Modulation detection interference: Effects of concurrent and sequential streaming

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The presence of amplitude fluctuations in one frequency region can interfere with our ability to detect similar fluctuations in another (remote) frequency region. This effect is known as modulation detection interference (MDI). Gating the interfering and target sounds asynchronously is known to lead to a reduction in MDI, presumably because the two sounds become perceptually segregated. The first experiment examined the relative effects of carrier and modulator gating asynchrony in producing a release from MDI. The target carrier was a 900-ms, 4.3-kHz sinusoid, modulated in amplitude by a 500-ms, 16-Hz sinusoid, with 200-ms unmodulated fringes preceding and following the modulation. The interferer (masker) was a 1-kHz sinusoid, modulated by a narrowband noise with a 16-Hz bandwidth, centered around 16 Hz. Extending the masker carrier for 200 ms before and after the signal carrier reduced MDI, regardless of whether the target and masker modulators were gated synchronously or were gated with onset and offset asynchronies of 200 ms. Similarly, when the carriers were gated synchronously, asynchronous gating of the modulators did not produce a release from MDI. The second experiment measured MDI with a synchronous target and masker and investigated the effect of adding a series of precursor tones, which were designed to promote the forming of a perceptual stream with the masker, thereby leaving the target perceptually isolated. Four modulated or unmodulated precursor tones presented at the masker frequency were sufficient to completely eliminate MDI. The results support the idea that MDI is due to a perceptual grouping of the masker and target, and show that conditions promoting sufficient perceptual segregation of the masker and target can lead to a total elimination of MDI. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1373443]

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I. INTRODUCTION

There is mounting evidence from experimental and theoretical studies that many aspects of the perception of amplitude modulation (AM) can be modeled in terms of a bank of linear, overlapping bandpass filters in the modulation domain (Bacon and Grantham, 1989; Houtgast, 1989; Dau *et al.*, 1997a, 1997b; Lorenzi *et al.*, 1997; Dau *et al.*, 1999; Ewert and Dau, 2000). So far, models of this process have assumed that the output of each peripheral filter is processed independently so that, in effect, there is a separate and independent modulation filterbank at the output of each peripheral auditory filter (Dau *et al.*, 1997a, 1997b). In contrast, there is substantial evidence that AM within each peripheral channel is not always perceived independently and that instead significant interference, or crosstalk, can occur. This effect, known as modulation detection (or discrimination) interference (MDI), is fairly robust and occurs over very large carrier frequency separations, even when the masker and signal carriers are presented to opposite ears (Yost and Sheft, 1989; Yost *et al.*, 1989; Bacon and Opie, 1994).

The dependence of signal modulation thresholds on masker modulation frequency and bandwidth in MDI is similar to that found when the masker and signal both modulate a single carrier (Verhey and Dau, 2000). This single-carrier case is known as modulation masking (Bacon and Grantham, 1989; Houtgast, 1989). That fact that the same modulation frequency-specific tuning is observed in both MDI and modulation masking suggests that at some level, both effects are reflections of similar underlying mechanisms. In terms of modulation filters, this could be implemented in at least two ways: either the modulation filters receive inputs from several peripheral channels, and are therefore broadly tuned with respect to carrier frequency, or the outputs from modulation filters tuned to different carrier frequencies, but to similar modulation frequencies, converge at a higher level of processing (Yost *et al.*, 1989). Recordings from cat inferior colliculus have indicated sharp tuning to carrier frequency in modulation-selective neurons (Langner and Schreiner, 1988), whereas modulation-sensitive neurons in the gerbil auditory cortex have been found that are broadly tuned with respect to carrier frequency (Schulze and Langner, 1997, 1999). This

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could be interpreted in terms of convergence across carrier frequencies at higher levels of modulation analysis.

Psychophysical data from Hall and Grose (1991) argue against a simple ''hard-wired'' implementation of modulation filterbanks with broad tuning to carrier frequency. They found that the effect of MDI was greatly reduced if the masker was gated on before (and gated off after) the target. As pointed out by Hall and Grose (1991), this finding supports the idea that MDI occurs when the two carriers are grouped to form one perceptual object. Asynchronous gating, by as little as 100 ms, can lead to a perceptual segregation of the two carriers, thereby facilitating separate analysis of the modulation of each carrier. The reduction in MDI due to asynchronous gating has since been confirmed in many studies, although all have found some residual MDI, even when the masker is presented continuously (Moore and Jorasz, 1992; Moore and Shailer, 1992; Mendoza *et al.*, 1995a, 1995b).

