Notched-noise precursors improve detection of low-frequency amplitude modulation[a)]

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Amplitude modulation (AM) detection was measured with a short (50 ms), high-frequency carrier as a function of carrier level (Experiment I) and modulation frequency (Experiment II) for conditions with or without a notched-noise precursor. A longer carrier (500 ms) was also included in Experiment I. When the carrier was preceded by silence (no precursor condition) AM detection thresholds worsened for moderate-level carriers compared to lower- or higher-level carriers, resulting in a "mid-level hump." AM detection thresholds with a precursor were better than those without a precursor, primarily for moderate-to-high level carriers, thus eliminating the mid-level hump in AM detection. When the carrier was 500 ms, AM thresholds improved by a constant (across all levels) relative to AM thresholds with a precursor, consistent with the longer carrier providing more "looks" to detect the AM signal. Experiment II revealed that improved AM detection with compared to without a precursor is limited to low-modulation frequencies (<60 Hz). These results are consistent with (1) a reduction in cochlear gain over the course of the precursor perhaps via the medial olivocochlear reflex or (2) a form of perceptual enhancement which may be mediated by adaptation of inhibition. © *2017 Acoustical Society of America.*
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I. INTRODUCTION

The auditory system is sensitive to small changes in intensity over a wide range of sound levels [~120 dB (Viemeister, 1988)]. This wide perceptual range occurs despite the dynamic range of most auditory nerve fibers [i.e., high spontaneous rate (SR) fibers] being limited to ≤35 dB (Evans and Palmer, 1980). The ability to encode changes in intensity over the dynamic range of hearing is crucial for identifying, discriminating, and understanding environmental sounds (Green, 1983). For long (>100 ms) wide-band and narrow-band pedestals, intensity discrimination is constant (Miller, 1947) or improves with sound level (McGill and Goldberg, 1968; Rabinowitz *et al.*, 1976; Jesteadt *et al.*, 1977; Florentine and Buus, 1981), respectively. However, for short (≤30 ms), narrow-band pedestals, intensity resolution deteriorates at moderate pedestal levels (Carlyon and Moore, 1984; Nizami, 2006; Roverud and Strickland, 2015a). This deterioration has been termed the "severe-departure from Weber's law" (Carlyon and Moore, 1984) or the "mid-level hump" (Zeng *et al.*, 1991; Nizami, 2006) and is consistent with basilar membrane mechanics which exhibit compressive non-linearity at mid-to-high levels for tones presented at the characteristic frequency (CF) (Heinz *et al.*, 2001; Pienkowski and Hagerman, 2009; Roverud and Strickland, 2015a). Moreover, recent studies have shown that the mid-level hump is reduced (i.e., performance improves at moderate pedestal levels) when a short pedestal is preceded by a long (e.g., 150 ms) ipsilateral or bilateral noise ("precursor"), consistent with a reduction in cochlear gain over the course of the precursor, perhaps via the medial olivocochlear (MOC) reflex (Roverud and Strickland, 2015b).

In addition to intensity discrimination experiments, intensity resolution can be assessed by measuring amplitude modulation (AM) detection. Much of the semantic information contained in speech is carried by gross amplitude fluctuations over time, known as the stimulus envelope (Rosen, 1992). AM detection assesses the sensitivity of the auditory system to a range of envelope frequencies. Based on intensity discrimination studies (e.g., Roverud and Strickland, 2015a,b), the first experiment of this study tested the hypothesis that AM detection with short carriers is relatively poorer

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at moderate compared to lower or higher levels, consistent with cochlear compression. Furthermore, this study tested whether the presence of a precursor improves AM detection thresholds at moderate carrier levels, consistent with a reduction in cochlear gain, similar to what has been used to describe other precursor effects in masking (Schmidt and Zwicker, 1991; Strickland, 2001; Bacon and Savel, 2004; Jennings *et al.*, 2009), and intensity discrimination (Roverud and Strickland, 2015a,b). The second experiment assessed whether AM detection with and without a precursor depends on modulation frequency by measuring temporal modulation transfer functions (TMTFs).

The expected improvements in AM detection as a result of a reduction in cochlear gain are illustrated in Fig. 1, which displays a schematized input/output (I/O) function for an auditory filter centered on the carrier frequency. For short carriers (e.g., 50 ms) preceded by silence [Fig. 1(A)], cochlear compression limits the effective (post-cochlear) modulation depth when the carrier is presented at moderate-to-high levels.

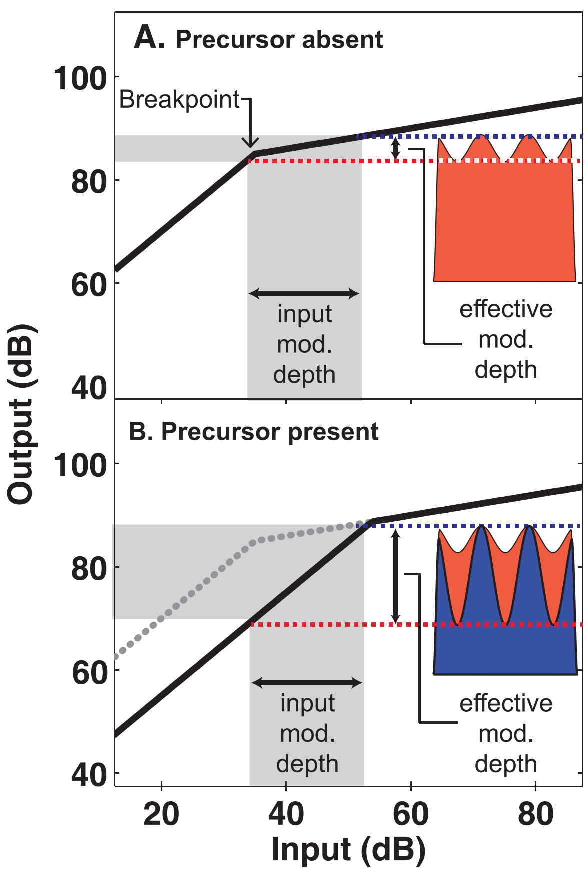

FIG. 1. (Color online) Schematic of the expected effects of a reduction in cochlear gain on effective modulation depth. Cochlear response growth through an auditory filter centered on the carrier frequency grows linearly at low carrier levels, and compressively at mid-to-high carrier levels (solid line), where linear and compressive regions intersect at a breakpoint. The presentation of a precursor is assumed to reduce cochlear gain, resulting in a rightward shift in the compression breakpoint. For moderate-level carriers preceded by silence [(A) precursor absent] or by a precursor [(B) precursor present] the effective modulation depth is smaller or roughly equal to the input modulation depth, respectively. The solid line in (A) is replotted in (B) as a gray dotted line. Horizontal double arrows show the input modulation depth. Horizontal dash lines and vertical double arrows show the effective modulation depth.

