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SUMMARY

In random noise, masking is influenced almost entirely by noise components in a narrow band around the signal frequency. However, when the noise is not random, but has a modulation pattern which is coherent across frequency, noise components relatively remote from the signal frequency can actually produce a release from masking. This masking release has been called comodulation masking release (CMR). The present research investigated whether a similar release from masking occurs in the analysis of a suprathreshold signal. Specifically, the ability to detect the presence of a temporal gap was investigated in conditions which do and do not result in CMR for detection threshold. Similar conditions were investigated for the masking level difference (a binaural masking release phenomenon). The results indicated that suprathreshold masking release for gap detection occurred for both the masking-level difference (MLD) and for CMR. However, masking release for gap detection was generally smaller than that obtained for detection threshold. The largest gap detection masking release effects obtained corresponded to relatively low levels of stimulation, where gap detection was relatively poor.

1. INTRODUCTION

The results of many auditory masking experiments using random noise maskers can be accounted for well by the critical band or auditory filter model (Fletcher 1940; Green *et al.* 1959; Margolis & Small 1975; Patterson 1976): in general, only the masking noise components within a relatively narrow frequency band around the frequency of a pure-tone signal contribute significantly to the masking of the signal. Energy relatively remote from the signal frequency has a negligible effect in comparison to noise components near the signal frequency. This relatively simple auditory filter model does not apply well, however, when the masking noise is modulated such that noise components around the signal frequency have an envelope fluctuation that is correlated with the fluctuations of noise components away from the signal frequency; such noise is referred to as comodulated. Here, the presence of comodulated distal noise components results in an improvement in detection threshold (a release from masking). This phenomenon has been termed comodulation masking release, or CMR (Buus 1985; Carlyon *et al.* 1989; Cohen & Schubert 1987; Haggard *et al.* 1990; Hall *et al.* 1984; McFadden 1986; Moore *et al.* 1990; Moore & Schooneveldt 1990; Schooneveldt & Moore 1987; Wright & McFadden 1988).

Whereas some of the conditions of the present experiment investigated CMR in a signal detection paradigm, the main focus was the extent to which CMR applies in the analysis of a suprathreshold (partially masked) signal. There are very few data currently available on this issue. What little data do exist would suggest that masking release effects may be rather small for partially masked signals. For example, whereas Grose & Hall (1992) found consistent CMR effects for the detection of speech signals in noise backgrounds, CMR effects related to the recognition of speech were small or absent. This would imply that even though speech information may be more audible in comodulated noise, the quality of that information is, in some sense, poor. Interestingly, there is some precedent for this sort of finding in another masking release paradigm, the masking-level difference, or MLD (Hirsh 1948). The MLD for detection is often defined as the difference between two thresholds. In one, the same masking noise is presented to boh ears (in phase), and the signal is also presented to both ears in phase. This is referred to as NoSo. In the other condition, the noise is again presented to the two ears in phase, but the signal is presented 180° out of phase (NoSπ). The detection threshold for NoSπ is often approximately 15 dB better than for NoSo. Even though this relatively large masking release occurs at detection threshold, Henning (1991) has found that intensity and frequency discrimination are relatively poorer for NoSπ than for NoSo stimulation, when signals are presented at low equivalent sensation level (SL) above masked threshold. Robinson & Blakeslee (1971) likewise reported that effects of binaural masking release for the ability to discriminate differences in duration were relatively small.

The present experiments were concerned with the suprathreshold task of temporal gap detection (Grose *et al.* 1989; Penner 1977; Plomp 1964; Shailer &

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Moore 1983). Performance on this measure of temporal resolution was investigated for conditions giving an MLD and those giving a CMR.

2. METHODS

Three types of masking noise were used. The first type (on-signal band alone) was a 20-Hz-wide noise band centred on the signal frequency (1200 Hz). The second masker type (comodulated envelope) was composed of the 20-Hz-wide band centred on 1200 Hz, plus four additional 20-Hz-wide comodulated noise bands, centred on 400, 800, 1600 and 2000 Hz. The third masker type (random envelope) was identical to the second, except that the envelopes of the five bands were random with respect to each other. CMR for pure-tone detection threshold was measured both as the threshold difference between the case with the on-signal band alone and the case with the comodulated envelope, and as the threshold difference between the case with the random envelope and the case with the comodulated envelope. The MLD was measured only for the on-signal band alone (the threshold difference between conditions of NoSo stimulation and NoSπ stimulation). There were three parts to the experiment. The first part simply established masked pure-tone detection thresholds (0 dB sensation level), and the second and third parts investigated gap detection. Two well-practised subjects participated.