So far, studies measuring the effect of masker asynchrony on MDI have used stimuli that were modulated throughout their duration (Hall and Grose, 1991; Moore and Shailer, 1992; Mendoza *et al.*, 1995a, 1995b). Because of this, it is not clear whether the release from MDI is due to asynchronous gating of the carriers, the modulators, or a combination of both.[1] It is possible, for instance, that gating on the masker modulation before the target modulation could facilitate segregation even if the two carriers are gated synchronously. Conversely, gating the masker and target modulation on synchronously could conceivably lead to MDI even when the carriers are gated asynchronously. The paradigm used in the original MDI experiment of Yost and Sheft (1989) employed synchronously gated 1000-ms carriers and 500-ms target modulation, temporally centered within 1000-ms masker modulation. The fact that Yost and Sheft observed significant MDI suggests that modulation gating asynchrony is not sufficient to eliminate MDI. However, it is not known whether greater MDI would have been observed in their listeners if the modulators had been gated synchronously. To our knowledge, no one has examined the effect of gating the carriers asynchronously while gating the modulators synchronously. Our first experiment attempts to evaluate the roles of carrier and modulator gating asynchrony in the release from MDI by independently manipulating onset/offset relationships between the carriers and the modulators.

Auditory grouping mechanisms are known to extend over considerable time periods, such that nonsimultaneous sounds can be combined to form perceptual streams (such as melodies or running speech) based on parameters such as spectral similarity, spatial location, or fundamental frequency (Bregman and Campbell, 1971; van Noorden, 1975; Hartmann and Johnson, 1991; Vliegen and Oxenham, 1999). These sequential cues can sometimes override the grouping cues associated with concurrent sounds, such as common onset, spectral proximity, and harmonicity. A striking example of this is when a component within a harmonic complex is ''captured'' by a preceding sequence of repeated tones at the component frequency: not only is the component heard separately from the remaining components in the harmonic complex, but its contribution to the overall pitch and timbre of the complex is also greatly reduced (Darwin *et al.*, 1989; Darwin *et al.*, 1995), suggesting that at least part of the segregation occurs before the formation of higher-level percepts, such as pitch and timbre. Our second experiment investigates whether such sequential perceptual streaming can also lead to a release from MDI.

II. EFFECTS OF CARRIER AND MODULATOR ASYNCHRONY ON MDI

A. Stimuli

The target carrier was a 4.3-kHz sinusoid, presented at a level of 65 dB SPL. Both the carriers and the modulators were gated on and off with 50-ms raised-cosine ramps. The signal was 16-Hz sinusoidal amplitude modulation imposed on the target carrier, with a random starting phase in each trial and a total duration of 500 ms. The duration of the target carrier was 900 ms, providing 200-ms unmodulated fringes before and after the signal modulation. The masker carrier was a 1-kHz sinusoid, presented at a level of 65 dB SPL. The masker modulation was a narrowband Gaussian noise, set at an rms level of -10 dB (*re* unity), with a center frequency of 16 Hz and cutoff frequencies of 8 and 24 Hz. We used a random-noise modulator, as it has been shown that this generally produces more MDI than a sinusoidal modulator (Mendoza *et al.*, 1995a), and because our pilot impressions indicated that practice effects may be less pronounced than when using sinusoidal masker modulation.[2] A new sample of noise was generated for each interval of the experiment. In conditions where the carriers were gated synchronously, the masker carrier duration was also 900 ms. In conditions where the carriers were gated asynchronously, the masker carrier duration was increased by 400 ms, so that the masker carrier extended beyond the signal carrier by 200 ms at either end. The same procedure was used for the masker modulation, so that it was either synchronous with the signal modulation or extended beyond the signal modulation by 200 ms at either end. The conditions tested in this experiment are illustrated in Fig. 1. In the first condition, the target was presented alone (TA). In the following four conditions, the carriers (C) and the modulators (M) of the target and masker were gated either synchronously (s) or asynchronously (a). In the final condition, the masker carrier was gated synchronously with the target, but was unmodulated (CsMu). Each interval in a trial was separated by an interstimulus interval (ISI) of 300 ms. The stimuli were generated digitally and presented at a sampling rate of 32 kHz via a LynxStudio LynxOne DAC. The output of the DAC was passed through a programmable attenuator (TDT PA4) and headphone buffer (TDT HB6), and was delivered diotically to Sennheiser HD 580 headphones.

