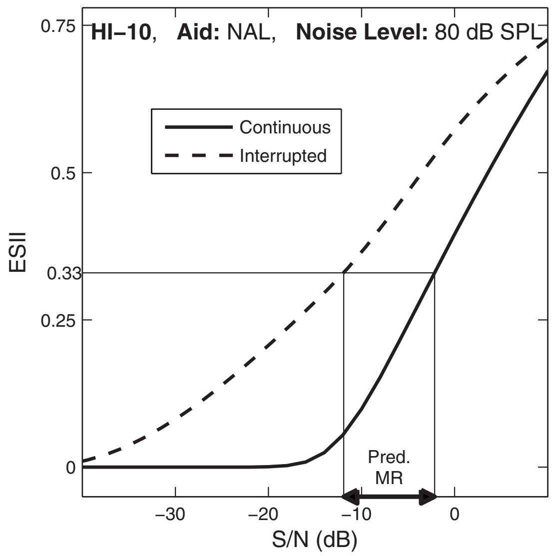

FIG. 8. ESII functions for continuous and interrupted noise at 80 dB SPL for subject HI-10 for the NAL-RP condition. A horizontal line is drawn at the point representing ESII=0.33 (the value of NH listeners for 50%-correct sentence reception). The S/N corresponding to the point at which this horizontal line intersects the ESII-I curve and the ESII-C curve are then found (shown by the two vertical lines, respectively). The predicted masking release (9.8 dB) is the difference between the S/N values that yield ESII of 0.33 on the continuous- and interrupted-noise psychometric functions (−2.1 and −11.9 dB, respectively).

Because the ESII-I functions generated according to Rhebergen *et al.* (2006) are generally to the left of the corresponding same-noise-level ESII-C functions, all ESII-predicted MR values for the current study were positive. None of the negative MRs that were observed in the data (see Fig. 7) were predicted. Also note that the ESII-predicted MR is a function of the value of ESII. The relative shapes of the ESII-C and ESII-I curves indicate a tendency for MR to decrease as ESII increases, in agreement with Bernstein and Grant (2009).

Figure 9 shows plots of continuous-versus interrupted-noise ESII values (ESII-C versus ESII-I) for the individual subjects for each of the four noise-level and amplification combinations. The top row of panels shows ESII values for all test conditions, while the lower row of panels shows ESII values only for those conditions deemed to have effective noise maskers. The three subject groups (HI, AM-SIM, and NAM-SIM) are indicated using three different marker types, and ESII-C=ESII-I is indicated by the diagonal line. For comparison purposes, we also plot mean data in the two unaided conditions for a group of young normal-hearing (NH) listeners[2] without hearing-loss simulation as the bold-edged diamonds. For all four noise/amplification conditions, both including and excluding the ineffective noise masker conditions, the computed values of ESII-C and ESII-I were quite similar (as demonstrated by the proximity of the data points to the diagonal line in the subplots). For the unaided test conditions, average values of ESII-C and ESII-I for the NH, HI, AM-SIM, and NAM-SIM groups over effective-noise-masker only cases were roughly 0.39, 0.34, 0.37, and 0.38, respectively, for the 65-dB SPL noise and roughly 0.39, 0.36, 0.34, and 0.36, respectively, for the 80-dB SPL noise. For the NAL-RP test conditions, average values of ESII-C and ESII-I for the HI, AM-SIM, and NAM-SIM groups over effective-noise-masker only cases were roughly 0.38, 0.39, and 0.39, respectively for the 65-dB SPL noise and roughly 0.44, 0.35, and 0.36, respectively, for the 80-dB SPL noise. The observed increase in ESII values for HI group listening to the 80-dB SPL NAL-RP condition is due almost entirely to two HI subjects (HI-6 and HI-7). Both of these subjects required ESII-C and ESII-I that were similar to each other but clearly higher than those for the other listeners for both continuous and interrupted noise conditions (roughly 0.58 for HI-6 and 0.64 for HI-7 and consistent with their correspondingly high S/N values for these conditions as shown in Fig. 6).

