Detection of frequency modulation at low modulation rates: Evidence for a mechanism based on phase locking

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These experiments tested the hypothesis that detection of frequency modulation (FM) at very low rates depends mainly on temporal information (phase locking to the carrier) for carriers below about 5 kHz, whereas FM detection at higher rates (10 Hz and above) depends mainly on changes in the excitation pattern (a ''place'' mechanism). In experiment 1, thresholds for detecting FM were measured for a wide range of carrier frequencies (0.25–6 kHz) for modulation rates, f_m, of 2, 5, 10, and 20 Hz. Thresholds were determined when FM only was present and when the carriers in both intervals of a forced-choice trial were amplitude modulated at the same rate as the FM with a modulation index of 0.333. The phase of the amplitude modulation (AM) relative to the FM was randomly selected on each trial, in order to disrupt cues for FM detection based on changes in the excitation pattern. For carrier frequencies up to 4 kHz, the deleterious effect of the added AM increased with increasing f_m. For the 6-kHz carrier, the deleterious effect was independent of f_m. In experiment 2, psychometric functions were measured for detecting combined FM and AM of a 1-kHz carrier, with $f_m=2$ Hz, as a function of the relative phase of the modulators. The modulation depths for AM and FM were chosen so that each would be equally detectable if presented alone. This was done both in quiet and in the presence of noise designed to mask either the lower or the upper side of the excitation pattern. In contrast to earlier results obtained with $f_m=10$ Hz [Moore and Sek, J. Acoust. Soc. Am. **96**, 741–751 (1994)], only small effects of relative modulator phase were found. Experiment 3, was similar to experiment 2, except that all measurements were done in quiet, and carrier frequencies of 0.25, 1.0, and 6.0 kHz were used. There were no effects of relative modulator phase for the 0.25-kHz carrier, small effects for the 1-kHz carrier, and large effects for the 6-kHz carrier. The pattern of results is consistent with the hypothesis that both temporal and place mechanisms are involved in FM detection. The temporal mechanism dominates for carriers below about 4 kHz, and for very low modulation rates. The place mechanism dominates for high carrier frequencies, and for lower carrier frequencies when stimuli are frequency modulated at high rates. © *1996 Acoustical Society of America.*

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INTRODUCTION

Traditionally, there have been two classes of theory to explain the ability to detect frequency changes in sinusoids. One class assumes that frequency discrimination is based on changes in the place distribution of activity in the auditory system. For example, Zwicker (1956, 1970) proposed a model based on the concept of the excitation pattern. He suggested that a change in frequency could be detected if the excitation pattern changed at any point by more than about 1 dB. We have proposed a similar model, but one in which information is combined from all points of the excitation pattern (Moore and Sek, 1994). Although these models are based on excitation patterns derived from psychoacoustic data, it is generally assumed that the excitation pattern is related to a rate-place representation in the peripheral auditory system, i.e., it is related to the driven neural firing rate as a function of characteristic frequency, and does not depend on neural synchrony (phase locking) to the fine structure of the stimulus.

The alternative class of theory assumes that frequency discrimination is based on information contained in the temporal patterns of firing in the auditory nerve (phase locking) (Siebert, 1970; Goldstein and Srulovicz, 1977). Note that phase locking here refers to synchronization to the audio frequency, rather than to any subaudio modulation that the stimulus might contain. However, phase locking to sinusoids appears to break down above 4–5 kHz in the mammalian auditory nerve, so this mechanism probably does not work over the whole audible frequency range.

It is possible that the mechanisms involved in frequency discrimination vary depending on the exact nature of the stimuli. Frequency discrimination has been measured using two main methods. One method involves the detection of frequency modulation (FM) (Shower and Biddulph, 1931; Harris, 1952; Zwicker, 1952; Jesteadt and Sims, 1975; Moore, 1976; Moore and Glasberg, 1989; Sek and Moore, 1995). Typically, the subject is required to distinguish an unmodulated sinusoid from a sinusoid that is frequency modulated at a low rate. We will refer to thresholds measured in this way as frequency modulation detection limens (FMDLs). A second method involves presenting a pair of successive tone pulses differing in frequency, and requiring the subject to indicate whether the first or second was higher in frequency (Harris, 1952; Moore, 1973; Wier *et al.*, 1977;

Nelson *et al.*, 1983; Moore and Glasberg, 1989). We will refer to thresholds measured in this way as difference limens for frequency (DLFs).

There is evidence that different mechanisms determine FMDLs and DLFs. For example, the variation of DLFs with center frequency is somewhat different from the variation of FMDLs (Moore, 1974; Wier *et al.*, 1977; Coninx, 1978; Demany and Semal, 1989; Moore and Glasberg, 1989; Sek and Moore, 1995), although Demany and Semal (1989) found that the variation was similar for FMDLs and DLFs determined with 25-ms tone bursts, for frequencies up to 2 kHz. Also DLFs and FMDLs are poorly correlated across subjects (Harris, 1952; Moore, 1976). Moore and Glasberg (1986) measured FMDLs and DLFs in hearing-impaired subjects, and also estimated the shapes of the auditory filters in the same subjects. They concluded that it was not possible to account for both FMDLs and DLFs with an excitation-pattern model of the type proposed by Zwicker. On the whole, excitation-pattern models appear to work better in accounting for FMDLs than for DLFs (Moore and Glasberg, 1989; Sek and Moore, 1995).

Moore and Sek (1995) suggested that both place mechanisms and temporal mechanisms may contribute to the detection of FM, the relative contribution of the two depending on the carrier frequency and modulation rate. They measured psychometric functions for the detection of amplitude modulation (AM) or FM, using a 2AFC task. Carrier frequencies were 125, 1000, and 6000 Hz, and modulation rates were 2, 5, and 10 Hz. For the two lower carrier frequencies, FM detection tended to be best at the lowest modulation rate while AM detection was best at the highest rate. For the 6000-Hz carrier, both AM and FM detection tended to be poorest at the lowest modulation rate. Sek and Moore (1995) confirmed some of these findings in a separate experiment in which FMDLs were measured over a wide range of carrier frequencies (0.25–8 kHz) for modulation rates of 2, 5, and 10 Hz. For carriers of 2 kHz and below, FMDLs usually worsened with increasing modulation frequency. Above 4 kHz, FMDLs improved with increasing modulation frequency.

Moore and Sek (1995) suggested that FM detection at a 10-Hz modulation rate is based largely on changes in excitation level for all carrier frequencies. For a 2-Hz modulation rate, and for the two lowest carrier frequencies, they suggested that an extra mechanism, probably based on phase locking, plays a role in the detection of FM. This mechanism appears to sample the frequency at different instants in time, and it may be ineffective at high modulation rates because the stimuli spend insufficient time at frequency extremes. In other words, the mechanism based on phase locking may show a form of ''sluggishness'' akin to the sluggishness that has been observed in binaural processing of phase-locking information (Grantham and Wightman, 1978).