(*a*) *Pure-tone masked detection thesholds*

In the first part of the experiment, masked detection thresholds were obtained. NoSo thresholds were obtained using all three types of masking noise, to measure CMR. NoSπ thresholds were obtained only using the on-signal band alone noise. The signal was a 1200 Hz pure tone (400 ms with 50 ms cosine^2 rise fall). The stimuli were presented via Sony MDR V6 earphones. All noise stimuli were presented continuously at a pressure spectrum level of 50 dB Hz. The comodulated Gaussian noise bands were created by multiplying (Analog Devices AD534LH) a digitally synthesized complex tone composed of 5600, 5200, 4800, 4400 and 4000 Hz by a bandpass noise from 5990 Hz to 6010 Hz. Following multiplication, the upper sidebands were filtered out, leaving 20-Hz-wide bands centered on 400, 800, 1200, 1600 and 2000 Hz. These bands were recorded (using a digital audio tape recorder). The on-signal band alone was created in a similar way, but only the 4800 Hz pure tone was multiplied by the bandpass noise. The random noise was created by digitally filtering (Trinder 1983) a wideband noise source, using a sampling rate of 5.0 kHz.

(*b*) *Gap detection thresholds for a fixed-SL pure-tone: temporal gap varied adaptively*

In the second part of the experiment, the duration of a gap was varied to obtain gap detection thresholds for a signal presented at a fixed SL above masked threshold. Again, the So signal was presented in each of the three types of masking noise, and the Sπ signal was presented only in the on-signal band alone noise. In each interval of a trial, the pure tone was gated on for 1.2 s. In the target interval, the gap began 450 ms after stimulus onset and its duration was subtracted from the remaining portion of the interval to keep the total duration constant at 1.2 s. The pure-tone stimuli were gated on and off via a Wilsonics gate, set to fast (less than 10 µs) rise–fall time. To minimize spectral cues for gap detection (energy splatter), the output of the gate was digitally filtered to a 20-Hz bandwidth around the signal frequency. This procedure effectively imposes a relatively slow rise–fall time on the pure-tone signal. We measured the rise–fall time as the time taken for the amplitude of the sine wave to fall from 90% to 10% of its peak value. This time was approximately 38 ms. Gap detection thresholds were determined for masked SLs of 5, 10, 15, 20, 25 and 30 dB. It was found that for some low SL conditions, the just detectable gap was quite large (greater than 350 ms), and performance was highly variable. Data were therefore not obtained on conditions for which thresholds were not consistently smaller than 350 ms.

(*c*) *Gap detection thresholds for a fixed-gap signal: signal SPL varied adaptively*

In the third part of the experiment, the level of a pure-tone signal, having a gap of fixed duration, was varied to obtain the level at which the gap could be detected. Again, the So signal was presented in each of the three types of masking noise, and the Sπ signal was presented in the on-signal band alone. In each interval of a trial, the pure tone was gated on for 1.2 s. During the gap interval a fixed silent period was introduced. The gap began 450 ms after stimulus onset and its duration was subtracted from the remaining portion of the interval to maintain a 1.2 s total duration. The fixed gap values investigated were 25, 50 and 250 ms. Gating and digital filtering were used as above to generate gaps with minimal spectral spread.