B. Procedure

An adaptive three-interval 3AFC procedure was used in conjunction with a 2-down 1-up tracking rule to estimate the 70.7% correct point on the psychometric function. The intervals were marked on a computer monitor and feedback was provided after each trial. Listeners responded via the computer keyboard or mouse. At the start of a run, the signal

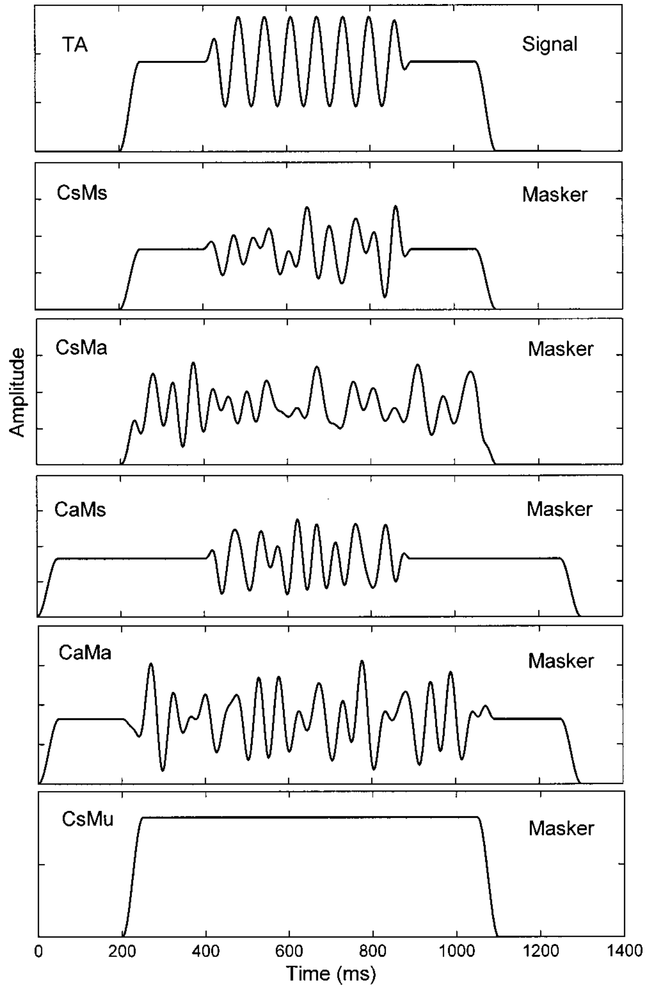

FIG. 1. Schematic diagram of the stimulus envelopes used in experiment 1. The upper panel shows the envelope of the target (TA). The remaining five panels show the envelope of the masker for the four combinations of carrier (C) and modulator (M) gated synchronously (s) or asynchronously (a) with the target, and for the unmodulated masker (CsMu). The ordinate scale is arbitrary.

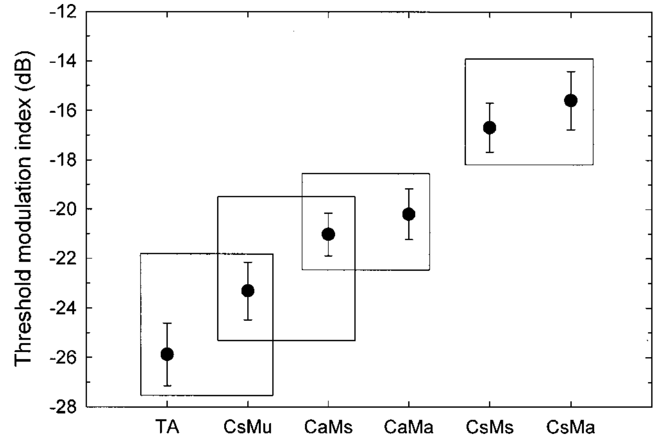

FIG. 2. Mean results from experiment 1. Thresholds are shown for the target carrier alone (TA), for unmodulated interferer (CsMu) gated synchronously with the target carrier and for the four combinations of carriers (C) and modulators (M) gated synchronously (s) or asynchronously (a). Error bars represent ±1 standard error of the mean. Symbols that fall within the same box are not statistically different from each other ($p>0.05$) using an all-pairs Bonferroni *post hoc* comparison.

modulation (m) was set to −6 dB. The initial step size was 4 dB, which was reduced to 1 dB after four reversals. The run was terminated after a further six reversals, and threshold was defined as the mean of the levels at the last six reversals. The conditions were presented in random order, such that all six conditions were tested before any were repeated. New random orders were generated for each repetition and each listener. Four threshold estimates were obtained from each listener in each condition.

