Across-frequency envelope correlation discrimination and masked signal detection

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This study compared the dependence of comodulation masking release (CMR) and monaural envelope correlation perception (MECP) on the degree of envelope correlation for the same narrowband noise stimuli. Envelope correlation across noise bands was systematically varied by mixing independent bands with a base set of comodulated bands. The magnitude of CMR fell monotonically with reductions in envelope correlation, and CMR varied over a range of envelope correlations that were not discriminable from each other in the MECP paradigm. For complexes of 100-Hz-wide noise bands, discrimination thresholds in the MECP task were similar whether the standard was a comodulated set of noise bands or a completely independent set of noise bands. This was not the case for 25-Hz-wide noise bands. Although the data demonstrate that CMR and MECP exhibit different dependencies on the degree of envelope correlation, some commonality across the two phenomena was observed. Specifically, for 25-Hz-wide bands of noise, there was a robust relationship between individual listeners' sensitivity to decorrelation from an otherwise comodulated set of noise bands and the magnitude of CMR measured for those same comodulated noise bands.
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I. INTRODUCTION

Pure-tone signal detection in a complex masker consisting of multiple narrow bands of noise is usually more acute when the multiple noise bands share the same modulation pattern than when their patterns are random with respect to each other (Hall *et al.*, 1984). The lower signal level at threshold in the comodulated case relative to the random case is termed comodulation masking release (CMR), and indicates that the auditory system is sensitive to envelope correlation across frequency. Another phenomenon that indicates sensitivity of the auditory system to envelope correlation across frequency is monaural envelope correlation perception (MECP). This refers to the ability to discriminate between stimuli made up of multiple bands of noise on the basis of envelope correlation across bands. Because both phenomena rely on envelope correlation, there has been an on-going interest in the relationship between the two functions (Richards, 1987; van de Par and Kohlrausch, 1998).

The main focus of this study is the comparative dependence of CMR and MECP on the degree of envelope correlation. Most studies of CMR that have used maskers consisting of multiple noise bands have restricted the bands to the dichotomy of having either completely coherent (comodulated) or completely incoherent (random) envelopes. Although a few studies have examined CMR for envelopes that are partially correlated, little attention has been paid to the question of how much envelope correlation is necessary to produce CMR. Similarly, most studies of MECP have examined exclusively the discrimination of noise-band envelopes that are either completely coherent or completely incoherent. The question of how much envelope correlation is sufficient to enable accurate discrimination has received scant attention since the original work of Richards (1987). It is the purpose of this study to assess both CMR and MECP as a function of the degree of envelope correlation for the same stimulus set. The motivation was that, by incorporating this stimulus commonality, further insights could be gained on the functional relationship between the two phenomena. The study itself proceeded in two phases, where each phase dealt with a separate set of stimuli differing primarily in terms of harmonicity and bandwidth. Within each phase both CMR and MECP paradigms were implemented. The structure of this logical progression will be maintained here by reporting two phases, with two experiments per phase.

II. PHASE 1, EXPERIMENT 1. CMR AS A FUNCTION OF ACROSS-FREQUENCY ENVELOPE CORRELATION: HARMONIC STIMULI

The results of several studies indicate that a positive CMR can be obtained if the noise band centered on the pure-tone signal is only partially correlated with the flanking noise bands (McFadden, 1986; Moore and Schooneveldt, 1990; Eddins and Wright, 1994; Buss and Richards, 1996; Grose *et al.*, 2001; Buss *et al.*, 2009). These studies involved such manipulations as "mixed" modulations across subsets of the bands, or time-shifted envelopes across bands. For example, Moore and Schooneveldt (1990) showed that for a pair of 25-Hz-wide noise bands, a positive CMR was still observed in conditions where time-shifting the envelopes diminished the envelope correlation to $r = 0.77$. However, these studies did not specifically address the question of how much

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correlation is necessary to elicit a CMR. This question received a preliminary examination in an unpublished report by Mendoza *et al.* (1996) in which the envelope correlation across the individual bands in a multi-band masker was systematically varied by corrupting each comodulated band with an independent band of noise at a fixed comodulated-to-independent ratio. The magnitude of CMR was found to vary monotonically with correlation coefficient, at least in normal-hearing listeners. The purpose of the present experiment was to apply a similar approach to measure CMR magnitude; a complementary experiment was performed to measure MECP for the same stimuli (Phase 1, Experiment 2).

A. Method

Twelve young adults (11 female) participated, ranging in age from 18 to 27 yr (mean = 22 yr). All had audiometric thresholds <20 dB hearing level (HL) across the octave frequencies 250 to 8000 Hz (ANSI, 2010), and none reported any history of ear disease.

The signal was a 2000-Hz pure tone, 300 ms in duration including 20-ms raised-cosine onset/offset ramps. The masker consisted of five narrow bands of noise, each 20 Hz in bandwidth, centered at 1200, 1600, 2000, 2400, and 2800 Hz. The use of 20-Hz bandwidths and harmonic spacing was based on the preliminary work of Mendoza *et al.* (1996). The maskers were generated at a sampling rate of 12207 Hz using a digital signal processing platform (RPvds, Tucker-Davis Technologies, Alachua, FL). A quadrature multiplication technique was employed wherein two base sets of maskers were generated: One base set comprised five comodulated noise bands; the other base set comprised five independent bands. For the base set of comodulated bands, two independent Gaussian noises were low-pass filtered at 10 Hz using a sequence of five cascaded, first-order Butterworth filters, and then each low-pass band was separately multiplied by a respective complex of five tones spaced at 400-Hz intervals between 1200 and 2800 Hz. The tones in one complex (for multiplication with one low-pass noise) were in quadrature phase relative to the tones in the other complex (for multiplication with the second low-pass noise). Within each tonal complex, the starting phases of the tones were staggered by $2\pi/5$ radians. Following the parallel multiplications, the products were summed, yielding a complex of five comodulated 20-Hz-wide bands of Gaussian noise centered at the five chosen frequencies. For further comment on this quadrature method to generate Gaussian noise, see van der Heijden and Kohlrausch (1995). For the independent set of noise bands, a similar procedure was used except that each tone in each of the two complexes of quadrature-phase tones was multiplied by a separate, and independent, 10-Hz low-pass filtered Gaussian noise. The resulting set of five narrow bands of noise therefore had envelopes that were random with respect to each other. These two base sets of masker bands constituted the endpoints of the range between fully comodulated and fully independent maskers.