For short carriers preceded by noise precursors [Fig. 1(B)], cochlear gain is expected to decrease over the course of the precursor, resulting in a local increase in I/O function slope and an improvement in effective modulation depth. Inherent to the theoretical framework presented in Fig. 1 is the assumption that AM detection depends only on the output of the auditory filter centered on the carrier frequency (i.e., off-frequency listening does not occur), and the decision variable for detecting AM is based only on the effective AM depth. Thus, the model makes the following predictions: (1) for short carriers preceded by silence [Fig. 1(A)], AM detection thresholds should worsen as the carrier level is increased from low-to-mid levels due to the compressive I/O function at moderate-to-high levels; (2) for short carriers preceded by a precursor or for long carriers (e.g., 500 ms) preceded by silence [Fig. 1(B)], AM detection thresholds are expected to improve at moderate levels due to decompression (linearization) of the I/O function via a reduction in cochlear gain over the time course of the precursor.

II. GENERAL METHODS

A. Apparatus and stimuli

Stimuli were digitally generated using custom-built MATLAB® (The MathWorks, Natick, MA) software (Bidelman *et al.*, 2015) and output through a LynxTWO-B (Lynx Studio Technology, Costa Mesa, CA) sound card (sampling rate, 44.1 kHz; 24-bit resolution) to listeners' right ear via a ER-2 (Etymotic Research, Inc., Elk Grove, IL) insert earphone driven by a headphone buffer [Tucker-Davis-Technologies (TDT), HB7, Alachua, FL]. AM detection thresholds were measured using a low-fluctuating, narrow-band-noise (NBN, bandwidth = 100 Hz) carrier, whose spectrum was arithmetically centered on 5000 Hz (f_c). Low-fluctuating noise was generated by iteratively (ten iterations) dividing filtered noise by the Hilbert envelope as described by Kohlrausch *et al.* (1997). Narrow-band noise carriers were used because this study was part of a larger set of experiments that involved comparing AM thresholds for fluctuating- and flat-envelope carriers. High-frequency carriers were used because cochlear amplifier gain is greatest in the base of the cochlea (Cooper and Rhode, 1995) and previous studies have shown the largest mid-level effects on AM detection at high carrier frequencies (>4000–6000 Hz, Long and Cullen, 1985). Sinusoidal AM was applied in cosine phase over the duration of the carrier as follows:

$$x(t) = [1 + m\cos(f_m t)]y(t),$$

where m is the modulation index, f_m is the modulation frequency, and $y(t)$ is the noise carrier. Modulated carriers were scaled to the desired root-mean-square (rms) level after applying AM. Carriers were 50 ms [Experiments (Exps.) I and II] or 500 ms (Exp. I), excluding 2 ms onset/offset ramps. The precursor was a 40 dB sound pressure level (SPL) (overall level) notched noise, where low- and high-frequency noise bands extended from 1500 to 4500 Hz and 5500 to 8500 Hz, respectively. Notched-noise precursors were used because pilot studies were consistent with forward masking in the

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modulation domain (Wojtczak and Viemeister, 2005) from precursors with spectral energy at the carrier frequency. Precursor duration was 200 ms, including 5 ms onset/offset ramps. There was no delay between the offset of the precursor and the onset of the carrier. Off-frequency listening (Johnson-Davies and Patterson, 1979; O'Loughlin and Moore, 1981) was restricted by gating an additional notched noise simultaneously with the carrier, where the noise level was 50 dB/Hz below the carrier spectrum level (Nelson *et al.*, 2001). The spectral notch of the off-frequency listening noise extended from $0.9 * f_c$ to $1.2 * f_c$ (i.e., 4500–6000 Hz), similar to Oxenham and Plack (1997). The outer frequency cutoffs of the off-frequency listening noise were 2000 and 8000 Hz. Figure 2 shows the time waveform (top panel) and spectrogram (bottom panel) of the 50-ms AM carrier preceded by the 200-ms, notched-noise precursor.

B. Procedure

Subjects participated in the experiment in a sound-attenuating booth. The dependent variable was AM detection threshold, expressed as modulation depth (m) in dB. AM detection thresholds were measured using an adaptive three-interval, three-alternative forced-choice task. During a trial, the carrier was presented in each interval separated by 500 ms and marked by lighted squares on a computer monitor. The carrier and precursor (when present) noises were independently generated for each observation interval (i.e., frozen noises were not used). In order to eliminate level cues, the power of the carrier was the same in all observation intervals (Viemeister, 1979). During a randomly chosen interval, the carrier was sinusoidally amplitude modulated. The subject pressed a button on a keyboard to indicate the interval in which the modulation was perceived. Visual feedback was provided to indicate a correct or incorrect response.

