# Effect of fast-acting compression on modulation detection interference for normal hearing and hearing impaired listeners

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To determine the effects of hearing loss and fast-acting compression on auditory grouping based on across-frequency modulation, modulation detection interference (MDI) was measured in listeners with normal hearing and hearing loss. MDI, the increase in the amplitude-modulation detection threshold of a target presented with an interferer distant in frequency, was measured using a 500-Hz target and a 2140-Hz interferer, both modulated with narrow-band noises of the same bandwidth. The two modulated tones were presented at equal loudness levels to listeners with normal hearing and hearing loss in the absence (Exp. 1) and in the presence (Exp. 2) of fast-acting compression applied to the interferer. Modulation detection thresholds increased with increasing modulation depth of the interferer by similar amounts for the two groups of listeners, suggesting that across-frequency grouping based on amplitude modulation is not altered by hearing impairment. Compression provided an additional increase in thresholds for both groups, indicating that compression algorithms might alter across-frequency grouping cues. Partial support for an idea that compression's effect of sharpening the onsets after each envelope valley is provided by a third experiment which found somewhat greater interference produced by square-wave modulation than sine-wave modulation at larger interferer modulation depths.

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## I. INTRODUCTION

Current digital hearing aids commonly employ compression in their amplification scheme. Compression algorithms adjust the amount of amplification based on stimulus levels providing more gain to low-level sounds than to high-level sounds. In this way, low-level sounds become audible or louder but high-level sounds do not become uncomfortably loud. Such algorithms allow the wide dynamic range present in the environment to be compressed into the reduced dynamic range of the hearing-impaired listener. These algorithms do have one significant drawback, which is that the temporal envelope of the stimulus can be distorted (Stone and Moore, 1992). If hearing-aid wearers must rely on these cues to understand speech in noise, then the temporal distortion imposed by the algorithm could counteract some of the benefits of the restored audibility.

These compression algorithms have been demonstrated to not significantly limit the use of temporal envelope cues in speech recognition among hearing impaired listeners when speech is presented in quiet or in steady-state noise (Souza and Turner, 1996, 1998). However, compression algorithms have been shown to be detrimental in competing-talker tasks when only temporal envelope cues are available to the listeners (Stone and Moore, 2003, 2004). One possible reason for this result is that distortion of temporal envelope cues present in speech alters a person's ability to determine which components of a combined sound are part of a single sound (grouping) and which components belong to separate sounds (segregation; Plomp, 1988; Stone and Moore, 1992). To address this possible explanation, the current study uses a modulation detection interference (MDI) paradigm to evaluate whether temporal distortions imposed by compression algorithms impair the auditory segregation/grouping process for both normal-hearing and hearing-impaired listeners.

Yost and Sheft (1989) showed that the modulation detection threshold can be elevated by presenting a simultaneous, amplitude-modulated off-frequency carrier (interferer). The elevation in threshold compared to when the off-frequency sound is unmodulated is termed modulation detection interference (MDI). Previous studies have suggested a link between MDI and perceptual grouping or sound-segregation capabilities (Yost and Sheft, 1989; Yost *et al.*, 1989; Hall and Grose, 1991; Moore and Jorasz, 1992). One argument is that the modulation of the off-frequency interferer fuses with the modulation of the target, thereby leading to difficulty detecting the modulation of the target sound. This type of across-frequency grouping could be important for speech understanding in competing-talker environments as similarities in across-frequency modulation might allow the auditory system to determine which components are speech versus noise. As such, studying the effects of hearing loss and compression on MDI might further our understanding of auditory grouping processes in listeners with hearing loss and the impact of amplification devices on these processes.

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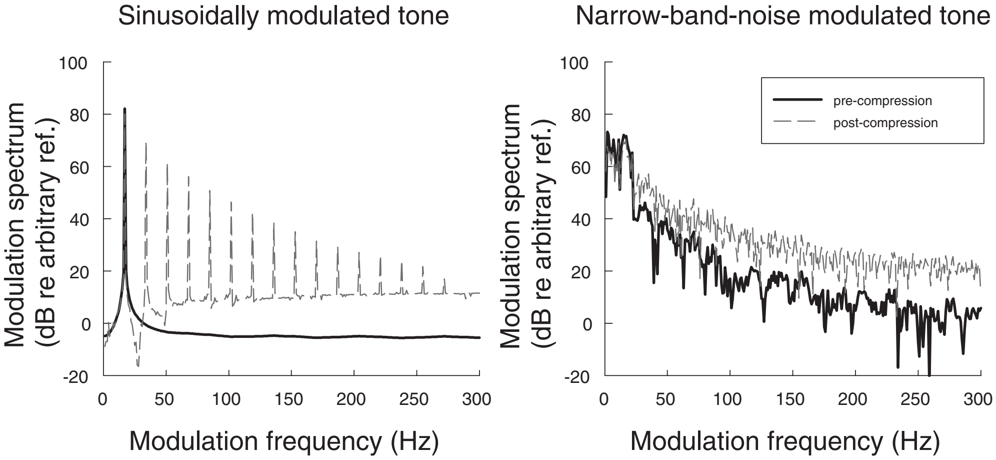

FIG. 1. The effect of a fast-acting compression algorithm on the envelope spectra of a sinusoidally amplitude modulated tone (left panel) and a narrow-band noise modulated tone (right panel). Both of the stimuli are fully modulated ($m=1$). The envelope spectra of the two test stimuli before being processed by the compressor are shown in solid black, and the spectra after compression are shown with dashed gray curves. The attack and release times of the compressor used for generating the figure are 1.6 and 37 ms respectively, the same used in Exp. 2.

Generally, there have been relatively few studies that have evaluated MDI in normal-hearing (NH) and hearing-impaired (HI) listeners. All of those studies used sinusoidal modulation, and they all also demonstrated similar MDI effects in normal-hearing and hearing-impaired listeners. Grose and Hall (1994) and Bacon and Opie (2002) measured MDI for the two groups using a classic MDI experimental paradigm (Yost and Sheft, 1989) in which both the target and the interferer (distant in frequency from the target) were sinusoidally modulated puretone carriers. For these studies, various interferer stimulus levels were tested. Grose and Hall (1994) presented the target and interferer stimuli at the same sound pressure levels whereas Bacon and Opie (2002) did the same but also attenuated the high-frequency interferer by 40 dB (for NH listeners) to approximate equal sensation levels. Both studies, regardless of the stimulus levels used, demonstrated similar performance for NH and HI groups on the MDI tasks despite the poorer audibility and reduced frequency selectivity of the HI listeners. More recently, Koopman *et al.* (2008) measured MDI in listeners with steeply sloping hearing losses and presented target and interferer modulated tones at a sensation level of 25 dB SL and also at 50 dB SL for listeners with normal hearing. Again, HI listeners performed as well as NH listeners in their experiment.

To expand upon these previous findings and to investigate the effect of compression on amplitude-modulation-based auditory grouping abilities, we measured MDI in NH and HI listeners with and without processing the interferer through fast-acting compression. Narrow-band noise was used to amplitude modulate the target and interferer carriers instead of sinusoidal modulators.