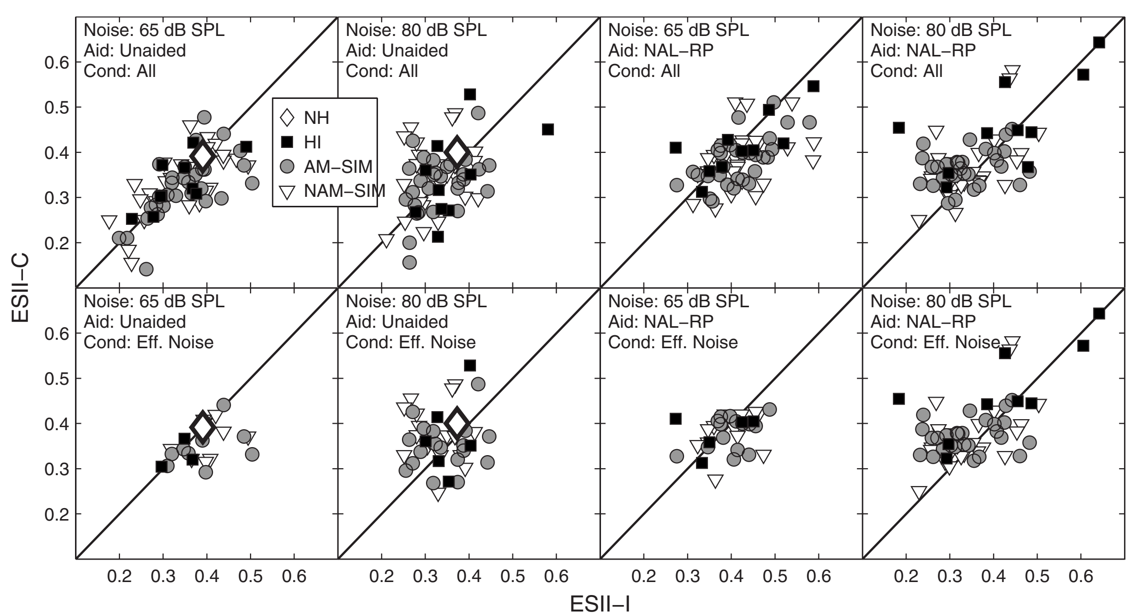

FIG. 9. ESII-C plotted as a function of ESII-I for each HI listener and for each AM-SIM and NAM-SIM listener for unaided and NAL-RP processing at two noise levels. Upper panels show results for all test conditions. Lower panels show results for conditions with effective noise maskers. Diagonal line is ESII-C=ESII-I. For the two unaided conditions, mean results are also shown for a group of young NH listeners without hearing-loss simulation.