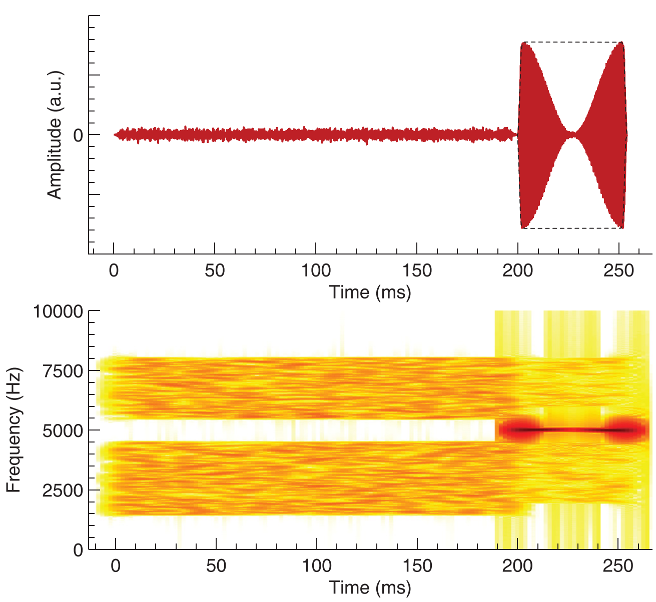

FIG. 2. (Color online) Time waveform (top) and spectrogram (bottom) of the 200-ms, notched-noise precursor, followed by the 50-ms (plus 2-ms rise/fall ramps) narrowband, amplitude-modulated carrier. The dashed line in the top panel shows the envelope of the unmodulated carrier. Off-frequency listening was limited by gating an additional notched noise with the carrier. For the spectrogram, dark colors represent relatively higher amplitudes, while light colors represent relatively lower amplitudes. (a.u.: arbitrary units.)

During a threshold run, the modulation depth was adjusted using a two-down, one-up rule which measures the modulation depth necessary to achieve 70.7% correct on the psychometric function (Levitt, 1971). The initial 8-dB step size was decreased to 2 dB after the second reversal. Twelve reversals were obtained and the mean modulation depth of the last eight reversals was defined as the AM threshold for that run. Thresholds from four runs were averaged to compute the final threshold of each condition. Runs with a standard deviation greater than 5 dB were discarded and the run was repeated. The need to obtain an additional threshold occurred a total of 9 times of the measured experimental thresholds (1.7% of thresholds in Exp. I; 3.7% of thresholds in Exp. II).

Learning was measured by calculating the change in threshold per repetition (i.e., slope) across these four runs. If the slope was greater than 3 dB/repetition, an additional threshold was obtained and the slope was recalculated. This process was continued until the slope fell below 3 dB/repetition. Although learning effects were monitored, none of the subjects exceeded the 3 dB/repetition criterion; therefore, only the initial four thresholds were averaged to compute the final threshold.[1] Experimental sessions were limited to 1.5–2 h. Training lasted at least 2 h and involved measuring two consecutive AM thresholds from a representative sample of conditions from Exp. I including several carrier levels, two carrier durations, and the presence/absence of the precursor. Thresholds measured during training were discarded.

III. EXPERIMENT I: AM DETECTION WITH AND WITHOUT A PRECURSOR AS A FUNCTION OF CARRIER LEVEL

This experiment investigated the effects of carrier level with and without a notched-noise precursor to test two hypotheses: (1) AM detection thresholds will be poorer at moderate levels, compared to low levels, consistent with the effects of cochlear compression on the effective modulation depth of the carrier; (2) AM detection thresholds for short carriers with a precursor or for long carriers will be better than those measured with short carriers without a precursor, particularly at moderate carrier levels. This hypothesis is based on the assumption that cochlear gain decreases during the presentation of the precursor or during the forward fringe of the long carrier, resulting in an improved effective modulation depth as schematized in Fig. 1.

A. Method

1. Subjects

Seven subjects (ages 20 to 32 years, 5 males) participated in the experiment. Subjects had thresholds ≤20 dB hearing level at audiometric frequencies between 250 and 8000 Hz, and normal middle ear function based on tympanometry. The right ear of each subject was tested. Subjects were inexperienced with psychoacoustic tasks except subject

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1 (S1), who is the first author. All subjects, except S1, were paid hourly for their participation. Due to time constraints, two subjects (S6, S7) could not participate in the long-carrier condition and one subject (S2) participated in only three of five carrier levels for the long carrier condition.

2. Stimuli

A modulation frequency of $f_m = 20$ Hz was used because previous studies show that, compared to gated carriers, improvements in AM thresholds with continuous carriers or the presentation of a forward fringe of noise are greatest at low-modulation frequencies (2–20 Hz, Sheft and Yost, 1990). Carrier levels were 50, 55, 60, 65, 75, and 85 dB SPL. In the short-carrier conditions, AM detection thresholds were measured with and without a precursor (6 carrier levels $*$ 2 precursor conditions = 12 conditions), while in the long-carrier conditions, AM detection thresholds were measured without a precursor (six conditions). Conditions were randomized by carrier level. For a given carrier level, AM thresholds were first obtained for short carriers without a precursor, followed by thresholds for short carriers with a precursor. After measuring thresholds for short carriers with and without precursors, AM detection thresholds were measured for 500-ms carriers.

B. Results and discussion

1. 50-ms carrier without a precursor

AM detection thresholds improved and then worsened as the level of the 50-ms carrier was increased to 65 dB SPL, above which thresholds improved monotonically, except some subjects showed a slight (S7) or modest (S3, S5) increase in thresholds at the highest carrier level (Fig. 3, open circles). The significantly poorer AM detection thresholds at mid, compared to lower or higher carrier levels [$t(6) = 6.9$, $p < 0.001$] is similar to results from Long and Cullen (1985), who concluded that this nonmonotonic behavior may be a general characteristic of intensity processing at high frequencies (4000–6000 Hz and above). For comparison, intensity discrimination thresholds (ΔI in dB) from Carlyon and Moore (1984) were converted to modulation index values based on the equation by Long and Cullen (1985), where $m = [10^{\Delta I_{\mathrm{dB}}/20} - 1]/[1 + 10^{\Delta I_{\mathrm{dB}}/20}]$. These thresholds are shown as the thin gray line in the lower right panel of Fig. 3. AM detection thresholds for 50-ms carriers without a precursor, and the intensity discrimination thresholds from Carlyon and Moore (1984) are qualitatively similar, with thresholds peaking at 65 dB SPL. The relatively higher thresholds from Carlyon and Moore (1984) are likely due to differences between AM detection and intensity discrimination and due to their pedestal being roughly half the duration of the 50-ms carrier. The mid-level hump seen in intensity discrimination studies (e.g., Carlyon and Moore, 1984; Zeng *et al.*, 1991) was originally hypothesized to be due to a threshold gap between low- and high-SR fibers. A quantitative evaluation of this hypothesis (Heinz *et al.*, 2001) showed that (1) the transition in coding from high-, to low-SR fibers was at higher levels than those associated with the mid-level effects observed psychophysically, and (2) the presence of medium-SR fibers (Liberman, 1978) eliminated the putative threshold gap, casting doubt on this hypothesis.