To check on this, Moore and Sek (1995) measured psychometric functions for the detection of FM and AM using quasi-trapezoidal modulation with a rate of five periods per second and carriers of 250, 1000, and 6000 Hz. With this form of modulation, the stimuli remain at the extremes of frequency or amplitude for relatively long durations, with rapid transitions between the extremes. The quasi-trapezoidal modulation produced improvements in performance relative to that obtained with 5-Hz sinusoidal modulation, and, for the two lower carrier frequencies only, the improvements were markedly greater for FM than for AM detection. This is consistent with the idea that the use of phase-locking information depends on the time that the stimuli spend at frequency extremes.

In summary, the work of Moore and Sek suggests that phase locking may play a role in the detection of FM, but only for carrier frequencies below about 6000 Hz and only for very low modulation rates. For rates of 10 Hz and above, it appears that FM detection can be explained in terms of excitation-pattern models (Moore and Sek, 1994; Sek and Moore, 1995). This paper presents a series of experiments designed to provide further tests of these ideas.

I. EXPERIMENT 1. DETECTION OF FM WITH SUPERIMPOSED RANDOM-PHASE AM

A. Rationale

FMDLs were compared for two conditions. In one, subjects were required to identify which of two sequentially presented sinusoidal carriers was frequency modulated. The second condition was similar to the first except that a fixed amount of AM was imposed on both stimuli in a forced-choice trial. The modulation frequency was the same for the AM and the FM, but the phase of the AM relative to the FM was randomly selected on each trial. The AM was intended to disrupt cues for FM detection based on changes in the excitation patterns of the stimuli. A similar experiment was conducted by Moore and Glasberg (1989), using a single modulation frequency of 4 Hz. They found that the added AM did make performance worse and that the amount of degradation of performance was consistent with an excitation-pattern model.

The present experiment extends their work by measuring FMDLs over a wide range of carrier frequencies (0.25–6 kHz), using four modulation rates, 2, 5, 10, and 20 Hz, chosen to span the range from where phase locking is useful (2 Hz) to where it is probably not useful (20 Hz). Our predictions were as follows. For carrier frequencies for which phase locking occurs (up to 4–5 kHz), the added AM should produce a greater impairment of performance at high modulation rates (where excitation-pattern cues dominate) than at low modulation rates (where phase-locking cues dominate). For high carrier frequencies, for which phase locking no longer occurs, the added AM should impair performance roughly equally for all modulation rates.

B. Method

1. Stimuli

The carrier frequency (f_c) was 0.25, 0.5, 1.0, 2.0, 4.0, or 6.0 kHz. The level for both unmodulated and modulated stimuli was always 70 dB SPL. Stimuli were delivered monaurally to the subject's preferred ear, using a Sennheiser HD 414 earphone. This earphone is designed to mimic the free-field response of the ear. Hence, the response at the eardrum is not flat at high frequencies, but it does vary smoothly.

FM-induced amplitude changes, measured on Brüel & Kjær type 4153 artificial ear, were less than 0.3 dB for all carrier frequencies and modulation depths used in this experiment. Measurements using a probe microphone close to the eardrum (Rastronics Portarem 2000) confirmed this figure. It seems reasonable to assume, therefore, that the results were not affected by spurious amplitude changes at the eardrum.

On each trial, two successive stimuli were presented, one frequency modulated and the other unmodulated. The order of the two stimuli in each pair was random. Each stimulus had an overall duration of 1000 ms, including raised-cosine rise/fall times of 20 ms. The time interval between the stimuli was 500 ms. Modulation frequencies were 2, 5, 10, and 20 Hz. In one set of conditions, the only modulation applied was the FM. In a second set of conditions, AM was imposed on both stimuli in a trial. The AM had a fixed modulation index of 0.333, corresponding to a peak-to-valley ratio of 6 dB. This is the same AM depth as used by Moore and Glasberg (1989). It was chosen to be large enough to disrupt cues for FM detection based on changes in excitation level, but not so large that it would induce substantial level-related pitch shifts (Verschuure and van Meeteren, 1975; Emmerich *et al.*, 1989). The AM had the same frequency as the FM. The starting phase of the FM for each stimulus was chosen randomly from four possible values: 0, $\pi/2$, π, and $3\pi/2$. The phase of the AM relative to the FM was random, and was chosen independently on each trial.

The signals were digitally generated using a Masscomp 5400 computer system via a 16-bit digital-to-analog converter (DAC, Masscomp model DA04H). For carriers up to 2 kHz, the sampling frequency was 10 kHz and the output of the DAC was low-pass filtered (Kemo VBF8/04, 90 dB/oct) with a cut-off frequency 4 kHz. For the carriers of 4 and 6 kHz, the sampling rate was 25 000 Hz, and the output of the DAC was low-pass filtered at 8 kHz.

2. Procedure

Thresholds were measured using a three-down one-up, two-interval, two-alternative, forced-choice adaptive procedure. This estimates the 79.4% correct point on the psychometric function. The FM depth was changed by a factor of 1.5 until four reversals had occurred and by a factor of 1.26 thereafter. Each run consisted of 12 reversals, and the threshold estimate for that run was taken as the geometric mean of the FM depths at the last eight reversals. Six estimates were obtained for each subject, and the thresholds reported here are based on the geometric mean of the last four estimates. The standard deviation of the logarithm of the four estimates had an average value of 0.08; the maximum value was 0.28.

Lights were used to mark the observation intervals and to provide feedback. Subjects were allowed as long as they wanted to make a response. The next trial began one second after a response had been made. Subjects were tested individually in a double-walled sound-attenuating chamber.

3. Subjects

Three subjects were tested. Subject AS was the second author. The other two subjects were paid for their services. All subjects had absolute thresholds less than 10 dB HL at all audiometric frequencies and had no history of hearing disorders. All had previous experience in psychoacoustic tasks. They were given practice in all conditions until their performance appeared to be stable; this took between 10 and 15 h. The thresholds gathered during the practice sessions were discarded.

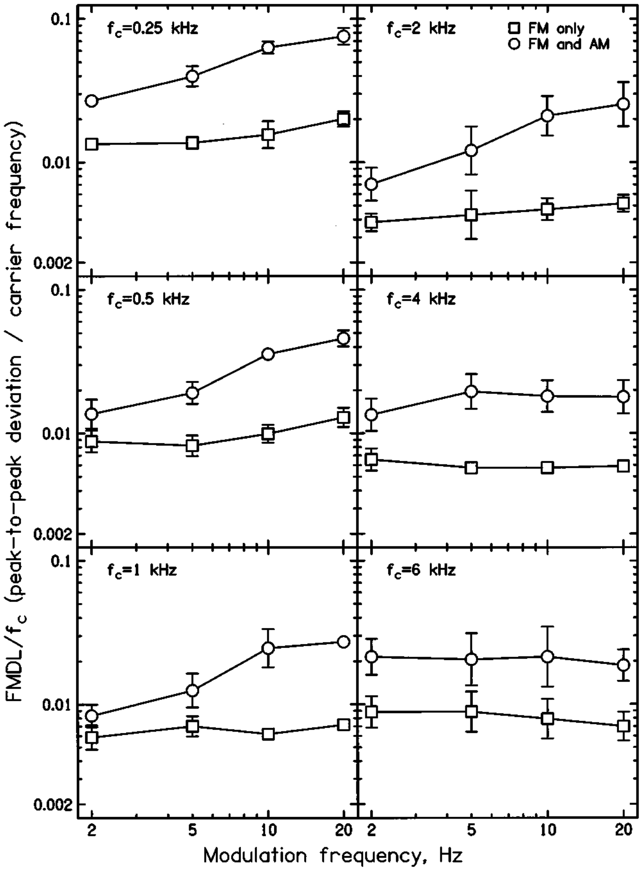

FIG. 1. FMDLs expressed as peak-to-peak deviation divided by center frequency and plotted as a function of modulation frequency. Squares show FMDLs when FM alone was used, in one interval of a forced-choice trial. Circles show FMDLs when random-phase AM of the same rate was present in both intervals of a trial. Each panel shows results for one carrier frequency. Results are averaged across three subjects. Error bars show the standard error across subjects. They are omitted when they would be smaller than the symbol used to represent a given data point. The increased size of the error bars for the 6-kHz carrier reflects differences in overall performance across subjects, rather than differences in the pattern of results.

