Features of across-frequency envelope coherence critical for comodulation masking release

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(Received 10 December 2008; revised 7 August 2009; accepted 13 August 2009)

The masking release associated with coherent amplitude modulation of the masker is dependent on the degree of envelope coherence across frequency, with the largest masking release for stimuli with perfectly comodulated envelopes. Experiments described here tested the hypothesis that the effects of reducing envelope coherence depend on the unique envelope features of the on-signal masker as compared to the flanking maskers. Maskers were amplitude-modulated tones (Experiments 1 and 3) or amplitude-modulated bands of noise (Experiment 2), and the signal was a tone; across-frequency masker coherence was manipulated to assess the effects of introducing additional modulation minima in either the on-signal or flanking masker envelopes of otherwise coherently modulated maskers. In all three experiments, the detrimental effect of disrupted modulation coherence was more severe when additional modulation minima were introduced in the flanking as compared to on-signal masker envelopes. This was the case for both ipsilateral and contralateral flanking masker presentations, indicating that within-channel cues were not responsible for this finding. Results are consistent with the interpretation that the cue underlying comodulation masking release is based on dynamic spectral features of the stimulus, with transient spectral peaks at the signal frequency reflecting addition of a signal. © 2009 Acoustical Society of America. [DOI: 10.1121/1.3224708]

PACS number(s): 43.66.Dc, 43.66.Ba [MW]

Pages: 2455–2466

I. INTRODUCTION

Detection thresholds for a pure-tone signal in a narrow-band masker can be reduced under some stimulus conditions by the introduction of flanking maskers with the same pattern of amplitude modulation as the on-signal masker. This finding, described as comodulation masking release (CMR), has been hypothesized to rely on a wide range of cues, including across-channel processes (Hall *et al.*, 1984; Hall and Grose, 1988; Grose and Hall, 1989; Buus *et al.*, 1996; van de Par and Kohlrausch, 1998b), within-channel cues (Schooneveldt and Moore, 1987; Berg, 1996; Verhey *et al.*, 1999), or some combination of within- and across-channel cues (Schooneveldt and Moore, 1987; Piechowiak *et al.*, 2007). CMR is largest when masker envelopes are perfectly correlated across frequency, but partial correlation supports a reduced CMR effect (McFadden, 1986; Eddins and Wright, 1994). There is evidence that tone detection in coherently modulated maskers is dominated by signal energy coincident with masker modulation minima (Buus, 1985; Hall and Grose, 1991; Buus *et al.*, 1996), consistent with the idea that modulation minima in the flanking maskers are associated with increased stimulus weights during epochs of improved signal-to-noise ratio (SNR); this idea is sometimes described as “cued listening.” If the detection advantage conferred by the presence of comodulated flanking maskers is due to off-frequency modulation minima coinciding with epochs of advantageous SNR at the signal frequency, then matches in modulation pattern *per se* may not be critical to CMR, pro-

vided that the minima of the off-frequency masker modulation pattern accurately cue minima of the masker at the signal frequency. The present set of experiments tested this hypothesis by manipulating the modulation pattern of on- and off-frequency maskers.

If flanking masker envelope minima cue the optimal listening epochs for signal detection, then introducing additional minima into the pattern of the on-signal masker should have little impact on performance. This manipulation would not disrupt the use of signal information coincident with other on-frequency minima, as cued by the flanking maskers. However, introducing additional minima to off-frequency maskers could provide inappropriate “cues,” resulting in increased weight during epochs of disadvantageous SNR and therefore hurting performance. In other words, minima in the on-signal masker that are not present in the flanking maskers should be of little consequence to detection, whereas the converse situation should be very detrimental to performance. One consideration that could impact this prediction is the possibility that a reduction in masker modulation coherence could result in auditory stream segregation (Bregman *et al.*, 1985). Some studies of CMR have proposed that modulation-based auditory grouping may play an important role in CMR (Hall and Grose, 1990; Dau *et al.*, 2004; Dau *et al.*, 2009; Grose *et al.*, 2009), so reduced envelope coherence itself could reduce CMR, quite apart from effects related to the relative timing of specific envelope features. Therefore, while unmatched envelope minima in the on-signal masker may reduce CMR by promoting sound segregation, larger reductions in CMR should be observed with

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unmatched minima in the flanking maskers, where segregation and inaccurate cueing may combine to reduce sensitivity.

Cued listening is not the only account of CMR consistent with the prediction that the introduction of additional modulation minima to an otherwise coherent pattern of modulation across frequency will have less detrimental effects in the on-signal masker than flanking maskers. In early reports of CMR, the cue underlying detection in a comodulated masker was likened to a dynamic profile analysis (Hall *et al.*, 1984; Fantini and Moore, 1994; Eddins, 2001). In the no-signal interval, the short-term power spectrum of a comodulated masker rises and falls coherently as a function of time, such that the short-term spectrum computed at any point in time is flat as a function of frequency. Addition of a signal disrupts this coherence, in most cases introducing a spectral peak at the signal frequency. For typical CMR stimuli, this cue is most pronounced for signal energy coincident with modulation minima, where the SNR is largest. This cue would also be available for signals that produce a consistent spectral peak and no change in modulation pattern across frequency. For example, Hall and Grose (1988) showed that the detection advantage conferred by coherent modulation does not depend on the signal introducing an envelope discrepancy in the modulation pattern across frequency. In that study, masking release occurred even when the signal was a copy of the narrowband, on-signal masker to which it is added (see also Green and Nguyen, 1988). If a signal in comodulated masking noise is detected by virtue of a spectral peak cue, then a “false positive” could be associated with stimuli in which flanking masker modulation minima are coincident with on-frequency masker modulation maximum. Under these conditions, portions of the on-signal masker could be mistaken for a signal by virtue of the transient spectral peak at the signal frequency that is present even in the absence of an added signal. On the other hand, modulation minima in the on-signal masker envelope that are not associated with flanking masker minima could be of little perceptual consequence. Reductions in level of one tone in the context of a set of otherwise equal-amplitude tones has been shown to be less salient than a level increment (Ellermeier, 1996), suggesting that transient decrements in a dynamic spectral profile could have rather subtle perceptual consequences.

