Effects of carrier frequency, modulation rate, and modulation waveform on the detection of modulation and the discrimination of modulation type (amplitude modulation versus frequency modulation)

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Initially, psychometric functions were measured for the detection of amplitude modulation (AM) or frequency modulation (FM), using a two-alternative forced-choice (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. Then, pairs of values of AM and FM were selected that would be equally detectable, and psychometric functions were measured for the discrimination of AM from FM, again in a 2AFC task. For carrier frequencies of 125 and 1000 Hz, the ability to discriminate AM from FM was always poorest at the highest modulation rate (10 Hz); at this rate some subjects were essentially unable to discriminate AM from FM when the detectability of the modulation was relatively low (d' of 1.16 and below). For a modulation rate of 2 Hz, and when the detectability of the modulation was moderate (d' up to about 2), some subjects discriminated the type of modulation as well as they detected the modulation. For a carrier frequency of 6000 Hz, the effect of modulation rate varied across subjects, but there was still a trend for poorer discrimination of modulation type at the highest modulation rate. It is 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 lower carrier frequencies, an extra mechanism, possibly based on phase locking, may play a role in the detection and discrimination of FM. This mechanism may be ineffective at modulation rates above about 5 Hz because the stimuli spend insufficient time at frequency extremes. To check on this, psychometric functions were measured for the detection of FM and AM using quasitrapezoidal modulation with a rate of five periods per second and carriers of 250, 1000, and 6000 Hz. This 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.

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INTRODUCTION

In a series of earlier papers (Moore and Sek, 1992, 1994b; Sek and Moore, 1994), we have examined the question of whether amplitude modulation (AM) and frequency modulation (FM) are coded in the auditory system by a single underlying mechanism, or by different mechanisms. Most of our earlier work used a single modulation rate of 10 Hz. To account for our results, we have proposed a single-mechanism model which is an extension of the model originally proposed by Zwicker (1956, 1970) and by Maiwald (1967) and is based on the concept of the psychoacoustical excitation pattern. The latter can be defined as the output of the auditory filters as a function of center frequency (Moore and Glasberg, 1983, 1987). In our model (Moore and Sek, 1994b) it is assumed that detection is based on an unweighted sum of decision variables across all channels (all regions of the excitation pattern) that are above threshold and that have a positive signal-to-noise ratio (when background noise is present); we refer to this model as the nonoptimal multichannel model, since the subjects are assumed not to weight the information in each channel in an optimal manner (in contrast to the multichannel model evaluated by Moore and Sek, 1992).

In our earlier work, we showed that this model was able to account reasonably well for changes in the detectability of combined AM and FM [mixed modulation (MM)] as a function of modulator phase, both for stimuli presented in quiet, and for stimuli presented with noise designed to mask selectively either the lower or the upper side of the excitation pattern (Moore and Sek, 1994b). However, in order to get a quantitative fit to the data, it was necessary to assume that the excitation patterns were sharper than those usually inferred from experiments on simultaneous masking (Moore and Glasberg, 1983; Glasberg and Moore, 1990). We argued that this was not unreasonable, since a process of suppression may sharpen excitation patterns, but this process seems not
to be revealed in simultaneous masking (Houtgast, 1974; Moore and O'Loughlin, 1986). In addition, the notched-noise maskers often used to estimate auditory filter shapes may generate combination products that lead to a reduction in the upper slopes of the derived filters (which would in turn lead to a reduction in the lower slope of excitation patterns calculated from such filters); such combination products would not occur for slowly modulated sinusoids, and so their excitation patterns might be sharper than estimated using noise stimuli (Glasberg and Moore, 1994; Moore et al., 1995).

One test of the adequacy of the nonoptimal multichannel model comes from studies of the ability of subjects to discriminate AM from FM. Demany and Semal (1986) used a task where two successive stimuli were presented, one modulated and the other unmodulated. The type of modulation (AM or FM) was randomly selected for each trial and subjects were required both to detect the modulation (i.e., to indicate whether the first or second stimulus was modulated) and to identify the type of modulation (AM or FM). When the modulation frequency was very low (1.67 Hz), detection performance was roughly equal to identification performance. At higher modulation rates, detection tended to be better than identification.