C. Subjects

Eight listeners, of which five were female, participated as paid subjects in this experiment. All had thresholds at or lower than 15 dB HL at octave frequencies between 250 and 8000 Hz and none reported any history of hearing difficulties or disorders. Their ages ranged from 19 to 29 years (mean age of 23) and all but two were college students. All listeners received at least 4 h training before data were collected.

D. Results and discussion

Figure 2 shows the mean data from the six conditions. The error bars denote ±1 standard error of the mean. The trends observed in the mean data are representative of the individual data, although there were considerable differences in overall sensitivity to modulation. The leftmost condition represents the mean threshold for the target alone (TA). The next condition (CsMu) shows the threshold when the masker and signal carriers were gated synchronously, but the masker was unmodulated. The remaining four conditions show the combinations of having the carriers (C) or modulators (M) gated synchronously (s) or asynchronously (a). The two rightmost conditions represent classic MDI, with the carriers gated synchronously (CsMs and CsMa). The maximum amount of MDI (about 7 dB when compared with the unmodulated masker, or 10 dB when compared with the target alone) is in good agreement with data from the literature for comparable levels of noise masker modulation (Mendoza *et al.*, 1995a; Moore *et al.*, 1995).

The effects of modulator and carrier gating synchrony were investigated with a two-way within-subjects ANOVA, using only the four conditions from Fig. 2 in which the masker was modulated. The effect of carrier gating synchrony was found to be highly significant ($F_{1,7}=27.8$, $p=0.001$), while the effect of modulator gating synchrony was not ($F_{1,7}=3.34$, $p=0.1$). There was no significant interaction between the two factors ($F_{1,7}<1$, NS). Bonferroni *post hoc* paired comparisons were also made across all six conditions. The results of these comparisons are shown in Fig. 2 as boxes. Conditions that lie within the same box are not significantly different at the level of $p=0.05$. Another, less conservative test, Fisher's least significant difference (LSD) test, as used in a recent study of frequency MDI (FMDI; Gockel and Carlyon, 2000), produces more significant differences, with only the CaMa/CaMs and CsMa/CsMs differences remaining not significant at the level of $p=0.05$. However, all tests, including the ANOVA, confirm that there was no significant effect of modulator gating synchrony.

Gating the carriers asynchronously produces a release from MDI, regardless of the modulator gating synchrony. However, some interference is still present, at least when compared with thresholds for the target alone (TA). This is consistent with other studies investigating the role of asynchronous gating (Moore and Jorasz, 1992; Moore and Shailer, 1992; Mendoza *et al.*, 1995a). This remaining interference was the topic of a recent investigation of FMDI by Gockel and Carlyon (2000). They found that the interference was significant according to Fisher's LSD test, and that it persisted even when the interfering carrier was switched off during the presentation of the target carrier, suggesting that something other than simultaneous modulation was responsible for the residual interference. Their findings are addressed further in the discussion of experiment 2.

Modulator gating asynchrony had no significant effect on thresholds, regardless of whether the carriers were synchronous or not. It seems that listeners cannot use a modulation onset/offset difference of 200 ms to help segregate the two carriers in order to perform modulation detection. Conversely, simultaneous onset of masker and signal modulation does not lead to more MDI if the carriers are gated asynchronously. Although we found no effect of modulator asynchrony, we cannot rule out the possibility that modulation fringes longer than the 200 ms employed in the present study may lead to some release from MDI.