Not all accounts of CMR predict a differential effect of introducing additional minima into the pattern of modulation of the flanking maskers as compared to the on-signal masker. Adding a pure-tone signal to a comodulated masker reduces the coherence of stimulus envelopes across frequency, and it has been suggested that this change could form the basis of the detection cue, quantified as a reduction in envelope correlation or covariance (Richards, 1987; van de Par and Kohlrausch, 1998a). Viewed in this way, CMR could be seen as a special case of monaural envelope correlation perception (Richards, 1987; Strickland *et al.*, 1989). The change in across-frequency envelope coherence with addition of a pure-tone signal in the CMR paradigm has also been characterized as an equalization and cancellation (EC) process (Buus, 1985; Piechowiak *et al.*, 2007), wherein envelopes

across frequency are normalized and subtracted, with a residual at the EC output reflecting addition of a signal. Models of the cue underlying CMR, based on envelope decorrelation, and those based on a remainder in an EC process, are fundamentally similar approaches (Green, 1992), both reflecting sensitivity to a reduction in modulation coherence across frequency. A special emphasis on modulation coherence synchronous with modulation minima may be achieved in this modeling approach with compression prior to envelope comparison (Buus *et al.*, 1996). However, there is no basis for a differential effect of additional envelope minima introduced to the flanking as compared to on-signal maskers—in both cases, modulation coherence would be reduced to the same extent by these additional minima.

The experiments reported here measure CMR for two envelope rates, one *slow* and the other *fast*; all minima in slow envelope coincide with minima in the fast envelope, but there are additional minima in the fast envelope that occur during epochs when the slow envelope is high in amplitude. Masker envelopes applied to the on-signal and flanking maskers are either the same (e.g., slow/slow) or different across frequency (fast/slow or slow/fast, defined as the envelope of the on-signal/flanking maskers). Under these conditions, CMR was expected to be largest for conditions in which the masker envelope is the same across frequency. For conditions in which the maskers were not perfectly comodulated across frequency, it was predicted that a fast on-signal masker envelope and slow flanking masker envelope (fast/slow) would be associated with greater CMR than the converse (slow/fast). This expectation is based on the degree to which minima of the flanking masker envelope coincide with modulation minima in the on-signal masker. In the matched envelope conditions, each flanking masker minimum coincides with an on-signal envelope minimum. Similarly, in the fast/slow condition, every minimum in the slow modulation of the flanking maskers coincides with a minimum in the fast on-signal masker modulation. In contrast, in the slow/fast condition, some of the minima in the fast modulation of the flanking maskers coincide with maxima of the slow on-signal masker envelope, resulting in transient spectral peaks at the signal frequency in the short-term spectrum. This could result in false positives because on-signal masker maxima could be confused with an added signal. If all flanking masker modulation minima coincide with on-signal masker minima, as in the matched envelope or fast/slow conditions, the short-term spectrum of the masker would never have a peak at the signal frequency. By this account, the presence of a flanking masker envelope minimum is not always associated with a false positive prediction—just in cases where the on-signal masker is at a high envelope value during a flanking masker minimum.

II. EXPERIMENT 1: EFFECT OF UNMATCHED MINIMA IN ON-SIGNAL VS FLANKING MASKER ENVELOPES FOR TONAL CARRIERS

Stimuli for the first experiment are similar to those used by Grose and Hall (1989). In that study, the signal was a pure tone at 700 Hz, and there were maskers at the 3rd–11th harmonics of 100 Hz, each presented at 50 dB sound pressure

level (SPL). In the coherent modulation condition, all nine masker components were modulated via multiplication with a raised 10-Hz cosine. The signal was composed of three “pips,” 50 ms in duration including 20-ms raised-cosine ramps. A masking release was observed if these signal pips were presented synchronously with consecutive envelope minima of the comodulated masker, but thresholds were poor if those pips coincided with masker envelope maxima. Moore *et al.* (1990) performed a follow-up study using stimuli similar to those of Grose and Hall (1989), but in that case omitting the flanking maskers at the sixth and eighth harmonics. This manipulation was designed to assess the contribution of flanking maskers close to the signal frequency, and therefore the effects that might be attributed to within-channel cues. Results were similar with and without those proximal maskers, suggesting that the effects observed with the full complement of maskers are relatively unaffected by within-channel cues. Flanking maskers at the sixth and eighth harmonics were nevertheless omitted in the present study in order to minimize possible effects related to stimulus interaction at the periphery.

A. Methods

1. Observers

Study participants were 13 adults, ages 18–54 (mean of 26.8 years). All had pure-tone detection thresholds of 15 dB hearing level (HL) or less at octave frequencies 250–8000 Hz in the test ear (ANSI, 1996), and none reported a history of ear disease. Eleven observers provided data in the first set of conditions. A subset of five observers went on to complete a second set of conditions, along with two additional observers. These groups were approximately balanced for age and gender. All observers had previously participated in psychoacoustic studies.

2. Stimuli

The signal to be detected was a 700-Hz pure tone, ramped on and off with 25-ms raised-cosine ramps and no steady state. The on-signal masker was an amplitude-modulated (AM) tone at 700 Hz, with the same carrier phase as the signal. Flanking maskers were 100% sinusoidally AM tones at 300, 400, 500, 900, 1000, and 1100 Hz. Both the on-signal and flanking maskers were played continuously over the course of a threshold estimation track, with all carriers starting in sine phase. Two types of envelopes were used, as illustrated in the top two panels of Fig. 1. The fast envelope was a raised 20-Hz cosine. The slow envelope was based on a raised 20-Hz cosine, but the envelope was held at the peak amplitude value for 50 ms on every other period of AM, beginning with the cosine phase of modulation. The signal, when present, was temporally centered in an envelope, minimum of both the fast and slow masker modulation patterns, as illustrated in the bottom panel of Fig. 1.

The flanking maskers were either ipsilateral or contralateral with respect to the ear presented with the signal and the on-signal masker. In the first set of conditions, the peak amplitude of each AM masker tone was 55 dB SPL (the “equal peak” conditions). In the second set, the level of each masker

FIG. 1. Basic features of the temporal envelopes used in Experiment 1 are illustrated. The fast pattern of AM was a 20-Hz raised sinusoid, as shown in the top panel. The slow AM stimulus was generated, based on the 20-Hz cosine, with the envelope held constant at the peak amplitude for every other modulation period. The signal was equivalent to a single period of 20-Hz modulation (i.e., 50-ms total duration), with the temporal center of the signal coincident with a minimum in both the fast and slow envelope patterns.

tone with slow AM was reduced by 6 dB, for a peak of 49 dB SPL per masker. This adjustment in level was based on initial data indicating that thresholds in the on-signal masker conditions were approximately 6 dB higher for the slow than the fast AM conditions. As such, this set of conditions will be referred to as the “equal on-signal” conditions.