Six additional sets of masker bands were then constructed that had degrees of envelope correlation that fell between the endpoints of fully comodulated and fully independent maskers. These additional masker sets were generated by mixing the base comodulated and independent masker sets at prescribed intensity ratios; specifically, comodulated-to-independent ratios of 0, 5, 10, 15, 20, and 25 dB. These ratios translate to Pearson correlation coefficients across any pair of noise-band envelopes of $r = 0.23$, 0.55, 0.81, 0.93, 0.98, and 0.99, respectively.[1] All maskers were presented at a level of 65 dB sound pressure level (SPL) per noise band.

Signal thresholds were measured using a 3-alternative, forced-choice (3AFC) procedure that incorporated an adaptive 3-down, 1-up stepping rule to converge on the 79.4% correct level. In each observation interval of a 3AFC trial, the selected masker was gated on for 368 ms including 34-ms raised-cosine ramps. In one of these observation intervals at random, the 300-ms signal was presented during the 300-ms "full-on" segment of the masker. The initial step-size of the adaptive procedure was 8 dB; this was halved after the first two reversals in level direction, and again after the subsequent two reversals. The step size remained at 2 dB for the remainder of the track, which was terminated after a total of ten reversals. The mean signal level at the final six reversals was taken as the estimate of threshold for that track. Tracks were rejected and replaced if the standard deviation (SD) of the signal level at the final six reversals was ≥ 4 dB. Across all subjects and conditions, this occurred in 20 instances. For each condition, at least three valid estimates were collected, with a fourth added if the range of the first three exceeded 3 dB. The final threshold estimate for each condition was the mean of all valid estimates collected.

B. Results and discussion

Performance across observers was relatively similar and is well represented by the group means. These data are shown as filled circles (-1 SD error bars) in Fig. 1, which plots signal threshold level (left ordinate) as a function of the comodulated-to-independent masker intensity ratio. For reference, the Pearson correlation coefficients between the envelopes of any pair of bands for these respective intensity ratios are shown along the top axis.[2] The data show that signal level at threshold decreased monotonically with an increasing comodulated-to-independent ratio. This was supported by a repeated measures analysis of variance (ANOVA) that indicated a significant effect of masker condition on signal threshold [$F(3.11,34.25) = 63.18$; $p < 0.01$]. Note that for the repeated measures ANOVA, Mauchly's test of sphericity was significant, and therefore Greenhouse-Geisser adjustments to degrees of freedom have been incorporated.

In terms of masking release, the difference between the level of the signal at threshold in the independent masker and the level at threshold in the comodulated masker represents a common measure of CMR. This derivation of CMR is sometimes referred to as CMR(U-C) (Uncorrelated–Correlated) in contrast to CMR(R-C) (Reference–Correlated) where signal threshold in the comodulated condition is referenced to threshold in the condition where just a single band of masking noise centered on the signal is present (Schooneveldt and Moore, 1987). Some studies advocate for the CMR(U-C) derivation, particularly in conditions of dynamic and/or binaural masking (e.g., Epp and Verhey, 2009; Verhey *et al.*, 2013). Using the CMR(U-C) derivation, the average CMR magnitude here was 9.1 dB. For each subject, the masking release associated with each of the other comodulated-to-independent ratio conditions was also derived; i.e., the difference between the threshold in the independent masker and the threshold in every other condition was also computed. These mean masking release data are also shown in Fig. 1 as open circles (+1 SD error bars), referenced to the right ordinate. Also referenced to the right ordinate, and shown as gray squares, are mean data from the unpublished report of Mendoza *et al.* (1996). Whereas the masking release magnitudes are similar across the two data sets for the smaller comodulated-to-independent ratios, they diverge somewhat at higher ratios. This might be due to methodological differences between the two studies, such as the use of masker bands with a closer harmonic spacing (250 Hz) and a lower signal frequency (1000 Hz) in the study of Mendoza *et al.*

The main point of interest in this experiment was the dependence of masking release magnitude on degree of envelope correlation. To highlight this, pre-planned contrasts were undertaken to determine the comodulated-to-independent ratio at which signal thresholds first differed significantly from the independent masker condition. This analysis revealed that even at 0 dB, the least favorable comodulated-to-independent ratio tested, the signal thresholds had declined significantly from the random baseline [$F(1,11) = 11.17$; $p < 0.01$]. This demonstrates that, in terms of signal detection, observers can benefit from a degree of across-frequency envelope correlation ($r = 0.23$) that is markedly lower than $r = 1$. This raises the question of whether the perception of monaural envelope decorrelation is similarly acute for these stimuli.

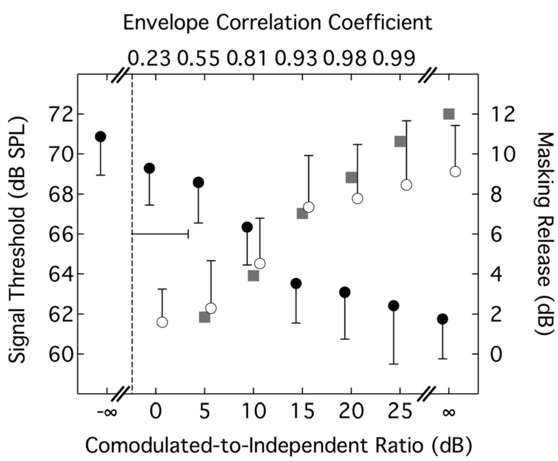

FIG. 1. Group mean signal threshold (filled circles re. left axis) and group mean masking release (open circles re. right axis) plotted as a function of the comodulated-to-independent masker intensity ratio (lower axis); the associated envelope product moment correlation coefficients are also indicated (upper axis). Error bars are 1 SD. Gray squares are mean masking release data from Mendoza *et al.* (1996). The vertical dashed line, with horizontal error bar indicating +1 SD, is the group mean comodulated-to-random ratio for the discrimination of partially decorrelated from fully comodulated envelopes (Experiment 2).