III. RELEASE FROM MDI IN CONDITIONS PROMOTING SEQUENTIAL STREAMING

The second experiment examines the effect of sequential streaming on MDI. The question was whether such streaming, which must be based on longer-term analysis, is sufficient to produce a release from MDI, allowing independent analysis of the modulation on the two carriers. The paradigm used in this experiment is similar to that employed by Darwin and colleagues (Darwin *et al.*, 1989, 1995; Darwin and Hukin, 1997). In some conditions, the test stimuli (masker and target carrier) were preceded by a sequence of four tones at the masker carrier frequency. The assumption was that the preceding tones would form a perceptual stream with the masker carrier, leaving the target carrier perceptually isolated.

A. Method

The target carrier was a 4.3-kHz sinusoid, with a total duration of 187.5 ms, gated with 20-ms raised cosine ramps. The masker carrier was a 1-kHz sinusoid which, when present, was always gated synchronously with the target carrier. The signal modulation was a 16-Hz sinusoid with a random starting phase, which was present throughout the target carrier. The masker modulation was again a Gaussian noise with a center frequency of 16 Hz, a bandwidth of 16 Hz, and an rms level of -10 dB (re. unity), which was present throughout the masker carrier. The four precursor tones were all the same duration as the target and masker and were separated by gaps of 62.5 ms, giving an overall repetition period of 250 ms. Six conditions were tested, as illustrated in Fig. 3: (1) Target alone (TA); (2) target with un-

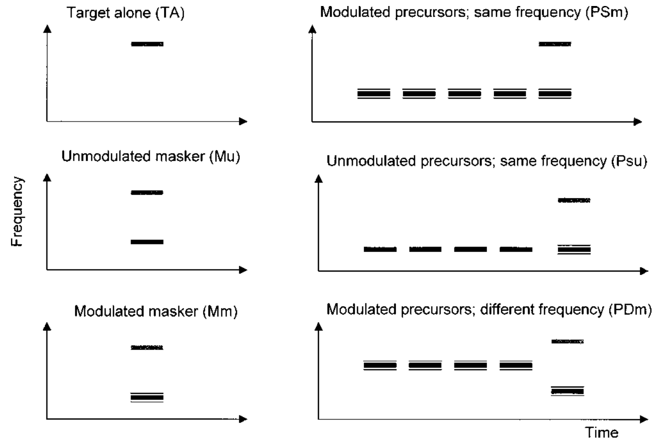

FIG. 3. Schematic diagram of the conditions tested in experiment 2, drawn in the form of a spectrogram. The masker carrier was at 1 kHz, while the signal carrier was at 4.3 kHz.

modulated masker (Mu); (3) target with modulated masker (Mm; classical MDI condition); (4) target and modulated masker preceded by four precursors at the masker frequency and modulated with the same Gaussian statistics as the masker (PSm); (5) target and modulated masker preceded by four unmodulated precursors at the masker frequency (PSu); (6) target and modulated masker preceded by four modulated precursors with a carrier frequency of 1750 Hz (PDm).

Condition 5 (PSu) was run in order to examine the effect of modulating the precursors. It may be that the sequential binding between the masker and the precursors is reduced if only the masker is modulated. In condition 6 (PDm), the precursor frequency was sufficiently remote from both the masker and the target to make any sequential binding unlikely. Thus, this condition served as a control for any general effect of preceding the target stimulus with modulated precursors.

The procedures and the listeners were the same as in experiment 1. As all listeners had completed experiment 1 before embarking on this experiment, they already had substantial practice in MDI tasks.

B. Results and discussion

The mean results from this experiment are shown in Fig. 4. The mean pattern of results is representative of the individual data, but again the differences between subjects in absolute values were substantial. Thresholds are generally higher than in experiment 1, which is due to the shorter duration of the target in this experiment (Sheft and Yost, 1990). As in experiment 1, there is a difference of about 3 dB in thresholds between the target alone (TA) and the unmodulated masker (Mu) conditions. As expected, gating a modulated masker with the target (Mm) results in substantial MDI. However, MDI is totally eliminated by introducing precursors at the masker frequency, whether they are modulated (PSm) or not (PSu). When the precursors are at a different carrier frequency (PDm), MDI is substantially restored. A Bonferroni *post hoc* test in an all-pairs comparison confirmed these impressions: the Mm and PDm conditions were not significantly different from each other, but they