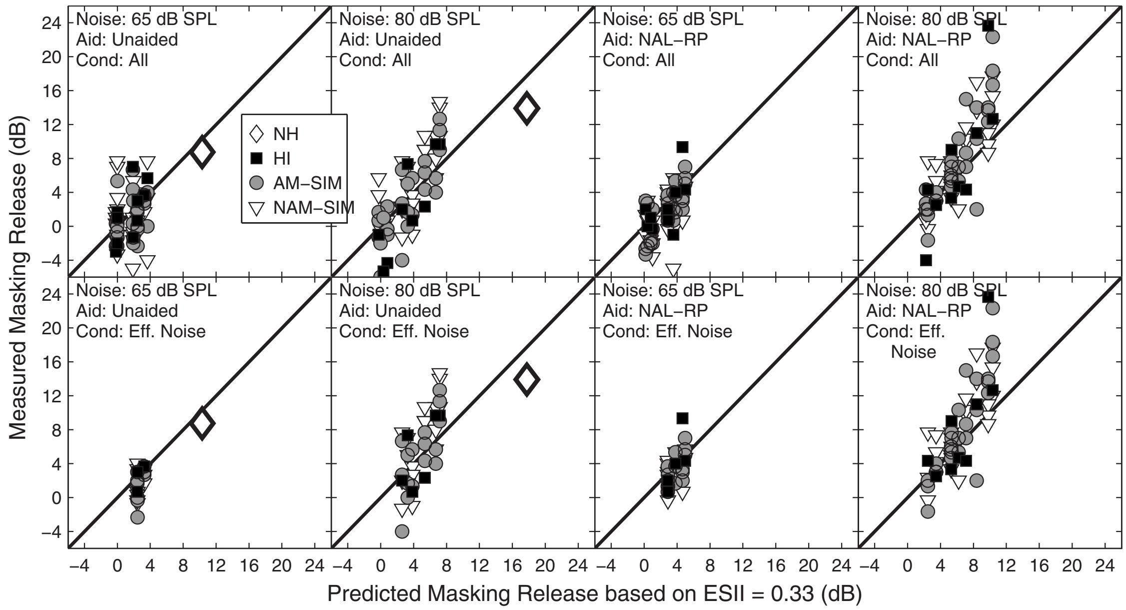

FIG. 10. Measured masking release (MR) plotted as a function of predicted MR based on ESII=0.33 for each HI, AM-SIM, and NAM-SIM listener for unaided and NAL-RP processing at two noise levels. Upper panels show results for all test conditions. Lower panels show results for conditions with effective noise maskers. Diagonal line represents Measured MR=predicted MR. For the two unaided conditions, mean results are also shown for a group of young NH listeners without hearing-loss simulation.

Figure 10 plots the predicted versus actual measured MR for each subject under the four test conditions defined by the two noise levels (65 and 80 dB SPL) and the two amplifications (unaided and NAL-RP). The top row of panels shows ESII values for all test conditions, while the lower row of panels shows ESII values only for those conditions with effective noise maskers. In each plot, the solid diagonal line indicates predicted-equals-actual MR. In addition to data for individual listeners in the HI, AM-SIM, and NAM-SIM groups, mean data are also shown for the NH listeners for the two unaided conditions only.

In general, the data points for the HI, AM-SIM, and NAM-SIM groups cluster similarly and describe similar predicted-MR-versus-measured-MR relationships. For the two unaided conditions, the predicted and observed MR values of the NH group are substantially higher than any of those obtained in groups with real and simulated hearing loss. For the 65-dB noise level in the unaided condition for effective-noise-masking cases only, most of the measured MR data points lie between ±5 dB for the HI, AM-SIM, and NAM-SIM listeners compared to a measured MR of 8.75 dB for the NH group. No predicted MR was found to be less than 0 dB. As the audibility of the noise increases (either through amplification or through increased noise level), the relationship between predicted and actual MR becomes more structured and is similar for the HI, AM-SIM, and NAM-SIM groups. For effective-masking-cases only in the unaided 80 dB SPL condition, an increase is seen in the range of the predicted and observed MR values. The observed MR was roughly 5.3, 5.1, and 6.7 dB for the HI, AM-SIM, and NAM-SIM groups, respectively. These values are substantially lower than that for the NH group with an observed MR of 13.9 dB. For the NAL-RP conditions, mean observed MR was 4.1, 3.2, and 3.4 dB for HI, AM-SIM, and NAM-SIM, respectively, at the 65-dB noise and 8.4, 8.3, and 8.1 dB, respectively, at the 80 dB SPL noise. For listeners with real and simulated hearing impairment, a tendency is seen for over-prediction of MR at smaller values of MR (i.e., <5 dB) and under-prediction at higher values of MR (i.e., >7 dB), particularly for the 80-dB noise levels. For the NH listeners without simulated hearing-loss, the predicted MR values were 1 to 3 dB higher than the observed values.

IV. DISCUSSION

A. Age effects

Comparisons of the performance of the AM-SIM groups to the NAM-SIM groups show no strong evidence of age-related effects on the magnitude of either S/N or masking release. Only three cases of significantly higher S/N values for older compared to younger subjects were observed in the simulations of any of the 10 HI listeners (all between the AM-SIM and NAM-SIM groups for HI-7 under NAL amplification). The largest age differences between the AM-SIM and NAM-SIM groups occurred for HI-3, HI-7, and HI-8 whose ages were 64, 69, and 68 years, respectively. For these three subjects, the age of the AM-SIM groups averaged roughly 62 years compared to an average age of roughly 21 years for the NAM-SIM groups (a difference of roughly 41 years). Even in these cases, the performance of the older simulated-loss groups was generally similar to that of the younger groups. These trends are also observed in the ESII data, with nearly identical mean ESII-C and ESII-I values for the AM-SIM and NAM-SIM groups.