3. Procedures

Stimuli were played out of a real-time processor (RP2, TDT), routed to a headphone buffer (HB7, TDT), and presented over circumaural headphones (Sennheiser HD 265). The experiment was controlled using MATLAB script and RPVDS software (TDT). Observers were seated in a double-walled sound-attenuating booth. A hand-held response box was used to visually indicate listening intervals, collect observer responses, and provide feedback.

Thresholds were measured using a three-alternative forced choice procedure, with each listening interval lasting 350 ms and a 300-ms delay between intervals. When present, the signal coincided with the modulation minimum closest to the temporal center of the listening interval. Feedback was provided visually after every trial. The signal level at the outset of the track was selected to be clearly audible, between 5 and 10 dB above expected threshold. The level was then adjusted based on observer response according to a three-down one-up procedure, estimating the signal level associated with 79% correct (Levitt, 1971). At the beginning of a track, the signal level was adjusted in steps of 4 dB, and steps were reduced to 2 dB after the second track reversal. A track continued for a total of 8 reversals, and a threshold estimate was computed as the average signal level at the last 6 reversals. Three such estimates were obtained in each condition, with a fourth in cases where the first three varied by 3 dB or more, and the final threshold was the average of all such estimates. Observers completed all thresholds in a condition before proceeding to the next condition, and the order of conditions was random across observers.

FIG. 2. Mean signal detection thresholds in the equal peak conditions are plotted as a function of flanking masker condition, with filled symbols and line styles reflecting the modulation pattern of the on-signal masker, and open symbols reflecting the modulation pattern of the flanking maskers. Error bars indicate ± 1 standard error of the mean.

B. Results and discussion

Mean thresholds across the 11 listeners in the first block of equal peak conditions are plotted in Fig. 2 as a function of flanking masker condition. Symbols and line style indicate the pattern of masker modulation. For the on-signal masker, the slow pattern is indicated by filled down-pointing triangles and dashed lines, and the fast pattern is indicated by filled up-pointing triangles and solid lines. In conditions including flanking maskers, the slow rate is indicated with an open down-pointing triangle, and the fast pattern is indicated by an open up-pointing triangle. The error bars around baseline thresholds show 1 standard error of the mean (sem); no error bars are shown for conditions in which the flanking maskers were present because symbol size exceeds 1 sem.

Thresholds in the absence of flanking maskers (at the left edge of the figure) are about 6 dB lower for the fast than the slow envelope rate. The overall level of the masker in the *fast/none* condition was 2.6 dB lower than that in the *slow/none* condition due to the larger number of modulation minima. Forward masking could therefore play a role in the difference in on-signal masker thresholds. Inclusion of flanking maskers tended to improve thresholds. As expected, this effect was more pronounced when the masker envelope was comodulated across frequency (slow/slow and fast/fast conditions), and thresholds tended to be lower for ipsilateral than contralateral presentation of the flanking maskers. Thresholds in the fast/slow conditions were relatively low, within several decibels of thresholds in comparable matched-modulation conditions. This was particularly evident in thresholds for ipsilateral flanking masker presentation. In contrast, thresholds were relatively high in the slow/fast conditions. For both ipsilateral and contralateral flanker presentations, mean thresholds in this condition were less than 2

TABLE I. CMR, computed as the change in threshold with introduction of flanking maskers relative to the threshold measured with the on-signal masker alone.

Flanking masker condition		On-signal masker condition	
		Fast	Slow
Ipsilateral, equal peak	Fast	8.21	-0.73
	Slow	7.71	11.30
Contralateral, equal peak	Fast	4.61	1.42
	Slow	3.03	5.60
Ipsilateral, equal on-signal	Fast	10.77	-0.54
	Slow	7.35	9.74

sem away from threshold in the slow/none baseline condition.

The effect of including flanking maskers, described here as the CMR, was computed as the change in threshold relative to the associated no-flanker baseline. Values of CMR, based on the data in Fig. 2, are shown in the top four rows of Table I. The CMR for ipsilateral masker presentation was evaluated using a repeated measures analysis of variance. There were two levels of on-signal masker envelope rate (slow and fast) and two levels of across-frequency masker coherence (same and different). This analysis resulted in a main effect of coherence ($F_{1,10}=87.48, p<0.0001$) and no main effect of on-signal masker envelope rate ($F_{1,10}=2.60, p=0.14$). The interaction was significant ($F_{1,10}=35.11, p<0.0001$). This interaction reflects the fact that a mismatch in modulation patterns across frequency has relatively little effect when the AM associated with the on-signal masker is more rapid than that associated with the flankers (fast/slow) but is pronounced when the modulation pattern associated with the on-signal masker is slower than associated with the flanking maskers (slow/fast).

Estimates of CMR for contralateral masker presentation were also submitted to a repeated measures analysis of variance. As in the previous analysis, there were two levels of on-signal masker envelope rate (slow and fast) and two levels of across-frequency masker coherence (same and different). There was a main effect of coherence ($F_{1,10}=35.77, p<0.0001$) and no main effect of on-signal masker envelope rate ($F_{1,10}=0.03, p=0.87$). The interaction was significant ($F_{1,10}=12.70, p<0.01$), consistent with the conclusion that the interaction observed with ipsilateral flanking maskers was also evident with contralateral maskers.

One aspect of these results that could complicate interpretation of the effects of masker modulation differences across frequency is the masker level discrepancy and the 6-dB difference in baseline, on-signal masking thresholds. To assess the consequences of this difference, a subset of observers repeated the ipsilateral masker conditions of the experiment with the level of all slow masker stimuli reduced by 6 dB, including both slow on-signal and slow flanking maskers. Thresholds for the equal on-signal conditions appear in Fig. 3, and associated values of CMR appear in the bottom two rows of Table I. The CMRs for these conditions

FIG. 3. Mean thresholds for the equal on-signal conditions, with the level of maskers with the slow rate of AM reduced by 6 dB, are plotted as a function of flanking masker condition. Plotting conventions follow those in Fig. 2.

were submitted to a repeated measures analysis of variance, with two levels of on-signal masker envelope rate (slow and fast) and two levels of across-frequency masker coherence (same and different). Results indicate a main effect of on-signal masker envelope rate ($F_{1,10}=8.86, p<0.05$), reflecting better thresholds for the fast envelope rate, and a main effect of coherence ($F_{1,10}=194.63, p<0.0001$), reflecting better thresholds for matched than unmatched rates across frequency. The interaction was also significant ($F_{1,10}=47.47, p<0.01$), confirming that the interaction observed in the original data set was not attributable solely to a discrepancy in baseline masking thresholds for the slow/none and fast/none conditions.