(*d*) *Threshold estimation procedures*

All (variable-signal-level and variable-gap-duration) thresholds were determined using a three-alternative forced-choice (3AFC), three-down, one-up adaptive procedure, estimating the 79.4% detection threshold (Levitt 1971). For level variation conditions, an initial step-size of 8 dB was reduced to 4 dB after two reversals, and further reduced to 2 dB after two more reversals. A threshold run was stopped after 12 reversals, and the average of the levels at the last eight reversals was taken as the detection threshold for a run. For gap variation, the gap size was reduced or increased by a factor of 1.2 according to the three-down one-up rule. Six reversals in duration were measured and threshold was estimated as the geometric mean of the gap values at the final four reversals. The inter-stimulus interval was 300 ms. At least four threshold runs were averaged to compute the final detection threshold for a condition. Visual

Table 1. *Masked detection thresholds and the* MLDs *and* CMRs *derived from the three types of masking noise*

$\text{CMR}_{\text{on-com}}$ refers to the CMR derived by subtracting the threshold in comodulated envelope noise from the threshold in the on-signal band alone; $\text{CMR}_{\text{ran-com}}$ refers to the CMR derived by subtracting the threshold in comodulated envelope noise from the threshold in random envelope noise. CMRs are derived from NoSo stimuli.

	on-signal band			random	comodulated		
	NoSo	NoSπ	MLD	NoSo	NoSo	$\text{CMR}_{\text{on-com}}$	$\text{CMR}_{\text{ran-com}}$
S1	61.5	44.3	17.2	61.7	47.7	13.8	14.0
S2	61.4	48.6	12.8	60.5	47.8	13.6	12.7
avg.	61.4	46.4	15.0	61.1	47.8	13.7	13.4

feedback was provided after each response. Stimulus presentation and response collection were controlled by an IBM AT microcomputer.

3. RESULTS AND DISCUSSION

(*a*) *Pure-tone masked detection thesholds*

Although the primary focus of the present experiments was on suprathreshold performance, the basic masked threshold data (table 1) will also be considered briefly. CMR is defined both in terms of the difference (in dB) between the threshold for the on-signal band alone condition and the threshold for the comodulated envelope condition, and the difference between the threshold for the random envelope condition and the threshold for the comodulated envelope condition. For NoSo, the thresholds in the on-signal band alone and random envelope noise cases were similar; thus for NoSo, the two measures of CMR were approximately the same (13–14 dB). MLD effects for the on-signal band alone are seen by comparing the NoSo thresholds to the NoSπ thresholds: the MLD was approximately 13–17 dB.

(*b*) *Gap detection thresholds as a function of pure-tone* SL

The gap detection thresholds as a function of the SL of the partially masked pure-tone signal are shown in figure 1. The non-masking release conditions are shown by filled symbols (circles for on-signal band, NoSo; filled triangles for random envelope, NoSo), and the masking release conditions are shown by the open symbols (open circles for the on-signal band, NoSπ; open triangles for comodulated envelope, NoSo). In the conditions where there was no masking release, gap detection improved with increasing SL, and then approached asymptote by about 15–25 dB SL. Gap detection was generally slightly better for the So on-signal band alone condition than for the So random-envelope condition. This is probably related to an effect reported by Grose & Hall (1988). In that experiment, gaps were detected in a narrow band of noise. In one condition, only the signal band was present. In the other, a second narrow band noise, which did not contain a gap, was also present. In the latter situation, the gap threshold was up to two times higher. It was hypothesized that it was the amplitude fluctuations of the noise at the distal frequency that made the gap difficult to detect at the target frequency. We have speculated (Hall & Grose 1991) that this gap detection effect is related to the modulation detection interference (MDI) phenomenon described by Yost & Sheft (1989, 1990). In the present experiment, the fluctuations of the flanking noise components in the multiband cases may have made the temporal modulation at the target frequency more difficult to detect. For this reason, of the two non-masking release