Thus, our results indicate that sentence intelligibility in both continuous and interrupted noise appears to depend primarily on factors other than subject age for NH subjects in the presence of the TN or TN/MBE hearing-loss simulations employed here. These results are in agreement with those of Takahashi and Bacon (1992), who found only a weak correlation between age and masking release when absolute thresholds were accounted for. The age effects observed by Peters *et al.* (1998) for HI listeners in NAL-RP-amplified interrupted noise and by Dubno *et al.* (2002, 2003) and Gifford *et al.* (2007) for interrupted noise in groups of NH younger and older subjects are not apparent in the current results. In our results, comparisons of listeners with equal audibility under unaided and NAL-RP-amplified speech did not yield significant age effects; however, it should be noted that our results are based on a small number of older subjects and include no subjects over the age of 69 years. Further work is required to extrapolate these results to listeners over the age of 70 years who constitute roughly half of current hearing-aid users (Kochkin, 2005).

B. Comparisons of real and simulated hearing impairments

To the extent that the performance of the hearing-loss simulation groups is comparable to that of the HI listeners, we can conclude that the effects of audibility are capable of explaining the performance of HI listeners for speech reception in continuous and interrupted noise. Our results indicate that the simulations were generally effective in reproducing the S/N levels required for 50%-correct reception of sentences in interrupted and continuous noise for both ineffective and effective masker conditions. Only three statistically significant group differences in S/N were observed in the ineffective masker conditions (in the data of HI-7 for NAL-RP, 65-dB continuous and interrupted noise and of HI-9 for NAL-RP, 80-dB interrupted noise, see Fig. 6). Five cases of statistically significant differences in S/N between listeners with real and simulated hearing impairment were observed for the effective masker conditions, all for NAL-RP-amplified conditions (see Fig. 6). Previous studies have also reported that the speech-reception performance of HI listeners is less well-matched by hearing-loss simulations for speech materials with high-frequency emphasis compared to flat gain (e.g., Zurek and Delhorne, 1987; Duchnowski and Zurek, 1995; George *et al.*, 2006). Masking-release values of the HI listeners, however, were generally well-produced by the TN and TN/MBE simulations for both ineffective (where MR averaged roughly 0 dB) and effective maskers (where MR averaged roughly 6 dB).

Recent investigations (Bernstein and Grant, 2009; Oxenham and Simonson, 2009) have demonstrated a dependence of MR on S/N such that MR decreases with an increase in S/N. Bernstein and Grant (2009) measured psychometric functions for the reception of key words in low-context sentences in backgrounds of continuous and temporally-fluctuating noise in listeners with normal and impaired hearing. They then plotted MR as a function of the S/N needed for 50%-correct performance in continuous noise. A straight-line fit to their HI data (solid line) is plotted in Fig. 11, along with data from the effective-masking cases only of the current study. The range of S/N values for these cases in the current study is roughly −4 to +8 dB compared to a range of −3.5 to +3.8 dB for Bernstein and Grant's HI listeners. Our task requires 50%-correct sentence intelligibility, as opposed to Bernstein and Grant's task of 50%-correct key word

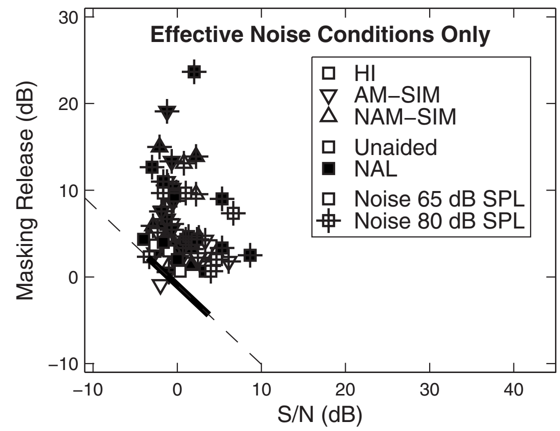

FIG. 11. Masking release (MR) plotted as a function of S/N in continuous 65 and 80 dB SPL noise for unaided and NAL-RP processing. Mean MR for each condition is shown for individual HI listeners and averaged across the three listeners in each AM-SIM and NAM-SIM group. Results are shown only for conditions with effective noise maskers. The dotted line is an extrapolation of the fit to the HI data (thick solid line) reported by Bernstein and Grant (2009).

reception, and thus may account for several dB of the difference in S/N range (see Boothroyd and Nittrouer, 1988). Nearly all of our measurements of MR are higher than those obtained by Bernstein and Grant when examined over the same range of S/N, indicating that our measures of S/N for 10-Hz square-wave interrupted noise are lower than those of Bernstein and Grant obtained with one-talker speech-modulated noise or for a single interfering talker. Despite these differences, a general trend is also observed in our data for higher MR at low S/N and for a disappearance of MR for S/N>0 dB [as also noted by Oxenham and Simonson (2009) for NH listeners with filtered speech].