These results are consistent with the initial hypothesis that the effect of introducing envelope pattern discrepancies across frequency depends on the details of that mismatch. In these results, performance appears to be more detrimentally affected by inclusion of additional modulation minima in the flanking than the on-frequency masker envelope. This result is observed when maskers with the two rates are matched for peak amplitude and for maskers approximately matched for threshold in the baseline conditions. The spectral separation of the maskers used in the present study has been argued to reflect across-channel rather than within-channel cues (Moore *et al.*, 1990), providing some support for interpretation of these results in terms of across-channel cues. Whereas similar effects were observed for ipsilateral and contralateral flanking masker presentations, the magnitude of CMR was smaller for contralateral flanking masker presentation. This result could be interpreted as showing that within-channel effects play an important role in the ipsilateral masker results, augmenting a relatively small across-channel CMR.

Whereas some studies of CMR have demonstrated comparable masking release for ipsilateral as compared to contralateral flanking masker presentation (Cohen and Schubert, 1987; Schooneveldt and Moore, 1987), others have reported little or no masking release in the contralateral condition (Hicks and Bacon, 1995; Ernst and Verhey, 2006). It was recently argued that this range of results could be due in part to stimulus features related to auditory grouping (Buss and Hall, 2008). It is widely believed that grouping of the on-signal and flanking maskers into a single auditory stream is a prerequisite for CMR to occur (Dau *et al.*, 2009; Grose *et al.*,

2009). In the present paradigm, it is possible that contralateral masker presentation reduced CMR by reducing auditory grouping of the ipsilateral and contralateral maskers, and further that this effect could have been exacerbated by discrepancies in modulation pattern across maskers in the slow/fast and fast/slow conditions. Therefore, the small contralateral masker effects may not accurately reflect the magnitude of across-channel effects in ipsilateral conditions. This issue will be revisited in the context of Experiment 3.

III. EXPERIMENT 2: EFFECT OF UNMATCHED MINIMA IN ON-SIGNAL VS. FLANKING MASKER ENVELOPES FOR NOISE CARRIERS

The results of Experiment 1 provide support for the idea that the instantaneous level of flanking maskers controls weighting of information at the signal frequency, possibly through cued listening or dynamic spectral profile cues. One limitation of Experiment 1 was the specialized stimulus configuration. Whereas that experiment made use of highly controlled periodic envelopes, this is not representative of more natural auditory stimuli for which masker envelopes are frequently complex. The goal of Experiment 2 was to determine whether the findings of Experiment 1 generalize to a broader set of stimulus conditions.

In Experiment 2 there were two types of signals: a brief signal coincident with a masker modulation minimum and a longer signal that spanned more than one period of modulation. Maskers were bands of noise, either Gaussian noise or low-fluctuation noise, and those bands were multiplied by a raised 10-Hz cosine modulator. These stimuli are analogous to those used in the previous experiment in that the multiplied Gaussian noise contained more numerous prominent modulation minima than the multiplied low-fluctuation noise due to inherent envelope fluctuation, but the long-term power spectra were similar. Both maskers shared envelope minima associated with the 10-Hz periodic modulation. As in Experiment 1, it was hypothesized that additional modulation minima in an otherwise coherent pattern of modulation would be more detrimental when introduced to the pattern of flanking masker AM than when introduced to the on-signal masker AM.

A. Methods

1. Observers

Participants were six adults, ages 19–54 (mean of 31.2 years). All had pure-tone detection thresholds of 15 dB HL or less at octave frequencies 250–8000 Hz in the test ear (ANSI, 1996), and none reported a history of ear disease. All had previously participated in psychoacoustic studies, including one observer who previously participated in Experiment 1.

2. Stimuli

The masker was made up of 30-Hz wide bands of noise, each 60 dB SPL and played continuously throughout a threshold estimation track. All masker bands were multiplied by the same 10-Hz raised cosine. The on-signal band was centered on 1000 Hz, and flanking bands were centered on

FIG. 4. Basic features of the stimuli used in Experiment 2 are illustrated. The top panel shows a masker with fast amplitude modulation, composed of both relatively rapid inherent fluctuation of a 30-Hz wide band of Gaussian noise and a slower 10-Hz sinusoidal amplitude modulation. The next panel shows a masker with predominantly slow AM and very little inherent modulation, constructed using a sample of low-fluctuation noise. The bottom two panels illustrate the two signal conditions. The brief, 100-ms signal is temporally centered in the minimum of slow masker modulation.

525, 725, 1380 and 1904 Hz. These frequencies were selected based on previous work indicating that within-channel CMR cues related to envelope beats are minimal or absent for log-spaced maskers, and that across-channel cues dominate CMR for a 1000-Hz signal with flanking maskers offset 240 Hz or more from the signal frequency (Grose *et al.*, 2009).

A band of Gaussian noise centered on 1000 Hz was generated in the frequency domain by defining the real and imaginary components within the 30-Hz passband using random draws from a normal distribution. The low-fluctuation noise was generated following procedures described by Kohlrausch *et al.* (1997). Briefly, the Hilbert envelope was extracted from a bandpass noise, and the band was divided by that envelope. The waveform was then transformed into the frequency domain, all components falling outside the original 30-Hz bandwidth were assigned a magnitude of zero, and the result was transformed back into the time domain. This process was repeated ten times. Maskers were generated using arrays that were 2^{17} points long. When played out at a 12207-Hz sampling rate, these arrays played for 10.7 s before repeating seamlessly. Either the low-fluctuation or the Gaussian noise masker at 1000 Hz was loaded into the RPVDS circuit (TDT), where it was AM via multiplication with a raised 10-Hz cosine. The Gaussian masker was loaded in the fast on-signal masker conditions, and the low-fluctuation masker was loaded in the slow on-signal masker conditions. Example stimuli in each condition appear in the top panels of Fig. 4, plotted as a function of time.

Flanking maskers were generated based on the associated 1000-Hz on-signal masker, either low-fluctuation (slow)

or Gaussian noise (fast). The values defining the spectral components of the 1000-Hz band were shifted either up or down in frequency and the result transformed to the time domain. The flanking bands were always based on a single set of magnitude and phase values, those associated with either the slow or fast condition. As in the previous experiment, the pattern of modulation was either the same across the on-signal masker and flanking maskers (slow/slow or fast/fast) or different (slow/fast or fast/slow). The array defining the flanking maskers was loaded into the RPVDS circuit and multiplied by the same raised 10-Hz cosine as used in modulation of the on-signal masker. The array defining the flanking maskers was filled with zeros in conditions for which no flanking maskers were present (slow/none and fast/none).