There are a number of advantages to using narrow-band noise modulators over sinusoidal modulators for this experiment. First, Mendoza *et al.* (1995) found that larger MDIs could be measured using narrow-band noise modulators over sinusoidal modulators. As such, using narrow-band noise modulators might produce larger effects of compression and hearing loss on MDI, making these effects more easily detectable. Second, the probabilistic nature of the noise modulator could potentially preclude training effects during the experiment (Oxenham and Dau, 2001), allowing fewer trials to be conducted. A third advantage can be seen by examining envelope/modulation spectra of the modulated stimuli before and after compression (see two examples depicted in Fig. 1). The left panel shows that the modulation spectrum of sinusoidal modulation contains a single spectral peak at the modulation frequency. Compression results in harmonic distortion in the modulation frequency domain and produces spectral peaks at multiples of the modulation frequency. In contrast, the narrow-band noise modulated stimuli (right panel of Fig. 1) experience a much more moderate increase in spectral density at all modulation frequencies in the presence of compression. In part, this result occurs because the modulation spectrum prior to compression already contains a broad frequency representation. So, the distortion produced by compression does not introduce new modulation frequencies, though it does modify the relative importance of those frequencies. Further, many naturally occurring sounds, including human speech, have contiguous long-term modulation spectra like those of narrow-band noise modulated tones. Consequently, narrow-band noise modulation was preferred over sinusoidal modulation in the present experiments.

A major consequence of compressing the interferer is reducing its modulation depth, and therefore, a reduction of MDI is expected in the presence of compression. In the experiments presented here involving hearing-impaired listeners, the target and the interferer are presented at equal-loudness levels to ensure audibility of the target and interferer and to account for individual differences in the degree of hearing loss. It will be shown that although fast-acting compression reduces the modulation depth of the interferer, the amount of interference increases in the presence of compression. These unexpected results provide valuable information toward understanding the mechanisms underlying MDI and to furthering our understanding of the effect of compression on auditory grouping/segregation.

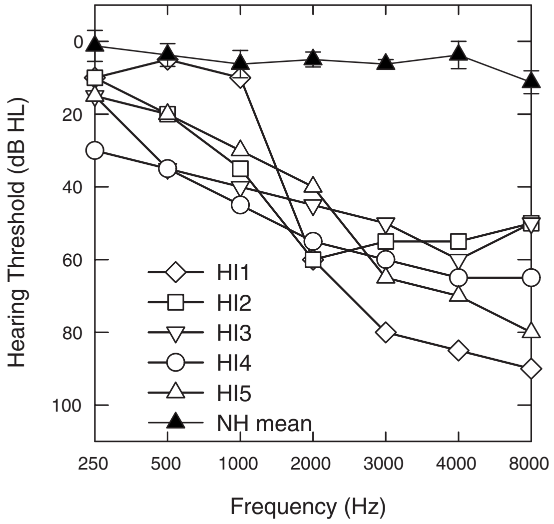

FIG. 2. Audiometric thresholds for the individual hearing-impaired listeners and average thresholds for the normal-hearing listeners are shown. Thresholds for the various HI listeners are plotted with different unfilled symbols. Filled symbols denote average hearing thresholds of the normal-hearing ears, with error bars indicating ± one standard error of the mean.

## II. EXPERIMENT 1: MDI WITH NARROW-BAND NOISE MODULATORS

The purpose of this experiment is to evaluate whether listeners with hearing loss experience similar patterns of MDI to normal-hearing listeners using randomly fluctuating (narrow-band noise) modulators. Specifically, whether the two listener groups exhibit comparable amounts of MDI across a range of interferer modulation depths and modulator bandwidths is investigated here.

### A. Methods

#### *1. Subjects*

Four normal hearing (NH) listeners [including the first (NH2) and the second (NH1) authors] and five hearing impaired listeners participated. The ages of the normal-hearing listeners (2 female) ranged from 27 to 67 years (mean age of 49 years). All NH listeners had audiometric thresholds less than or equal to 15 dB HL between 250 and 8000 Hz in both ears, with the exception that NH4 had a threshold of 20 dB HL at 8000 Hz. Average hearing thresholds across these ears are shown in Fig. 2 as filled symbols. All NH listeners had previous experience in psychoacoustic experiments.

The five hearing impaired (HI) participants (3 female) had ages ranging from 33 to 65 years (mean age of 50.4 years). All listeners had bilateral, symmetric hearing losses with sloping audiograms. The ear with the better hearing thresholds was used in the experiment for each subject. If thresholds did not differ between the two ears, the right ear was used. Audiometric thresholds of these test ears are plotted in Fig. 2 as unfilled symbols. Using the conversion factors for TDH earphones (ANSI, 2004), the mean audiometric threshold at 500 Hz is 34.5 dB SPL (the target frequency, described below) and is about 62.5 dB SPL at the interferer frequency (2140 Hz).[1] Two of the HI listeners had previous experience in psychoacoustic experiments.

#### *2. Stimuli*

Modulation detection thresholds of a 500-Hz amplitude modulated tone (target) were measured in the presence of a simultaneously modulated tone at 2140 Hz (interferer). Both target and interferer were amplitude modulated with narrow-band noise modulators. The modulators were generated by summing pure tones spanning, in separate conditions, 10, 20, or 40 Hz in 0.1-Hz steps. The frequency of the lowest tone was always 2 Hz. The amplitudes of the tones were Rayleigh distributed with starting phases uniformly distributed in the range of $2\pi$. The long-term average modulation rates, in term of peaks per second, given by these narrow-band noise modulators are approximately 9.3,17.0, and 32.5 Hz (Rice, 1954). The bandwidths of the modulators were chosen such that these rates cover the typical region of modulation frequencies that are pertinent for speech perception (Apoux and Bacon, 2008) and similar rates have been demonstrated to yield some level of MDI (e.g., Yost *et al.*, 1989). A 10-s waveform was generated for each modulator bandwidth and stored on the computer. A 500-ms modulator $N(t)$ was randomly drawn from the 10-s stimulus each time a target or an interferer was generated. The modulator was then normalized so that its rms amplitude was unity. Both the target and the interferer took the form

$$s = \left(1 + \frac{1}{\sqrt{2}} m N(t)\right)\cos(2\pi f_c t), \qquad (1)$$

where $N(t)$ is the modulator, $f_c$ is the carrier frequency, and $m$ is the modulation depth. To enable comparison between previous studies that have used sinusoidal modulators, which have an rms amplitude of $\frac{1}{\sqrt{2}}$, the modulation depth, $m$ was scaled by a factor of $\frac{1}{\sqrt{2}}$. Such normalization allows a direct comparison between the thresholds obtained here and those reported by Mendoza *et al.* (1995) as well.

Because $N(t)$ was a narrow-band noise, the envelope, given by $1+\frac{1}{\sqrt{2}}mN(t)$, may drop below 0 when $m$ is relatively large (highly modulated). This would cause "overmodulation" and hence alter the rate and the depth of the intended amplitude modulation. In such instances, the negative portions of the envelope were set equal to zero. One consequence of this operation is local splatter of the envelope spectrum. In these experiments, rectification was rarely necessary for modulation depths of $m<0.5$ (or below $-6$ dB in $20 \log m$ units) but occurred more frequently when $m \geq 0.5$. For $m=1$, almost every trial contains at least one instance of a rectified envelope. However, the power density of the spectral splatter is at least 20 dB lower than that of the modulator, and as such, has a negligible effect on overall modulation depth.

A 500-ms target and interferer were presented simultaneously by gating them on and off together with 50-ms raised-cosine ramps. Targets were presented at an overall level of 80 dB SPL, a level well above all listeners' audiometric thresholds at 500 Hz. Interferers were presented at levels of equal loudness compared to the targets, which were determined through a loudness-matching procedure described later. The modulation depths of the interferers were 0, 0.25, 0.5, 0.75, or 1.