More recent studies have shown that poorer intensity discrimination thresholds at moderate compared to lower stimulus levels are consistent with cochlear compression (Heinz *et al.*, 2001; Pienkowski and Hagerman, 2009; Roverud and

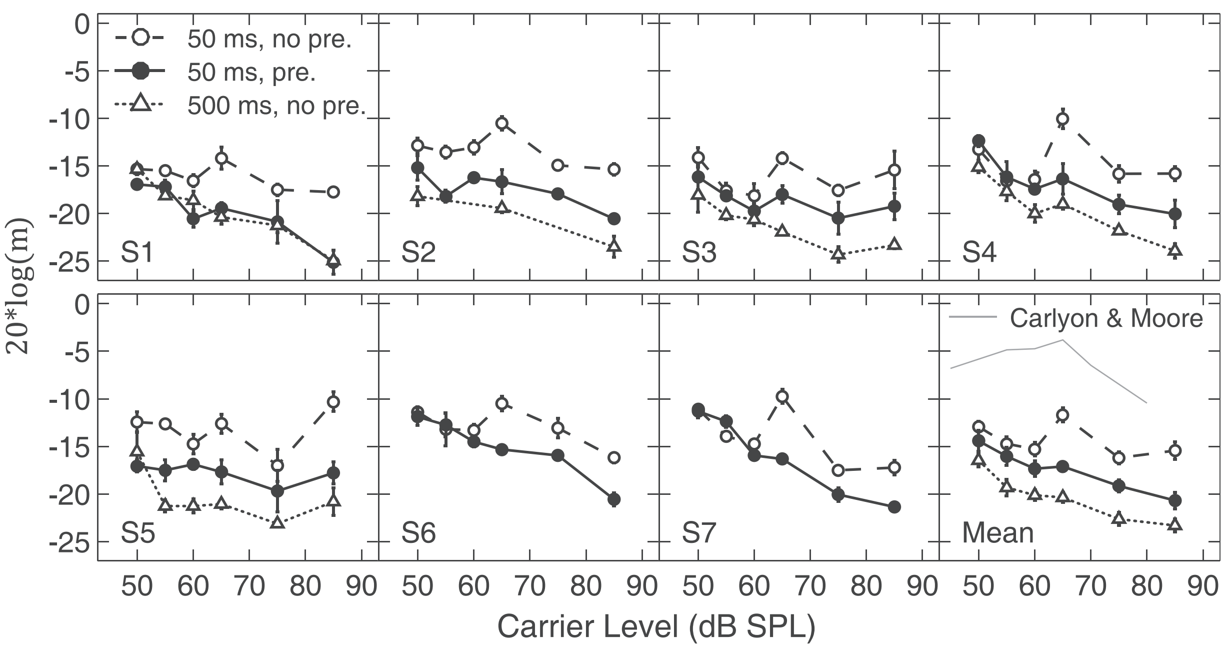

FIG. 3. Modulation depth at threshold as a function of carrier level for short (open circles) and long (open triangles) carriers preceded by silence, or for short carriers preceded by a notched-noise precursor (closed circles). Lower values represent better AM detection [i.e., lower modulation depth (m) at threshold]. Panels are results for individual subjects except the lower right panel, which displays the mean data. The modulation frequency was 20 Hz. Mean data from Carlyon and Moore (1984) are shown by the gray line in the lower right panel to illustrate the mid-level hump observed in some intensity discrimination experiments. Error bars are the standard error of the mean.

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Strickland, 2015b). For example, Heinz *et al.* (2001) compared model predictions of psychophysical intensity discrimination thresholds using linear and non-linear versions of an analytical model of the auditory periphery. A mid-level hump in intensity discrimination was predicted by the non-linear model due to strong compression; whereas, the linear model predicted monotonically decreasing intensity discrimination thresholds with increasing pedestal level. Furthermore, Roverud and Strickland (2015a) found a significant correlation for most subjects (7/10) between intensity discrimination thresholds for short (30 ms), 6000 Hz pedestals and psychophysical estimates of cochlear compression. Specifically, intensity discrimination thresholds from low-to-moderate levels were significantly higher (poorer) for subjects with the shallowest I/O function slopes (i.e., the most compression). Finally, using a roving-level paradigm and a 4000 Hz pedestal, Pienkowski and Hagerman (2009) compared intensity discrimination of 300-ms and 4-ms tones between listeners with normal hearing and listeners with mild-to-moderate sensorineural hearing loss, who are expected to have more linear I/O functions (i.e., less compressive slopes). In normal-hearing listeners, they observed a mid-level hump for intensity discrimination of 300 ms tones with pedestal levels roved over a wide range. For the same conditions, intensity discrimination thresholds for hearing-impaired listeners improved monotonically with pedestal level and were equal to or slightly better than normal-hearing listeners, consistent with more linear response growth in hearing-impaired than in normal-hearing listeners.

The improvement in AM detection thresholds with carrier level for levels above 65 dB SPL (Fig. 3, open circles) is reminiscent of the "near miss" to Weber's law, which has been modeled by assuming greater spread of excitation at higher compared to lower stimulus levels (Florentine and Buus, 1981). For example, at low-to-moderate levels where spread of excitation is likely minimal (Nelson *et al.*, 2001) intensity discrimination is expected to be mediated by auditory filters near the pedestal frequency where response growth may be compressive. At higher pedestal levels, spread of excitation results in the recruitment of auditory filters centered on frequencies remote from the pedestal frequency where responses are expected to grow more linearly. Thus, as discussed by Heinz *et al.* (2001), better intensity discrimination thresholds at higher than at more moderate levels is consistent with recruitment of additional off-frequency auditory filters, some of which have a more linear response growth than the filter centered on the pedestal frequency. In the current experiment, off-frequency listening was restricted by presenting a notched noise simultaneously with the carrier; however, as discussed later this noise may not have been effective at the highest carrier levels. Poorer thresholds at the lowest carrier levels than at slightly higher levels may be due to near-threshold effects (Plack and Skeels, 2007) where the effective AM is reduced after being mixed with internal noise.