The signal was a 1000-Hz pure tone, gated on and off using 50-ms raised-cosine ramps. In one set of conditions, the offset ramp was initiated as soon as the onset had been completed, such that the signal had a total duration of 100 ms. In a second set of conditions, the offset ramp was initiated 200 ms after completion of the onset ramp, for a total duration of 300 ms. In both cases, initiation of the signal onset ramp coincided with a masker modulation maximum in the slow (10-Hz) pattern of AM, such that the signal reached its full amplitude coincident with the temporal center of a modulation minimum. The relationship between signal presentation and masker modulation is illustrated for each signal condition in bottom two panels of Fig. 4.

3. Procedures

Threshold estimation procedures were identical to those of the previous experiment. Stimuli were played out of a real-time processor (RP2, TDT), routed to a headphone buffer (HB7, TDT), and presented over circumaural headphones (Sennheiser HD 265). Listening intervals were 350 ms, with the signal approximately temporally centered in an interval, and the interstimulus interval was 300 ms. Feedback was provided after every response. Thresholds were collected blocked by condition, but all conditions were run in a different order for each observer.

B. Results and discussion

Figure 5 shows mean thresholds across the six listeners, plotted as a function of flanking masker condition. The left panel shows results for the 100-ms signal, and the right for the 300-ms signal. As in previous data figures, the filled down-pointing triangles and dashed lines indicate a slow on-signal AM, and filled up-pointing triangles and solid lines indicate a fast on-signal AM. Larger unfilled symbols indicate the flanking masker pattern. Error bars indicate 1 sem. No error bars are shown for conditions in which the flanking maskers were present because the symbol size exceeded 1 sem.

For the short duration signal, thresholds are higher for the fast than the slow on-signal masker conditions, with means of 63.3 and 56.2 dB, respectively. This result is in contrast to the results of Experiment 1, where thresholds in the absence of flanking maskers were higher in the slow than

FIG. 5. Mean signal detection thresholds are plotted as a function of flanking masker condition, with symbols and line styles reflecting masker modulation patterns, as defined in the legend. Error bars indicate ± 1 sem. The left panel shows results for the brief, 100-ms signal, and the right for the longer, 300-ms signal.

the fast envelope conditions. Thresholds were similar for the two masker types with the 300-ms signal, with mean of 49.6 dB in both the fast and slow modulation conditions. It is not clear why thresholds would differ for the two modulation rates for the brief but not for the longer signal duration. One possibility has to do with the unpredictable envelope events characterizing inherent modulation of the Gaussian noise (fast) masker, events that could be confused for a brief signal. In contrast, for the low-fluctuation (slow) masker, the predictable 10-Hz modulation alone may pose less of a challenge to detection of a brief signal. The long signal may be more easily distinguished from features of the masker in both slow/none and fast/none envelope conditions. The comparable thresholds for the long-duration signal in the two masker types might seem at odds with previous results indicating better threshold in low-fluctuation than Gaussian noise (Hartmann and Pumplin, 1988; Kohlrausch *et al.*, 1997). However, it should be kept in mind that the noises used here were sinusoidally modulated. This additional source of envelope fluctuation could have introduced cues related to low-rate envelope periodicity and/or interfered with cues related to the introduction of envelope fluctuation associated with the addition of a tonal signal to a low-fluctuation noise.

Similar to the results of Experiment 1, thresholds tend to improve with inclusion of flanking maskers in all except for the slow/fast condition, when the envelope of the on-signal masker was slow and the flanking masker envelope was fast. The CMR was computed as the change in thresholds with introduction of flanking maskers, with mean results appearing in Table II. All values of CMR from Experiment 2 were

TABLE II. CMR, computed as the change in threshold with introduction of flanking maskers relative to the threshold measured with the on-signal masker alone.

		On-signal masker condition	
		Fast	Slow
100-ms signal	Fast	15.39	-1.53
	Slow	9.80	9.33
300-ms signal	Fast	8.62	0.19
	Slow	4.66	7.50

submitted to a repeated measures analysis of variance. There were two levels of on-signal masker envelope rate (fast and slow), two levels of across-frequency masker coherence (same and different), and two levels of signal duration (100 and 300 ms). There was a main effect of coherence ($F_{1,5}=48.35, p<0.001$), a main effect of on-signal masker envelope rate ($F_{1,5}=26.61, p<0.005$), and a main effect of duration ($F_{1,5}=10.05, p<0.05$). All three of the two-way interactions were significant ($6.98 \geq F_{1,5} \leq 14.56, p<0.05$). The three-way interaction was not significant ($F_{1,5}=0.64, p=0.46$). These results replicate the finding of a reduced effect of modulation pattern mismatch when the higher rate modulation is applied to the masker at the signal frequency, and the lack of a three-way interaction demonstrates that this finding is not dependent on signal duration. This can be seen in Fig. 5 as the more consistent detection advantage that is obtained with inclusion of flanking maskers when the on-signal masker has the fast envelope, as compared to the relative variability in masking release when the on-signal masker has a slow envelope.

The paradigm of Experiment 2 in some ways resembles that of Eddins and Wright (1994). In one set of conditions in that study, pure-tone detection thresholds were measured in a set of five maskers made up of 100-Hz wide bands of Gaussian noise that had been multiplied by a raised 10-Hz cosine. Modulation coherence was defined in terms of the inherent modulation of the bands and/or the phase of sinusoidal AM. Inherent modulation in this experiment could be seen as analogous to the fast modulation in the present experiments, and the 10-Hz sinusoidal modulation as the slow rate. Inherent modulation coherence improved thresholds by approximately 5 dB regardless of the phase of the sinusoidal modulator, and coherence of the sinusoidal modulator improved thresholds by approximately 19 dB regardless of the coherence of inherent modulation. The best thresholds were obtained when both aspects of envelope modulation were coherent across frequency. In contrast to the present experiment, however, both the slow (multiplied) and fast (inherent) modulation patterns were always present in both on-signal and flanking maskers of the Eddins and Wright (1994) study. The present paradigm adds to this work by assessing the detrimental effects of including unmatched modulation minima into the AM pattern of either the on-signal masker or the flanking maskers, rather than both simultaneously.