Stimuli were generated digitally and presented at a sampling rate of 22 050 Hz. Experimental procedures were carried out by custom software running on a PC. Stimuli were digitally converted to analog via a Digital Audio Laboratories CardDeluxe sound card, passed through a programmable attenuator (Tucker-Davis Technology PA4) and a headphone buffer (Tucker-Davis Technology HB6), and then presented monaurally to one earphone of a Sennheiser HDA280 headset. All measurements were conducted in a double-walled, sound-attenuating booth.

### *3. Procedure*

A 2AFC adaptive procedure was used with a 3-down 1-up tracking rule to estimate the modulation detection threshold at 79.4% correct (Levitt, 1971). On each trial, two sound intervals consisting of a target plus interferer were presented in sequence separated by 400 ms. One of the two intervals contained a modulated target tone (signal interval), and the other interval contained an unmodulated target tone (non-signal interval). Participants selected the signal interval using a button box and received correct-answer feedback via a computer monitor. Adaptive tracking of the target modulation depth was done in $20 \log m$ (dB) units. The starting level of the tracking procedure was always 0 dB ($m=1$), the initial step size was 5 dB, and the step size was reduced to 2 dB after four reversals. Each track had a total of ten reversals with the threshold determined by the average of the last six reversals.

The 20-Hz modulator-bandwidth conditions were tested first followed by the 10-Hz and the 40-Hz conditions. Within each modulator bandwidth, the five different interferer modulation depths were tested in random order. Modulation detection thresholds were also measured without the presence of the interferer as a baseline measure. Once all depths were tested a single time, the process was repeated until at least four threshold estimates were obtained in each condition. Depending on the listeners' availability, more repetitions were measured to enhance the reliability of the results. Final thresholds for each of conditions were the average across the final four threshold estimates. Before the data collection started, listeners received at least 1 h of training on various conditions.

### *4. Loudness matching*

The level of the 2140-Hz interferer that was estimated to be equally loud as the 80-dB SPL, 500-Hz target was determined using a loudness matching procedure similar to the one described by Jesteadt (1980). In this procedure, listeners heard a 500-Hz reference tone followed by a 2140-Hz signal tone (each lasted 500 ms separated by 400 ms). Listeners then indicated whether the signal tone was louder than the reference tone. No feedback was provided.

The equal loudness level was estimated using an adaptive tracking procedure consisting of two separate adaptive tracks. The first "up" track followed a 2-up, 1-down rule and started with a signal level much lower than the anticipated equal-loudness level. When a listener indicated the signal sound was softer than the reference on two consecutive trials, the level of the signal was increased, and the signal level was decreased after a single louder response. The second "down" track followed a 2-down, 1-up rule, and the signal starting level was higher than the anticipated equal-loudness level, decreased after two consecutive louder responses, and increased after a single softer response. Both tracks had an initial stepsize of 10 dB which was reduced to 5 dB after the first two reversals and to 2.5 dB after the fourth reversal. Both tracks had a total of 11 reversals. The mean value of the last 5 reversals in each track provides a biased estimate of the equal-loudness level. Estimates from the up and down track were then averaged together to yield the final loudness estimate.

Loudness matching was done at the beginning of each experimental session for all participants. The measured equal-loudness level from the first session was used in the experiment as the interferer level, but these levels were rechecked periodically throughout the experiment. Table I shows the interferer level used for Exp. 1 and the mean and the range of all matched levels measured.

TABLE I. Levels in dB SPL of the 2140-Hz tone that were estimated to be equally loud as an 80 dB SPL, 500-Hz tone during the first experimental session, which was implemented as the interferer level in Exp. I. The averages and the ranges of all equal-loudness levels measured are also shown.

| | First | Average | Range |
|---|---|---|---|
| HI1 | 102.5 | 100.2 | 97.3–102.5 |
| HI2 | 89.2 | 88.1 | 87.1–89.2 |
| HI3 | 82.1 | 83.5 | 82.1–85.0 |
| HI4 | 86.5 | 85.9 | 82.7–87.5 |
| HI5 | 77.9 | 77.2 | 73.8–79.8 |
| NH1 | 77.1 | 83.6 | 77.1–86.3 |
| NH2 | 82.3 | 82.6 | 82.3–82.9 |
| NH3 | 73.8 | 74.7 | 73.8–75.6 |
| NH4 | 75.2 | 86.4 | 75.2–93.8 |

## B. Results

Modulation detection thresholds are shown in Fig. 3 for the hearing-impaired (left panels) and normal-hearing listeners (right panels), and average data for the two listener groups are depicted in Fig. 4. Thresholds, presented as $20 \log m_t$ in dB (where $m_t$ is the target modulation depth at threshold), are plotted as a function of interferer modulation depth $m_i$. One of the hearing impaired listeners (HI2) had difficulty with the task in the 40-Hz-bandwidth condition, and so only data from the 10- and 20-Hz conditions are included in Figs. 3 and 4.

Figures 3 and 4 show that, as expected, modulation detection thresholds increase with increasing $m_i$ for all listeners, but the amount of interference produced by the noise-modulated interferers is slightly less than reported by Mendoza *et al.* (1995). In their study, the modulator had frequencies ranging from 0–10 Hz, and they measured a 12 dB threshold difference between $m_i=0.5$ and no interferer ("Q") whereas we report a threshold difference across the same two conditions of 8 dB.

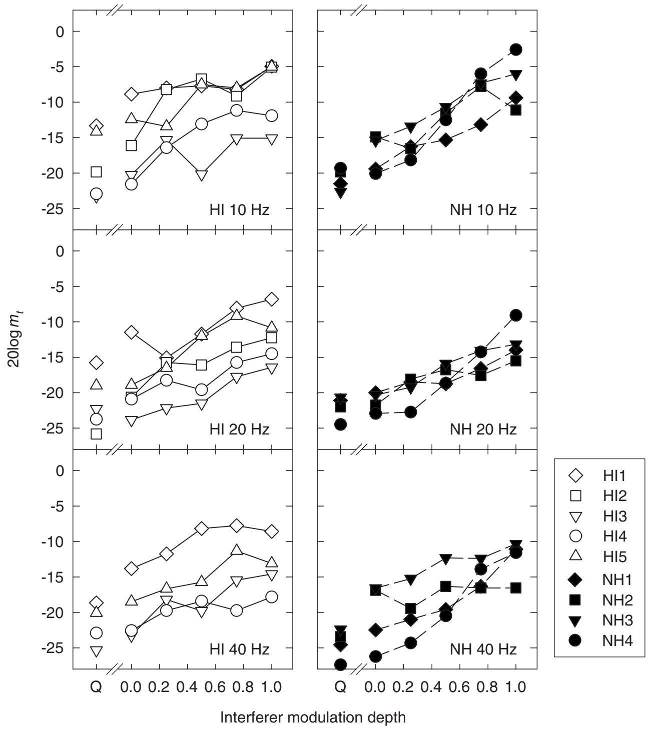

FIG. 3. Individual modulation detection thresholds measured for the hearing impaired listeners (left panels) and normal-hearing listeners (right panels) in Exp. 1 are shown. In each panel, thresholds are plotted as a function of the interferer modulation depth together with the thresholds measured with the absence of the interferer (labeled as "Q"). Data from three modulator bandwidths (10 Hz, 20 Hz, and 40 Hz) are plotted in separate panels.

Hearing impaired (HI) and normal hearing (NH) groups also have very similar functions relating modulation detection threshold to interferer modulation depth. On average, the MDI, defined as the difference in threshold between the fully modulated interferer condition ($m_i$=1) and the unmodulated interferer condition ($m_i$=0) is similar across listener groups with hearing-impaired listeners and normal-hearing listeners having average MDIs of 9.2 and 11.5 dB, respectively. Note, however, that the across-observer variability is quite high for the hearing-impaired group, with individual modulation thresholds varying widely in most conditions. The general result of similar MDI between NH and HI groups is consistent with previous studies that also compared MDI between HI and NH listeners (Bacon and Opie, 1994; Grose and Hall, 1994; Koopman *et al.*, 2008) but used sinusoidal modulators and did not match for equal loudness.