2. 50-ms carrier with a precursor

AM detection thresholds with a precursor (Fig. 3, closed circles) improved monotonically with carrier level (S6, S7) or had a small "bump" between 60 and 70 dB SPL (S1–S5). For two participants, thresholds worsened slightly at the highest carrier level (S3, S5). A repeated measures analysis of variance (rmANOVA) was performed on data collected with a short carrier with and without a precursor. Condition (precursor / no precursor) and carrier level (50, 55, 60, 65, 75, 85 dB SPL) were submitted as within-subject repeated measures. The main effects of condition [$F(1,6) = 64.5$, $p < 0.001$] and carrier level [$F(5,30) = 11.6$, $p < 0.01$] were significant, as was the condition*carrier level interaction [$F(1,6) = 14.4$, $p < 0.01$]. *Post hoc* analyses revealed that thresholds for the 50-ms carrier were similar with and without a precursor at low carrier levels [50 and 55 dB SPL, $t(6) = 1.8$, $p = 0.12$]; whereas, at mid-to-high levels (60 dB SPL and above) thresholds were significantly better with than without a precursor [$t(6) = 15.1$, $p < 0.001$]. These findings are consistent with Roverud and Strickland (2015b) who showed that intensity discrimination thresholds for mid-level pedestals improve when the pedestal is preceded by an ipsilateral broad-band noise precursor than when preceded by silence.

3. 500-ms carrier

AM detection thresholds were lower (better) for long carriers (Fig. 3, triangles) than for short carriers (i.e., with or without a precursor), with exception of S1, where thresholds were similar for long carriers and short carriers with precursors (compare filled circles and open triangles in Fig. 3). An rmANOVA was performed on AM thresholds with long carriers and short carriers with a precursor. This analysis was chosen because the total durations of the precursor and long carrier conditions were similar, thus revealing the effect of increasing the number of modulation cycles without also increasing total duration. Condition (long carrier vs short carrier with a precursor) and carrier level (50, 55, 60, 65, 75, 85 dB SPL)[2] were submitted as repeated measures. The main effects of condition [$F(1,4) = 12.7$, $p = 0.02$] and carrier level [$F(1,4) = 16.7$, $p < 0.005$] were significant. The condition $*$ carrier level interaction did not reach significance [$F(5,20) = 1.59$, $p = 0.21$]. These findings indicate that thresholds for long carriers improved by a constant compared to those for short carriers with precursors, regardless of carrier level. A parsimonious explanation for this improvement is the tenfold increase in the number of modulation cycles for long compared to short carriers, leading to the opportunity for "multiple looks" (Viemeister and Wakefield, 1991). Sheft and Yost (1990) presented a simple multiple looks model for predicting the improvement in AM detection thresholds based on the assumptions that (1) detectability increases by the square root of n (Green and Swets, 1966) and (2) an exponential relationship exists between d' (sensitivity) and modulator power. Based on their Eq. (1) with $k = 1$ (see Sheft and Yost, 1990), predicted thresholds for the long carrier are as follows:

$$20 \log 10(m) = \theta - 5 \log 10(n), \tag{1}$$

where θ is the threshold in the short carrier condition with a precursor and n is the ratio of modulation cycles for the long

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carrier to that of the short carrier (i.e., 10/1 cycles). When averaged across carrier levels and subjects, the improvement in AM detection thresholds for long carriers compared to short carriers with a precursor was 2.1 dB for the current experiment, which is appreciably smaller than the 5 dB improvement predicted by multiple looks. Lee and Bacon (1997) reported a critical duration of ∼4 cycles for AM detection using sinusoidal carriers modulated at 20 Hz. This suggests that although ten cycles of the long carrier were available to listeners, only four of these cycles contributed to improvements in thresholds compared to thresholds for short carriers with a precursor. Based on a four-cycle critical duration for detection of 20 Hz AM, predicted improvements in thresholds with long carriers relative to those with short carriers with precursors are 3.01 dB, which are closer to the 2.1 dB observed from the current data.

4. Interpretation of precursor / carrier duration effects based on reductions in cochlear gain

A significant precursor effect at mid, but not low carrier levels is consistent with decompression of the cochlear I/O function via a reduction in cochlear gain. At low carrier levels, the effective modulation depth is expected to be roughly equal to the input modulation depth regardless of the presence/absence of the precursor, due to linear basilar membrane response growth. At moderate levels, where the basilar membrane growth is compressive, a reduction in cochlear gain over the course of the precursor is expected to decompress a portion of the cochlear I/O function (see Fig. 1), consistent with better AM detection with compared to without the precursor (Fig. 3).

The theoretical framework presented in Fig. 1 predicts that AM thresholds without a precursor should worsen from low to high carrier levels due to the transition between linear and compressed regions of the cochlear I/O function. Similarly, this model predicts that improvements in AM detection thresholds with the introduction of a constant-level precursor (precursor–no precursor difference) should be largest for mid-carrier levels, and smaller for low- or high-carrier levels. The smaller precursor–no precursor difference at high-carrier levels is expected based on the framework in Fig. 1 because (1) detection is assumed to depend only on the auditory filter centered on the carrier frequency (Viemeister, 1983), (2) the constant-level precursor is assumed to produce a constant reduction in gain for all carrier levels (see Warren and Liberman, 1989), and (3) cochlear gain is minimal at high levels (Robles and Ruggero, 2001). For the average data, the precursor–no precursor difference was largest at 65 dB SPL and decreased at higher levels, as expected based on the theoretical framework. Despite this, the precursor–no precursor difference was larger for 85 dB SPL than 75 dB SPL carriers, which is inconsistent with the theoretical framework in Fig. 1. A caveat in using this theoretical framework to interpret the data obtained with high carrier levels is the finding that AM detection for short carriers without a precursor improves with increasing carrier level above 65 dB SPL (Fig. 3). This finding is consistent with the detection of AM in remote auditory filters via the upward spread of excitation (Florentine and Buus, 1981), which is a violation of the first assumption of the theoretical framework (i.e., AM detection depends only on the auditory filter centered on the carrier frequency). Moreover, this finding suggests that the noise used to restrict off-frequency listening was not effective at the highest carrier levels. The advantage of listening off frequency is the expectation that basilar membrane growth is more linear through off- than through on-frequency auditory filters (Oxenham and Plack, 1997). It is beyond the scope of this study to speculate about the degree to which AM stimuli are compressed (no precursor condition) and decompressed (precursor condition) in these off-frequency auditory filters. In other words, the interpretation of the precursor–no precursor difference at high-carrier levels in terms of a reduction in cochlear gain through an auditory filter centered on the probe frequency is encumbered by evidence consistent with off-frequency listening.