If decisions were based only on the sum of decision variables across channels, listeners should have difficulty identifying the type of modulation. In terms of excitation-pattern models, identification of the type of modulation requires comparison of the modulation in excitation level on the high- and low-frequency sides of the pattern. Two types of comparisons might be made; comparison of modulation phase and comparison of modulation magnitude. If the modulation is in phase on the two sides of the pattern, this indicates that AM is present. If the modulation is in opposite phase on the two sides of the pattern, this indicates that FM is present. If the modulation is larger on the high-frequency side of the pattern, this indicates that AM is present (this happens because of the expansive nonlinear growth of excitation level on the high-frequency side of the pattern with increases in signal level). If the modulation is larger on the low-frequency side of the pattern, this indicates that FM is present (this happens because the excitation pattern is usually steeper on the low-frequency side). To explain the results of Demany and Semal in terms of an excitation-pattern model, it has to be assumed that subjects are able to compare the modulation on the two sides of the excitation pattern, i.e., they do not always simply sum information across all parts of the excitation pattern.

We (Moore and Sek, 1994a) re-examined some of the issues raised by the study of Demany and Semal (1986); specifically, we compared the ability to detect modulation with the ability to discriminate one type of modulation from the other. However, we used a different method, intended to overcome some problems in the experimental design of Demany and Semal (see Moore and Sek, 1994a, for a discussion of these problems). We started by measuring psychometric functions for the detection of AM and of FM. Then we selected pairs of sounds, one amplitude modulated and one frequency modulated, for which the modulation was equally detectable, and used those stimuli in a two-alternative forced-choice discrimination task; subjects had to discriminate the order “AM then FM” from the order “FM then AM.” For a 10-Hz modulation rate and a 1000-Hz carrier, the ability to discriminate AM from FM was poorer than the ability to detect the modulation. When the detectability of the AM and FM was low (d' = 0.66), two subjects were essentially unable to discriminate AM from FM. This was true both for stimuli presented in quiet and for stimuli presented with continuous noise chosen to mask either the lower or the upper side of the excitation pattern.

Edwards and Viemeister (1994) also examined the ability to discriminate AM from FM, using a 1000-Hz carrier frequency. In their first experiment, they used a three-interval task, with FM in two intervals and AM in the other one; the subject had to identify the odd interval. They used an adaptive procedure to find the modulation depths necessary to achieve 70.7% correct. The AM and FM were intended to be kept at equally detectable values, based on prior measurements of the detectability of AM and FM, but this involved some extrapolation as rather large modulation depths were called for by the adaptive procedure. Their results indicate a poor ability to discriminate AM from FM, although the discrepancy between detection thresholds and discrimination thresholds decreased as the modulation rate decreased from 64 to 4 Hz.

In a second experiment, they used only a 16-Hz modulation rate. The modulation depth of the AM signal was chosen to give various fixed levels of detectability, and psychometric functions were measured for discrimination of AM from FM as a function of the modulation depth for FM, β. The functions showed distinct minima; for certain values of β subjects had great difficulty distinguishing AM from FM. This result differs from our results obtained using a similar experiment (Moore and Sek, 1994a); although our subjects discriminated AM from FM more poorly than they detected the AM or FM, there were not distinct minima at particular values of β. This is surprising since our task was actually harder than that of Edwards and Viemeister; our subjects had to distinguish the order AM then FM from the order FM then AM, while Edwards and Viemeister used a task where subjects could pick the “odd one out.”

The reason for the discrepancy between the studies is not clear. One possibility is that the subjects of Edwards and Viemeister focused on a different detection cue, specifically the overall impression of amount of modulation. At some value of β, the “modulation strength” becomes very similar for AM and FM, and subjects relying on this as a discrimination cue will perform very poorly. In our experiment, subjects probably did not use modulation strength as a cue, since it would have been unreliable; we used several different FM depths within a block of trials, so the FM stimulus sometimes sounded more modulated and sometimes sounded less modulated than the AM stimulus. For very large modulation depths, the subjects of Edwards and Viemeister performed better than our subjects. This probably happened because, in their experiment, modulation strength would have provided a reliable cue when β was very large.

