Effects of frequency and amplitude modulation on the pitch of a complex tone with a mistuned harmonic

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It has previously been found that when a single low-numbered harmonic of a complex tone is progressively mistuned, for mistunings up to about 3%, the pitch of the complex changes in the direction of the mistuning but for larger mistunings (by about 8%) the pitch returns to its original value. This result is compatible with the operation of a mechanism such as a graded harmonic sieve, which can reject from the calculation of pitch those frequency components that are implausibly distant from a harmonic frequency. The first experiment shows that the tolerance of such a sieve is increased when all the components of the complex tone (including the mistuned component) share a common pattern of frequency modulation at a rate of 6 Hz. The second experiment shows that the tolerance of the sieve is not increased when the components share a common pattern of amplitude modulation at 17 Hz. The third experiment replicates these findings and further shows that the increase in sieve tolerance for FM, but not for AM, occurs at both 6 and at 17 Hz.

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INTRODUCTION

Our everyday experience shows that the human auditory system is able to perceive the appropriate pitch of individual instruments or voices when more than one sound source is present. It is well established that the pitch of a complex tone is predominantly determined by the frequencies of its (resolved) low-numbered harmonics, but when more than one pitch is present at a time, how does the system determine which harmonics should contribute to the pitch of which complex tone? Three factors that affect such allocation are harmonicity, lateralization, and onset asynchrony.

When a low-numbered harmonic of a complex is progressively mistuned, the pitch of the complex changes. The pitch change reaches a maximum at about 3% mistuning and by about 8% mistuning the pitch of the complex has returned to its original value (Moore *et al.*, 1985). This variation of pitch with mistuning can be modeled by assuming that the contribution that a harmonic makes to the pitch of a complex declines with mistuning following a Gaussian envelope (Darwin, 1992). The width of the distribution defines the tolerance of the pitch mechanism to mistuning.

If the (3%) mistuned harmonic is led to the opposite ear to that receiving the other components of the complex tone, it still contributes to the pitch, although this contribution is slightly reduced (Darwin, 1992). This finding is in keeping with previous work on the perception of simultaneous pitches with harmonic two-tone complexes (Beerends and Houtsma, 1986). Lateral position, then, determines only weakly how much a frequency component contributes to the pitch of a particular complex tone.

Onset asynchrony also influences the contribution that a (3%) mistuned harmonic makes to the pitch of a complex. When the mistuned component leads the remaining components of a complex by more than about 80 ms, the associated change in pitch of the complex is reduced. An onset asynchrony of about 300 ms is needed to prevent the mistuned component making any contribution to the complex's pitch (Darwin and Ciocca, 1992). Since this contribution can be reinstated by manipulations that cause the leading part of the mistuned component to be grouped separately from its continuation, it is likely that the effect of onset asynchrony is largely due to auditory grouping rather than to a peripheral mechanism such as auditory-nerve adaptation (Ciocca and Darwin, 1993). Whatever the mechanism though, it is clear that onset asynchrony can strongly influence which frequency components contribute to the pitch of a complex tone.

A fourth and a fifth factor, common frequency or amplitude modulation, are the subject of the present paper. Experiment 1 deals with frequency modulation (FM), experiment 2 with amplitude modulation (AM), and experiment 3 with both.

The pitch excursions of speech and musical sounds impose a common FM on harmonics. This common pattern of movement could in principle indicate to the auditory system that the harmonics originate from a common source. But the actual use that the auditory system makes of common FM appears to be surprisingly limited. Although a vowel presented against a background of other vowels becomes more prominent when its fundamental frequency is modulated than when it is static, this prominence is the same whether the background vowels have the same or a different pattern of FM (McAdams, 1989). In addition, differential patterns of FM do not help the listener to identify one vowel against a vowel-like background (Summerfield and Culling, 1992), or to segregate a particular harmonic (Gardner and Darwin, 1986) or formant (Gardner *et al.*, 1989) from the perception of vowel quality. A basic psychophysical limitation that may underly these results has been proposed by Carlyon (1991). Carlyon found that listeners cannot *directly* detect the difference between coherent and incoherent FM across different groups of harmonics. Listeners are unable to discriminate between stimuli in which two sets of (inharmonic) components have coherent FM and stimuli in which two sets of components have incoherent FM. The most obvious way in which this difference can be detected *indirectly* is by the breakdown in otherwise harmonic relations that incoherent FM necessarily causes. Although Carlyon's claim has been challenged, more recent evidence (Carlyon, 1994) strongly supports the original proposal.