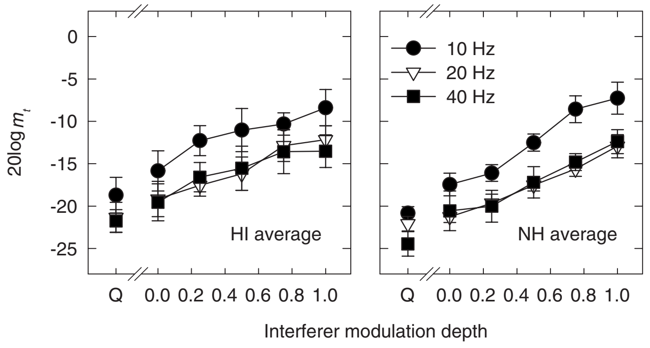

FIG. 4. Average modulation detection thresholds measured for hearing-impaired (left panel) and normal-hearing listeners (right panel) in Exp. 1 are plotted as functions of interferer modulation depth. Results from the conditions where the interferer is absent are also shown (labeled as "Q"). Different modulator bandwidths (10 Hz, 20 Hz, and 40 Hz) are denoted with different symbols.

A mixed-design analysis of variance (ANOVA) was conducted on the data from the eight listeners who were able to complete all conditions. Listener group was treated as a between-subject factor, whereas interferer modulation depth $m_i$ and modulator bandwidth were treated as within-subject factors. Although, on average, listeners with hearing loss exhibited a somewhat smaller MDI than listeners with normal hearing, no significant effect of listener group was revealed $[F(1,6)=0.27,\ p=0.621]$. The large across-observer variability present in the hearing-impaired listener group might contribute to this result, but Fig. 4 illustrates that the average modulation detection thresholds of the hearing-impaired listeners are quite similar to those of the normal-hearing group in all conditions. In contrast, the main effects of interferer modulation depth $[F(4,24)=25.45,\ p<0.001]$ and modulator bandwidth were significant $[F(2,12)=26.10,\ p<0.001]$. Increasing threshold (increasing interference) is associated with increasing interferer modulation depth, and the 10-Hz modulation rate tends to be associated with higher modulation detection thresholds than the other modulation rates. None of the interactions reached statistical significance.

Taken together, the results indicate that although increasing the modulation depth of the interferer increases the amount of interference, hearing-impaired listeners may not experience different interference patterns or modulation detection thresholds than normal-hearing listeners. This experiment has demonstrated this result for randomly varying modulators. If these MDI results can be considered as an indicator of auditory grouping/segregation ability based on temporal envelope cues, the results here provide further evidence that this ability may not be significantly altered by hearing impairment.

## III. EXPERIMENT 2: EFFECTS OF COMPRESSION ON MDI

The following experiment tests whether a standard compression algorithm, which reduces modulation depth, also leads to reduced interference for normal-hearing and hearing-impaired listeners.

### A. Methods

The same listeners from Exp. 1 participated in Exp. 2. The stimuli and the procedure in Exp. 2 were the same as in Exp. 1 except that the stimuli were passed through a compression algorithm, described below, before being presented to the listeners.

The compression algorithm was implemented as a two-channel, time-domain compressor. The stimuli were first filtered into two bands, one low frequency and one high frequency, using a 3rd order Butterworth filter. The crossover frequency (and therefore cutoff frequency for each filter) between the two channels was 1500 Hz. In the low-frequency channel, no compression and no gain were applied. In the high-frequency channel, the compressor had a compression

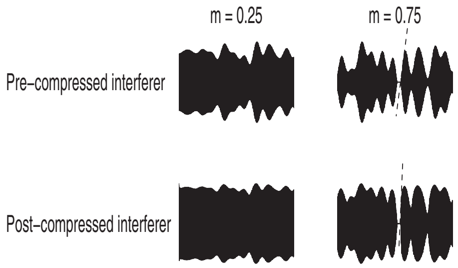

FIG. 5. Examples of pre- and post-compressed interferers in Exp. 2. The pre-processed stimulus is an 80 dB SPL, noise-modulated 2140-Hz carrier. The bandwidth of the modulator is 20 Hz. Stimuli before and after compression are shown for 0.25 (left) and 0.75 (right) modulation depths in the upper and lower panels, respectively. The amplitudes of the stimuli in the four panels are normalized to span the same range.

threshold of 45 dB SPL (input controlled) and a compression ratio of 3:1. Compression was fast-acting, with an attack time of about 1.6 ms and a release time of about 37 ms (ANSI, 2003). The gain of the compressor was 30 dB at 50 dB SPL and 10 dB at 80 dB SPL. This algorithm caused only the 2140-Hz interferer to be compressed and amplified, while no change was imposed on the 500-Hz target.

Figure 5 shows examples of two interferers, one with $m_i$ of 0.25 (left panels) and one with $m_i$ of 0.75 (right panels), before (top panels) and after (bottom panels) being passed through the compressor. By comparing the interferers before and after compression, a general reduction in modulation depth can be observed after compression. An estimate of the equivalent modulation depth after compression, $\tilde{m}_i$, was made by passing interferer stimuli 1 s in duration (fixed at 80 dB SPL) through the compressor. The waveforms were re-scaled so that the long-term rms of their envelopes was unity. Next, the envelope, $e_i(t)$, was derived using the Hilbert transform and normalized to have unity rms value. $\tilde{m}_i$ was then calculated from

$$\tilde{m}_i = \sqrt{\frac{2}{T}\int_0^T (e_i(t) - 1)^2 dt}, \qquad (2)$$

where $T=1$ s is the duration of the waveform.[2] $\tilde{m}_i$ was calculated for four separate interferers at each of the three modulator bandwidths used in Exp. 2 (10 Hz, 20 Hz, and 40 Hz). The average modulation depths after compression are shown in Table II, which illustrates that compression reduces the modulation depth of the stimuli by 31% ($m_i$=1.0, 40-Hz bandwidth) to 60% ($m_i$=0.1, 10- and 20-Hz bandwidths). Further, it can be seen that the amount of modulation depth reduction decreases with increasing modulation depth and modulation rate (see also Plomp, 1988; Stone and Moore, 1992, 2003). Additional acoustic analysis also reveals that the amount of the reduction in modulation depth decreases only slightly at very low and very high overall levels.