C. Results

The pattern of results was similar across subjects, so only data averaged across subjects (geometric means) will be presented. Figure 1 shows FMDLs plotted as a function of modulation frequency for the two conditions: FM only (squares) and FM with superimposed AM on all stimuli (circles). Thresholds are plotted as the peak-to-peak frequency deviation divided by the carrier frequency. In the absence of added AM, the FMDLs vary only slightly with modulation rate. However, there is a trend for FMDLs to

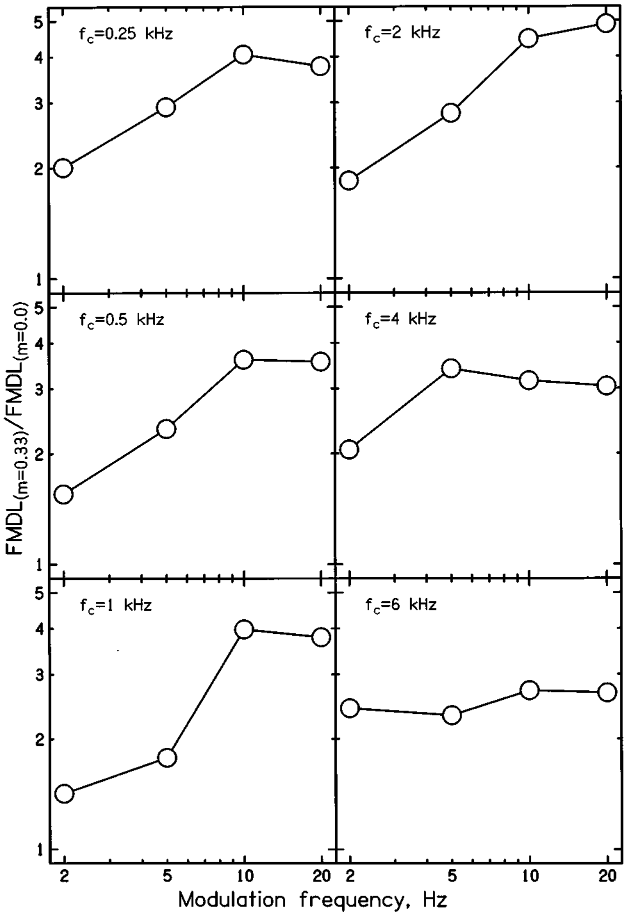

FIG. 2. Ratios of the FMDLs for the conditions with and without added AM. Ratios greater than 1 indicate that the AM had a deleterious effect.

increase with increasing FM rate for carrier frequencies up to 2 kHz, and for FMDLs to decrease with increasing FM rate for the 6-kHz carrier. For the 4-kHz carrier there is no effect of modulation rate. These effects are in the same direction as found by Sek and Moore (1995), and they are consistent with the idea that there is a mechanism for FM detection based on phase locking which only operates for low modulation rates and for carriers below 4–5 kHz. The added AM clearly impairs performance for all conditions; the circles lie above the squares. For carrier frequencies up to 2 kHz, the amount of impairment increases with increasing modulation frequency.

Figure 2 shows the ratios of the (geometric) mean FMDLs for the conditions with and without superimposed AM; the larger the ratio the greater the deleterious effect of the AM. For the carrier frequencies of 0.25, 0.5, 1.0, and 2 kHz, the ratio increases with increasing modulation frequency up to 10 Hz, but is roughly the same for modulation frequencies of 10 and 20 Hz. For $f_c=4$ kHz, the ratio increases as the modulation frequency increases from 2 to 5 Hz, and then remains roughly constant. For $f_c=6$ kHz, the ratio is roughly independent of modulation frequency. The ratios found for a modulation frequency of 5 Hz are similar to, but on average slightly larger than, those found by Moore and Glasberg (1989) for a modulation rate of 4 Hz; they found an average ratio of 1.75.

To assess the statistical significance of the effects described above, the ratios were subjected to an analysis of variance (ANOVA) with factors subject, carrier frequency (six values) and modulation frequency (four values). To make the variance more uniform, the analysis was performed on the logarithms of the ratios. The GENSTAT package used gave estimates of the standard errors of the differences between the mean scores for the different conditions. These standard errors were used to assess the significance of the differences between means using the degrees of freedom associated with the residual term in the analysis of variance (Lane *et al.*, 1987, p. 110). The main effect of carrier frequency was marginally significant $[F(5,30)=2.3,\ p=0.07]$ while the effect of modulation rate was highly significant $[F(3,30)=27.8,\ p<0.001]$. The effect of subject was also significant $[F(2,30)=7.18,\ p=0.003]$, although individual differences only accounted for a small proportion of the variance in the data. The interaction between modulation rate and carrier frequency was marginally significant $[F(15,30)=1.79,\ p=0.085]$. Planned comparisons revealed that the ratio for a rate of 20 Hz was significantly greater than the ratio for a rate of 2 Hz for carriers of 0.25 kHz ($p<0.01$), 0.5 kHz ($p<0.001$), 1 kHz ($p<0.001$), and 2 kHz ($p<0.001$). The difference was marginally significant for the 4-kHz carrier ($p<0.1$) and was not significant at 6 kHz ($p>0.5$).

Overall, these analyses confirm that the addition of random-phase AM made FM detection more difficult with increasing modulation rate for carriers up to 2 kHz, but not for the 6-kHz carrier. The results are consistent with our predictions based on the idea that for low and medium frequency carriers, FM detection depends mainly on a temporal mechanism for low modulation rates and a place (excitation pattern) mechanism for higher rates. The temporal mechanism is less disrupted by random-phase AM than the place mechanism. It is noteworthy, however, that the added AM did impair performance somewhat in all conditions, including those where the temporal mechanism is assumed to dominate, i.e., for the lowest modulation rate and for the carriers of 4 kHz and below. This could be interpreted in two ways. It is possible that for very low modulation rates the FM is coded *both* by temporal mechanisms and by changes in the excitation pattern. The random-phase AM may disrupt the second code, but not the first. Alternatively, FM at very low rates may be coded almost entirely by a temporal mechanism, but this mechanism may be disrupted by the AM, possibly because of small changes in pitch with level (Verschuure and van Meeteren, 1975; Emmerich *et al.*, 1989). Such pitch changes tend to be larger for very low frequencies than for medium frequencies, so this explanation leads to the prediction that the deleterious effect of the AM for a 2-Hz modulation rate should decrease as the carrier frequency is increased from 0.25 to 1 kHz. A trend in this direction is apparent in the data, but it is of marginal significance ($p=0.1$).