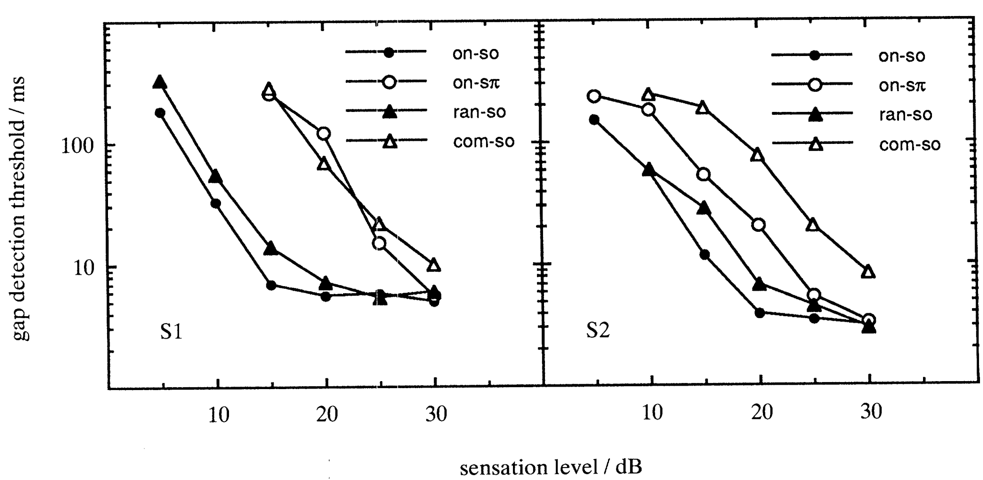

Figure 1. Gap detection thresholds (ms), plotted as a function of the SL (dB) of the partially masked pure-tone signal. On-so and on-sπ refer to NoSo and NoSπ conditions for the on-signal band alone masker; ran-so refers to the NoSo condition for the random envelope masker; com-so refers to the NoSo condition for the comodulated envelope masker.

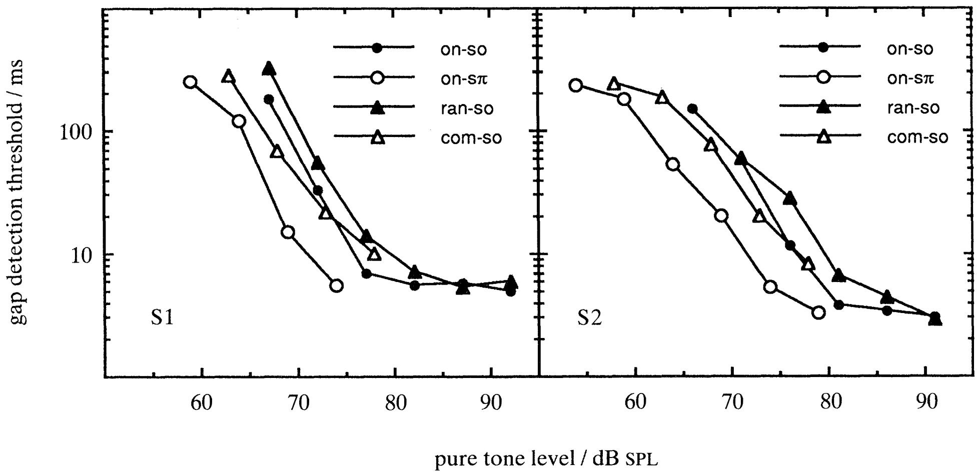

Figure 2. Gap detection thresholds (ms), plotted as a function of the SPL (dB) of the partially masked pure-tone signal. On-so and on-sπ refer to NoSo and NoSπ conditions for the on-signal band alone masker; ran-so refers to the NoSo condition for the random envelope masker; com-so refers to the NoSo condition for the comodulated envelope masker.

conditions, the So random envelope condition is probably a more appropriate control condition than the So on-signal band alone condition, when making comparisons to the multiband masking release condition.

A general result which can be seen in figure 1 is that the conditions associated with masking release (for masked signal detection) resulted in relatively poor gap detection thresholds at low SLs. For example, S1 did not demonstrate a reliable gap detection threshold for SLs less than 15 dB for the So signal in comodulated noise, and Sπ signals in the on-signal band alone. S2 also showed inferior performance for the masking release conditions, although this subject was able to achieve stable performance at low SLs in all four conditions. The results of the two subjects, considered in terms of SL above masked detection threshold, indicate that gap detection is relatively poor in conditions associated with MLDs or CMRs.