TABLE II. Comparisons between the interferer modulation depths $m_i$ and the equivalent modulation depth after the compression $\tilde{m}_i$ in Exp. 2.

| | $\tilde{m}_i$ | | |
|---|---|---|---|
| $m_i$ | 10 Hz | 20 Hz | 40 Hz |
| 0.1 | 0.04 | 0.04 | 0.05 |
| 0.25 | 0.09 | 0.10 | 0.13 |
| 0.5 | 0.21 | 0.28 | 0.30 |
| 0.75 | 0.42 | 0.44 | 0.51 |
| 1 | 0.60 | 0.64 | 0.69 |

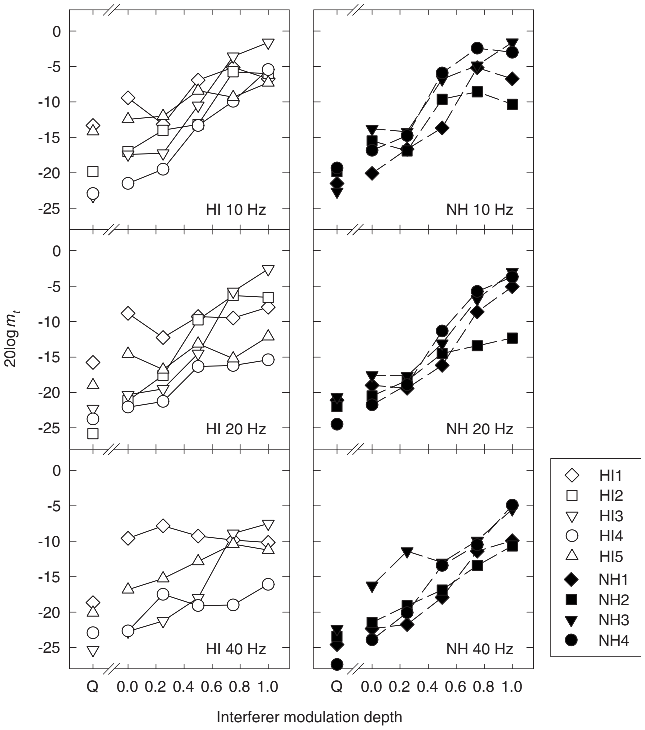

FIG. 6. As in Fig. 3, except that modulation detection thresholds in the presence of compression (Exp. 2) are shown. Thresholds without the interferer (labeled as "Q") are re-plotted from Fig. 3.

As with Exp. 1, the interferer was presented at a level estimated to be equally loud as the target. For this purpose, the interferer level at the input of the compression algorithm was determined by the loudness matching procedure described in Exp. 1 for each individual listener.[3] These matched levels led to very similar interferer levels at the output of the compressor compared to the levels used in Exp. 1. Averaged across all listeners, the level difference across the loudness-matched stimuli was about 3 dB. As in the previous experiment, the matched levels were re-checked periodically. All listeners showed good consistency in their results except for listener HI5. For this listener, the presentation level of the interferer was derived from the loudness-match result in Exp. 1.[4]

## B. Results

The individual results from Exp. 2 are shown in Fig. 6 for the hearing impaired listeners (left panels) and the normal hearing listeners (right panels). The average results are shown in Fig. 7 for the two listener groups in separate panels. As in Exp. 1, listener HI2 was not able to complete the condition with 40-Hz modulator bandwidth, and so only his data from the 10- and 20-Hz conditions are shown.

In general, the pattern of results is somewhat similar to those observed for Exp. 1. Listeners were sensitive to the modulation depth of the interferer—the greater the interferer

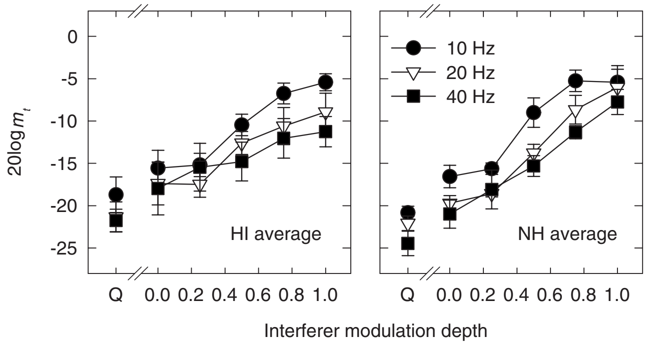

FIG. 7. As in Fig. 4, except that modulation detection thresholds in the presence of compression (Exp. 2) are shown.

modulation depth, the greater the threshold. While greater variability is observed in the modulation detection thresholds across the listeners with hearing loss versus those with normal hearing, no obvious group differences are apparent. To verify these results, a mixed-design ANOVA was conducted to assess significant effects. No significant effect of listener group was found $[F(1,6)=0.00,\ p=0.99]$ nor was any interaction involving listener group,[5] suggesting that even when the interferer is compressed, listeners with normal hearing and hearing loss have similar sensitivity to modulation depth. The effect of $m_i$ was statistically significant $[F(4,24)=25.86,\ p<0.001]$ consistent with the result that the modulation detection threshold increases with increasing $m_i$. The effect of modulator bandwidth was also significant $[F(2,12)=28.02,\ p<0.001]$ with thresholds being higher for the 10-Hz modulator than the others. In contrast to Exp. 1, a significant interaction was revealed between $m_i$ and modulator bandwidth $[F(8,48)=3.24,\ p=0.005]$. In this case, the modulation detection threshold grows more steeply with increasing $m_i$ for the narrower modulator bandwidths than for the broader bandwidths. This interaction was not found in Exp. 1 to be significant, indirectly indicating that compression has a greater effect on the interference in the narrower bandwidth conditions than in the wider bandwidth conditions. Acoustic analysis (Table II) also confirms a bandwidth dependent effect with more distortion caused by compression at narrower bandwidths.

Because the same listeners were tested in Exp. 1 (no compression) and Exp. 2 (compression), we can investigate the effect of the compression algorithm on modulation detection interference. The acoustic analysis shows that the compressor reduces the effective modulation depths of the interferers, and so we might expect a reduction of MDI after the application of compression. Such results would indicate that compression algorithms in hearing aids have the potential to alter auditory grouping cues.

Figure 8 shows modulation detection thresholds from the two experiments for the two listener groups (in separate columns) and for the three modulator-bandwidths (in separate rows). The average results from Exp. 1 and Exp. 2 across listeners are plotted as filled and unfilled symbols, respectively. For most modulator types and listener groups, the thresholds measured with and without the compression are similar for the unmodulated interferers ($m_i$=0). In contrast, when the interferers are modulated, thresholds are typically higher with the use of compression algorithm, especially at higher modulation depths (e.g., $m_i \geq 0.5$). Because the amount of MDI is defined as the threshold increase between a modulated interferer and an unmodulated interferer, the results shown in Fig. 8 suggest that the compression leads to a greater MDI.

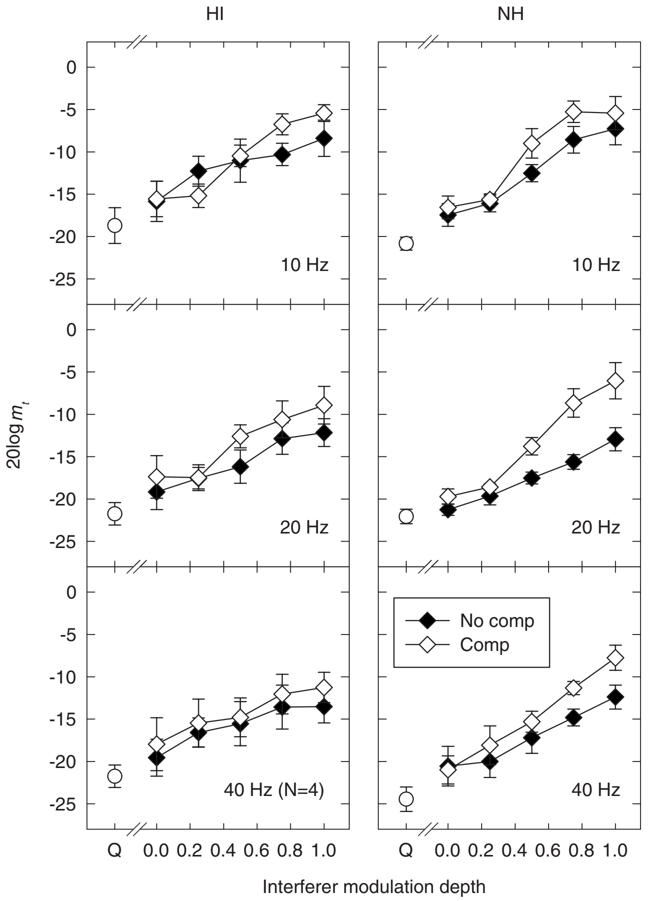

FIG. 8. Average modulation detection thresholds across listeners as a function of interferer modulation depth derived from Exp. 1 and Exp. 2 for the two listener groups (in columns) and for the three modulator-bandwidth conditions (in rows). Error bars indicate ± one standard error of the mean. Thresholds without the use of compression (from Exp. 1) are shown as filled symbols, and the thresholds with compression (from Exp. 2) are shown as unfilled symbols. Average thresholds measured in the absence of the interferer are shown as circles.