II. EXPERIMENT 2. DETECTION OF MIXED MODULATION IN QUIET AND IN NOISE

A. Rationale

Excitation-pattern models predict strong effects of relative modulator phase on the detection of combined AM and FM, referred to as mixed modulation (MM) (Coninx, 1978; Moore and Sek, 1992, 1994). Relative modulator phase, $\Delta\varphi$, is defined as in our earlier studies (Moore and Sek, 1992, 1994); a value of 0 indicates that the frequency goes up when the amplitude goes up, while a value of $\Delta\varphi=\pi$ means that the frequency goes up when the amplitude goes down. In previous experiments we showed that phase effects did occur, for a 10-Hz modulation rate (Moore and Sek, 1992). In one study (Moore and Sek, 1994), we started by measuring psychometric functions for the detection of AM alone and FM alone, in three conditions: in quiet; in the presence of a noise, designated high-band (HB) noise, intended to mask the upper side of the excitation pattern evoked by the 1-kHz carrier; and in the presence of a noise, designated low-band (LB) noise, intended to mask the lower side of the excitation pattern. Then, psychometric functions were measured for MM. The modulation depths for AM and FM were chosen so that each would be equally detectable if presented alone. Using a 10-Hz modulation rate, we found very large effects of the relative modulator phase for the AM and the FM. For example, with the LB noise, performance was best when the AM and FM were in phase and was worst when the AM and FM were in opposite phase (relative modulator phase, $\Delta\varphi$, equal to π radians). Performance for $\Delta\varphi=\pi/2$ and $3\pi/2$ was intermediate. When HB noise was used, performance was best for $\Delta\varphi=\pi$ and worst when $\Delta\varphi=0$. These effects of relative modulator phase were explained using a model based on the concept of the excitation pattern—the non-optimal multichannel excitation pattern model (Moore and Sek, 1994).

If FM detection for very low modulation rates is based on phase locking rather than on changes in the excitation pattern, then the effects of relative modulator phase should be reduced or absent when a very low modulation rate is used. That prediction was tested in the present experiment, which was similar to our earlier experiments, except that a 2-Hz modulation rate was used.

B. Method

1. Stimuli

The level and timing of the 1-kHz carrier were the same as in experiment 1. The starting phase of the FM for each stimulus was chosen randomly from four possible values: 0, $\pi/2$, π, and $3\pi/2$. The modulation rate was 2 Hz. The noises, when present, were continuous throughout a run. The noises were identical to those used by Moore and Sek (1994). Each noise band was digitally synthesized by summing sinusoids spaced at 0.1-Hz intervals (giving a repetition period of 10 s). The amplitudes of the sinusoids were drawn randomly from a Rayleigh distribution, and the phases were drawn randomly from a rectangular distribution (0°–360°). Each noise was generated via a 16-bit digital-to-analog converter (Masscomp model DA04H) at a sampling frequency of 10 kHz. The output of the DAC was low-pass filtered (Fern EF16, 100 dB/oct) with a cutoff frequency of 4 kHz. The noise was played cyclically and recorded onto digital audio tape (DAT). During the experiment, the noise was replayed from the DAT, passed through a manual attenuator and mixed with the carrier.

The noise spectra were essentially rectangular. For the LB noise, designed to mask the low-frequency side of the excitation pattern, the band edges were at 512 and 826 Hz, and the spectrum level within the passband was 49 dB (*re*: 20 μPa). For the HB noise, designed to mask the high-frequency side of the excitation pattern, the band edges were at 1090 and 1515 Hz, and the spectrum level within the passband was 46 dB (*re*: 20 μPa).

2. Procedure

The method for measuring psychometric functions was identical to that described in Moore and Sek (1992, 1994). Psychometric functions were first measured for the detection of AM alone and FM alone, both in quiet and in the presence of each of the two noises described above. Then, detectability was measured for MM using pairs of values of AM and FM that would be equally detectable if presented alone, both in quiet and with the appropriate type of noise present. This was done for four values of the relative modulator phase for AM and FM, namely $\Delta\varphi=0$, $\pi/2$, π, and $3\pi/2$.

3. Subjects

Three subjects were tested. Subject AS was the second author. The other two subjects were paid for their services. All subjects had absolute thresholds less than 10 dB HL at all audiometric frequencies and had no history of hearing disorders. Subjects AS and SF had extensive previous experience in similar psychoacoustic tasks. Subject VC had little previous experience. Subject VC was given 10 h of practice before data collection began.

C. Results

Psychometric functions for the detection of AM alone and FM alone are shown in Fig. 3. The percent correct scores have been converted to the detectability index, d' (Hacker and Ratcliff, 1979), and are plotted as a function of the modulation index for AM or the peak-to-peak frequency deviation in Hz for FM. In previous work using a modulation rate of 10 Hz, we found that d' was roughly a linear function of the modulation index squared (Moore and Sek, 1992, 1994). However, the present data for a modulation rate of 2 Hz did not fit this pattern. The data were fitted with functions of the form:

$$d'=Sm^{\alpha} \tag{1}$$

and

$$d'=S\beta^{\alpha}, \tag{2}$$

where m and β are the modulation indices for AM and FM, respectively, and S and α are constants. The values of S and α were adjusted to minimize the sum of the squared differences between the data and the fitted values. The resulting