The hearing impairment of HI-10 appears to be the least well simulated of any of the losses studied here both in terms of simulating her elevated thresholds and in terms of matching her speech-reception results in noise. In the 30-dB continuous noise condition for unaided and NAL-RP-amplified listening, the speech-reception thresholds of HI-10 were roughly 10 dB lower than those measured in both the AM-SIM and NAM-SIM groups. In addition, this listener had significantly lower S/N values in interrupted noise compared to the simulated-loss groups for the NAL-RP listening conditions, which translated into larger release from masking at both 65 and 80 dB noise levels. In fact, the −22 dB S/N value for NAL-RP and interrupted 80-dB noise is the lowest S/N value obtained in this study–including pilot S/N data taken on NH subjects without hearing loss simulation. One possible source of the simulation errors observed here, with better performance on the part of the HI listener, may be the 11-dB lower threshold at 4000 Hz for HI-10 compared to the SIM groups. Perhaps the additional speech cues available to HI-10 in the vicinity of 4000 Hz contributed to her superior performance. It should also be noted, however, that other such examples of simulation errors with superior performance on the part of the HI listener have been reported in the literature (e.g., see Zurek and Delhorne, 1987; Duchnowski and Zurek, 1995; Bacon *et al.*, 1998).

The hearing-loss simulation methods employed here (i.e., TN or TN/MBE) were generally successful in reproducing the size of the masking release experienced by HI listeners for HINT sentences. Other investigators using noise-masked simulations, however, have observed smaller amounts of MR in HI listeners than in their noise-masked NH counterparts. Bacon *et al.* (1998) observed good simulation of MR in sentences for only 5 of their 11 HI listeners (even though S/N values were not significantly different between their groups of HI and noise-masked NH listeners). For the additional 6 HI listeners, less masking release was observed for HI than for noise-masked normals. The size of the masking release decreased with an increase in pure-tone thresholds and was best simulated for MR greater than 5 dB. Bacon *et al.*'s (1998) finding that masking release was less well simulated for smaller differences (i.e., less than 5 dB) in S/N between interrupted and continuous noise is not apparent in the current data.

George *et al.* (2006) observed more failures of their hearing-loss simulations of masking release with aided compared to unaided conditions. In their adaptive-gain data, masking release for only 7 of their 29 HI listeners fell within the range of the simulated-loss values (6 to 10 dB); the remainder of their HI listeners had values that ranged from roughly 0 to 5 dB. In our highest-level listening condition (80-dB NAL-RP), the masking release ranged from −4 to 24 dB across the HI subjects and averaged 7.2 dB compared to 7.8 dB for the AM-SIM group and 7.4 dB for the NAM-SIM group.

Differences between MR results of the current study and those obtained by Bacon *et al.* (1998) and George *et al.* (2006) may be related to several methodological differences. First, these previous studies employed noise-masking simulations of hearing loss while most of the hearing losses in the current study were simulated through a combination of masking noise and multi-band expansion. Second, the current study employed custom simulation of individual hearing losses (as did Bacon *et al.*, 1998), as opposed to the simulation of an average high-frequency and an average flat loss by George *et al.* (2006). Third, different formulas were employed for applying selective gain to compensate for hearing loss. George *et al.* (2006) employed a gain designed to place the presentation noise level in the middle of the third-octave-band dynamic range (defined by the authors as halfway between the dB SPL threshold of hearing and 110 dB SPL), whereas our study applied the NAL-RP gain to both 65 dB SPL or 85 dB SPL noise. The main difference between these two approaches was that the noise in the George *et al.* (2006) study was guaranteed to be audible above the threshold of hearing, while the noise for the current study was not necessarily audible at all frequencies. Their gain, however, may have led to the use of a frequency-gain characteristic that is different from that typically encountered by HI listeners in real-world listening either with or without a hearing aid. Fourth, most of our HI listeners were experienced hearing-aid users and thus may have been accustomed to listening to amplified speech; the hearing-aid use of the subjects in George *et al.* (2006) was not indicated.