An ANOVA was conducted based on the experimental data from a subgroup of listeners (4 HI and 4 NH) who completed all conditions, in which modulator bandwidth, compression and $m_i$ were three within-subject factors. The between-subject factor, listener group, was not statistically significant $[F(1,6)=0.009,\ p=0.781]$, but all other main effects, compression $[F(1,6)=8.92,\ p=0.024]$, $m_i$ $[F(4,24)=35.81,\ p<0.001]$, and modulator bandwidth $[F(2,12)=41.91,\ p<0.001]$, were significant. The significant interactions include compression$\times m_i$ $[F(4,24)=2.90,\ p=0.043]$, which indicates that the application of the compression onto the interferer introduced extra interference, especially when the interferer modulation depth was relatively large. This extra interference occurred even though the overall modulation depth of the interferer was reduced by the compressor. This phenomenon did not depend on the hearing status of the listeners. A second interaction between bandwidth and $m_i$ $[F(8,48)=2.36,\ p=0.032]$ was also revealed, consistent with the previous results that the narrower bandwidth conditions led to a greater change in interference with increasing $m_i$. All other interactions did not reach significance.

One of the HI listeners in our experiments (HI1) exhibits moderately severe hearing loss at the interferer frequency (2140 Hz) and a severe loss at higher frequencies. This listener showed a reduced MDI compared to other HI listeners with milder hearing losses. For this listener, thresholds were almost independent of the interferer modulation depths $m_i$ when compression was applied to the interferer (see diamonds in Fig. 5). This result is in contrast to the data obtained from the other listeners for whom the growth of the interference with $m_i$ increased by the use of compression. Further work evaluating the role of severe hearing loss and MDI could be warranted, as this listener's data hint at differences related to severity of hearing loss.

### C. Discussion

The previous two experiments demonstrated that normal-hearing and hearing-impaired listeners experience similar degrees of MDI, even for narrow-band noise modulators. Further, when the interferers were passed through a compression algorithm, modulation detection thresholds and subsequently, the amount of MDI, increased. This result was not anticipated because compression reduces the effective modulation depth of narrow-band noise-modulated tones, and previous literature and Exps. 1 and 2 illustrate smaller MDI for lower modulation depths. As such, these results indicate that the modulation depth of the interferers is not the sole determinant of the MDI produced by them.

One potential explanation for this result is that the compression algorithm introduces harmonic distortion at frequencies near the interferer, and this distortion energetically masks the target. This possibility seems unlikely, however, because the spectral density of the interferer at the target frequency (500 Hz) is estimated to be about 80 dB below the spectral density at the interferer frequency (2140 Hz) for $m_i=1$. As such, at 500 Hz, the power of the target is at least 60 dB higher than the interferer. It is doubtful that a stimulus 60 dB down would produce any masking, even for the HI listeners, who typically were presented with higher interferer levels than normal-hearing listeners.

An alternative explanation for the increased interference with the application of compression comes from a close inspection of the compressed waveforms. The compressor not only reduces the modulation depths of the interferers but also distorts the shape of the temporal envelopes (Stone and Moore, 1992). The amount of distortion is related to the time constants of the compressor and the fluctuation rates within the stimulus. For example, in response to an abrupt level increment in a stimulus tone, the compressor does not lower the gain (hence apply compression) immediately after the onset of the level increment, rather it takes some time for the gain to drop to the new steady state (described by the attack time). As a consequence, a sharp peak corresponding to the increment onset occurs in the waveform. As shown in Fig. 5 and marked with dashed lines, when $m_i$ of the interferer is large, there is a rapid increase in level after a deep temporal valley. The overshoot of the compression enhances this envelope slope, resulting a sharpened onset of the following temporal peak. The deeper valleys in the envelope are the most sensitive to this effect. As a consequence, greater interference is expected at the larger modulation depths because sharpened onsets are more likely to occur there.

It is worth pointing out that sharpening of the temporal envelope is also accompanied by broadening of the envelope spectrum. One illustration of this effect of compression in the modulation domain was presented in Fig. 1. The extra amount of MDI at large modulation depths could also be a consequence of broadening of the envelope spectrum. At this point, we cannot exclusively separate the effects of temporal envelope sharpening and changes to the modulation spectrum.

The idea that temporal envelope sharpening contributes to MDI was first tested by Shailer and Moore (1993) who measured MDI with targets and maskers that varied along a continuum with a sinusoidal modulator at one end and a square-wave modulator at the other. They manipulated the rise/fall time of the modulator but held the modulation rate (10 Hz) and the modulation depth (fully modulated) constant. Their results revealed that MDI increased with increasing rise/fall time of the interferer. As a consequence, the data suggest that the rate of envelope change influences the size of the MDI.

To establish whether sharpening of the interferer envelope could have given rise to additional interference in Exp. 2, we compared the amount of MDI elicited by two types of interferers which differ in the sharpness of their temporal envelopes in a third experiment. For one type of interferer, a sinusoidal modulator is used to achieve a smoothly varied envelope. For the other type, a square-wave modulated interferer is used for its sharply varied envelope. If MDI depends on the sharpness of the interferer envelope, we expect to see more MDI from the square-wave modulated interferer, especially at large interferer modulation depths. In contrast to the Shailer and Moore (1993) study, the target is always a narrowband noise modulated tone and various interferer modulation depths are tested to establish whether this effect increases with increasing modulation depth.

## IV. EXPERIMENT 3: SINE-WAVE VS SQUARE-WAVE MODULATED INTERFERERS

### A. Methods

A similar experimental design to the previous two experiments was used in Exp. 3. The modulation detection threshold of a 500-Hz target was measured in the presence of a 2140-Hz interferer. The target was modulated by a narrowband noise with a 20-Hz bandwidth. During stimulus generation, a 500-ms modulator $N(t)$ was randomly drawn from a stored 10-s, 20-Hz narrow-band noise, and the target tone was modulated according to Eq. (1). The interferer, on the other hand, was modulated by either a sine wave or a square wave. The sinusoidally modulated interferer took the form

$$s_{\text{sine}} = (1 + m_i \sin(2\pi f_m t))\cos(2\pi f_c t), \tag{3}$$

where $m_i$ is the interferer modulation depth, $f_m$ is the modulation frequency, and $f_c$ is the carrier frequency. Similarly, the square-wave modulated interferer is given by

$$s_{\text{square}} = (1 + m_i \ \text{square}(2\pi f_m t))\cos(2\pi f_c t), \tag{4}$$

and the square-wave function is defined as

$$\text{square} \ (x) = \begin{cases} 1, & 2n\pi \leq x < 2(n+\alpha)\pi, \\ -1 & \text{otherwise}, \end{cases} \qquad n = 1,2, \ldots , \tag{5}$$

where $\alpha$=0.5 is the duty cycle, or the proportion of the period in which the signal is positive. By defining modulation depth this way, one should be aware that the rms amplitude of the square-wave modulator is 1 instead of $\frac{1}{\sqrt{2}}$, as in the sine-wave (interferer) or the narrow-band-noise (target) modulators. Because the sine- and square-wave modulators both have a peak amplitude of 1, they are referred to as being peak-based normalized. An alternative, and equally reasonable, way to report the square-wave modulation is to normalize the modulator to have an rms amplitude of $\frac{1}{\sqrt{2}}$, or rms-based normalization. Peak-based normalization was implemented in Exp. 3 for data collection. For completeness, the measured thresholds were also converted into equivalent values as if they were measured using rms-based normalization. Details about this conversion procedure are presented in the results section. In the modulation frequency domain, the square-wave modulator also has a broader envelope spectrum, which consists of a series of harmonically related frequency components. To limit the spectral content of the interferer, the square-wave modulator was low-pass filtered at 300 Hz.