III. PHASE 1, EXPERIMENT 2. MECP: HARMONIC STIMULI

Most studies of MECP have focused on the discrimination of noise-band stimuli whose envelopes are either wholly correlated or completely independent across bands. However, the initial work on MECP by Richards (1987) also measured the amount of correlation required for discriminability of noise-band pairs with partially correlated envelopes from noise-band pairs with either comodulated or independent envelopes. Those results showed that, for 100-Hz-wide noise bands, pairs with partially correlated envelopes could be discriminated from pairs with completely correlated envelopes when the correlation coefficient dropped to about $r = 0.85$. The present experiment applied a similar MECP approach for the 20-Hz-wide noise bands that were used as maskers in Experiment 1. Specifically, the goal was to measure the amount of decorrelation across noise-band envelopes necessary for an observer to determine that the noise bands were no longer fully comodulated.

A. Method

The same subjects from Experiment 1 participated. However, one of the subjects could not perform the task despite extensive training; i.e., this listener could not reliably discriminate partially decorrelated envelopes from fully correlated envelopes within the limits of fully correlated and fully decorrelated (independent) envelopes. The results of this experiment are therefore based on the data of 11 subjects.

The same methodology and parameters were used to generate the noise bands as in Experiment 1. A base set of five comodulated noise bands and a base set of five independent noise bands were created, and the degree of envelope correlation across the five bands was manipulated by mixing the base comodulated and independent masker sets at a variable intensity ratio. The stimulus level remained at 65 dB SPL per band. Each observation interval of the 3AFC task was 368 ms in duration including 34-ms raised-cosine rise/fall ramps. In two of the observation intervals of a trial, at random, the five noise bands were fully comodulated. In the target interval the envelopes of the noise bands were partially decorrelated, having a comodulated-to-independent ratio that was adaptively varied. A 3-down, 1-up stepping rule was used to converge on the comodulated-to-independent ratio at which partially correlated noise bands could be discriminated from fully comodulated bands with 79.4% accuracy. The power-domain scaling factor that controlled the proportion with which the independent bands were mixed with the comodulated bands was initially adjusted in steps of 0.1 over a range of 0 (fully comodulated) to 1.0 (fully independent). After two reversals in the comodulated-to-independent ratio, the step size was changed to 0.05 and remained at this size until the track was terminated after ten reversals. The levels of the scaling factor over the last eight reversals were averaged, and used to derive an estimate of the comodulated-to-independent ratio at discrimination threshold. At least three estimates of the comodulated-to-independent ratio were collected, and the average of all estimates was taken to reflect the degree of decorrelation that allowed discrimination from fully comodulated bands.

Although some observers were immediately able to perform the task reliably, others required more extensive training. Those observers who exhibited initial difficulty with the task were given training on a familiarization (non-adapting) task in which the target interval was always known, and the stimulus in the target interval was always a complex of five independent bands. The observer could therefore repeatedly compare the comodulated and independent bands until the necessary cue(s) had been identified to accurately discriminate these endpoints of the comodulated-to-independent ratio range. As noted above, one observer failed to exhibit reliable discrimination even after multiple sessions over several days; no data were included from this observer.

B. Results and discussion

The group mean average from this experiment is shown in Fig. 1 as a vertical dashed line, with the horizontal error bar indicating +1 SD. This point represents the average comodulated-to-independent ratio at which the observers could just detect that the envelopes across the five noise bands were no longer fully comodulated; i.e., $r \neq 1.0$. The point corresponds to a pair-wise envelope correlation of $r = 0.12$.

Three aspects of the CMR and MECP data in Fig. 1 are noteworthy. First, the comodulated-to-independent ratio at which observers could just detect that the noise band envelopes were no longer comodulated was well below the range of ratios where the masked-signal threshold changed most rapidly in the CMR paradigm. In other words, masker envelope decorrelation markedly affected signal detection at the comodulated-to-independent ratios that were higher than those at which the observer could actually perceive the presence of decorrelation in the MECP paradigm. Second, the Pearson product moment correlation coefficient associated with this threshold discrimination ($r = 0.12$) is markedly smaller than the value of about $r = 0.85$ measured by Richards (1987). This is likely due to the difference in bandwidths across the two studies (20 Hz vs 100 Hz). MECP depends strongly on stimulus bandwidth, and sensitivity typically drops as the bandwidth is reduced [e.g., from 100 to 25 Hz (Moore and Emmerich, 1990; Buss *et al.*, 2013)]. Thus, MECP is inherently more difficult for very narrow bands of noise. Third, it is evident from the large SD of the comodulated-to-independent ratio thresholds that observers differed in their acuity for perceiving decorrelation.

Given these individual differences in MECP, it is informative to determine whether performance in the CMR task of Experiment 1 was related to sensitivity to decorrelation. Three correlations were performed on the data of the 11 observers who completed both experiments. Specifically, correlation coefficients were computed between the comodulated-to-independent ratio at discrimination threshold in the MECP task of Experiment 2 and: (1) The signal threshold in the completely comodulated masker of experiment 1; (2) the signal threshold in the completely independent masker of Experiment 1; and (3) the magnitude of CMR in Experiment 1. None of the relationships were significant, although the association between the comodulated-to-independent ratio at the MECP threshold and CMR magnitude showed a positive trend ($r = 0.43$, $p = 0.09$ [one-tailed]); that is, listeners with the greatest acuity in detecting decorrelation tended to have the largest CMRs. In line with this trend are the data from the 12th observer who was unable to perform the task in Experiment 2. In addition to not being able to reliably discriminate comodulated from partially correlated noise bands, this observer also had the lowest magnitude of CMR (4.1 dB)—due to a notably poor threshold in the comodulated masker.