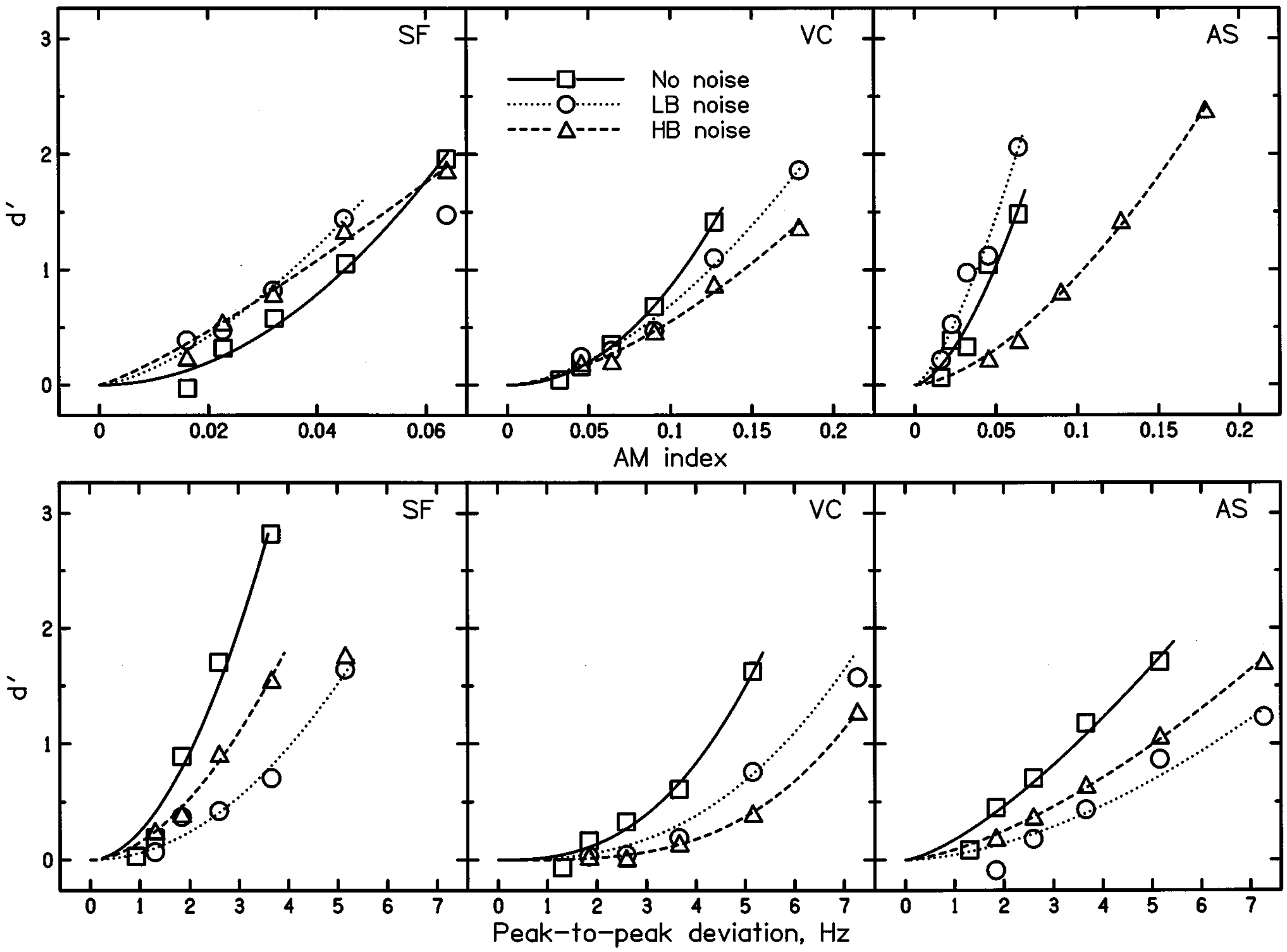

FIG. 3. Psychometric functions for the detection of AM alone (top row) and FM alone (bottom), for a 1-kHz carrier in three conditions: quiet (squares); with LB noise (circles); and with HB noise (triangles). Each panel shows results for one subject. The lines are fitted functions described in the text.

values of S and α are given in Table I. The best-fitting functions are shown as curves in Fig. 3. For the AM-detection data of subject SF, the detectability index for the largest modulation index seemed ''out of line'' with the other points, and the function was fitted to the data for the four smallest modulation indices only. This was done because the fitted functions were used to determine the modulation depths giving relatively small values of d' ($\leqslant 1.25$), for use in the second part of the experiment.

In our previous experiment using a 10-Hz modulation rate, AM detection was impaired by both bands of noise, and the impairment was markedly greater for the HB noise. The effects of the noise on AM detection in the present experiment were smaller, especially for subject SF. SF was also more sensitive overall than the other subjects (note the difference scales on the abscissae for the three subjects). It is somewhat unclear whether the difference in the effects of the noises across the two experiments is due to differences in modulation rate or to individual differences. Only subject AS was common to the two experiments and he showed a somewhat smaller effect of the noise in the present experiment.

Consider now the results for FM detection (lower panel

TABLE I. Values of the constants S and α characterizing the best-fitting functions to the data of experiment 2 for detection of AM alone and FM alone [see Eq. (1) and Eq. (2)].

		SF		VC		AS	
Condition	Modulator	S	α	S	α	S	α
Quiet	AM	491	2.0	108	2.1	124	1.6
LB noise	AM	150	1.5	35	1.7	96	1.4
HB noise	AM	51	1.2	22	1.6	38	1.6
Quiet	FM	3.45	1.9	0.83	2.6	1.23	1.4
LB noise	FM	0.97	2.0	0.38	2.6	0.47	1.7
HB noise	FM	1.85	1.8	0.18	3.3	0.71	1.5

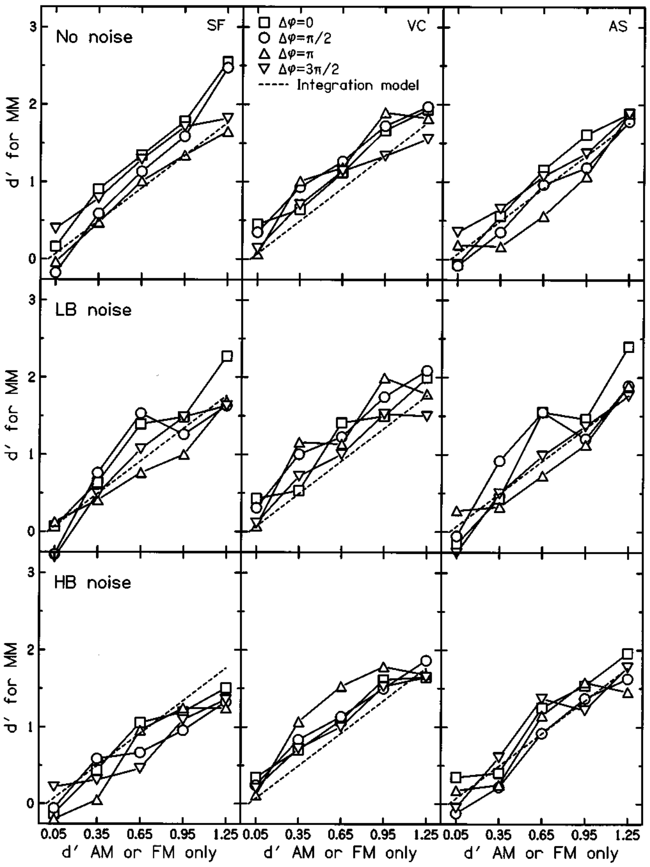

FIG. 4. Psychometric functions for the detection of MM. The detectability index, d', for MM is plotted as a function of the value of d' for AM alone or FM alone. Each row shows results for a different condition: quiet (top), with LB noise (middle) and with HB noise (bottom). Each panel shows results for one subject. Different symbols show results for different relative modulator phases, as indicated in the key. The dashed lines show predictions of the ''integration model'' described in the text.

in Fig. 3). For all three subjects, the addition of noise impaired performance. For subjects SF and AS, the LB noise had a greater effect than the HB noise, whereas for VC the opposite was true. The deleterious effect of the noise could be explained in terms of either of the two mechanisms postulated for FM detection: The noise would disrupt information from part of the excitation pattern, and it would also disrupt temporal information coded in patterns of phase locking.