Taking the results of all the studies together, there seems
to be a trend for better discrimination of AM from FM when the modulation rate is very low. To confirm this trend, we decided to repeat our earlier experiment but including modulation rates lower than 10 Hz. We also examined the effects of carrier frequency; the experiments of Moore and Sek (1994a) and Edwards and Viemeister (1994) used only the single carrier frequency of 1000 Hz. It is possible that the discrimination of AM from FM depends partly on the use of information derived from phase locking in the auditory nerve. It could be that this information is used most effectively when the modulation is at a very low rate. If this is the case, then one would expect to see a change in the pattern of results if the carrier frequency is above the range where phase locking occurs. In the present experiment we used three widely spaced carrier frequencies, including one (6000 Hz) that was above the upper limit for phase locking in most mammals (Palmer and Russell, 1986).

I. EXPERIMENT 1: DETECTION AND DISCRIMINATION OF AM AND FM

A. Procedure

Initially, psychometric functions were measured for the detection of AM and FM alone, using a two-alternative forced-choice (2AFC) task. On each trial, two successive stimuli were presented, one modulated and the other unmodulated. The order of the two stimuli in each pair was random. Then, pairs of values of AM and FM were selected that would be equally detectable, and psychometric functions were measured for the discrimination of AM and FM, again in a 2AFC task. In one interval, the sound was amplitude modulated and in the other it was frequency modulated, the order being random on each trial. The subject was required to indicate the order of the sounds by pressing the appropriate button on the response box. Subjects were tested in a double-walled sound-attenuating chamber. Correct-answer feedback was provided by lights on the response box.

The method for determining psychometric functions for detection of modulation was the same as described by Moore and Sek (1992, 1994a,b); the reader is referred to those papers for details. Each point on each psychometric function is based on 200 judgments. Functions fitted to these data (see below for details) were used to select pairs of values of m and fβ that would be equally detectable, and these pairs of values were used in the task requiring discrimination of the type of modulation. The modulation depths used corresponded to d' values for the detection of AM or FM of 0.66, 1.16, 1.66, 2.16, 2.66, and 3.16. The six pairs of values of modulation depth were presented in a cycle going from the largest to smaller values, and then jumping back to the largest values. A block consisted of 5 practice trials at the largest d' value, and 60 experimental trials, 10 at each value of d'. Twenty blocks were obtained for each condition.

B. Stimuli

The carrier was a sinusoid with frequency = 125, 1000, or 6000 Hz and level 70 dB SPL. The overall intensity was held constant regardless of modulation depth, to prevent detection of modulation on the basis of a change in overall intensity. The modulator was a sinusoid with frequency = 2, 5, or 10 Hz. The starting phase of the modulator was randomly chosen for each stimulus from one of four values: 0°, 90°, 180°, and 270°. This was done to prevent subjects from performing the task on the basis of a specific cue in the onsets of the stimuli. The signals were digitally generated using a Masscomp 5400 computer system via a 16-bit digital-to-analog converter (DAC, Masscomp model DA04H) at a sampling frequency of 20 kHz. The output of the DAC was low-pass filtered (Kemo VBF8/04, 90 dB/oct) with a cutoff frequency of 8 kHz. For both tasks, each stimulus had an overall duration of 1000 ms, including raised-cosine rise/fall times of 50 ms. The time interval between the stimuli was 300 ms.

Stimuli were delivered using one earpiece of a Sennheiser HD 414 headset. The headphone was chosen for its relatively smooth frequency response. This was important, since if the frequency response is irregular, FM can be transformed into a combination of FM and AM. Measurements using a probe microphone close to the eardrum showed that the response was very flat from 100 up to 1100 Hz. Around 6000 Hz, the response varied smoothly by ±2 dB over the range 5–7 kHz. For the range of frequency deviations used in this experiment (less than ±1% around 6000 Hz), the amount of spurious AM induced by the FM would have been less than 0.12 dB.