One limitation of this experiment was that the performance of most listeners was close to "floor" level; i.e., for most observers, the noise bands at discrimination threshold were almost completely decorrelated. Poor MECP performance was not unexpected because of the known decline in MECP at very narrow bandwidths (Moore and Emmerich, 1990; Buss *et al.*, 2013). The choice of 20-Hz bandwidths here was driven largely by the motivation to pattern the CMR experiment after the earlier work of Mendoza *et al.* (1996), which also used this bandwidth. A second limitation of this experiment was that it did not test the complementary condition wherein the standard stimulus comprised the independent bands ($r = 0$) and the listener's task was to detect an increase in correlation.[3] A third limitation was that the noise bands were harmonically spaced. This configuration of linear spacing means that any within-channel cues that might contribute to the detection of envelope correlation, such as beating patterns between neighboring bands, would be highly similar across frequency—a concern that applies also to the associated CMR experiment (cf. Grose *et al.*, 2009). A final limitation is that the experiment did not test a condition that might make the MECP paradigm conceptually more similar to the CMR task—viz., the detection of decorrelation from $r = 1$ but with only the center band becoming decorrelated while the flanking bands remain comodulated. Because of these limitations, a second pair of experiments was undertaken to compare more comprehensively CMR and MECP performance using similar stimuli between tasks. Coincidentally, a long-term study on MECP in our laboratory reached conclusion at this juncture making available a cohort of subjects who had been listening to MECP conditions for almost two years (Buss *et al.*, 2013).

IV. PHASE 2, EXPERIMENT 1. CMR AS A FUNCTION OF ACROSS-FREQUENCY ENVELOPE CORRELATION: INHARMONIC STIMULI

The purpose of this experiment was to measure the dependence of signal threshold on the degree of correlation across the masker bands in a CMR paradigm that tested two different bandwidths of the noise-band maskers. In addition, the bands themselves were spaced on a scale whose metric was the normal equivalent rectangular bandwidth (ERB) (Moore and Glasberg, 1983). As a later addendum to the experiment, supplementary conditions were tested that were intermediate with respect to CMR for pure-tone signals on the one hand and MECP for noise-band stimuli on the other hand. These conditions incorporated a noise-band signal, and the rationale for their inclusion is expanded upon below.

A. Method

Six adults (3 female) participated, ranging in age from 36.7 to 62.2 yr (mean = 49.1 yr). All had audiometric thresholds <20 dB HL across the octave frequencies 250 to 8000 Hz, and none reported any history of ear disease. All were experienced listeners in psychoacoustic tasks, and five had previously completed an extensive study in MECP.

The masker consisted of five narrow bands of noise, but two different bandwidths were used in separate sets of conditions: 25 and 100 Hz. These bandwidths were selected because MECP measurements for these bandwidths already exist (Buss *et al.*, 2013). The center frequencies of the five bands, rounded to the nearest integer, were 728, 1094, 1600, 2300, and 3268 Hz. These represent the center frequencies of ERBs separated by two intervening, non-overlapping ERBs. The method of masker generation was the same as Experiment 1 and, again, for each masker bandwidth two base sets of maskers were generated: (1) A base set comprising five comodulated noise bands; (2) a base set comprising five independent bands. These two base sets were mixed to yield maskers with comodulated-to-independent ratios of 0, 5, 10, 15, 20, and 25 dB. All maskers were presented at a level of 65 dB SPL per noise band. In the main CMR conditions, the signal was a 1600-Hz pure tone.

Two supplementary conditions were also included for each masker bandwidth that did not use a pure-tone signal but, rather, used a noise band centered at 1600 Hz as the signal. This signal band had the same bandwidth (25 or 100 Hz) as the 1600-Hz noise band within the respective masker to which it was being added, but was independent from that masker band. In one of the supplementary conditions for each of the two bandwidths, the 1600-Hz signal band was simply added to the 1600-Hz masker band (thus allowing for the level increment to be a viable detection cue). In the other supplementary condition, the summed masker-plus-signal band was rescaled prior to presentation to maintain an overall noise-band level of 65 dB SPL (thus removing the long-term level increment as a viable cue). The masker in these supplementary conditions was always the base set of the comodulated bands. The rationale for these supplementary conditions was twofold. First, the addition of the noise-band signal to its complementary masker band resulted in a composite waveform having envelope fluctuation statistics that remained representative of the associated noise bandwidth. As pointed out by Schooneveldt and Moore (1989), this is not necessarily the case when a pure-tone signal is added to the masker noise band. The second rationale was that the signal thresholds measured in the rescaled masker-plus-signal conditions compared directly to MECP thresholds when expressed as comodulated-to-independent ratios in dB. Thus, these supplementary conditions provided a segue between CMR conditions in which the signal is added to one band within a complex of comodulated masker bands and MECP conditions where just one band is decorrelated relative to the remaining comodulated bands. Only five of the six subjects were available to participate in the supplementary conditions, as these data were collected after those in the primary experiment. In all conditions, the duration and onset/offset ramps applied to the signal were the same as those in the companion experiment of Phase 1.

The same 3AFC procedure was used to measure signal threshold as in the previous CMR experiment. There were 16 conditions employing the pure-tone signal: The fully comodulated and fully independent masker plus the six sets of masker bands with varying comodulated-to-independent ratios (i.e., 0, 5, 10, 15, 20, and 25 dB) for each of the two masker bandwidths (i.e., 25 and 100 Hz). There were an additional four conditions employing the noise-band signal presented in the comodulated masker: The scaled and unscaled summed waveforms for each of the two masker bandwidths. All other aspects of the procedure were the same as in the companion experiment of Phase 1. Across all subjects and conditions, ten threshold estimation tracks were rejected and replaced because of a track SD >4 dB.