Although there is no evidence that frequency components can be grouped differentially according to different patterns of frequency movement, it is still possible that, in pitch perception, common FM may increase the tolerance of the system to mistuning. This prediction is compatible with a view of the role of frequency modulation in auditory grouping expressed by Carlyon (1994). If a set of frequency components maintain a (roughly) harmonic relation when they are frequency modulated then they are more likely to be from a common source than if they merely maintain harmonic relations while being static.

I. EXPERIMENT 1

The first experiment asks whether a mistuned component of a complex will contribute to its pitch at greater mistunings when all the frequency components are frequency modulated coherently than when all the components are unmodulated. It uses the pitch-matching paradigm introduced by Moore *et al.* (1985) and subsequently used by the present authors (Darwin and Ciocca, 1992; Ciocca and Darwin, 1993).

A. Method

On each trial subjects heard two complex tones to the left ear: a target tone followed by an adjustable comparison tone. Their task was to adjust the pitch of the second tone to match that of the first. The first tone could have its fourth harmonic mistuned by various amounts, but the second tone was always strictly harmonic (though varying in fundamental). Both target and comparison tones had 12 equal amplitude (58 dB SPL) frequency components. The comparison tone consisted of the first 12 harmonics of a fundamental around 155 Hz. The target tone had harmonics 1–3 and 5–12 of a 155-Hz fundamental, with the fourth harmonic mistuned by different amounts in different trials. The actual frequencies of the mistuned component were 550, 570, 580, 590, 600, 610, 620 (harmonic frequency), 630, 640, 650, 660, 670, or 690 Hz, corresponding to mistunings of −11.3%, −8.0%, −6.4%, −4.8%, −3.2%, −1.6%, 0%, +1.6%, +3.2%, +4.8%, +6.4%, +8.0%, and +11.3%, respectively. The target and comparison sounds each lasted 500 ms (including 5-ms rise/fall raised cosine ramps) and were separated by 500 ms of silence.

Both the target (plus mistuned component) and the comparison were either frequency modulated (FM6 condition) or unmodulated (NoM condition). In the FM6 condition, all the components were sinusoidally frequency modulated at a rate of 6 Hz, with a starting phase of 0 deg. The modulation depth was ±5%. These modulation values are similar to those used in the previous studies reviewed above and are comparable to the vibrato found in musical instruments and in singing (Horii, 1989). A modulation depth of ±5% corresponds to a variation of ±84.5 cents at each component frequency. When the target was frequency modulated, the matching tone was also frequency modulated so subjects always adjusted an FM6 comparison to match an FM6 target, or a NoM comparison to a NoM target.

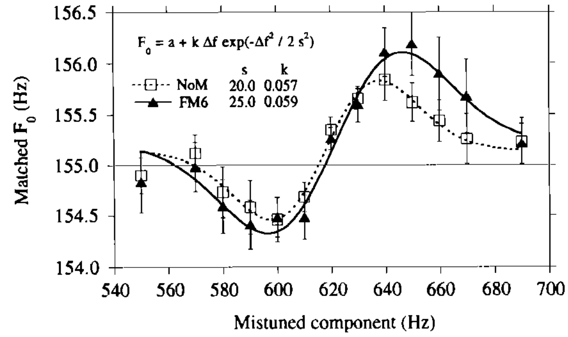

FIG. 1. Shift in matched fundamental frequency in experiment 1 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or ±5% FM at 6 Hz.

There were 26 experimental conditions in total (13 frequencies of mistuning by FM6 vs NoM condition). Each of these conditions was replicated six times in all across four counterbalanced experimental sessions blocked by FM6 vs NoM. Pairs of sessions (one FM6 and one NoM) were run on separate days. Six musically trained listeners participated, all of whom had taken part in previous pitch-matching experiments.

Stimuli were generated in real time using custom software for the 56001 processor on an Audiomedia board controlled by a Mac IIci. Subjects adjusted the pitch of the comparison sound using a rollerball. Further details of the experimental method are in Darwin and Ciocca (1992).