For moderate carrier levels, which avoid near-threshold effects and off-frequency listening, the precursor–no precursor difference is consistent with decompression of the cochlear I/O function. The degree of decompression for moderate carrier levels can be estimated by assuming that AM is detected at a constant effective modulation depth (Viemeister, 1979), expressed in decibels (k_{dB})

$$k_{\text{dB}} = \Delta I_{\text{dB}} c, \tag{2}$$

where ΔI_{dB} is the change in intensity in decibels of the AM stimulus at threshold and c is the average compression slope of the cochlear I/O function for the range of intensities spanned by ΔI_{dB}. Assume k_{dB} is constant for no precursor and precursor conditions and let subscripts $_0$ and $_{\text{p}}$ represent these conditions, respectively. The ratio of compression slopes can be solved by substitution and simplification of Eq. (2) to yield

$$c_0/c_p = \Delta I_{p\,\text{dB}}/\Delta I_{0\,\text{dB}}, \tag{3}$$

where $\Delta I_{p\,\text{dB}}$ and $\Delta I_{0\,\text{dB}}$ were calculated from the modulation index (m) using the formula described by Long and Cullen (1985). The ratio in Eq. (3) indicates the fraction of the compression slope in the precursor condition needed to yield the compression slope in the no precursor condition. Values less than 1 indicate steeper compression slopes in the precursor compared to no precursor condition, while values greater than 1 indicate shallower slopes. Table I displays the ratio of compression slopes for each listener and for the mean data. On average, the ratio of compression slopes was 0.53, indicating that slopes are nearly twice as steep in the precursor condition than in the no precursor condition, consistent with decompression of the cochlear I/O function. For example, if the compression slope in the precursor condition was 0.7 dB/dB, the corresponding slope for the no precursor condition is $0.7 * 0.53 = 0.37$ dB/dB. These numbers are for illustrative purposes only, as the absolute compression slopes cannot be determined without additional (and potentially invalid) assumptions.

A reduction in cochlear gain via the MOC reflex is traditionally thought of as a within channel process. This comes

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TABLE I. The ratio of basilar membrane compression slopes for the precursor and no precursor conditions (c_o/c_p) estimated from AM detection thresholds. AM detection thresholds were converted to intensity difference limens in dB (ΔI_{dB}). c_o/c_p was estimated by taking the ratio of intensity difference limens in the precursor ($\Delta I_{p\,\mathrm{dB}}$) and no precursor conditions ($\Delta I_{0\mathrm{dB}}$). See text for details.

Subject	$\Delta I_{0\,\mathrm{dB}}$	$\Delta I_{p\,\mathrm{dB}}$	$\Delta I_{p\,\mathrm{dB}}/\Delta I_{0\,\mathrm{dB}}$
S1	3.43	1.86	0.54
S2	5.32	2.57	0.48
S3	3.44	2.20	0.64
S4	5.64	2.66	0.47
S5	4.15	2.28	0.55
S6	5.35	3.01	0.56
S7	5.87	2.67	0.46
mean	4.63	2.44	0.53
std.	1.05	0.38	0.06

from early studies in laboratory animals showing that the MOC reflex is a frequency-specific feedback loop (Liberman and Brown, 1986). In other words, MOC neurons with a given CF feedback on auditory nerve fibers with roughly the same CF. Given this frequency specificity, it is expected that precursors with energy away from CF (such as the notched-noise precursors used in this study) would not reduce cochlear gain at the CF centered on the carrier frequency. However, recent otoacoustic emission (OAE) studies in humans (Lilaonitkul and Guinan, 2009) and neural labeling studies (Brown, 2014, 2016) in laboratory animals suggest that MOC feedback may be less frequency specific than previously thought. These OAE and neural labeling studies are consistent with the interpretation that MOC feedback may partially account for improvements in intensity discrimination (Roverud and Strickland, 2015a), and AM detection (current study) in the presence of a notched-noise precursor, compared to no precursor. Gain reduction via the MOC reflex shifts the dynamic range of individual auditory nerve fibers, thus producing a form of dynamic range adaptation (Kawase *et al.*, 1993; Chintanpalli *et al.*, 2012). The theoretical framework described in Fig. 1 explicitly assumes that cochlear compression is responsible for poorer effective modulation depths at moderate compared to higher or lower levels and that improved modulation depth with the introduction of a precursor results from a decrease in cochlear gain. It is equally likely that mechanisms such as neural saturation, and dynamic range adaptation in the auditory nerve (Wen *et al.*, 2009) or inferior colliculus (Dean *et al.*, 2005) could account for the mid-level deterioration in AM detection and improved AM detection thresholds with a precursor. Distinguishing between cochlear and more central mechanisms of dynamic range adaptation could be difficult since signal transformations in the cochlea are carried upstream to central auditory nuclei. Studies on the effects of contralateral stimulation on otoacoustic emissions, or cochlear microphonics elicited by ipsilateral amplitude modulated stimuli may verify the putative role of the MOC reflex in dynamic range adaptation. To our knowledge no such studies have been conducted. Thus, although Exp. I was motivated by cochlear mechanisms, better AM detection with than without a precursor may be due to dynamic range adaptation in more central auditory mechanisms.