B. Results and discussion

Considering first the main conditions using the pure-tone signal, the performance of the six subjects was relatively similar and is well represented by the group means. These data are shown in Fig. 2 where the upper panel plots

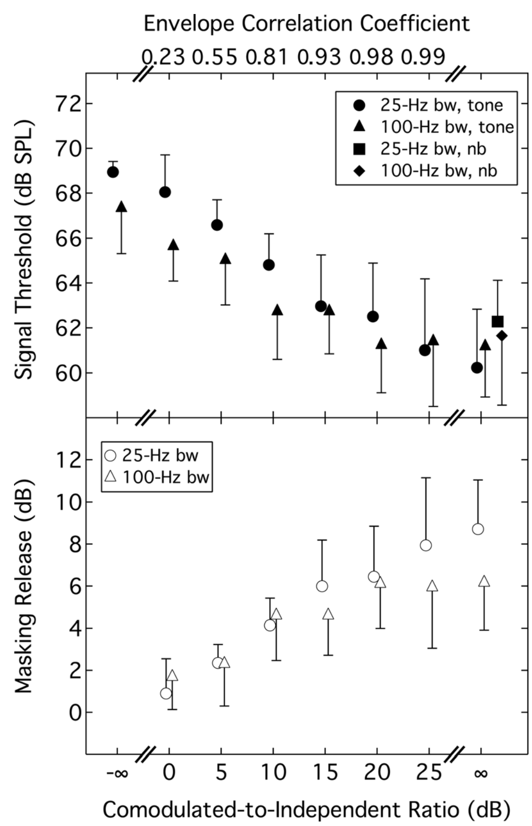

FIG. 2. Top panel: Group mean signal threshold plotted as a function of the comodulated-to-independent masker intensity ratio (lower axis); the associated envelope product moment correlation coefficients are also indicated (upper axis). Parameters are noise bandwidth and signal type, as indicated in the key. Error bars are 1 SD. Lower panel: Group mean masking release as a function of comodulated-to-independent intensity ratio; the parameter is noise bandwidth.

signal threshold as a function of the comodulated-to-independent ratio (filled symbols) and the lower panel plots the derived masking release relative to the signal threshold level in the independent masker (open symbols). As in Fig. 1, the correlation coefficients between the envelopes of any pair of bands for these respective comodulated-to-independent ratios are shown along the top axis. The parameter in each panel is the bandwidth of the noise bands comprising the masker. For both the 25-Hz (circles) and 100-Hz (triangles) bandwidths, signal threshold declined as a nearly monotonic function of the comodulated-to-independent ratio. Thresholds were also generally higher in the 25-Hz bandwidth than the 100-Hz bandwidth for the smaller comodulated-to-independent ratios but converged at the higher ratios. This was confirmed by the results of repeated-measures ANOVA that tested the factors of bandwidth and comodulated-to-independent ratio. The analysis showed a significant effect of bandwidth [$F(1,5) = 11.84$; $p = 0.018$], a significant effect of the comodulated-to-independent ratio [$F(7,35) = 52.15$; $p < 0.001$], and a significant interaction between these factors [$F(7,35) = 3.56$; $p = 0.005$]. The interaction was due to the convergence of the two sets of thresholds as the comodulated-to-independent ratio increased. This convergence pattern was also captured by the within-subjects polynomial contrasts associated with the interaction, wherein only the linear term reached significance [$F(1,5) = 15.69$; $p = 0.011$].

The lower panel of Fig. 2 shows the derived masking release magnitudes (relative to the signal threshold in the independent masker) as a function of the comodulated-to-independent ratio of the masker. For the 25-Hz bandwidth, the magnitude of masking release increased monotonically with the comodulated-to-independent ratio. For the 100-Hz bandwidth, the increase in masking release appears to reach asymptote at the higher ratios, such that the difference in masking release magnitude between the two bandwidths increases at the higher ratios. This data pattern was supported by the results of repeated-measures ANOVA on the factors of bandwidth and comodulated-to-independent ratio. Whereas the main effect of bandwidth was not significant [$F(1,5) = 0.88$; $p = 0.39$], the main effect of the comodulated-to-independent ratio was [$F(6,30) = 38.02$; $p < 0.001$], as was the interaction between the two factors [$F(6,30) = 4.16$; $p = 0.004$]. The significant interaction reflects the divergence of the masking release magnitudes at the higher ratios. The inverse relationship between CMR and the bandwidth of the noise bands comprising the masker has been noted previously (Schooneveldt and Moore, 1987; Hatch *et al*., 1995). The present data set indicates that, under the conditions tested here, the increase in masking release magnitude reflects primarily an elevation in signal threshold in the 25-Hz bandwidth random masker rather than a decrease in signal threshold in the 25-Hz bandwidth comodulated masker. The higher threshold in the 25-Hz bandwidth reference condition relative to the 100-Hz bandwidth reference condition is likely the result of the perceptually salient fluctuations inherent to very narrow bands of noise that impair pure-tone detection (Bos and de Boer, 1966). The average difference of about 1.6 dB observed here is less than the 1.5 dB/octave expected for narrow bandwidths based on the study by van de Par and Kohlrausch (1999).

To assess the dependence of masking release magnitude on the degree of envelope correlation, pre-planned contrasts were undertaken to determine the comodulated-to-independent ratio at which signal thresholds first differed significantly from the independent masker condition. This analysis was carried out separately on each of the two bandwidth data sets. For the 25-Hz bandwidth, the analysis revealed that signal threshold for the 0-dB comodulated-to-independent ratio did not differ from the independent masker baseline [$F(1,5) = 1.77$; $p = 0.241$], but that thresholds for all remaining ratios did ($p < 0.01$). For the 100-Hz bandwidth, the analysis indicated that signal threshold even in the 0-dB comodulated-to-independent ratio condition had declined from baseline [$F(1,5) = 7.80$; $p = 0.037$]. These findings demonstrate that signal detection is facilitated even when the partial correlation of the noise-band envelopes across frequency is quite modest.

Five of the listeners returned at a later time to participate in the supplemental conditions wherein the signal was an independent narrow band of noise. Thresholds for this signal presented in the comodulated masker (*without* rescaling of the summed signal-plus-masker band) are shown as a filled square and diamond in the upper panel of Fig. 2 for the 25- and 100-Hz bandwidths, respectively. A repeated-measures ANOVA comparing these thresholds to their pure-tone signal counterparts indicated no effect of signal type [$F(1,4) = 2.85$; $p = 0.166$], bandwidth [$F(1,4) = 0.18$; $p = 0.693$], or interaction between these factors [$F(1,4) = 1.20$; $p = 0.336$]. Lack of an effect of signal type is compatible with the results of Fantini *et al*. (1993) who also compared signal detection for pure tone vs an independent narrow band of (non-Gaussian) noise presented in a comodulated masker, and found no consistent effect across their three listeners. Their rationale for testing this comparison was that, *a priori*, there was reason to expect that the two signals might have different effects on the summed waveform envelope. (Consideration of the remaining supplemental conditions that involved rescaling the summed signal-plus-masker band to maintain equivalence with the other masker bands is deferred to the next experiment because of the conceptual similarity of these conditions to MECP.)