B. Results

The average matched fundamental frequencies to each of the 26 experimental conditions, averaged across the six subjects, are shown in Fig. 1 together with their standard errors. The data replicate previous work using this paradigm, with significant variation in the matched fundamental frequency as the frequency of the mistuned component is varied [$F(12,60)=11.5$, $p<0.0001$]. The data are fitted with a function that is based on the assumption that the contribution that a mistuned harmonic makes to pitch decreases with mistuning according to a Gaussian envelope. The predicted matched fundamental frequency in Hz (F_0) thus consists of a constant (a) plus a term that is proportional to the mistuning in Hz (Δf) multiplied by a constant (k) times a Gaussian function of Δf with a standard deviation s.

$$F_0=a+k\Delta f\,\exp(-\Delta f^2/2s^2).$$

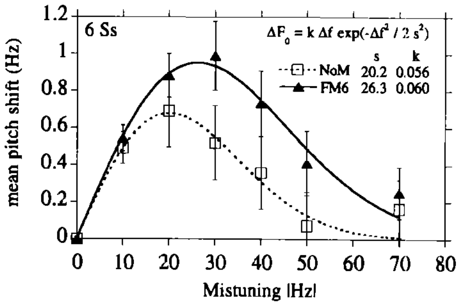

FIG. 2. Mean shift in matched fundamental frequency in experiment 1 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or ±5% FM at 6 Hz.

The parameters a, k, and s were optimized for each curve fit. This curve provides a good fit to both the NoM and the FM6 data explaining 96% of the variance in both cases. Although the overall scaling factor, parameter k, is very similar for the two curves, the parameter s (the standard deviation in Hz of the underlying Gaussian) differs. This parameter provides a measure of the tolerance of the harmonic sieve, the maximum and minimum values of the function occurring at $\pm s$. The parameter s increases from 20.0 for the NoM condition to 25.0 for the FM6 condition. This difference in shape of the curves is reflected in a significant interaction in a repeated-measures analysis of variance [$F(12,60) = 4.44$, $p < 0.0001$].

Mean shifts in pitch matches for each absolute value of mistuning were calculated as half the difference between the pitch matches to positive and negative mistunings. Figure 2 shows these mean shifts together with their standard error across the six subjects and also the best-fitting curves on the same model as above (but omitting parameter a). The pattern of mean shifts for the NoM condition replicates earlier findings using this paradigm. The maximum occurs at around 3% (or c.20 Hz) mistuning. For the FM6 condition, the pitch shifts follow a different pattern, with the maximum shift occurring at a greater level of mistuning as reflected in the larger s parameter (26.3 for the FM6 condition, 20.2 for the NoM condition). Standard errors are not noticeably larger in the FM6 condition.

The significance of this difference between the two modulation conditions was assessed with a two-way ANOVA on the mean shifts; the factors were "level of mistuning" and "modulation." FM6 stimuli produced larger overall shifts than NoM {main effect of "modulation" [$F(1,5) = 10.11$, $p < 0.05$]}. Pitch shifts in the FM6 conditions were significantly larger than those for the NoM conditions at mistunings of 20 Hz ($p < 0.05$), 30 Hz ($p < 0.0001$), 40 Hz ($p < 0.0001$), and 50 Hz ($p < 0.005$; planned comparisons). In addition, the interaction between mistuning and condition was statistically significant [$F(5,25) = 5.08$, $p < 0.005$].

C. Discussion

Experiment 1 has shown that when all the components of a complex are frequency modulated, a mistuned component contributes to the pitch of the complex at greater degrees of mistuning than if there is no FM. In other words, the pitch perception mechanism is more tolerant of mistuning when the components are frequency modulated than when they are not frequency modulated. What the experiment has not established is whether this advantage for modulated signals depends on whether or not there is a common (coherent) pattern of FM across all the components. Unfortunately, the present paradigm is not able to address this question. FM that is incoherent between the mistuned component and the remainder would dynamically alter the degree of mistuning. It would therefore be difficult to predict what pitch shift to expect on the null hypothesis that the tolerance for mistuning had not changed. It may be the case that the effect of FM that we have found is not due to the components having a *common* pattern of FM, but merely to all the components being modulated rather than static.