C. Subjects

Three subjects with normal hearing at all audiometric frequencies were used. One was author AS. The other two subjects were paid for their services. All subjects had extensive experience in modulation detection tasks.

D. Results

The percent correct values for detection of modulation were converted to values of d' (Green and Swets, 1974; Hacker and Ratcliff, 1979). As found previously (Moore and Sek, 1992; 1994a,b), d' was approximately a linear function of the modulation index squared, for both AM and FM. Hence, Figs. 1–3 show values of d' plotted as a function of 1000m² or Δf², where m is the modulation index of the AM stimuli and Δf is the peak frequency deviation of the FM stimuli from the nominal carrier frequency.1 Note the changes in the abscissa values for FM across Figs. 1–3; the FM depth required to achieve a given value of d' increases with increasing carrier frequency, as has often been observed in the past. Each row shows results for one subject. Within each panel, results for the three different modulation rates are shown. The data were fitted with functions of the form

\[ d' = S_AM m^2 \]  

and

\[ d' = S_FM \Delta f^2, \]

where S_AM and S_FM are the slopes of the best-fitting lines for AM and FM, respectively. These lines are shown in the figures. As can be seen, the lines generally fit the data reasonably well, although the fit is somewhat less good for the
lower modulation rates than for the highest rate.

The procedure used to fit the straight lines to the data gave estimates of the standard errors (s.e.’s) of the slopes. These s.e.’s, which were typically between 5% and 10% of the actual slope values, were used to estimate the significance of the differences between slopes in specific cases.

Consider first the results for the 125-Hz carrier (Fig. 1). The slopes of the psychometric functions, which provide a measure of the detectability of the AM or FM, varied with modulation rate, although the exact pattern of results differed across subjects. For FM (left column), performance tended to be best for the 2-Hz rate (squares). For subjects LB and AS, the slope was significantly greater for the 2-Hz rate than for the two higher rates (p<0.05). For all three subjects, the slope for the 5-Hz rate was less than for the 2- or 10-Hz rates, although the difference from the 10-Hz rate was statistically significant only for AS (p<0.05) and for CL (p<0.01). This poorer performance at the 5-Hz rate might indicate a transition between two mechanisms, one working more effectively at a 10-Hz rate (possibly based on the detection of changes in excitation level) and the other working more effectively at the lowest modulation rate (possibly based on the use of phase-locking information); at a 5-Hz rate, neither mechanism may operate optimally. For AM (right column), performance was best for the 10-Hz rate. The slopes for the 10-Hz rate were significantly greater than the slopes for the two lower rates (p<0.05) for all three subjects.

For the 1000-Hz carrier (Fig. 2), the detectability of FM varied somewhat less with modulation rate. However, subject CL again showed a significantly lower slope for the 5-Hz rate than for the 2- or 10-Hz rates (p<0.01). The detectability of AM was best or close to best for the 10-Hz rate, and worst for the 2-Hz rate. This effect was particularly marked for subject CL. For all three subjects, the slope for the 2-Hz rate was significantly lower than the slopes for the two higher rates (p<0.01).

For the 6000-Hz carrier (Fig. 3), the detectability of FM was consistently and significantly poorer for the 2-Hz rate than for the other rates (p<0.01), a very different result from that for the 125- and 1000-Hz carriers. For AM detection, performance was also poorest for the 2-Hz modulation rate, although the effect of modulation rate was small for subject AS. For subjects CL and LB, the slope was significantly lower for the 2-Hz rate than for the two higher rates (p<0.01).
were conducted, one for the FM data and one for the AM data. 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 t tests and the degrees of freedom associated with the residual term in the analysis of variance (Lane et al., 1987, p. 110). The analyses were conducted on the logarithms of the slopes of the psychometric functions, since the s.e.'s of the slopes were roughly a constant proportion of the slopes. The factors were carrier frequency and modulation rate. For the FM data, the effect of carrier frequency was significant \(F(2,4) = 70.2, p<0.001\), reflecting the fact that the FM depth required to achieve a given value of \(d'\) increased with increasing carrier frequency. The main effect of modulation rate was not significant \(F(2,3) = 2.55, p=0.19\), but there was a significant interaction of carrier frequency and modulation rate \(F(4,8) = 19.8, p<0.001\), reflecting the fact that the effect of modulation rate varied with carrier frequency. For the AM data, the effect of carrier frequency was significant \(F(2,4) = 7.74, p=0.042\), performance being somewhat better at 1000 than at 125 or 6000 Hz. The effect of modulation rate just failed to reach the 0.05 significance level \(F(2,4) = 6.55, p=0.055\). However, a t test showed that the mean slope for the 2-Hz rate was significantly less than that for the 10-Hz rate \(p<0.05\). The interaction of carrier frequency and modulation rate was not significant \(F(4,8) = 1.44, p=0.306\).