5. Other interpretations

The precursor–no precursor difference observed in Exp. I may also be explained by mechanisms other than a reduction in cochlear gain. Two potential mechanisms are discussed here. First, the precursor may have facilitated AM detection by serving as a reference for the absence of amplitude modulation. In other words, AM detection with a precursor may be mediated by detecting the change from a flat, to a fluctuating temporal envelope. According to this interpretation, AM detection is better with than without a precursor because the precursor provides a more salient reference of an unmodulated stimulus than the comparison stimulus presented in the other two observation intervals of the forced choice task. The drawback to this interpretation is the lack of a clear explanation for why the effect of the precursor is smaller at lower than at mid-to-high levels.

A second alternative explanation is based on the finding that thresholds for detecting a target harmonic within a harmonic complex are better if a precursor is presented containing all harmonics except the target harmonic (Viemeister, 1980). This general phenomenon is often referred to as "perceptual enhancement" and has many variations including signal enhancement (Viemeister, 1980), masker enhancement (Viemeister and Bacon, 1982), and vowel spectrum enhancement (Summerfield *et al.*, 1984; Summerfield *et al.*, 1987). There is converging psychophysical (Byrne *et al.*, 2011) and neurophysiological evidence (Nelson and Young, 2010) to suggest that this enhancement is due to adaptation of inhibition. If inhibition adapts over the course of a precursor, the ensuing target (or masker) is released from inhibition that would otherwise be present if the target onset were coincident with the precursor's onset. Although there are no psychophysical studies designed to test enhancement of AM detection, there is neurophysiological evidence showing that the presence of off-frequency spectral components enhances AM coding in neurons in the cochlear nucleus (Moller, 1975).

A notable difference between the current study and previous enhancement studies is the difference in level between off-frequency and probe frequency components. The notched noise used to restrict off-frequency listening in the current experiment was 50 dB/Hz below the spectrum level of the carrier, while in previous studies components of off-frequency maskers are usually above the level of the probe when enhancement is observed (Viemeister and Bacon, 1982; Byrne *et al.*, 2011; Viemeister *et al.*, 2013). Moreover, effects of suppression and inhibition weaken as the probe level increases relative to a constant-level, notched-noise suppressor/inhibitor (e.g., Rhode and Greenberg, 1994). This suggests that enhancement effects (if present) were relatively weaker in the current study compared to previous studies. Future studies are needed to fully determine to what extent the notched noise used to restrict off-frequency listening may have facilitated enhancement.

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IV. EXPERIMENT II: AM DETECTION WITH AND WITHOUT A PRECURSOR AS A FUNCTION OF MODULATION FREQUENCY

Results from Exp. I show that a notched-noise precursor presented before a high-frequency carrier improves AM detection at moderate-to-high carrier levels for low ($f_m = 20$ Hz) modulation frequencies. Experiment II assessed whether these improvements apply to other modulation frequencies by measuring TMTFs for short carriers with and without a precursor.

A. Method

1. Subjects

Five young, normal-hearing listeners (S1, S2, S3, S4, and S5) from Exp. I also participated in this experiment.

2. Stimuli

The precursor, off-frequency listening noise, and short carrier were the same as in Exp. I. Thresholds for long carriers were not tested. The 65 dB SPL carrier was modulated at $f_m = 20$, 40, 60, 80, 100, or 500 Hz, resulting in 12 total conditions (6 modulation frequencies $*$ 2 precursor conditions). Conditions were randomized by modulation frequency. For a given modulation frequency, AM thresholds were obtained for the no-precursor condition, followed by the precursor condition.

B. Results and discussion

1. 50-ms carrier without a precursor

Temporal modulation transfer functions measured with the 50-ms carrier in the absence of a precursor are displayed as open circles in Fig. 4. AM detection thresholds improved with increasing modulation frequency up to 80–100 Hz, where the average improvement between thresholds for 20 and 100 Hz modulation frequencies was 5.5 dB. For $f_m = 500$ Hz, AM thresholds were worse (except S5) by 3–5 dB (S1, S2), or 1–2 dB (S3, S4) compared to $f_m = 100$ Hz.

2. 50-ms carrier with a precursor

Filled circles in Fig. 4 display TMTFs for the 50-ms carrier with a precursor. AM thresholds for $f_m \leq 80$ Hz are roughly constant (S1, S3), or improve slightly with increasing modulation frequency (S2, S4, S5). On average, this improvement was 2.1 dB, which is smaller than that observed for the 50-ms carrier without a precursor. A two-way rmANOVA was conducted with condition (precursor, no precursor) and modulation frequency (20, 40, 60, 80, 100, 500 Hz) as repeated measures. The main effects of condition [$F(1,4) = 69.63$, $p < 0.005$], and modulation frequency [$F(5,20) = 19.21$, $p < 0.005$] were significant, as was the condition * modulation frequency interaction [$F(5,20) = 11.30$, $p < 0.01$]. Consistent with this interaction, *post hoc* tests revealed that the precursor–no precursor difference was significantly larger when averaged across $f_m \leq 60$ Hz than $f_m \geq 80$ Hz [$t(4) = -3.85$, $p = 0.018$], suggesting that the effect of the precursor is largest at low modulation frequencies.

The larger precursor–no precursor difference at low compared to high modulation frequencies is similar to better AM thresholds for continuous than gated carriers reported in previous studies (Viemeister, 1979; Sheft and Yost, 1990). Adaptation is a common explanation for poorer thresholds with gated than with continuous carriers (Viemeister, 1979; Sheft and Yost, 1990; Klump and Okanoya, 1991; Moody, 1994). This explanation posits that, with gated carriers, cycles of modulation occurring during the onset response of auditory nerve fibers are less informative than cycles occurring during the steady-state response. Presumably this "onset insufficiency" (Sheft and Yost, 1990) influences the detection of low-frequency AM more than high-frequency AM for gated carriers because more cycles of modulation occur after the onset response for high- than for low-frequency AM, thus increasing the opportunity for multiple looks (Viemeister, 1979; however, see Yost and Sheft, 1997).