II. EXPERIMENT 2

Two types of experiment have provided evidence that different frequency regions may be perceptually grouped together if they share a common pattern of AM. First, a common pattern of AM between two noise bands remote in frequency can increase the detectability of a tone centered in one of them (Hall *et al.*, 1984). This "comodulation masking release" (CMR) may arise partly from the auditory system grouping together noise bands that share a common pattern of AM (Hall and Grose, 1990). Second, perceptual grouping of frequencies that share a common pattern of AM may also be responsible (Moore, 1992; Moore and Shailer, 1992) for part of the effect known as "modulation detection (or discrimination) interference" (MDI). MDI is the impairment in detection of a change in the depth of AM of one tone in the presence of a similarly modulated tone at a different frequency (Yost and Sheft, 1989; Moore *et al.*, 1991; Moore, 1992).

Using a threshold task similar to that used by Demany and Semal (1990), Summerfield and Culling (1992) have found no evidence for auditory grouping for vowel identification based on differential rates or phases of AM. They obtained identification thresholds for vowels masked by other vowel-like sounds. They found no change in the thresholds when the vowels and the maskers had different rates of AM (2.5 Hz for the target and between 3.4 and 19 Hz for the maskers). In addition, they showed that the small effects of differential AM phase that they found were more than accounted for by local variations in target/masker S/N ratio.

Both CMR and MDI are tasks that measure minimum detectable differences. The only evidence that grouping by AM is used in suprathreshold tasks (including speech perception) comes from experiments that have used rates of AM in the pitch range. For instance, Bregman *et al.* (1990) asked subjects to rate how clearly they could hear a 3-kHz tone amplitude modulated at 125 Hz when mixed with another tone (around 2 kHz) that was either amplitude modulated at the same or at a different rate. Subjects found it easier to hear out the higher tone when the modulation rates of the two tones were different. Using a different paradigm, Carrell and Opie (1992) measured the phonetic accuracy with which listeners could recognize sine-wave speech consisting of three tones that tracked the formant frequencies of short sentences. Their accuracy improved from about 60% to over 90% when each of the three tones was amplitude modulated at 100 Hz. This improvement was reduced by about 20% when the three tones had different amplitude modulation rates (97, 79, and 113 Hz).

Experiment 2 asks whether coherent AM at a subpitch rate (similar to rates used in the detection experiments referred to above) can influence whether a mistuned harmonic contributes to the pitch of a complex tone.

A. Method

The experimental stimuli were similar to those employed in the previous experiment, except that amplitude modulation (AM) was used instead of frequency modulation. The NoM condition was identical to the NoM condition of experiment 1. In the AM17 condition, the components were amplitude modulated by a 17-Hz sinusoidal function with a starting phase of 0 deg. The extent of the modulation was 50%. The choice of 17-Hz rate, instead of 6 Hz as in the FM experiment, was influenced by three factors. First, unpublished experiments by the present authors showed that a mistuned component in an unmodulated target gave pitch shifts that were virtually identical when the mistuned component was either unmodulated or slowly modulated (5, 7, or 11 Hz), but were slightly though insignificantly reduced when the mistuned component had a 17-Hz modulation rate; second, the size of that part of the CMR that is attributable to across-frequency comparison of envelopes probably varies little with modulation rate, except at very high rates (Carlyon *et al.*, 1989); third, although MDI declines monotonically with modulation rate, substantial MDI still occurs at 20 Hz (Yost *et al.*, 1989). Six subjects participated in this experiment (three of whom had participated in the FM experiment). Five subjects were musically trained. The procedure and the structure of the sessions were the same as in the first experiment.

B. Results

Mean shifts in pitch matches, calculated in the same way as in the previous study, are displayed in Fig. 3. The results of the NoM condition replicate those of the (identical) NoM condition in experiment 1 (the slightly smaller pitch shifts in the NoM condition here than in the NoM condition of experiment 1 are attributable to the fact that three of the six subjects are different). However, unlike experiment 1, the addition of AM produces no detectable change in the pitch shifts.