The functions fitted to the data in Fig. 3 were used to determine amounts of modulation for AM alone and FM alone that would give values of d' of 0.05, 0.35, 0.65, 0.95, and 1.25. The modulation depths giving these values were then used to determine psychometric functions for MM, in each of the three conditions (in quiet, with LB noise, and with HB noise). The results are shown in Fig. 4. Each row shows results for one condition. The different symbols represent different relative modulator phases, as indicated in the key to the figure. In contrast to our previous results obtained using a modulation rate of 10 Hz, which showed very large effects of relative modulator phase (Moore and Sek, 1994), the present results show only small effects of relative modulator phase. In quiet (top row) SF and AS show a trend for better performance with in-phase modulation (squares) than with antiphase modulation (up-pointing triangles), but VC does not show such a trend. In the presence of LB or HB noise (lower two rows), there is no clear effect of relative modulator phase. This is not consistent with the predictions of excitation-pattern models. It is noteworthy that subject AS was also used in our earlier experiments using a 10-Hz modulation rate (Moore and Sek, 1994), and in those experiments he did show substantial effects of relative modulator phase.

To assess the significance of the phase effects, a within-subjects ANOVA was conducted, with factors the ''input'' d' (five values), condition (no noise, LB noise and HB noise), and relative modulator phase (four values). As expected, the main effect of ''input'' d' was highly significant, $F(4,8)=214.2$, $p<0.001$, but neither of the other two main effects was significant ($p>0.1$). There was a significant interaction between condition and relative modulator phase: $F(6,12)=9.07$, $p<0.001$. *Post hoc* comparisons indicated that in the no-noise condition, d' was significantly greater for in-phase modulation than for antiphase modulation. No other significant effects of relative modulator phase were found.

The diagonal dashed lines show predictions of the ''integration model'' (Green and Swets, 1974) which assumes that information about AM and FM is coded independently and the information from them is combined optimally. Generally, the obtained d' values lie reasonably close to the predicted values, so the data are consistent with the idea that the AM and FM are coded independently. There are some cases where the data appear to lie mostly above the predicted values (e.g., subject VC in all three conditions) or below the predicted values (e.g., subject SF in the presence of HB noise). These small deviations could well have been due to errors in estimating the psychometric functions for AM alone and FM alone. For subject VC, the deviations may also reflect a long-term practice effect; she was the least experienced of the three subjects and the psychometric functions for detection of AM alone and FM alone were determined at the start of the experiment.

Overall, the small effects of relative modulator phase, and the fact that obtained scores were close to the predictions of the integration model, suggest that AM and FM at a 2-Hz rate are not coded via a common mechanism based on the excitation pattern. At most, the excitation-pattern mechanism makes a minor contribution to performance. The results are consistent with our proposal that FM is coded primarily by a temporal mechanism for very low modulation rates.

III. EXPERIMENT 3. DETECTION OF MIXED MODULATION AS A FUNCTION OF CARRIER FREQUENCY

A. Rationale

The proposed mechanism based on phase locking should not operate at very high carrier frequencies, since phase locking does not occur in the mammalian auditory nerve for frequencies above about 5 kHz (Palmer and Russell, 1986). We assume that, for high carrier frequencies, FM is coded by changes in the excitation pattern even for very low modula-

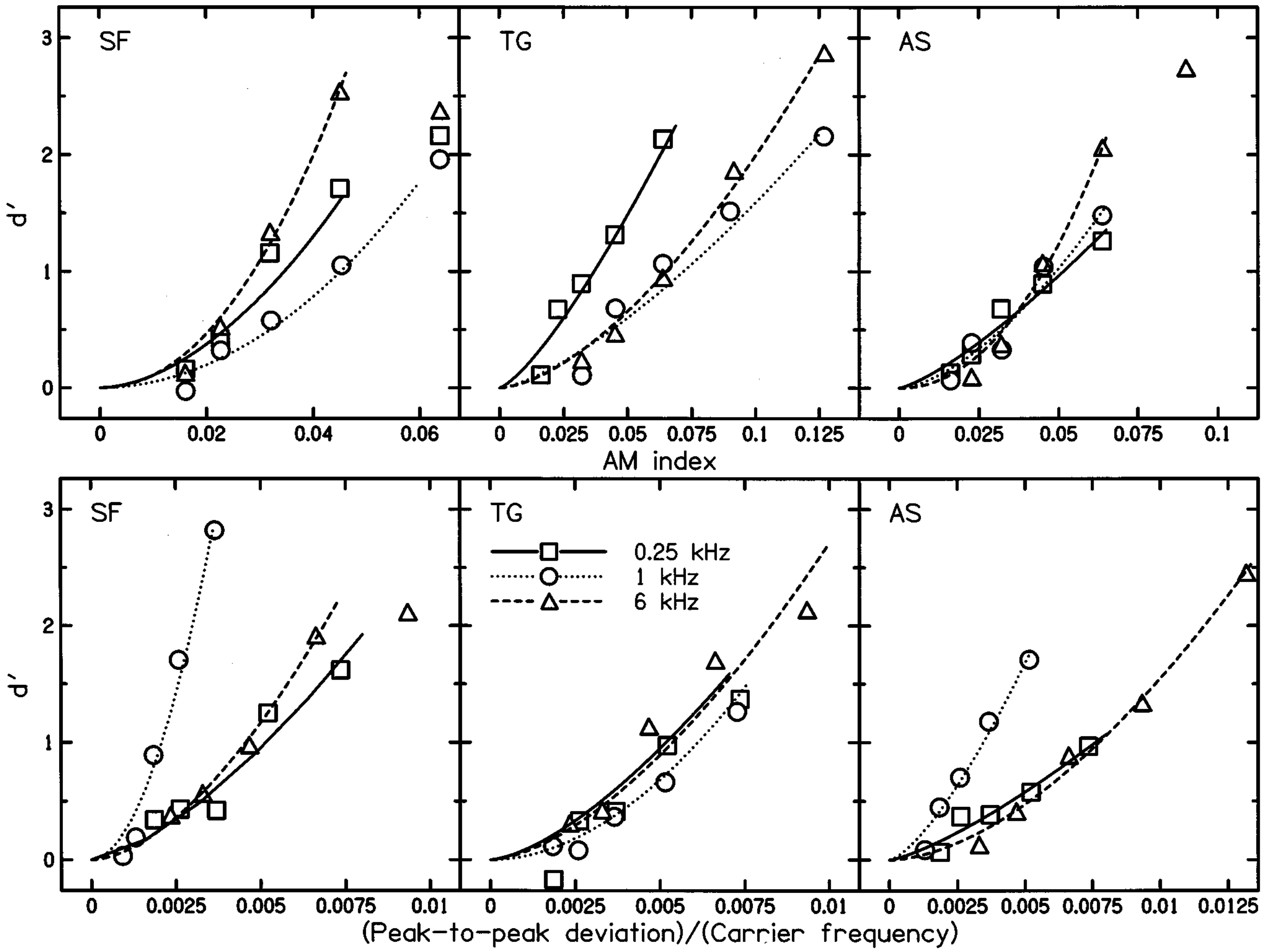

FIG. 5. As Fig. 3, but with each symbol representing a different carrier frequency: 0.25 kHz (squares), 1 kHz (circles), and 6 kHz (triangles). No background noise was used.

tion rates. If that is the case, then, in the detection of MM at low modulation rates, effects of relative modulator phase should be observed for high carrier frequencies, but not for low carrier frequencies. That prediction was tested in the third experiment.