The data in figure 1 may be somewhat misleading in terms of the relative advantage or disadvantage for gap detection in the masking release conditions. Although the data in figure 1 show clearly that gap detection is better in the non-masking release conditions than in the masking release conditions at low SL, it should be remembered that the signal is at a higher signal-to-noise ratio in the non-masking release conditions than in the masking release conditions, given a fixed SL. It is also possible to consider the result in terms of the SPL of the partially masked pure-tone signal. Figure 2 plots the gap detection results as a function of the SPL of the pure-tone signal (the data are the same as in figure 1, but plotted in terms of pure-tone signal SPL rather than SL above masked threshold). The data plotted in this way show that, in general, stable gap detection performance was obtained at lower SPLs for the masking release conditions than for the non-masking release conditions. Comparisons between the filled and open circles provide an indication of the MLD effect, and comparisons between the filled and open triangles provide an indication of the CMR effect. These comparisons indicate that masking release (MLD and CMR) did occur in the suprathreshold gap detection task. However, the masking release is smaller than that associated with masked detection threshold (table 1). Some of the data in figure 2 suggest that masking release the gap detection may be generally greater at low SPLs, where gap detection in general is relatively poor, than at higher SPLs. The question of the magnitude of the masking release for suprathreshold gap detection is addressed more precisely by considering the data from conditions where the level of the signal was varied to obtain threshold for the detection of a fixed-duration gap.

(*c*) *Gap detection thresholds as a function of fixed-gap duration*

Figure 3 shows signal levels at which subjects could detect the signal containing a gap, as a function of the fixed gap duration. The figures indicate that the conditions resulting in masking release at detection threshold generally resulted in some degree of masking release for the detection of a gap in a pure-tone signal. Table 2 shows the signal level at which gap threshold was obtained for NoSo and NoSπ conditions, as well as derived MLDs and CMRs. Even though CMRs are shown using both the on-signal band alone baseline and the random envelope baseline, the random envelope baseline is probably the more appropriate (see discussion above), and only these CMRs will be addressed. NoSo CMRs for gap detection (Table 2) were typically rather small, except for the 250 ms gap, where the CMR was from 7–9 dB. Even this CMR was smaller than that obtained at detection threshold (table 1). S1's MLDs for the detection of temporal gaps were considerably smaller than those obtained for masked detection threshold. S2's gap detection MLD was small for the shortest gap, but her MLDs were sizeable for the 50 and 250 ms gaps (10.4 and 11.4 dB, respectively). Again, there was a trend for the gap

Table 2. *Thresholds at which gaps could be detected and gap detection* MLDs *and* CMRs *derived from the three types of masking noise*

CMR_{on-com} refers to the CMR derived by subtracting the threshold in comodulated envelope noise from the threshold in the on-signal band alone; $CMR_{ran-com}$ refers to the CMR derived by subtracting the threshold in comodulated envelope noise from the threshold in random envelope noise. CMRs are derived from NoSo stimuli.

	on-signal band			random	comodulated		
	NoSo	NoSπ	MLD	NoSo	NoSo	CMR_{on-com}	$CMR_{ran-com}$
25 ms gap							
S1	72.1	67.8	4.3	73.2	70.2	1.9	3.0
S2	70.0	62.6	7.4	70.3	65.9	4.1	4.4
avg.	71.0	55.2	5.8	71.8	68.0	3.0	3.8
50 ms gap							
S1	69.6	65.9	3.7	71.9	67.3	2.3	4.6
S2	68.9	58.5	10.4	69.4	65.8	3.1	3.6
avg.	69.2	62.2	7.0	70.6	66.6	2.7	4.1
250 ms gap							
S1	66.1	60.2	5.9	69.6	60.3	5.8	9.3
S2	66.2	54.8	11.4	66.9	59.6	6.6	7.3
avg.	66.2	57.5	8.7	68.2	60.0	6.2	8.3

detection MLD to increase slightly with increasing value of the gap.

4. GENERAL DISCUSSION

The present study showed two main effects: (i) at equal, low SL, gap detection performance was better under non-masking release conditions than masking release conditions; (ii) at equal signal SPLs, both MLD and CMR masking release occurred, but the magnitude of the effects was generally less than obtained for detection threshold. As regards the MLD, these results are generally consistent with previous investigations of suprathreshold signal analysis (Gebhardt *et al.* 1971; Henning 1991; Robinson & Blakeslee 1971; Townsend & Goldstein 1971).