A two-way ANOVA was applied to the mean shifts, with the "modulation condition" and "mistuning" as experimental factors. Only the effect of "mistuning" was found to be statistically significant [$F(5,25)=9.59$, $p<0.0001$]. Unlike frequency modulation, introducing amplitude modulation did not affect either the overall size of

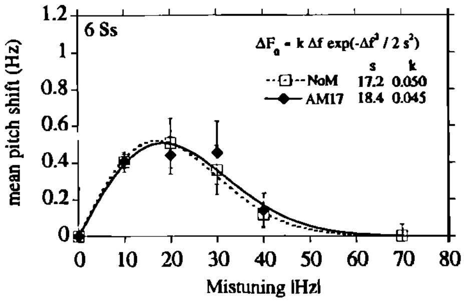

FIG. 3. Mean shift in matched fundamental frequency in experiment 2 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or 50% AM at 17 Hz.

pitch shifts or the amount of mistuning which gave maximal pitch shifts.

III. EXPERIMENT 3

The two previous experiments have shown a possible difference between the effect of amplitude and frequency modulation on grouping for pitch perception. But the two experiments used different rates of modulation. The third experiment aims to replicate and extend the first two experiments, removing the confounding variable by using each type of modulation at both rates.

A. Method

The method was essentially the same as in the first two experiments, except that there were five experimental conditions: three of which, NoM, FM6, and AM17, were identical to those used in the earlier experiments, together with two new conditions at the complementary rates FM17 and AM6. Eleven subjects took part in the experiment but one was excluded for failing to give consistent enough results. One subject of the remaining ten had also taken the first two experiments. Each condition was taken in two blocks of three replications at each mistuning. The order of the blocks was counterbalanced across subjects.

B. Results

The matched fundamental frequencies, averaged across the ten subjects, are shown in Figs. 4 and 6. The

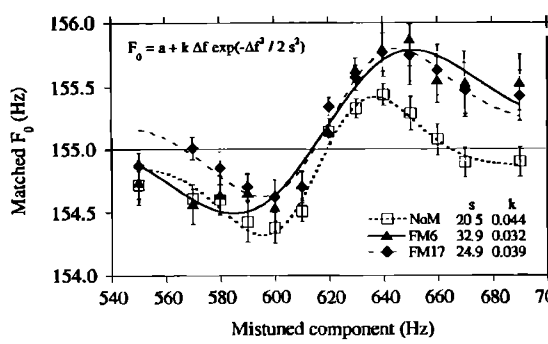

FIG. 4. Shift in matched fundamental frequency in experiment 3 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or 6% FM at 6 or 17 Hz.

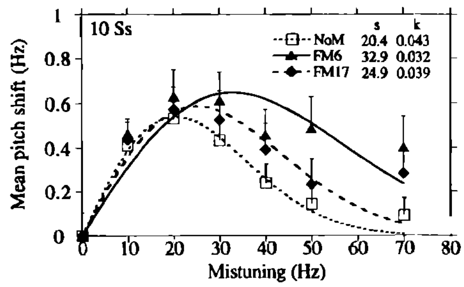

FIG. 5. Mean shift in matched fundamental frequency in experiment 3 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or 6% FM at 6 or 17 Hz.

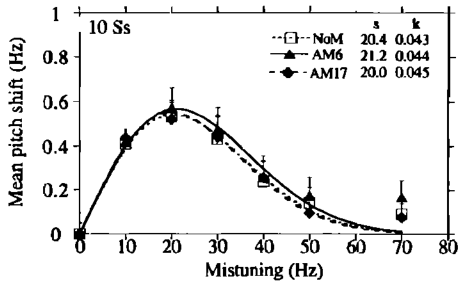

FIG. 7. Mean shift in matched fundamental frequency in experiment 3 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or 50% AM at 6 or 17 Hz.

data replicate the results of experiment 1 for the NoM and FM6 conditions. The s parameter of the fitted curve is smaller for the NoM ($s=20.5$; 96% of variance) than for the FM6 condition ($s=32.9$; 93% of variance) indicating that FM at 6-Hz increases the tolerance of the harmonic sieve. The new condition FM17 falls between the two ($s=24.9$; 92% of variance). The differences in shape of the curves are reflected in significant interactions in analyses of variance comparing the NoM condition with either FM6 [$F(12,108)=3.4$, $p<0.0005$] or FM17 [$F(12,108)=2.4$, $p=0.007$]. A very similar picture emerges for the mean shifts shown in Fig. 5, although the curve fits here are less good (66% of variance for FM6 and 72% of variance for FM17).