To summarize the results, the detectability of AM tended to be poorest at the lowest modulation rate for all three carrier frequencies. This is consistent with earlier work on AM detection for sinusoidal and for noise carriers, and is characteristic of what happens when gated carriers are used (Viemeister, 1979; Sheft and Yost, 1990). It may happen partly because, for a given stimulus duration, the number of cycles of the modulator decreases with decreasing modulation rate. However, it may also reflect a sensitivity to dynamic aspects of the stimuli; the detectability of changes in level may improve with increasing rate of change up to a certain point.

For the 6000-Hz carrier, the detectability of FM was also poorest for the lowest modulation frequency, which is consistent with the idea that the AM and FM were detected by similar mechanisms. In contrast, for carriers of 125 and 1000 Hz, FM detection was not worse for the 2-Hz modulation rate than for the two higher rates, and was often better. This may indicate the existence of an extra mechanism for FM detection at very low modulation rates, possibly based on phase-locking information. Consistent with our results, Demany and Semal (1986) found that thresholds for detecting AM and FM varied with modulation rate in a different way.

Psychometric functions for the discrimination of type of modulation are shown in Figs. 4-6. Each panel shows results for one subject. Within each panel, the three curves represent the three modulation rates. The values of \(d'\) for discrimination of AM from FM are plotted as a function of the value of \(d'\) for detection of AM or FM.

For the 125-Hz carrier (Fig. 4), performance was consistently best for the 2-Hz modulation rate, and was generally poorest for the 10-Hz rate. For the 10-Hz rate, subject LB performed essentially at chance when the value of \(d'\) for the detection of AM or FM was 1.66 or less. For the 5- and 10-Hz rates, the \(d'\) values for discrimination of AM from FM were consistently well below the \(d'\) values for detection of AM or FM. However, for the 2-Hz rate, two subjects, CL and AS, showed discrimination performance that was about as good as detection performance for values of \(d'\) for detection up to 2.16.

For the 1000-Hz carrier (Fig. 5), performance again tended to be poorest for the 10-Hz modulation rate, and best for the 2-Hz rate, although subject LB showed little difference between the 2- and 5-Hz rates. For the 10-Hz rate, subject CL performed essentially at chance, and subject AS performed very poorly when the value of \(d'\) for detection of AM or FM was 2.16 and below. This pattern of results is consistent with that obtained by Moore and Sek (1994a) who used a 1000-Hz carrier and a 10-Hz modulation rate. For the 2-Hz modulation rate, subjects LB and AS showed discrimination performance almost as good as detection performance, when the value of \(d'\) for detection was moderate. This pattern of results is consistent with that found by De-
FIG. 4. Values of \( d' \) for the discrimination of AM from FM, plotted as a function of the values of \( d' \) for modulation detection; for each point, the AM and FM were chosen to be equally detectable. The carrier frequency was 125 Hz. The parameter is modulation rate. The solid diagonal line indicates where the data would lie if \( d' \) for discrimination was equal to \( d' \) for detection.

many and Semal (1986) for a 1.67-Hz modulation rate. However, subject CL consistently showed lower \( d' \) values for discrimination than for detection.

For the 6000-Hz carrier (Fig. 6) only subject LB showed a clear effect of modulation rate, discrimination performance being markedly worse at 10 than at 2 or 5 Hz. For subject LB, discrimination performance was similar to detection performance for modulation rates of 2 and 5 Hz and for values of \( d' \) for detection up to 2.16. For the other two subjects, discrimination performance was generally worse than detection performance at all modulation rates, except for subject AS at a modulation rate of 2 Hz, for values of \( d' \) for detection up to 1.66.