As noted above, CMRs (and, perhaps, MLDs) for gap detection were often greater for the 250 ms gap than for the shorter gap durations. There are at least two factors that may account for this result as regards CMR. One is related to the fact that previous research has shown that the information contributing to CMR occurs in the dip regions of the noise (Grose & Hall 1989). In gap conditions where the gap is short, the probability that part of the gap will occur in a dip region of the masker will be relatively low. However, when the gap is long, the probability will be greater that part of the gap will occur in a dip region. An across-frequency analysis in such a dip region would indicate a good correlation of envelope at the signal frequency with envelopes at flanking frequencies. This could cue the presence of a gap in the pure-tone signal (when the gap is not present, the signal will cause the envelope at the signal frequency to differ from that at the flanking

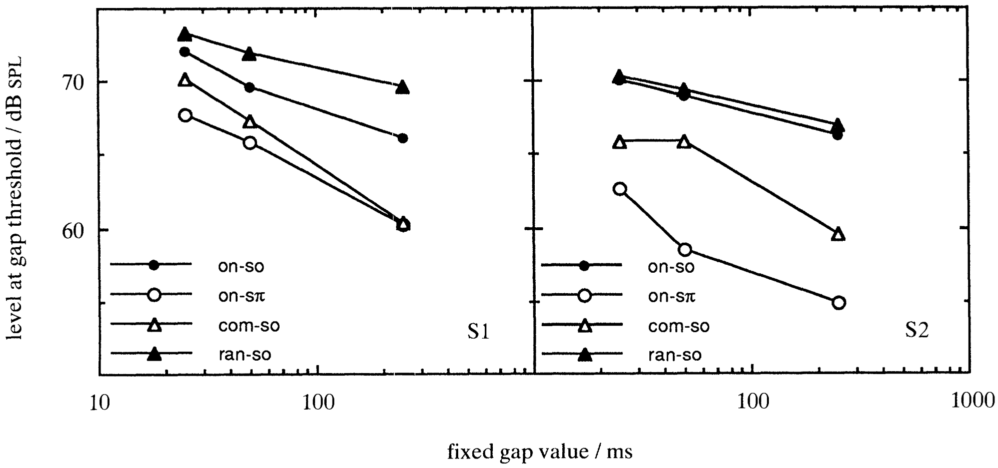

Figure 3. SPL (dB) at gap threshold, plotted as a function of the fixed gap value (ms) of the pure-tone signal. On-so and on-sπ refer to NoSo and NoSπ conditions for the on-signal band alone masker; ran-so refers to the NoSo condition for the random envelope masker; com-so refers to the NoSo condition for the comodulated envelope masker.

frequencies, and the envelope correlation will be relatively poor). The second reason that CMR might be greater at large gap values applies also to the MLD. This is simply that when the level of the signal is sufficiently high, performance will be near optimal both for masking release and non-masking release conditions; that is, at a high enough signal-to-noise ratio, the masking noise becomes essentially inconsequential. In this respect, masking release effects must be confined to relatively low signal-to-noise ratios. One way of interpreting the data of the present experiment is that masking release for gap detection is relatively large at signal-to-noise ratios where gap detection is poor (e.g. the 250 ms gap). That is, masking release occurs for suprathreshold signals, but the masking release is large only when the precision of temporal resolution called for is relatively coarse. When the temporal resolution must be relatively precise (e.g. 25 ms or better), masking release is likely to be small.

There are two caveats that should be mentioned regarding the present study. One is that the conclusions reached here are based upon the results of only two subjects and a limited number of test conditions. In this sense, the present results are preliminary. The second caveat concerns the MLD. The gap detection MLD effects for suprathreshold signals obtained here are comparable to the trends that have been reported for other measures of suprathreshold binaural masking release: that is, suprathreshold masking release effects are generally smaller than found for detection threshold. However, previous work has used low-frequency signals where the MLD is relatively large, and presumably based primarily upon cues of interaural time difference. The present study used a 1200 Hz pure tone signal. Even though the MLD is relatively large for this frequency when the noise bandwidth is narrow, the stimulus envelope cues are probably more important at the 1200 Hz frequency than at the lower frequencies that have been used in previous studies. It is possible that there are important differences between suprathreshold MLDs that are based upon fine structure time cues and suprathreshold MLDs based upon envelope cues. Comparisons between the present MLD results and the MLD results of studies that have used low-frequency signals should therefore be made with caution.

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