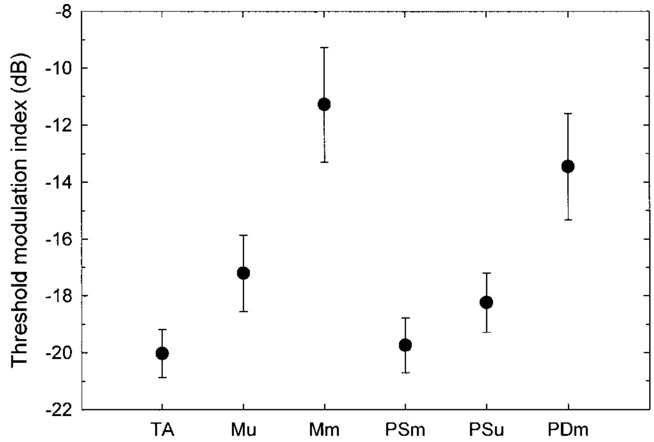

FIG. 4. Mean results from experiment 2. From left to right, thresholds are shown for the target alone (TA), the target with the unmodulated masker (Mu), the target with the modulated masker (Mm), the target and modulated masker with modulated precursors at the same frequency as the masker frequency (PSm), the target and modulated masker with unmodulated precursors at the same frequency as the masker frequency (PSu), and target and modulated masker with modulated precursors at a different frequency (PDm). Error bars represent ±1 standard error of the mean.

were both significantly different from all the other conditions at the level of $p=0.05$. There were no other significant differences, meaning that the conditions with the precursors at the same frequency as the masker (PSm and PSu) were not significantly different from the target alone condition (TA). In this experiment a reanalysis using Fisher's LSD test resulted in essentially the same conclusions: the Mm and PDm conditions were not significantly different from each other but were significantly different from all other conditions, and the PSm and PSu conditions were not significantly different from the TA condition at the level of $p=0.05$. One difference between the tests was that the LSD test detected a significant difference between the TA and the Mu conditions, as has also been reported in previous studies (e.g., Moore and Shailer, 1992).

To our knowledge, this is the first study to explicitly examine the effects of sequential streaming on MDI. However, one condition studied by Moore and Shailer (1992) has some similarities to those studied here. They used a preceding unmodulated ''cue'' tone at the target carrier frequency to help listeners concentrate on the target and ignore the masker. This manipulation had very little effect on MDI. The main differences between their experiment and ours are the frequency of the cue (masker frequency in ours and target frequency in theirs); the gap between the cue and the test stimulus (62.5 ms in ours and 300 ms in theirs); and the number of cue tones (four in ours and one in theirs). We speculate that the most important parameter may be the number of cue tones. Increasing the number of repetitions generally leads to an increased tendency for a separate perceptual stream to be formed. The single cue tone used by Moore and Shailer may not have perceptually separated the target from the masker sufficiently to reduce MDI.

If the results from a frequency MDI experiment can be compared with those from an amplitude MDI experiment, our results appear to be in conflict with those of Gockel and Carlyon (2000).[3] They found that nonsimultaneous modulated maskers (one presented before and one after the target), centered around 2300 Hz, could interfere with FM detection for a 1000-Hz target, whereas our experiment 2 shows that the addition of nonsimultaneous modulated maskers can eliminate MDI in the presence of a simultaneous masker. In the framework of the present study, the results of Gockel and Carlyon can be understood in terms of the maskers and target forming one perceptual stream and the masker modulation within that stream interfering with the detection of the target modulation, even though they do not physically overlap in time. Gockel and Carlyon found that increasing the gaps between the maskers and the target had little or no effect on the amount of FMDI measured. They argued that the longest gaps should have resulted in the three tones being clearly perceived as separate auditory events, thereby presumably ruling out effects of concurrent, or quasi-concurrent, grouping in assigning masker modulation to the target. However, the longest gaps they employed were only 200 ms. While three auditory events (masker–target–masker) would have been clearly perceived, it is possible that they were perceived as belonging to one auditory stream: the segregation of streams based on frequency differences is known to take time to build up (Bregman, 1978), such that the first few repetitions of a tone sequence are often perceived as a single stream, even for large frequency differences. It is therefore possible that the FMDI observed by Gockel and Carlyon was a result of the maskers and target forming a single auditory stream, thereby making the task of analyzing the target modulation separately from masker modulation more difficult. The present results suggest that the interference observed by Gockel and Carlyon (2000) might be eliminated simply by adding more masker bursts prior to the target, thereby encouraging the perceptual segregation of the masker bursts from the target.