For either type of the interferer modulators (sine or square wave), the modulation frequency $f_m$ was set to 16 Hz. This modulation rate was selected to be similar to the nominal modulation rate of the 20-Hz narrow-band target modulator, where large amounts of MDI would be expected. Because the interferer was gated on and off simultaneously with the target, it consists of 8 periods of the modulator in its entirety. The starting phase of the modulator was randomly assigned for each presentation of the interferer.

The experimental procedure was identical to the previous two experiments except that for each of the two modulator types, the threshold was measured at four interferer modulation depths ($m_i$=0, 0.25, 0.5, and 0.75). Three additional normal hearing listeners (one of whom had listening experience in psychoacoustic experiments) and the second author participated in this experiment ($N$=4). Their ages range from 19 to 37 years. The audiometric thresholds of all listeners were below 15 dB HL from 250 to 6000 Hz, and the ear with better thresholds was used in the experiment.

### B. Results and discussion

The left panel of Fig. 9 plots peak-based normalized detection thresholds averaged across four listeners as a function of interferer modulation depth. It appears that the square-wave modulator (unfilled symbols) provides more overall interference than the sine-wave modulator (filled symbols), as the square-wave modulator leads to greater modulation detection thresholds than the sine-wave modulator for $m_i$ values greater than 0. However, a within-subject analysis of variance (ANOVA) with modulator type and interferer modulation depth $m_i$ as within-subjects factors reveals only a significant main effect of $m_i$ $[F(3,9) = 26.85,\ p < 0.001]$. Neither the main effect of modulator type $[F(1,3) = 9.96,\ p = 0.051]$ nor the interaction between $m_i$ and modulator type $[F(3,9) = 3.70,\ p = 0.055]$ are significant, though the $p$ values are very close to 0.05.

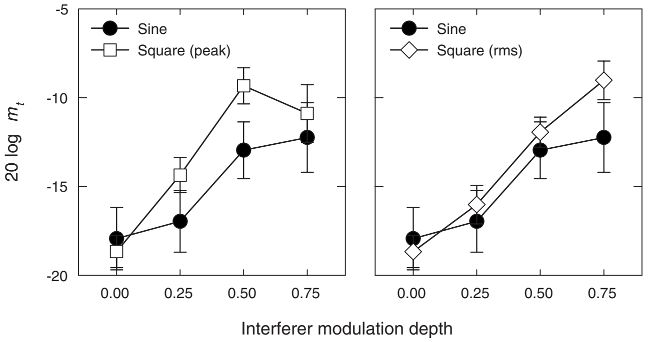

FIG. 9. Average modulation detection thresholds across four normal hearing listeners in Exp. 3 with error bars indicating ± one standard error of the mean are shown. Thresholds are plotted as a function of interferer modulation depth $m_i$ for the sine-wave modulator (circles) and the square-wave modulator (squares). Left and right panels indicate peak-normalized thresholds and rms-normalized thresholds, respectively. rms-normalized thresholds for the square-wave condition were derived using cubic spline interpolation.

In order to determine whether the type of normalization alters the interpretation of the data, the thresholds and the nominal modulation depths ($m_i$) were estimated using rms-based normalization. In this case the thresholds in the square-wave modulator condition were measured at equivalent modulation depths of 0, 0.354, 0.707, and 1.061, because the rms-based $m_i$ is larger than peak-based $m_i$ by a factor of $\sqrt{2}$. To enable comparisons between the results for the two modulator types, a cubic-spline interpolation was implemented to estimate the thresholds at the rms-based $m_i$ values of 0, 0.25, 0.5, and 0.75 in the square-wave conditions.$^6$ These rms-normalized thresholds were then averaged across subjects and are shown in the right panel of Fig. 9. The pattern of interference provided by the square-wave modulator is now monotonic between the rms-based $m_i$ of 0 and 0.75. With this conversion from peak-based to rms-based normalization, the threshold difference between the sine-wave and the square-wave conditions becomes smaller. Yet, a within-subject ANOVA with modulator type and $m_i$ as the two factors found a significant effect of $m_i$ $[F(3,9) = 27.56,\ p < 0.001]$, a significant interaction between $m_i$ and modulator type $[F(3,9) = 3.896,\ p = 0.049]$ but no effect of modulator type $[F(1,3) = 2.37,\ p = 0.222]$. Because sharp temporal edges are more pronounced for the higher modulation depths, the significant interaction between modulator type and $m_i$ is consistent with the hypothesis that sharp edges in the temporal envelope lead to greater modulation detection interference. As presented previously, this interaction failed to reach statistical significance when peak-based normalization was used, and here, the effect size is relatively small.

Results from the current experiment suggest that the amount of MDI for highly modulated interferers tends to depend on the sharpness of the interferer envelope but that the effects are rather small. Although this result lends credence to the hypothesis that the greater interference measured in the presence of compression (Exps. 1 and 2) is related to the enhanced edges of the compressed modulator, the small size of the effect tempers this conclusion. The increase in interference associated with the compression algorithm was also larger in Exps. 1 and 2 than the difference in interference between the square-wave and sine-wave modulators in the current experiment, even though Exp. 3 used extreme choices of modulators aimed at promoting extra interference from the sharpening of the temporal envelopes. For example, at $m_i=0.75$, the increase in interference provided by compression from Exp. 1 and 2 was about 8 dB on average (for the 20-Hz bandwidth), while the increase in interference provided by the square-wave modulator in Exp. 3 was about 3 dB. One possibility is that the additional frequencies present in narrow-band noise produce additional interference. Yet, previous studies of the additivity of MDI suggest that the amount of MDI does not significantly depend on the number of frequency components in a complex interferer (Moore and Shailer, 1994; Bacon *et al.*, 1995). A second possibility is that periodic modulators are not as effective in creating large increments of MDI because of the discrete frequency components in their spectra.

## V. GENERAL DISCUSSION

In the present study, we aimed to expand upon previous studies of MDI in hearing-impaired listeners (Grose and Hall, 1994; Bacon and Opie, 2002; Koopman *et al.*, 2008) and to investigate (1) whether narrow-band noise modulators yield different amounts of MDI for HI and NH listeners with loudness-matched presentation levels, and (2) whether the amount of MDI changes when the interferers are modified by fast-acting compression.

The lack of effect of listener group observed for Exps. 1 and 2 is consistent with the results of previous MDI studies that have used sinusoidal amplitude modulators (Grose and Hall, 1994; Bacon and Opie, 2002; Koopman *et al.*, 2008) even though this experiment used narrow bands of noise. One possible explanation for this result is that listeners with hearing loss have similar abilities to listeners with normal hearing when grouping sounds based on amplitude modulation.