IV. EXPERIMENT 3: CONDITIONS PROMOTING THE USE OF ACROSS-CHANNEL CUES

Discussion of the results from the first two experiments has focused on the use of across-channel cues. Both cued listening and the use of dynamic spectral cues assume that the beneficial effects of coherent masker modulation are based on a comparison of auditory filter outputs distributed across frequency. The assumption of minimal within-channel effects is justified to some extent by the selection of masker frequencies that have been argued elsewhere to result in primarily across-channel cues (Moore *et al.*, 1990; Grose *et al.*, 2009). However, it is also possible that within-channel cues could have also contributed to masking release. One aspect

of the results that is qualitatively consistent with this possibility is the small effect obtained with contralateral masker presentation in Experiment 1; in those conditions, CMR in the fast/slow conditions was only 1.6 dB larger than CMR in the slow/fast condition (see Table I). This might be interpreted as indicating that the 8.4-dB difference in the CMR observed under comparable ipsilateral conditions was dominated by within-channel effects. However, this result could also reflect reduced auditory grouping associated with contralateral masker presentation (e.g., Buss and Hall, 2008).

The goal of the final experiment was to quantify the CMR obtained with ipsilateral and contralateral flanking maskers under conditions designed to facilitate grouping of the on-signal and flanking maskers. In this paradigm, manipulation of envelope coherence was limited to the listening intervals, and masker modulation was perfectly coherent between trials and between intervals. This stimulus configuration was expected to promote modulation-based grouping based on previous work showing that grouping may be affected by envelope coherence over a relatively protracted period of time (Grose and Hall, 1993; Mendoza *et al.*, 1998; Dau *et al.*, 2009; Grose *et al.*, 2009).

A. Methods

1. Observers

Participants were six adults, ages 21–54 (mean of 36.9 years). All had pure-tone detection thresholds of 20 dB HL or less at octave frequencies 250–8000 Hz bilaterally (ANSI, 1996), with one exception: one observer had a threshold of 30 dB at 4000 Hz in her left ear. No observer reported a history of ear disease. All had previously participated in psychoacoustical studies unrelated to the present research.

2. Stimuli

The masker was made up of amplitude-modulated tones, each with a peak level of 60 dB SPL and played continuously throughout a threshold estimation track. As in Experiment 2, the on-signal masker was centered on 1000 Hz, and flanking maskers were centered on 525, 725, 1380, and 1904 Hz. Masker modulation in most conditions was unpredictable, comprised of sequences of 100- and 200-ms modulation periods. This *mixed* envelope pattern was generated based on 100-ms time segments. On odd-numbered segments, the envelope was single period of a raised 10-Hz cosine, consisting of a 50-ms offset followed immediately by a 50-ms onset. On even numbered segments, the envelope was either a single period of 10-Hz cosine or a steady “on” plateau; these two possibilities were equally likely, selected based on a random draw from a uniform distribution. The signal, when present, was a copy of the 1000-Hz tone used to generate the on-signal masker, ramped on and off with 50-ms raised-cosine ramps and no steady state. The signal was temporally centered in an odd-numbered envelope segment, ensuring that it coincided with a modulation minimum. The top two waveforms in Fig. 6 illustrate the temporal relationship between the signal and masker modulation. In this example, the signal (top) is presented in the second of three listening intervals, synchronous with a modulation minimum in a series

FIG. 6. Basic features of the temporal envelopes used in Experiment 3 are illustrated. The top waveform shows a brief signal presented in the second listening interval. Below that is an example of a mixed masker envelope. The bottom two rows show comparable flanking maskers in the mixed/slow and mixed/fast modulation conditions. Modulation in these conditions is coherent with that of the on-signal masker except inside the three listening intervals, indicated by vertical bars, where the pattern reverted to a consistently slow or fast pattern of AM, respectively.

of fast (10-Hz) modulations of the on-signal masker (second trace from the top).

This method of masker modulation intersperses fast and slow modulation periods, while ensuring that the signal is presented under conditions of comparable energetic masking (i.e., an envelope minimum). One consequence of this randomization was to increase thresholds by eliminating masker regularity as a possible detection cue, while holding energetic masking relatively constant. To assess the effects of on-signal masker modulation irregularity, on-signal masker thresholds were also measured in conditions of regular modulation, either consistently fast or consistently slow (not shown in Fig. 6), in addition to the mixed pattern shown in Fig. 6.

Flanking masker conditions were all based on mixed on-signal modulation. In some conditions, the four flanking maskers were presented ipsilateral to the signal and on-signal masker, and in others, they were presented contralaterally. In all cases, the on-signal and flanking maskers were perfectly comodulated between trials and between listening intervals, and conditions differed only with respect to modulation coherence within the three listening intervals of each trial. In the *mixed/mixed* flanking masker condition, the on-signal and flanking maskers were coherently modulated within the listening interval, whereas in the *mixed/fast* and *mixed/slow* conditions, masker modulation coherence was disrupted during the listening interval. In the *mixed/slow* condition, the flanking masker modulation during the listening interval was defined with 100-ms plateaus on odd-numbered segments of the masker, regardless of on-signal masker modulation. In the *mixed/fast* condition, the flanking masker modulation during the listening interval was defined with periods of raised 10-Hz cosine for both odd- and even-numbered masker segments. Examples of the *mixed/slow* and *mixed/*

FIG. 7. Mean signal detection thresholds are plotted as a function of the on-signal masker envelope condition. Symbols indicate individual observer's thresholds, and the horizontal bars show the mean threshold.

fast flanking masker conditions are illustrated in the bottom half of Fig. 6.

Both the signal and masker were generated in the RPVDS circuit, including randomization of masker modulation pulse type.

3. Procedures

Threshold estimation procedures were identical to those of the previous two experiments. Listening intervals were 400 ms, separated by 400-ms interstimulus intervals. The signal was exactly temporally centered in one of the three listening intervals, selected at random. Thresholds were collected blocked by condition, but all conditions were run in a different order for each observer.