In summary, the results of the CMR experiment confirm a strong dependence of masking release on the degree of envelope correlation across masker bands. For both masker bandwidths, signal detection benefited from even modest levels of envelope correlation. The minimum signal threshold in the comodulated masker was similar across masker bandwidths, but as the degree of envelope correlation diminished, thresholds in the narrower bandwidth masker increasingly diverged to higher levels. The difference in envelope statistics associated with the addition of a pure-tone signal versus a noise-band signal did not appear to be critical for CMR under the conditions tested here. Attention turns now to the companion MECP experiment that addresses the issue of envelope correlation discrimination for the same noise-band stimuli tested in the CMR paradigm.

V. PHASE 2, EXPERIMENT 2. MONAURAL ENVELOPE CORRELATION PERCEPTION: INHARMONIC STIMULI

A. Method

The subjects and noise-band stimuli were the same as in the companion Phase 2 CMR experiment. The procedure was the same as in the previous Phase 1 MECP experiment, with the addition of the condition testing the discrimination of the stimulus comprising partially correlated envelopes (signal, $r > 0$) from the stimulus comprising fully independent envelopes (standard, $r = 0$). The comodulated-to-independent ratio was adaptively varied to converge on the point at which the partially (de)correlated signal could be discriminated from the standard bands with 79.4% accuracy. When the standard stimulus was comodulated ($r = 1$), sequences of correct responses in the adaptive track led to a decrease in the degree of correlation; when the standard stimulus was independent ($r = 0$), sequences of correct responses led to an increase in the degree of correlation. The step sizes were the same as in the previous MECP experiment. A further modification incorporated into the present experiment was that a criterion was implemented to reject and replace tracks with spuriously large deviations; this criterion was a track SD > 0.15. Across all subjects and conditions this criterion was exceeded in 23 instances. At least three valid replications of discrimination threshold were collected for each condition, and the mean of all estimates was taken as the final threshold for that condition.

B. Results and discussion

The mean data are displayed in Fig. 3 for each of the combinations of noise bandwidth (25 and 100 Hz) and across-band envelope pattern (comodulated and independent) comprising the standard stimulus. The data show that the effect of the standard stimulus on the discrimination threshold depended on bandwidth. For the 25-Hz bandwidth, the comodulated-to-independent ratio at which a partially decorrelated set of noise bands could be discriminated from a set of comodulated noise bands was lower than the ratio at which a partially correlated set of noise bands could be discriminated from a set of independent bands. This difference was not observed for the 100-Hz bandwidth. The data pattern was supported by a repeated-measures ANOVA having two within-subject factors: Bandwidth (25 Hz, 100 Hz), and envelope condition of the standard (comodulated, independent). The analysis indicated no main effect of bandwidth [$F(1,5) = 1.1$; $p = 0.342$] or of standard stimulus [$F(1,5) = 2.46$; $p = 0.178$], but a significant interaction between these factors [$F(1,4) = 14.12$; $p = 0.013$]. Simple effect testing (Kirk, 1968) indicated that the envelope pattern of the standard had a significant effect for the 25-Hz bandwidth ($p = 0.03$) but not for the 100-Hz bandwidth ($p = 0.946$). Another feature of this data pattern revealed by the simple effect testing was that, for the comodulated standard stimulus, the comodulated-to-independent ratio at discrimination threshold increased as the bandwidth increased from 25 to 100 Hz ($p = 0.013$), whereas for the independent standard stimulus it decreased as the bandwidth increased ($p = 0.036$).

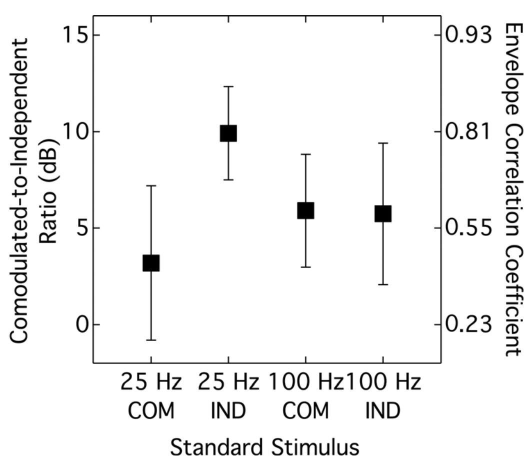

FIG. 3. Mean MECP discrimination thresholds for each of the combinations of standard stimulus noise bandwidth (25 Hz, 100 Hz) and across-band envelope pattern (comodulated [COM], independent [IND]). Left axis shows comodulated-to-independent ratio and right axis shows corresponding envelope correlation coefficient. Error bars are ±1 SD.

This pattern of MECP results indicates that when the bandwidth of the noise bands comprising the standard stimulus is 100 Hz, the degree of decorrelation needed to discriminate a partially correlated set of noise bands from either an independent set of noise bands or a completely comodulated set of noise bands is approximately the same. This degree of decorrelation, expressed in terms of the correlation coefficient between any pair of the bands, is on average about $r = 0.6$. This coefficient is lower than the $r \approx 0.85$ measured across three subjects by Richards (1987) for a pair of 100-Hz-wide noise bands. The reason for this disparity is not immediately clear, although for one of the six subjects tested here the correlation coefficient associated with the discrimination of partially correlated from fully correlated noise bands was also $r = 0.85$. It is possible, therefore, that individual differences across the two studies might underlie the disparity. For the 25-Hz bandwidth, the degree of decorrelation at the discrimination threshold was not the same for the comodulated and independent standards. When the standard was comodulated, a relatively large degree of *decorrelation* was necessary to permit discrimination. Conversely, when the standard was independent, a relatively large degree of *correlation* was necessary to permit discrimination. This suggests that, for very narrow noise bandwidths, there is a relatively wide range of envelope partial correlations that are not discriminable by a normal-hearing listener.