This result in MDI experiments is in direct contrast to the results from speech experiments in which HI and NH listeners typically show large differences in their ability to understand speech when the masking stimulus is also speech or fluctuating noise (e.g., Duquesnoy, 1983; Festen and Plomp, 1990). In these speech masking experiments, performance differences are likely due to two possible mechanisms. First, amplitude modulation in the competing speech stream (the masker) could enable dip-listening (e.g., Buus, 1985) or glimpsing (e.g., Miller and Licklider, 1950; Cooke, 2006), in which NH listeners but not HI listeners, can take advantage of low-energy portions of the masker where the signal-to-masker ratio is high. Second, across-frequency similarities in modulation might allow listeners to determine which components of combined signal belong to the target of interest and which do not. Sloping hearing loss could influence this process as varied degrees of loss of compression across frequency could influence the relative similarities in modulation across frequency. To some degree, MDI experiments test the ability of listeners to group sounds based on across-frequency modulation. Because a cohort of MDI studies have revealed no systematic differences in this ability between normal-hearing and hearing-impaired listeners, it is unlikely that the speech-understanding difficulties experienced by HI listeners in competing-talker situations can be accounted by the mechanisms underlying MDI.

Although hearing loss had little effect on the magnitude of MDI, the compression algorithm increased MDI for both HI and NH listener groups despite an overall reduction in the modulation depth of the interferer. This result was contrary to our expectation, as numerous studies have reported that interferers with shallower modulation depths produce less MDI. As such, this observation questions the common belief that MDI increases with increasing interferer modulation depth in a monotonic fashion. Acoustic features other than the average modulation depth also must contribute to the interference efficiency of a modulated sound. In this case, the relevant acoustic features must have been altered by applying compression. One possible explanation, explored here, is a change in the envelope slope at the more highly modulated portions of the waveform. This envelope slope describes how rapidly sound amplitude increases immediately following a temporal valley in the envelope. Due to the over-shoot of the compressor, some of the temporal onsets in the envelope are sharpened even though a global reduction in the modulation depth is also present. As mentioned earlier, the envelope sharpening effect occurs simultaneously with local broadening of the modulation spectrum. Therefore, even though our discussions focus on the envelope slope in the time domain, equivalent explanations could be made in the modulation frequency domain.

Local cues, such as onset slope, might explain the amount of interference produced by a modulated sound better than the long-term features of that sound. Many previous MDI studies have co-manipulated the envelope slope with modulation depth (a shallower envelope slope would be associated with a smaller modulation depth), and only a few studies are available that speak to this issue. Shailer and Moore (1993) demonstrated a large impact of the rate of envelope change on MDI with greater MDI being produced by envelopes with greater envelope slopes. In an experiment similar to Exp. 3, Sheft and Yost (2007) also measured MDI for periodic interferers with various slopes in their modulator and found that MDI increases with the perceptual prominence of the interferer in some cases. They argued that informational masking might be the major underlying mechanism for MDI rather than the common-modulation based auditory grouping. Our results of Exp. 3 are consistent with this argument as sharpening the temporal envelopes tends to increase the amount of MDI.

Recent data have also suggested that temporal envelope information could be coded based on local features in separate frequency channels. In an attempt to resolve whether temporal envelope information is coded locally or long-term, Nelson and Carney (2006) compared the abilities of psychophysical models to predict modulation detection data. The models were implemented with decision-making stages based on various acoustic cues. Nelson and Carney (2006) showed that, in general, both long-term and local cues accounted for the results equally well; however, local cues such as the envelope max/min ratio out-performed long-term cues when the latter were minimized in the experimental design. Their findings implicate the importance of local acoustic features in amplitude-modulation processing, and the data from Exp. 3 provide additional support to this idea. If temporal envelope information is coded based on local features, the outputs across channels could compete for common processing resources with limited capacities and therefore cause informational masking among the channels.[7] Enhancing local acoustic features in a sound stream (e.g., sharping the temporal onsets) could lead to more robustly coded envelope information, thereby masking other competing streams.

In this MDI experiment, the change in envelope slope imposed by compression algorithms was demonstrated to impair auditory grouping or perhaps increase informational masking for both HI and NH listeners. Stone and Moore (2003, 2004) also found support for such an idea using noise-vocoded speech in a competing-talker environment. Vocoded speech requires listeners to use mainly temporal envelope cues to recognize sentences (Shannon *et al.*, 1995) and to segregate the target speech from interfering speech. Stone and Moore (2003, 2004) showed that fast-acting compression has a negative effect on vocoded-speech performance, of which the envelope distortion introduced by the fast-acting compression is a partial contributor. The distortion might enhance informational masking among the sound streams, though this explanation needs to be further verified in future studies.

## VI. SUMMARY

In a series of experiments, the current study showed that applying fast-acting compression on a modulated interferer elevates the modulation detection threshold of a target more than when the modulated interferer is not compressed. This result holds for normal-hearing and for hearing-impaired listeners. One potential explanation for this additional interference comes from the distortion of the temporal envelope caused by the compression algorithm, though it appears that temporal envelope distortion cannot account for all of the greater interference produced by the compressed modulators. The results shown here imply a negative effect of the fast-acting compression on the auditory grouping/segregation capabilities based on the temporal envelope for both normal-hearing and hearing impaired listeners. The use of compression potentially enhances informational masking among multiple sound sources, making listening in fluctuating backgrounds more difficult.

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[1] This hearing level was obtained through linear interpolation between the thresholds at 2 and 3 kHz for each subject.

[2] $m_i$ was derived in the following way: The modulation depth $m$ is well defined for amplitude-modulated tones following the equation, $s(t)=A\left(1+\frac{1}{\sqrt{2}}mN(t)\right)\cos(2\pi f_c t)$, where $A\cos(2\pi f_c t)$ is the unmodulated carrier tone. $e(t)=1+\frac{1}{\sqrt{2}}mN(t)$ is the temporal envelope. The envelope has a long-term rms average of 1, and the modulator $N(t)$ is normalized to have a rms value of unity. Therefore, for this type of signal, $m$ can also be estimated from the extracted temporal envelope: $m \approx \sqrt{1/T\int_0^T(\sqrt{2}(e(t)-1)/N(t))^2 dt}$, where $T$ is the total duration of the signal. Since $\sqrt{1/T\int_0^T N(t)^2 dt} \approx 1$, we have $m \approx \sqrt{2/T\int_0^T(e(t)-1)^2 dt}$.

[3] This procedure was identical to the one in Exp. 1 except for the use of the compression algorithm. A 500-Hz reference tone was always presented at 80 dB SPL, and this level was unaltered after it was passed through the compressor. Through the adaptive tracking procedure, the level of a 2140-Hz tone at the input of the compressor that best balanced the loudness between two tones was determined for each listener. In Exp. 2, the interferer was then presented to the compressor at this matched level. Additional acoustic analysis showed that the interferer levels at the output of the compressor are similar across modulation depths and bandwidths for a given input level (within 1 dB).

[4] Here, the interferer level (before compression) was chosen such that for an unmodulated interferer, its level after the compression was approximately the equal-loudness level measured in Exp. 1.

[5] In Exp. 2, none of the interactions involving listener group was revealed to be significant by the ANOVA. These interactions include modulator bandwidth × listener group $[F(2,12)=0.23,\ p=0.80]$, $m_i$ × listener group $[F(4,24)=1.34,\ p=0.28]$, and modulator bandwidth × $m_i$ × listener group $[F(8,48)=1.74,\ p=0.11]$.

[6] The conversion from peak-based to rms-based normalization only affected data in the square-wave condition since the definition of $m_i$ did not change for the sine-wave modulated interferer.

[7] The term informational masking is used broadly here; it refers to any performance degradations due to the addition of a masker signal that cannot be accounted by energetic masking.

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