B. Results and discussion

Results in the on-signal masker conditions will be discussed first. On-signal masker data are shown in Fig. 7, with symbols indicating individual observer's thresholds, and the dark horizontal bars indicating the mean threshold. The ordering of masker conditions along the abscissa was determined according to expected threshold. At the outset, it was expected that the fast/none condition would be associated with lower thresholds than those in the slow/none condition. This expectation was based on the higher masker level associated with the slow rate, and by the results of Experiment 1. It was further anticipated that thresholds in the mixed/none condition would be higher than either of the regular modulation conditions, due to the disruptive effects of stimulus uncertainty (e.g., Watson and Kelly, 1981; Neff and Callaghan, 1988). These expectations were supported by the data, where mean thresholds were 48.4 dB in the fast/none condition, 53.4 dB in the slow/none condition, and 61.4 dB in the mixed/none condition. Most relevant to the present experiment, mixed/none thresholds were worse than those in either of the regular masker modulation conditions. Thresholds were 4.1–13.2 dB worse in the mixed/none than the slow/none condition, a significant result despite the substantial individual differences ($t_5=5.58, p<0.01$). This result cannot be explained in terms of energetic masking and is consistent with the expectation that an irregular pattern of

FIG. 8. Mean signal detection thresholds for mixed on-signal AM are plotted as a function of flanking masker condition. The mixed/none on-signal baseline condition is indicated with the filled circle and dashed line. Thresholds in the ipsilateral masker conditions are shown with open circles, and those for the contralateral conditions with asterisks. Error bars indicate ± 1 sem.

masker modulation eliminates rhythmic cues and introduces non-energetic masking, sometimes described as informational masking (Durlach, 2006).

Figure 8 illustrates the effect of presenting flanking maskers with a mixed on-signal masker. Mean thresholds are plotted as a function of flanking masker modulation condition, indicated on the abscissa. Symbol shape indicates flanking masker presentation condition, which was either ipsilateral (circles), contralateral (asterisks), or none (combined symbol). The dashed horizontal line indicates mean threshold in the mixed/none on-signal masker baseline condition, and error bars indicate 1 sem. The effect of including flanking maskers differed markedly as a function of masker modulation condition. For the mixed/mixed masker modulation conditions, threshold reductions were 21.3 dB for ipsilateral presentation and 17.0 dB for contralateral presentation. This masking release was slightly reduced for the mixed/slow masker modulation conditions, with means of 19.5 and 13.5 dB, respectively. In contrast, flanking maskers with the mixed/fast pattern of modulation failed to reduce thresholds relative to baseline. In these conditions, thresholds rose by 4.2 and 1.3 dB, respectively, though neither of these effects was significantly different from zero as assessed using paired t-tests ($\alpha=0.05$).

These results clearly support the conclusion that the corrupting across-frequency masker modulation coherence depends critically on the details of the across-frequency envelope discrepancy. A masking release on the order of 20 dB is obtained when envelope modulation is perfectly coherent across frequency. There is a relatively small reduction in masking release for conditions in which the on-signal masker modulation includes additional minima that are not present in the pattern of flanking masker modulation. In these conditions, masking release decreased by 1.8 dB (ipsilateral) and 3.5 dB (contralateral). In contrast, introducing additional modulation minima into the pattern of flanking masker modulation is very disruptive, eliminating masking release in the present experiment. Because this effect is seen for both

ipsilateral and contralateral presentation of the flanking maskers, it cannot be attributed to peripheral effects.

While these results are broadly consistent with those of the previous two experiments, the effects are larger, both in terms of the magnitude of masking release and differential effects of introducing additional minima to the on-signal or flanking maskers of an otherwise coherently modulated masker. The large contralateral masking release is particularly noteworthy, in light of the fact that previous studies have reported dichotic CMR of between 0 and 8 dB (Schooneveldt and Moore, 1987; Hicks and Bacon, 1995; Buss and Hall, 2008). One reason for the large masking release observed in the present experiment could be the use of an unpredictable on-signal masker modulation pattern. It has been argued that CMR is largest when performance in the on-signal masker condition is poor due to perceptual similarities between masker fluctuations and fluctuations associated with an added signal (e.g., Moore *et al.*, 1990). This effect could be described in terms of nonenergetic masking. Adding a signal to a masker with predictable modulation, such as periodic slow or fast on-signal modulation, might introduce cues based on a disruption of that regular pattern, whereas this cue would not be available with the mixed on-signal masker modulation. In this case, removing the rhythmic cue could be seen as increasing nonenergetic masking, to the extent that it affects identification rather than encoding of the signal. The effect of introducing masker modulation irregularities in the present experiment is on the order of 10 dB, as reflected in the thresholds measured in the regular (fast/none or slow/none) as compared to irregular (mixed/none) on-signal masker conditions. This could account in part for the approximately 10-dB larger masking release obtained in this experiment, as compared to Experiment 1 and the brief-signal conditions of Experiment 2.

Another aspect of the results that deserves mention is the large effect of contralateral flanking maskers in the present experiment, as compared to Experiment 1. Whereas some of this effect could be due to release from nonenergetic masking related to unpredictability of masker modulation, auditory grouping may also play a role. Previous work has been interpreted as showing that on-signal and flanking maskers must be grouped together in a single auditory stream in order to support CMR, an idea based in part on the observation that CMR can be corrupted by asynchronous onset (Grose and Hall, 1993; Dau *et al.*, 2004) or reduction in envelope coherence outside the listening interval (Grose *et al.*, 2009). Presenting the on-signal and flanking maskers in separate ears could further encourage segregation (Buss and Hall, 2008). In the present paradigm, maskers were coherently modulated across frequency between trials and between intervals even in the mixed/fast and mixed/slow masker AM conditions, a manipulation designed to facilitate grouping of the maskers. The larger masking release obtained in the present experiment could be due in part to stronger auditory grouping, an account which might be particularly applicable to contralateral conditions.

V. GENERAL DISCUSSION

As in previous work, data presented here show that disruption of masker envelope coherence across frequency disrupts CMR. The novel finding of the present study is that the nature of the masker envelope discrepancy across frequency affects the extent to which CMR is disrupted. Inclusion of additional envelope minima into an otherwise coherent pattern of masker modulation across frequency is of less consequence when those minima are introduced to the on-signal masker (fast/slow or mixed/slow conditions) and as compared to the flanking maskers (slow/fast or mixed/fast conditions). In the present conditions, CMR can be eliminated when envelope coherence is corrupted with epochs in which the level of the on-signal masker exceeds that of the flanking maskers, whereas the converse manipulation may only reduce CMR by a factor of 2 or less. The observation that this result is found for contralateral and ipsilateral presentations of the flanking maskers is inconsistent with an interpretation that within-channel processes play a major role in this result. As shown in Experiment 2, this effect is evident for a brief signal, synchronous with a single masker modulation minimum, and for longer signal durations, which span multiple modulation periods. It can also be demonstrated with both spectrally simple and complex patterns of amplitude modulation. The results of Experiment 3 show that the differential effect of disrupting envelope coherence can be quite large, on the order of 20 dB under some conditions, and can be found reliably when flanking maskers are presented contralateral to the signal.