B. Method

The general method was similar to that of experiment 2, except that no background noise was used, and the carrier frequencies were 0.25, 1, and 6 kHz. The modulation rate was 2 Hz. Two of the subjects, AS and SF were the same as for experiment 2. The other subject, TG, had normal hearing, and was trained until his performance appeared to be stable. This took 10 h. All other aspects of the experiment were the same as for experiment 2.

C. Results

The psychometric functions for the detection of AM alone and FM alone are shown in Fig. 5. Results for SF and AS for a 1-kHz carrier are taken from Fig. 3. For the detection of AM (top row), subject AS shows similar performance across carrier frequencies, while subject SF shows best performance for the 6-kHz carrier and subject TG shows best performance for the 0.25-kHz carrier. The detectability index for detection of FM (bottom row) is plotted as a function of peak-to-peak deviation divided by the carrier frequency. For subjects SF and AS, performance measured in this way is better for the 1-kHz carrier than for the 0.25- or 6-kHz carriers. This is consistent with our earlier results (Sek and Moore, 1995). However, for subject TG, performance is similar across the three carrier frequencies.

As for experiment 2, functions of the form specified by Eq. (1) and Eq. (2) were fitted to the data. For some of the data (subject SF for AM detection, subject AS for AM detection at 6 kHz, subject SF for FM detection at 6 kHz), the detectability indices for the largest modulation index seemed ‘‘out of line’’ with the other points, and the functions were fitted to the data for the four smallest modulation indices only, for the same reason as stated earlier. The constants defining the fitted functions are given in Table II. The functions were used to determine amounts of modulation for AM alone and FM alone that would give values of d' of 0.05, 0.35, 0.65, 0.95, and 1.25. The modulation depths giving these values were then used to determine psychometric functions for MM using four values of the relative modulator

TABLE II. Values of the constants S and α characterizing the best-fitting functions to the data of experiment 3 for detection of AM alone and FM alone [see Eq. (1) and Eq. (2)].

		SF		TG		AS	
Carrier, kHz	Modulator	S	α	S	α	S	α
0.25	AM	471	1.8	76	1.3	47	1.3
1.0	AM	491	2.0	40	1.4	124	1.6
6.0	AM	1719	2.1	79	1.6	666	2.1
0.25	FM	5.44	1.5	5.4	1.7	2.6	1.3
1.0	FM	3.44	1.9	0.447	1.9	1.23	1.4
6.0	FM	0.038	1.7	0.036	1.6	0.015	1.7

phase. The results are shown in Fig. 6. Each row shows results for one carrier frequency. Data for SF and AS for the 1-kHz carrier are taken from Fig. 4.

For the 0.25-kHz carrier frequency, there is no consistent effect of relative modulator phase. For the 1-kHz carrier there is a trend for performance with in-phase modulation (squares) to be better than that for antiphase modulation (up-pointing triangles), especially for subject TG. However, the effect is small. For both the 0.25-kHz and the 1-kHz carriers, the data generally lie reasonably close to the predictions based on the integration model, which assumes that the AM and FM are coded independently. The data for SF at 0.25 kHz and TG at 1 kHz lie slightly above the predicted line, but this could be the result of errors in estimating the psychometric functions for AM and FM alone and/or to long-term practice effects. In this context it should be noted that the psychometric functions for AM alone and FM alone for TG were determined first for the 1-kHz carrier, at a time when he was still relatively inexperienced. For AS, who was the most experienced subject, the observed performance for MM detection is very close to that predicted by the integration model.

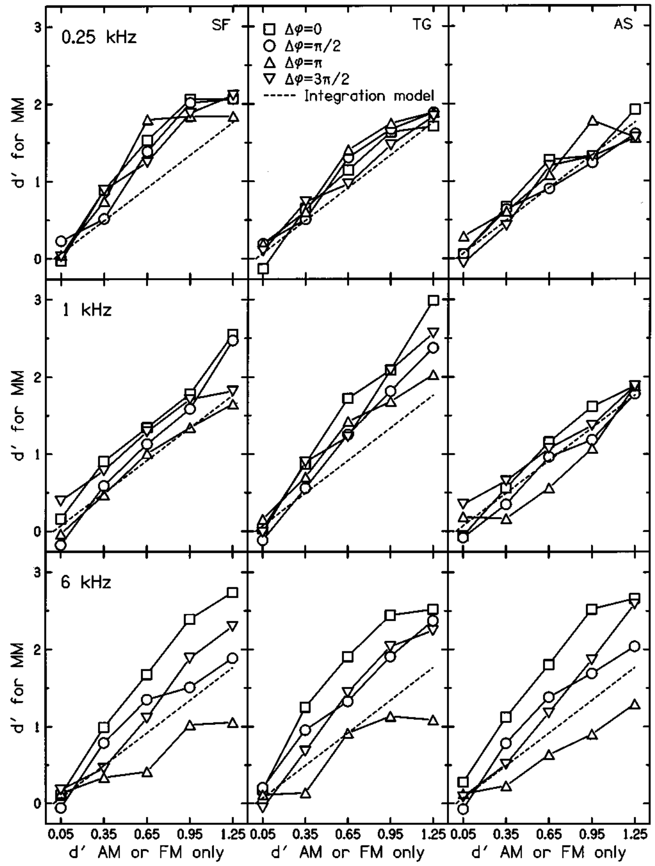

FIG. 6. As Fig. 4, but with each row showing results for a different carrier frequency. No background noise was used.

The pattern of results for the 6-kHz carrier is very different. Here, there are clear effects of relative modulator phase for all three subjects. Performance is best for in-phase modulation ($\Delta\varphi=0$), worst for modulation in opposite phase ($\Delta\varphi=\pi$) and intermediate for $\Delta\varphi=\pi/2$ and $3\pi/2$. This is the same pattern of results as observed in our earlier experiments using a 10-kHz modulation rate (Moore and Sek, 1992, 1994). However, in the earlier experiments this pattern was observed for a 1-kHz carrier as well as for a 6-kHz carrier. Here, the effect is very clear for the 6-kHz carrier, but is small or absent for the lower two carrier frequencies.

To assess the significance of the phase effects, a within-subjects ANOVA was conducted, with factors the ''input'' d' (five values), carrier frequency (three values), and relative modulator phase (four values). As expected, the main effect of ''input'' d' was highly significant: $F(4,8)=381.5$, $p<0.001$. The main effect of carrier frequency was not significant ($p=0.785$), but the main effect of modulator phase was significant: $F(3,6)=84.8$, $p<0.001$. There was also a significant interaction between carrier frequency and relative modulator phase: $F(6,12)=32.9$, $p<0.001$. *Post hoc* comparisons showed that there was no significant effect of relative modulator phase for the 0.25-kHz carrier. For the 1-kHz carrier, d' was significantly greater for in-phase modulation than for antiphase modulation ($p<0.001$), and d' was just significantly greater for $\Delta\varphi=3\pi/2$ than for $\Delta\varphi=\pi$ ($p=0.05$). For the 6-kHz carrier, d' was significantly larger for in-phase modulation than for all other relative modulator phases ($p<0.001$). d', not differ significantly for $\Delta\varphi=\pi/2$ and $\Delta\varphi=3\pi/2$, but d' for both these conditions was significantly greater than for $\Delta\varphi=\pi$ ($p<0.001$).