C. ESII comparison and predicting masking release from ESII curves

In the unaided conditions, ESII values at threshold S/N's were similar across the NH, HI, AM-SIM, and NAM-SIM listening groups for both noise levels and noise types. Two effects were observed in the NAL-RP-amplified conditions. First, there was a slight increase in ESII for all three groups (HI, AM-SIM, and NAM-SIM) compared to unaided conditions. Thus, all listeners needed higher ESII values under amplification compared to unaided listening. And second, the mean ESII values of the HI listeners increased from the 65-dB to the 80-dB NAL-RP noise, unlike those of the two simulated-loss groups which were similar for these two conditions.

Our results differ somewhat from those reported by George *et al.* (2006) for HI listeners and for noise-masked simulations of hearing loss in NH listeners. Their data were obtained using Dutch sentences presented in continuous and interrupted noise with two different spectral shapes: the long-term average speech spectrum or a noise created for each HI listener in which the level of the noise in 19 third-octave bands was set to the middle of the dynamic range in that particular band. In the latter case, their HI listeners required higher ESII values in interrupted compared to stationary noise, and nearly all of their interrupted-noise ESII values exceeded those obtained in the listeners with simulated hearing-loss. Such a clear trend is not obvious in the HI data of the current study. In the NAL-RP aided conditions, there is no indication of higher ESII values required for the HI listeners in interrupted versus continuous noise for either of the two noise levels (see Fig. 9). Two of our HI listeners exhibited higher ESII values (compared to the other 8 HI listeners as well as to the listeners with simulated hearing loss) in both interrupted and continuous 80-dB noise in the NAL-RP condition. Thus, greater difficulty in understanding speech for these two listeners in this condition was not confined to interrupted noise as was the case with the HI listeners in the study of George *et al.* (2006). This difference in the pattern of aided listening results between the two studies may be related to differences in the frequency-dependent gain in aided conditions as well as to differences in the methods used for calculating ESII. Not only did George *et al.* (2006) use an earlier version of the ESII reported by Rhebergen and Versfeld (2005) rather than the Rhebergen *et al.* (2006) method used here but also modified several model parameters (e.g., window length and filter type) to fit their own SRT results for a 16-Hz interrupted noise

The higher ESII values seen in some of the HI listeners for the 80-dB noise conditions (compared both to other HI listeners and to the NH listeners with simulated hearing loss) may be indicative of a suprathreshold deficit that is not entirely explained by audibility alone. For HI-6 and HI-7, their need for higher S/N values (and correspondingly higher ESII values) in the presence of NAL-RP amplification indicates difficulty in the use of amplified speech (even though both of these subjects reported routine use of hearing aids). Difficulties in the use of amplified speech by HI listeners have been reported previously (e.g., Rankovic, 1991; Ching *et al.*, 1998; Hogan and Turner, 1998; Hornsby and Ricketts, 2003,

2006) but often in the case of listeners with moderate-to-severe high-frequency hearing loss. Dead regions (i.e., areas of the cochlea with no functioning inner hair cells; see Moore *et al.*, 2000) have been proposed as an explanation for poor-use of high-frequency amplification in HI listeners. According to this hypothesis, high-level signals resulting from high-frequency amplification may actually be encoded by lower-frequency hair cells and thus may interfere with stimulation associated with the center frequencies of those cells. Dead-region testing was conducted on HI-6 and HI-7 using the 3I-3AFC procedure described in Sec. II D to measure detection of pure tones in broadband noise. For HI-6, the broadband noise was filtered to produce masked thresholds of 75 dB SPL in NH listeners at the octave frequencies in the range of 250 to 8000 Hz. At each of these frequencies, her masked thresholds were within the range of 78 to 80 dB SPL and thus showed no evidence for the presence of dead regions in her test ear. For HI-7, the broadband noise was filtered to produce masked thresholds of 80 dB SPL in NH listeners at frequencies of 250, 500, and 1000 Hz. His thresholds were within the range of 80 to 85 dB SPL at each of the three frequencies, showing no evidence of dead regions. The severity of this subject's hearing loss above 1000 Hz precluded the use of the dead-region test; thus, we cannot rule out the possibility of dead regions at higher frequencies. In any case, the higher ESII values observed in HI-6 and HI-7 suggest supratheshold auditory deficits; whether those deficits are peripheral or central remains to be determined.