The intent of this study was to determine the relationship between MECP performance and CMR performance for the same subjects and stimuli. Accordingly, for each of the two bandwidths, correlation coefficients were computed between the MECP comodulated-to-independent ratios at discrimination threshold (for both $r = 1$ and $r = 0$ standards) and: (1) The signal threshold in the completely comodulated masker of the CMR experiment; (2) the signal threshold in the completely independent masker of the CMR experiment; and (3) the magnitude of CMR itself. For the 25-Hz bandwidth, the matrix of correlations indicated significant associations between the MECP discrimination threshold for the *comodulated* noise band standard and both the signal threshold in the comodulated masker ($r=-0.91$, $p=0.011$) and the magnitude of CMR ($r=0.96$, $p=0.002$); the correlation with signal threshold in the independent masker was not significant ($r=-0.28$; $p=0.585$). None of the correlations with the MECP discrimination threshold for the *independent* noise band standard were significant. For the 100-Hz-wide noise band stimulus, a significant association existed between the MECP discrimination threshold for the *comodulated* standard and the signal threshold in both the comodulated masker ($r=-0.91$, $p=0.013$) *and* the independent masker ($r=-0.82$, $p=0.045$). However, both of these correlations must be treated with caution as they were strongly influenced by the data from a single subject who had a high MECP discrimination threshold (11.2 dB) and a correspondingly low 1600-Hz signal threshold in both the comodulated (57.3 dB SPL) and independent (63.9 dB SPL) maskers. The correlation between the MECP discrimination threshold for the *comodulated* standard and CMR magnitude was not significant ($r=0.41$, $p=0.416$). As with the 25-Hz bandwidth, none of the correlations with the MECP discrimination threshold for the *independent* 100-Hz-wide noise band standard were significant. At least for the 25-Hz bandwidth, therefore, these data suggest that a listener's ability to discriminate a set of noise bands with partially decorrelated envelopes from a comodulated standard is associated with a greater acuity for signal detection in the comodulated masker and, concomitantly, a larger CMR.

It might be argued that the perceptual task of discriminating a decrease in across-frequency envelope correlation relative to $r=1$ in the MECP task, where the decorrelation applies to each of the five bands comprising the stimulus, is not equivalent to the CMR task where four of the five bands remain comodulated when the signal is added to the fifth band. An experimental manipulation that addresses this argument is the one incorporated into the second set of supplementary conditions in the CMR experiment (Phase 2, Experiment 1) where the summed signal-plus-masker band was rescaled to maintain a level equivalent to the remaining four bands. Here, signal detection relies on sensitivity to the decorrelation of the signal-plus-masker band envelope relative to the remaining comodulated envelopes. These data, expressed as comodulated-to-independent ratios in dB for the five listeners, are shown as open symbols in Fig. 4, with the closed symbols showing the complementary MECP data from the main data set. Symbols on the abscissa with a downward-pointing arrow indicate an inability to obtain a reliable threshold at the limits of the task. It is evident that detecting decorrelation for a single band of noise relative to comodulated flanking bands is much more difficult for all listeners relative to the MECP case where all five bands are decorrelated (open symbols are all below the corresponding filled symbols). Two of the listeners could not perform the task at the 100-Hz bandwidth, and one of these could not perform the task also at the 25-Hz bandwidth.[4] Nevertheless, for each bandwidth (25- and 100-Hz), Pearson bivariate correlations were undertaken between the threshold comodulated-to-independent ratio in the supplementary condition and: (1) The corresponding ratio in the main MECP condition; (2) the pure-tone threshold in the comodulated CMR condition (CMR experiment, Phase 2); and (3) the magnitude of CMR in this latter condition. For these analyses, the task limit of a comodulated-to-independent ratio of -25 dB was used in the three instances where listener performance encroached on the limit in the supplementary conditions. For the 25-Hz bandwidth, all three correlations were significant (one-tailed): (1) $r=0.84$, $p=0.04$; (2) $r=-0.91$, $p=0.016$; and (3) $r=0.91$, $p=0.017$. For the 100-Hz bandwidth, only the correlations with the main MECP condition ($r=0.86$, $p=0.03$) and the magnitude of CMR ($r=0.82$, $p=0.044$) were significant (one-tailed), although the trend for the correlation with the pure-tone signal threshold in the CMR condition was in the expected direction ($r=-0.783$, $p=0.06$). Thus, despite the overall poorer thresholds in the supplementary conditions where only one of the bands was decorrelated relative to the main MECP conditions where all five bands were decorrelated, it is nevertheless the case that listeners who are more sensitive to across-frequency envelope correlation tend to exhibit larger CMRs for similar stimulus configurations.

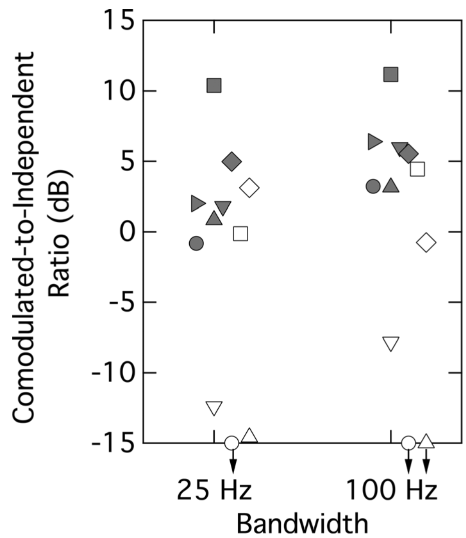

FIG. 4. Individual MECP discrimination thresholds (comodulated-to-independent ratios in dB) for each noise bandwidth (25 Hz, 100 Hz). Open symbols indicate conditions where just the center noise band was decorrelated; filled symbols indicate conditions where all five bands were decorrelated. Symbols with arrows on the abscissa indicate performance beyond the limits of the adaptive track.