For the corresponding AM conditions (shown in Figs. 6 and 7) the results are quite clear. AM has no effect at either rate. An analysis of variance on the matched fundamental frequency data comparing all the FM conditions with all the AM conditions showed that overall the AM and FM conditions differed [$F(1,9)=12.4$, $p<0.007$] and gave a significant interaction with mistuning [$F(12,108)=3.2$, $p<0.001$]. The mean shift data also show a significant difference between the average FM and the average AM data [$F(1,9)=8.2$, $p<0.02$].

IV. SUMMARY AND GENERAL DISCUSSION

The three experiments presented here have shown that: (i) a mistuned component in an otherwise harmonic complex continued to contribute to the pitch of that complex at larger mistunings when all the harmonics shared a common FM (6 or 17 Hz, ±5%), than when there was no FM; and (ii) there was no similar effect of common AM (6 or 17 Hz, 50%).

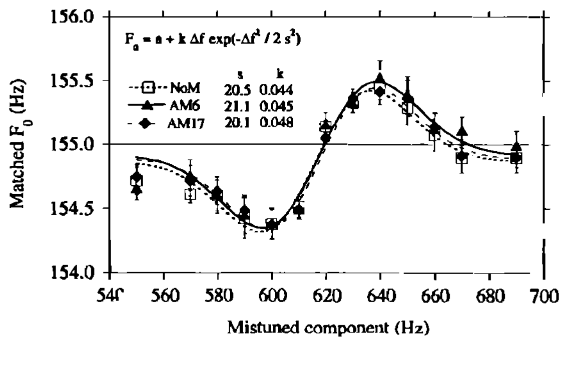

FIG. 6. Shift in matched fundamental frequency in experiment 3 when the fourth harmonic of a 155-Hz fundamental is mistuned. All components received either no modulation or 50% AM at 6 or 17 Hz.

The effect found in experiments 1 and 3 of FM increasing the tolerance of pitch perception to mistuning shows that the auditory system is more likely to group together sounds that are coherently modulated than those that are unmodulated. We cannot conclude that this effect is due to the coherence of the modulation because of (i) our inability to run an appropriate control (using this paradigm) for whether incoherent FM would have given similar results and (ii) the previous findings reviewed in the Introduction which showed that listeners are unable to group sounds *differentially* on the basis of differences in FM.

The most plausible conclusion from the present and previous studies is that both coherent and incoherent FM can help to bind together frequency components, but that FM cannot be used to segregate sound differentially on the basis of different FM rates or phases. One argument that has been used in support of this somewhat surprising inability of the auditory system to exploit coherent FM, is that coherent FM is naturally found only in sounds that already share harmonicity (Summerfield, 1992; Summerfield and Culling, 1992). Harmonic relations are so powerful that it has perhaps not been worth developing an FM mechanism that may be computationally expensive. The contribution of the present paper has been to show that (necessarily coherent) FM can alter the tolerance of the pitch perception mechanism to inharmonicity. Carlyon (1994) has suggested a possible reason why the pitch perception mechanism may be more tolerant of inharmonicity in sounds that are also moving than in sounds that are stationary. His argument is that if moving sounds maintain (roughly) harmonic relations, they are more likely to have originated from a common source than are stationary sounds where the harmonicity of a component from a different sound source may be purely fortuitous.

Experiments 2 and 3 failed to find any effect of coherent AM on the pitch perception mechanism's tolerance of inharmonicity. An inability of the system to exploit common AM is also reported in two recent experiments on the recognition of speech sounds in noise. First, Summerfield and Culling (1992) found that identification thresholds for target vowels masked by other vowel-like sounds were not lowered by imposing differential rates of AM on the target and the masker. A second study by Grose and Hall (1992) used a CMR paradigm. They measured detection thresholds and intelligibility for sentences that had been filtered into seven narrow passbands, each masked by uncorrelated noise that could have additional comodulated sidebands, located at frequencies between the seven passbands. Although the presence of these comodulated sidebands improved detection thresholds, it did not improve speech intelligibility. The authors concluded that "CMR is most evident in masked detection tasks and that diminishing returns are encountered as the signal-to-noise ratio is increased" (p. 1042).

Low-frequency AM in a particular frequency channel may in general be a less reliable feature for the auditory system to exploit for grouping than is FM, since many complex sounds (such as speech) will have at least partially uncorrelated AM changes across different frequency channels as, for instance, formant peaks change in frequency. It would be unfortunate if pitch perception broke down for sounds with dynamic changes in timbre.

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