The use of ESII to predict masking release for interrupted versus continuous noise indicated an orderly relationship between observed and predicted MR for listeners with both real and simulated hearing impairment. Systematic deviations from predicted-equals-observed MR were observed, however, for the three most audible conditions (i.e., excluding the unaided 65-dB noise condition). Specifically, the predicted values tended to be greater than actual values for lower levels of MR, while they tended to be less than observed for higher levels of MR. The trend of over-prediction for lower levels of MR was primarily because the predicted MR was always non-negative, while actual MR could be either positive or negative. Negative values of MR have also been reported by Bernstein and Grant (2009) for HI listeners based on psychometric functions for key-word reception in sentences. The trend for under-prediction is particularly evident for the two 80-dB noise conditions in cases where predicted MR exceeds 5 dB.

V. SUMMARY AND CONCLUSIONS

The intelligibility of HINT sentences was examined in continuous and interrupted background noise at two levels (65 and 80 dB SPL) for conditions of unaided and NAL-RP processing in ten individuals with sensorineural hearing loss. Each of the ten individual hearing losses was simulated in two groups of three NH listeners (one group that was matched in age to the HI listener and one group selected without regard to age) using a combination of threshold noise and multi-band expansion to achieve the desired frequency-dependent threshold elevations. Masking release (MR) achieved through listening in interrupted versus continuous noise was defined as the difference in S/N for 50% sentence intelligibility for continuous minus interrupted noise. The effects of signal audibility on MR were assessed through comparisons of the results of listeners with simulated hearing loss to those of the HI listeners and effects of age were examined through comparisons of the performance of the age-matched and non-age-matched groups associated with the hearing-loss simulations. The Extended Speech Intelligibility index (ESII) was used to model the performance of the HI and simulated-loss listeners as well as to predict MR. The major results of the study may be summarized as follows:

(1) Only minimal effects of age were observed between the age-matched and non-age-matched groups with simulated hearing loss for S/N or MR under any of the listening conditions. The results obtained with both groups of simulated-loss listeners were similar to those obtained by the hearing-impaired listeners whom they simulated.
(2) The effectiveness of the 65 and 80 dB SPL masking noises was assessed for each listener under both types of amplification. Maskers were deemed to be effective when the SRT was at least 10 dB greater than that obtained in the 30 dB SPL continuous noise. The performance of the HI listeners was generally well-matched by the TN and TN/MBE hearing-loss simulations in cases of both ineffective and effective masking conditions. The magnitude of MR averaged roughly 0 dB for ineffective maskers and roughly 6 dB for effective maskers and was similar in each case across the three listening groups. These values of MR were substantially lower than those obtained in NH listeners without hearing-loss simulation.
(3) ESII values for 50%-correct sentence reception were generally similar for continuous and interrupted noise, and mean values across the three subject groups were similar for all conditions except NAL-RP listening in the higher-level noise. In this case the ESII for both noise types for the HI group was higher than for the other two groups. This increase in ESII was due in large part to the performance of two of the ten HI subjects.
(4) For cases of effective maskers, the ESII-based predictions of MR showed a tendency of over-prediction of observed values for MR in the range of 0 to 5 dB and under-prediction for higher observed values of MR (>7 dB).
(5) Audibility effects appear to be capable of explaining most of the speech-reception results observed in HI listeners, with the exception of two subjects in higher-noise-level NAL-RP processing.

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[1]A third hearing-aid configuration using compressive processing based upon the architecture of Goldstein *et al.* (2003) was also tested. These results will be discussed in a future publication.

[2]A new group of four young normal-hearing listeners (2M, 2F; age range of 20 to 24 yrs; mean age of 21.75 yrs) listened to the HINT sentences without hearing-loss simulation. Each listener had audiometrically normal hearing in the test ear (i.e., thresholds of 15 dB HL or better at the octave frequencies between 250 and 8000 Hz). For the HINT testing, two SRTs were obtained on each listener for unaided speech in the five noise conditions. The mean S/N across listeners was 5.67 dB for continuous 30 dB SPL noise, −1.67 dB for continuous 65 dB SPL noise, −10.42 dB for interrupted 65 dB SPL noise, −0.33 dB for continuous 80 dB SPL noise, and −14.25 dB for interrupted 80 dB SPL noise. The mean release from masking was 8.75 dB for 65 dB SPL noise and 13.9 dB for 80 dB SPL noise.

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