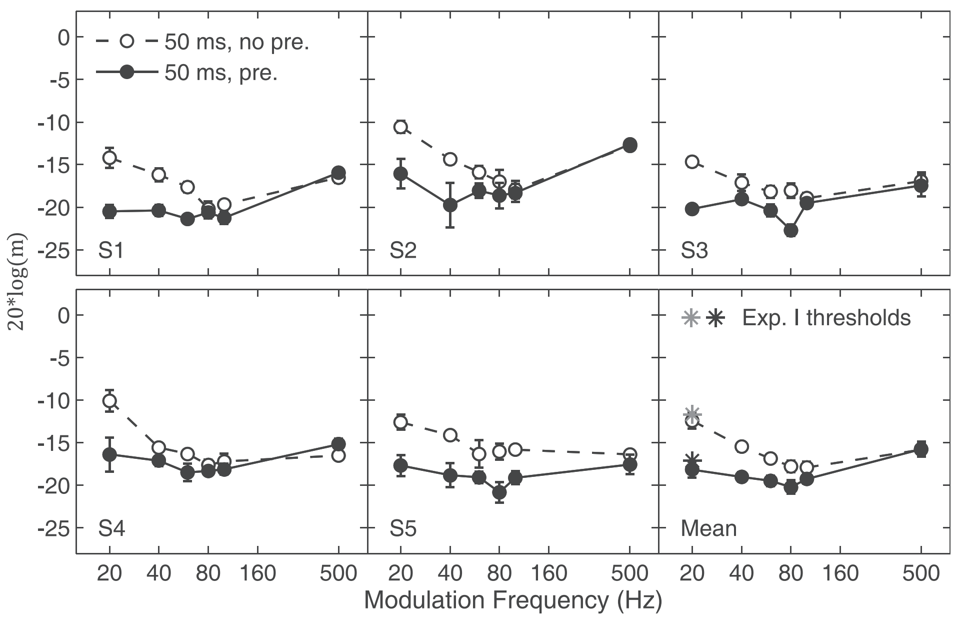

FIG. 4. Modulation depth at threshold as a function of modulation frequency for 65 dB SPL carriers preceded by silence (open circles) or by a notched-noise precursor (closed circles). Panels are results for individual subjects except the lower right panel, which displays the mean data. Mean data from Exp. I (black and gray asterisks), where $f_m = 20$ Hz are replotted in the lower right panel to show consistency between measurements. Error bars are the standard error of the mean.

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Consistent with this theory, the neural synchrony of auditory nerve fibers in starling is disrupted at the onset of gated AM stimuli more so for low- than for high-frequency AM (Gleich and Klump, 1995). Although adaptation and onset insufficiency hypotheses may partly explain why the precursor–no precursor differences are smaller at higher- than at lower-modulation frequencies, it is not clear how this hypothesis accounts for the level dependence of the precursor–no precursor difference reported in Exp. I. For example, it is not clear how onset insufficiency predicts precursor effects to be largest at mid-carrier levels, smaller at high-carrier levels, and absent at low-carrier levels. However, these level effects are accounted for by the theoretical framework in Fig. 1 based on a reduction in cochlear gain over the course of the precursor.

AM detection thresholds in the no precursor condition were generally poorer for lower than higher modulation frequencies. When the modulation index at threshold is expressed as ΔI in dB (Long and Cullen, 1985), average thresholds improve from 4.25 to 2.25 dB as modulation frequency increases from 20 to 100 Hz. This improvement is roughly consistent with the 1.3 dB improvement expected from multiple looks [Eq. (1)] and a four-cycle critical duration for AM detection (Lee and Bacon, 1997). Studies on forward masking suggest that growth of masking is not influenced by the slope of the cochlear I/O function unless masker and probe levels at threshold fall on parts of the cochlear I/O function with different slopes (Oxenham and Plack, 1997, 2000). In the context of AM detection, the valleys and peaks of the AM stimulus are analogous to the masker and probe in masking, respectively. Thus, decompression of the I/O function as a result of a reduction in cochlear gain from the precursor may only produce a substantial change in AM thresholds when thresholds without a precursor are relatively large (i.e., $f_m \leq 40$ Hz). At higher modulation frequencies (f_m from 60 to 100 Hz), thresholds without a precursor are relatively small (i.e., the acoustic peaks and valleys of the AM signal are processed similarly by the cochlear I/O function), thus a reduction in gain is expected to only mildly improve effective modulation depth at high modulation frequencies.[3]

V. SUMMARY AND CONCLUSIONS

Amplitude modulation detection thresholds for a short NBN carrier centered on 5000 Hz are better with than without a low-level, notched-noise precursor for moderate-to-high carrier levels, and low ($\leq$100 Hz) modulation frequencies. Improved thresholds with compared to without a precursor are consistent with a reduction in cochlear gain. A potential candidate for this reduction is the MOC reflex, which when stimulated by sound reduces outer hair cell gain with a time constant of roughly 70 ms (Backus and Guinan, 2006). The advantage of this interpretation is the ability to account for the level dependence of the precursor–no precursor difference; although off-frequency listening may complicate this interpretation at the highest carrier levels. From an ecological perspective, these results suggest that the auditory system may improve the effective modulation depth of modulated stimuli over the first several-hundred milliseconds of acoustic stimulation. This improvement may lead to robust neural coding of the amplitude envelope of speech and ultimately lead to robust speech perception in quiet and in background noise.

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[1]S5 reported difficulty hearing the target modulation for the 85 dB SPL carrier with a precursor. For this condition, S5 reported correctly guessing the target several times despite not actually perceiving it. Although this subject did not meet the criterion for learning (i.e., slope greater than 3 dB/repetition), four additional threshold runs for the 85 dB SPL carrier were obtained and averaged to determine the final threshold for this condition in this subject. To verify the stability of the data, one or two threshold runs were obtained for all subjects at several carrier levels. On average, these additional thresholds were within 1.28 dB ($\sigma = 2.17$ dB) of the original thresholds, suggesting that the data were stable. These additional thresholds were not included in the average thresholds for the experiments.

[2]Due to time constraints, S2 did not complete data collection for long carriers at 55 and 75 dB SPL; thus, for the statistical analysis, thresholds for this subject at these carrier levels were imputed using linear interpolation.

[3]Currently it is unclear why the precursor–no precursor difference is absent for $f_m = 500$ Hz despite the moderately higher thresholds at this frequency than at moderate modulation frequencies (60–100 Hz).

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