The finding of Gockel and Carlyon (2000) that nonsimultaneous maskers can produce some MDI, in combination with our finding of a total release from MDI in a sequential streaming paradigm, suggests that modulation analysis may be performed not only across concurrent sounds, forming auditory objects, but also across sequential sounds, forming auditory streams. This intriguing possibility has yet to be investigated. However, the explanation of interference based on perceptual stream formation is different from the one offered by Gockel and Carlyon (2000). Their explanation relates to the perceptual salience of modulated versus unmodulated tones, rather than to issues of perceptual grouping. For this reason, their explanation would not predict a release from MDI due to additional sequential masking tones.

The results of the present study show that stimuli designed to encourage sequential streaming can lead to a total elimination of MDI. The reduction in MDI found in this experiment therefore seems greater than that produced by introducing carrier gating asynchronies (experiment 1) where, consistent with previous results, some residual MDI remained. This could be interpreted as evidence that the perceptual segregation produced by a preceding sequence of tones is more complete than that produced by an onset/offset gating asynchrony. The results also argue against the conclusion of Moore and Shailer (1992) that factors other than perceptual grouping may be partly responsible for MDI. If their hypothesis were correct in all circumstances, some residual MDI would have been expected in our sequential tasks also. However, there are some circumstances, such as when the carriers are close in frequency, in which MDI can be attributed in part to within-channel processing (Bacon and Konrad, 1993). In these cases, it is unlikely that even total stream segregation would eliminate MDI.

While the present results emphasize the role of perceptual grouping mechanisms in MDI, it is important to remember that MDI exhibits the same modulation-frequency specificity as modulation masking on a single carrier (Verhey and Dau, 2000). This suggests that analysis of both modulation masking and MDI in terms of the same underlying mechanisms, such as modulation filters, may still be appropriate. Nevertheless, it is clear that such analysis takes place only after some degree of perceptual grouping has occurred and that MDI cannot be modeled in terms of ''hard-wired'' modulation crosstalk across peripheral frequency channels.

IV. SUMMARY

Two experiments investigated the role of perceptual organization on modulation detection interference (MDI). The first experiment independently manipulated the onset/offset asynchrony of the carriers and the modulators. An onset/offset asynchrony between the masker and target carriers led to a reduction in MDI; this reduction was the same whether the onset and offset of the modulators were synchronous or asynchronous. Similarly, when the carriers were gated synchronously, gating the modulators asynchronously produced no release from MDI.

The second experiment measured MDI for a synchronously gated masker and target in the presence of precursor tones, which were designed to form a perceptual stream with the masker and thus promote the perceptual segregation of the target. Introducing a sequence of four modulated or unmodulated precursor tones at the masker frequency led to a complete elimination of MDI. In contrast, presenting the precursors at a frequency remote from both the target and the masker produced no significant reduction in MDI. The results support the idea that MDI results from an inability to separate the target modulation from that of the masker because the two carriers are to some extent perceptually grouped. The finding that precursor tones can totally eliminate MDI, while an onset/offset carrier asynchrony produces a smaller reduction in MDI, suggests that segregation may be graded and that even a large onset/offset asynchrony may not result in the same degree of perceptual segregation (at least in terms of modulation analysis) as that produced by a sequence of precursor tones.

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[1]Moore and Jorasz (1992) tested AM depth discrimination in the presence of an interfering modulator and gated the increment or decrement in modulation depth separately from the interfering modulation. However, as both the reference and interfering modulation were still gated on and off together, this manipulation would have been unlikely to lead to segregation of the target modulation.

[2]Due to its random nature there is a finite probability of overmodulation (i.e., an instantaneous value of the modulator exceeding unity) when using a noise modulator. However, at −10 dB rms, the average probability is small (≈0.0015) and is therefore unlikely to affect the results. Furthermore, Mendoza *et al.* (1995a) found that much higher levels of overmodulation produced MDI results that were very similar to those produced with little or no overmodulation, suggesting that no qualitative differences result from overmodulation.

[3]Gockel and Carlyon (2000) used a modulation frequency of 15 Hz. Based on the results of Moore and Sek (1995), it is likely that at this modulation frequency listeners are detecting FM based on AM within individual auditory filters, thereby supporting a direct comparison between amplitude and frequency MDI.

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