VI. GENERAL DISCUSSION AND CONCLUSION

This study examined both CMR and MECP as a function of the degree of envelope correlation for the same stimulus set. Although it is clear that the phenomena of CMR and MECP both involve the correlation of amplitude envelopes, there are several strands of evidence that suggest a distinction between them. First, the two phenomena show disparate bandwidth effects: CMR is maximal for relatively narrow bands of noise (Moore and Schooneveldt, 1990; Eddins and Wright, 1994), whereas MECP declines with reducing bandwidth—at least over the range of bandwidths tested here (Moore and Emmerich, 1990; Buss *et al.*, 2013). Indeed, recent work in our laboratory indicates that MECP is viable for masker bandwidths as wide as 1600 Hz (Buss *et al.*, 2013), a bandwidth for which inherent envelope fluctuations are highly unlikely to support a CMR, although this remains to be tested. Second, models of CMR that are based on sensitivity to across-frequency decorrelation brought about by the addition of a signal appear to fail under some circumstances. For example, decorrelating only the peak portions of the masker with the addition of a signal does not result in a masking release (Moore *et al.*, 1990). Also, CMR can be observed under conditions where the signal does not result in any envelope decorrelation (Hall and Grose, 1988; Buss, 2010).

Some aspects of the present data offer further support for the distinction between CMR and MECP. Here, the magnitude of CMR continued to vary monotonically within a range of envelope correlation values that were not discriminable in the MECP paradigm. This pattern of results suggests that the envelope statistics providing optimal cues for MECP are not entirely the same as those that facilitate CMR; i.e., factors such as fluctuation rate and duration of envelope minima likely play different roles across the two phenomena. In light of this, it is probable that the relative balance observed here between MECP and CMR would be different if other noise band parameters were tested. For example, just as CMR was observed here for degrees of envelope correlation that were not discriminable to the listener, it is likely that negligible CMR would be observed for wide bandwidths (e.g., 1600 Hz) where significant envelope discrimination has been measured (Buss *et al.*, 2013). In addition, the overall number of noise bands might also affect the pattern of results; CMR magnitude approaches asymptote once the number of proximal flanking bands exceeds two, but the effect of band number has not been systematically tested for MECP (cf. Hall *et al.*, 1990; Hall and Grose, 1993).

Some aspects of the present data, however, suggest commonalities between CMR and MECP. The results of Phase 2 indicate a strong association between performance on the MECP task when the standard stimulus was a set of comodulated 25-Hz-wide bands and both the magnitude of CMR and the signal threshold level in the comodulated masker. There was a trend for a similar association in Phase 1 between CMR magnitude and MECP threshold; here, the bandwidth of the noise bands was 20 Hz. For the 100-Hz bandwidth in Phase 2, a significant association was also observed between MECP threshold and CMR, but this correlation was strongly influenced by the results of one subject. This pattern suggests that listeners who are very sensitive to degree of envelope correlation also exhibit large CMRs, and vice versa. The results of the supplemental conditions that maintained level equivalence across the noise bands also bolster this suggestion. Of course, it does not logically follow that the same cues are being used in the MECP and CMR tasks—only that some listeners appear to be better "envelope processors" than others.

The key observation that CMR magnitude varies within a range of envelope correlation values that are not discriminable in the MECP paradigm raises other questions relevant to CMR. For example, it is known that a temporal fringe comprising independent noise bands can reduce the benefit of comodulated flanking bands during a subsequent segment comprising comodulated noise bands (Grose *et al.*, 2009). However, based on the present findings it is not clear whether a similar effect would be observed with a temporal fringe made up of partially-correlated noise bands that are perceptually indiscriminable from independent noise bands. It would also be informative to examine the magnitude of CMR as a function of the degree of envelope correlation between the masking noise band centered on the signal and the remaining comodulated flanking noise bands in a paradigm similar to that used here; this focus would be distinct from that of previous studies whose focus has been on comparative envelope patterns between the noise band centered at the signal frequency and the remaining masking bands (McFadden, 1986; Moore and Schooneveldt, 1990; Eddins and Wright, 1994; Buss and Richards, 1996; Grose *et al.*, 2001; Buss *et al.*, 2009). Finally, the observation that the difference in CMR magnitude for the 25- and 100-Hz noise bandwidths is driven by signal threshold in the independent masker baseline and not in the comodulated masker invites further investigation.

In summary, the present study established that the magnitude of masking release for a signal masked by a complex of narrow bands of noise varies systematically as a function of the degree of correlation across the noise-band envelopes. This variation in signal threshold occurred even for ranges of envelope correlation that were not perceptually discriminable in the MECP paradigm. Although this demonstrates that CMR and MECP exhibit different dependencies on the degree of envelope correlation, the data also show some commonality across the two phenomena. Specifically, for narrow bands of noise, there is a robust relationship between sensitivity to decorrelation from an otherwise comodulated set of noise bands and the magnitude of CMR measured for those same comodulated noise bands.

ACKNOWLEDGMENTS

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[1]These correlation coefficients were computed using a MATLAB simulation wherein pairs of 20-Hz-wide noise bands having prescribed comodulated-to-independent ratios were digitally generated, the envelopes extracted using the Hilbert transform, and the Pearson product moment between pairs of envelopes calculated. For each given comodulated-to-independent ratio, the process was repeated 1000 times to obtain an average correlation coefficient. Although there has been a vigorous debate about whether cross-correlation or cross-covariance is the appropriate metric with which to quantify degree of envelope similarity (e.g., Bernstein and Trahiotis, 1996), the Pearson product moment correlation was selected here for two reasons: (1) It is the metric used in the study of Richards (1987), to which the present data are compared; and (2) the point of interest of this study is the comparative performance across CMR and MECP for the same stimuli, and hence the precise metric of envelope similarity is less important.

[2]Note that these correlation coefficients represent the long-term average values for any pairing of the noise-band envelopes across the matrix of five bands—including the pairing of each flanking noise band with the center band at the signal frequency. However, for any brief interval the pair-wise coefficients across the four pairings of the center band and each of the four flanking bands are likely to differ, except in the comodulated case.

[3]Initial plans called for inclusion of this complementary condition where the listener's task was to detect an increase in correlation from $r = 0$ (i.e., independent standard). However, preliminary testing indicated that

comparatively few listeners were able to attain a stable performance on this second condition, and therefore it was suspended.

[4]Interestingly, these two listeners who could not perform the task in at least one of the supplementary conditions, where all the stimuli were gated, had no difficulty obtaining reliable signal thresholds when the comodulated noise bands were presented continuously and the (rescaled) signal band was added during the target observation interval. This suggests that grouping cues associated with synchronous gating may have interfered with the ability to discriminate a decorrelation of the signal-plus-masker band envelope.

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