For the 6-kHz carrier, performance for $\Delta\varphi=0$ was well above that predicted by the integration model. Conversely, performance for $\Delta\varphi=\pi$ was below that predicted by the integration model. These results are not consistent with the idea that AM and FM are coded independently. The pattern of results is consistent with the non-optimal excitation pattern model proposed by Moore and Sek (1994), which predicts phase effects of the type observed.

In summary, the results for the 0.25-kHz carrier frequency suggest that for a modulation rate of 2 Hz AM and FM are coded by independent mechanisms; there was no consistent effect of relative modulator phase. The results for the 6-kHz carrier suggest that AM and FM are coded by a common mechanism, presumably based on changes in the excitation pattern produced by the modulation. The results for the 1-kHz carrier showed a small effect of relative modulator phase, consistent with a modest contribution to performance from excitation-pattern information, but a dominant contribution from temporal information.

IV. DISCUSSION

Overall, the results from all three experiments support the basic hypothesis described in the introduction, that both temporal and place mechanisms are involved in FM detection. Edwards and Viemeister (1994) have also presented evidence that more than one mechanism is involved in FM detection. The results suggest that the temporal mechanism, based on phase locking to the temporal fine structure of the stimuli, only operates for carriers below about 4 kHz, and for very low modulation rates. When the periodicity of the fine structure is changing too rapidly, the temporal mechanism appears not to operate. The place mechanism dominates for high carrier frequencies, and for lower carrier frequencies when stimuli are frequency modulated at rates of 10 Hz and above.

We suggested earlier that the temporal mechanism is sluggish (Moore and Sek, 1995; Sek and Moore, 1995); it appears to operate by sampling the stimuli at different points during the modulation cycle (Hartmann and Klein, 1980; Demany and Semal, 1989) and may be ineffective if the time spent at the extremes is too short (Moore and Sek, 1995). This may be a general characteristic of auditory processes based on the analysis of temporal fine structure. For example, it has been shown that detection of FM of the fundamental frequency ($f0$) of a complex tone is very poor when the tone contains only unresolved harmonics (Carlyon and Shackleton, 1994; Plack and Carlyon, 1995). Another example of sluggishness in temporal processing is the binaural sluggishness observed in the processing of interaural timing information (Grantham and Wightman, 1978, 1979; Grantham, 1995). In this context, it is noteworthy that the processing of interaural timing appears to be more sluggish than the processing of interaural amplitude differences (Blauert, 1972; Grantham, 1995).

It has been suggested previously that DLFs for frequencies below 4–5 kHz are determined by a temporal mechanism even for very brief tones (Moore, 1973; Goldstein and Srulovicz, 1977). If this is so, then it appears that the temporal mechanism can operate for brief stimuli, provided that the periodicity is fixed within each stimulus. It is noteworthy, however, that DLFs do increase markedly with decreasing duration, especially for low frequencies (Liang and Chistovich, 1961; Moore, 1973). Also, the ability to detect difference in $f0$ between two steady tones containing unresolved harmonics is very poor when the tones are brief (Plack and Carlyon, 1995). Thus even for steady tones, the temporal mechanism appears to work less effectively when the tones are brief.

It remains unclear *why* the temporal mechanism is sluggish. The limitation does not seem to be in the auditory nerve, since the short-term frequency of sounds that are frequency modulated is well represented in the responses of single neurons of the auditory nerve (Khanna and Teich, 1989). It is possible that the limitation arises from the stochastic nature of neural responses. In order to determine the frequency of a sound from the response of a single primary neuron, the sound must be sampled for some time, since, in general, a spike does not occur on every cycle of the stimulus; it is not possible to determine unambiguously the period of the sound from one, or a small number, of interspike intervals. Clearly, FM detection depends on the responses of more than just one neuron. However, it is possible that the phase-locking information in the auditory nerve is extracted at higher levels of the auditory system using a mechanism that analyses the timing information in single neurons, or small populations of neurons. Information may be combined across neurons after that analysis has taken place. The mechanism for analysing the timing information may have evolved to deal with ambiguity in the interspike intervals by sampling over fairly long time periods.

Another possibility is that the sluggishness arises in the process that combines temporal information across neurons. This combination process may take time to operate effectively. It is possible that, for a pulsed-tones frequency discrimination task, this process can operate on information stored in memory, after the end of each tone. This information may be available for a relatively long time, since each tone is followed by a period of silence. However, for FM detection, the stored information might be continuously overwritten. Hence temporal information could be used to code the frequency of brief pulsed tones, but not to code rapid FM.

Finally, it should be noted that the limitations of the temporal mechanism proposed here apply specifically to the relatively low modulation depths occurring in the region of the detection threshold for modulation. It is possible that a temporal mechanism can operate to some extent at modulation rates of 10 Hz and above when the modulation depth is well above the value required for threshold.

V. SUMMARY AND CONCLUSIONS

The most important experimental results of this paper are as follows:

(1) Thresholds for detecting FM increased when random-phase AM of the same rate was added to every stimulus. For carrier frequencies up to 2 kHz, the impairment produced by adding the AM increased as the modulation rate was increased from 2 to 20 Hz. For a carrier frequency of 6 kHz, the impairment did not vary with modulation rate.

(2) Psychometric functions for detecting combined FM and AM of a 1-kHz carrier, using a modulation rate of 2 Hz, were affected only slightly by the relative phase of the modulators for AM and FM. This was true both in quiet and in the presence of noise designed to mask either the lower or the upper side of the excitation pattern. This contrasts with

earlier results obtained using a 10-Hz modulation rate (Moore and Sek, 1994), which showed substantial effects of relative modulator phase. Both in quiet and in noise, the detectability of combined AM and FM at a 2-Hz rate was close to the values predicted on the assumption that AM and FM are coded independently and the information from the independent codes is combined optimally (the integration model).

(3) Psychometric functions for detecting combined FM and AM of a 0.25-kHz carrier in quiet, using a modulation rate of 2 Hz, were not affected by the relative phase of the modulators for AM and FM. However, large effects of relative modulator phase were found for the 6-kHz carrier; performance was best for in-phase modulation and was worst for antiphase modulation. Small effects of relative modulator phase were found for a 1-kHz carrier. For the 0.25 and 1-kHz carriers, the detectability of combined AM and FM was close to the values predicted by the integration model. For the 6-kHz carrier, performance for in-phase modulation was markedly better than predicted by the integration model, while performance for antiphase modulation was somewhat worse than predicted by the integration model.

The overall pattern of results is consistent with the following general interpretation. The detection of FM for carrier frequencies below 4 kHz is probably determined mainly by a temporal mechanism for very low modulation frequencies. The temporal mechanism appears to be sluggish; the stimuli have to spend sufficient time at frequency extremes for it to operate effectively. For modulation rates of 10 Hz and above, detection of FM probably depends primarily on a place mechanism based on changes in the excitation pattern. For rates between 2 and 10 Hz, both place and temporal mechanisms may contribute to FM detection for carrier frequencies up to 4 kHz. For carriers above about 4 kHz, the place (excitation pattern) mechanism probably dominates for both very low and medium modulation rates.

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