These findings are consistent with previous observations indicating that masker modulation minima are of special significance for CMR with a pure-tone signal, and that use of the associated cues is facilitated by the modulation pattern of the flanking maskers. This effect has been quantified in terms of lower thresholds for brief signals coincident with masker modulation minima (Hall and Grose, 1991) and greater perceptual weight applied to portions of a long-duration signal that coincide with masker modulation minima (Buus *et al.*, 1996). Buus *et al.* (1996) discussed preferential use of information coincident with masker modulation minima in terms of cued listening, whereby modulation minima in flanking maskers indicate “when to listen,” but also considered the idea that a similar effect could be obtained by applying a compressive transformation to the stimulus envelope in combination with some other type of across-channel process. After compression, envelope discrepancies occurring during modulation maxima would be small relative to comparable discrepancies during minima. Whereas recent work on within-channel cues available for detection of a tone in coherently modulated maskers have incorporated peripheral nonlinearities, including basilar membrane compression and suppression (Ernst and Verhey, 2008), the role of compression in preferential weighting of modulation minima has not been established. If epochs associated with modulation maxima were compressed relative to minima, this would effectively increase the relative magnitude of signal energy coincident with modulation minima. It would not, however, explain the differential effects of introducing unmatched

modulation minima to the on-signal as compared to the flanking maskers, as observed in the present study.

Data presented here are also qualitatively consistent with the hypothesis that CMR is based on short-term spectral cues, where the cue associated with detection of an added tone can be characterized as a level increment at the signal frequency in an otherwise coherent dynamic spectral profile. In the profile analysis literature, sensitivity to change in a flat spectral profile has been shown to depend on whether that change consists of an increment or decrement. [Ellermeier \(1996\)](#) measured thresholds for detection of either an increment or a decrement in one set of equal-amplitude tones distributed across frequency. He found that decrements were more difficult to detect than increments. This finding could be related to the differential effects of including unmatched modulation minima to on-signal as compared to flanking maskers. When flanking maskers have the slow pattern of modulation, the inclusion additional modulation minima associated with the fast modulation pattern of the on-signal masker could be perceptually subtle, analogous to occasional decrements in relative level at the signal frequency in an otherwise coherent spectrum. In contrast, when the flanking maskers have a fast pattern, the prolonged modulation maxima associated with the slow pattern of the on-signal masker could be perceptually salient, analogous to occasional increments in level at the signal frequency in an otherwise coherent spectrum. Such increments could be mistaken for the addition of a tonal signal, which would also produce occasional spectral peaks at the signal frequency synchronous with modulation minima.

The present results are inconsistent with models of CMR in which the signal is detected based on a change in the pattern of envelope coherence across frequency. Detection cues based on reduced modulation coherence have been quantified as a change in correlation ([Richards, 1987](#); [van de Par and Kohlrausch, 1998a](#)) or as a remainder at the output of an EC process ([Buus, 1985](#); [Piechowiak et al., 2007](#)). In both cases, introduction of additional modulation minima into an otherwise coherent pattern of masker modulation would have comparable results on envelope coherence, regardless of whether those minima are introduced to the on-signal masker or the flanking maskers. It is possible that envelope comparison models, based on envelope decorrelation or the output of an EC process, could be constructed in such a way as to more heavily weight envelope increments at the signal frequency as compared to decrements. However, it is unclear whether this emphasis would be purely data-driven or whether other theoretical motivations could be identified for such a weighting scheme. The finding of analogous preferential weighting of spectral peaks in the profile analysis literature could lend greater credibility to modeling based on dynamic spectral cues as compared to across-frequency envelope difference cues.

Greater perceptual significance of spectral peaks than dips in the CMR paradigm receives additional support from the results of [Moore et al. \(1990\)](#). That study reported thresholds for brief signals presented with a set of sinusoidally modulated masker tones, similar to the stimuli used in Experiment 1. In one set of conditions, the masker tones were

50% AM. The signal was a brief tone, 180° out of phase with the masker tone to which it was added, such that addition of the signal effectively increased modulation depth. Under these conditions, the inclusion of coherently modulated flanking maskers elevated thresholds. [Moore et al. \(1990\)](#) argued that this finding is inconsistent with models based on envelope comparison and dip listening, both of which would predict a detection advantage in the presence of comodulated flankers for a signal associated with a decrement in level at the signal frequency. This finding would be more consistent with an explanation of CMR based on a dynamic spectral profile, however, because in this case, the signal would be associated with a relatively subtle spectral dip at the signal frequency.

A special significance for spectral peaks as contrasted with dips has been noted in simultaneous vowel perception ([Assmann and Summerfield, 1989](#)) and may represent the preferred mode of processing broadband stimuli in general ([Lentz, 2006](#)). While the reason for differential sensitivity to increments and decrements in profile analysis is unknown, [Ellermeier \(1996\)](#) speculated that it could reflect the greater effects of spread of excitation from neighboring tones for a decremented as compared to an incremented target tone. That explanation would not provide a satisfactory account of the present CMR results, however, because the effects of corrupting envelope coherence were evident when flanking maskers were presented contralateral to the signal and on-signal masker. While there are some profile analysis data with contralateral flanker presentation, several authors have argued that these data do not reflect “real” profile analysis because the stimulus components presented to each ear are not fused into a single perceived sound source ([Green and Kidd, 1983](#); [Bernstein and Green, 1987](#)). The finding of CMR may also be undermined by segregation effects for dichotic presentation, though continuous presentation and coherent amplitude modulation may counteract these effects to some extent ([Buss and Hall, 2008](#)). The role of spectral profile cues in CMR and the differences in sensitivity to spectral peaks and dips is the topic of ongoing research.

VI. SUMMARY

Data reported here support the following conclusions.

- (1) Disruption of masker envelope coherence reduces CMR, but the nature of the masker envelope discrepancy across frequency affects the extent of CMR reduction. Masking release is more adversely impacted by inclusion of additional envelope minima to the flanking masker as contrasted with on-signal masker envelopes.
- (2) This reduction in masking release is evident for a brief signal, synchronous with a single masker modulation minimum, as well as for longer signal durations, spanning multiple modulation periods. This effect can be demonstrated for both spectrally simple (periodic) and spectrally complex (aperiodic) patterns of amplitude modulation.
- (3) The differential effect of including unmatched modulation minima to the on-signal and flanking masker envelopes can be quite large, on the order of 20 dB under

some conditions. These effects are observed for both ipsilateral and contralateral flanking masker presentations, supporting an interpretation in terms of across-channel central processes.

ACKNOWLEDGMENTS

This work was supported by a grant from the NIH NIDCD (Grant No. RO1 DC007391).

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