To assess the statistical significance of the effects of modulation rate and carrier frequency shown in Figs. 4–6, a within-subjects ANOVA was conducted with factors \( d' \) for detection, modulation rate, and carrier frequency. The main effect of modulation rate was significant \( [F(2,4)=42.7, p=0.002] \). The main effect of carrier frequency was not significant \( [F(2,4)=0.25, p=0.79] \). The interaction of modulation rate and carrier frequency approached but did not reach significance \( [F(4,8)=2.34, p=0.142] \). For the carrier frequencies 125 and 1000 Hz, the mean value of \( d' \) was significantly less for the 10-Hz modulation rate than for the 2-Hz rate \((p<0.05)\). For the carrier frequency of 6000 Hz, the mean value of \( d' \) did not differ significantly for the three modulation rates.

In summary, for the 10-Hz modulation rate, discrimination of AM from FM was always poorer than detection of AM or FM at all three carrier frequencies. This is consistent with the nonoptimal multichannel excitation-pattern model which assumes that the detection of AM or FM involves the summation of information across the whole of the excitation pattern. The discrimination of AM from FM probably requires a comparison of changes in excitation level on the two sides of the excitation pattern, and this leads to lower \( d' \) values than for modulation detection. However, for the 2-Hz modulation rate, discrimination performance was sometimes as good as detection performance. This is inconsistent with the nonoptimal multichannel excitation-pattern model. The effect of modulation rate was less clear for the 6000-Hz carrier than for the two lower carriers.
E. Discussion

The results provide preliminary evidence suggesting that FM may be detected in different ways for modulation rates of 2 and 10 Hz. If there were a single mechanism at all modulation rates, based on changes in excitation level, then the modulation rate leading to the best AM detection would also be expected to give the best FM detection. The results did not follow this pattern except for the 6000-Hz carrier. For the other two carriers, AM detection was generally best for the 10-Hz modulation rate, while FM detection was best for the 2-Hz modulation rate. In addition, for the 125-Hz carrier, all three subjects showed poorer FM detection for the intermediate modulation rate (5 Hz), which is suggestive of two mechanisms for FM detection, neither of which was very effective at the intermediate rate.

The idea that FM is detected by different mechanisms for very low modulation rates and for "medium" (10 Hz) rates is also consistent with the results for discrimination of modulation type. For the 10-Hz modulation rate, discrimination was always worse than detection, as would be expected if discrimination of modulation involves a comparison of changes on the two sides of the excitation pattern. In contrast, for the 2-Hz modulation rate, discrimination was sometimes as good as detection, as was also found for a 1.67-Hz rate by Demany and Semal (1986). This is not consistent with the nonoptimal multiband excitation-pattern model, and suggests that information about AM or FM is coded partly by something other than changes in excitation level.

As suggested earlier, it is possible that FM is coded partly by changes in the pattern of phase locking evoked by the stimulus. A problem with this interpretation is the finding that, at least for one subject, discrimination was as good as detection for a 2-Hz modulation rate even when the carrier frequency was as high as 6000 Hz. It is generally assumed that the upper limit for phase locking in mammals is about 4 to 5 kHz, although the exact limit varies from one species to another (Palmer and Russell, 1986). It is possible that, in humans, some weak phase-locking information exists even at 6 kHz.

If phase locking does play a role in coding FM at very low rates, we need some explanation as to why it appears to be ineffective at a rate of 10 Hz. Frequency changes at such a rate are well coded in interspike intervals at the level of the auditory nerve (Khanna and Teich, 1989). However it is possible that the mechanism that "decodes" the phase-locking information at a higher level is "sluggish," being unable to process rapid changes in the pattern of phase locking. This would be similar to the binaural sluggishness that has been observed in the processing of interaural differences. For example, the binaural system appears to be unable to follow changes in interaural timing when those changes occur at rates above a few hertz (Granatham and Wightman, 1978). To detect FM using phase locking, it may be necessary to take "snapshots" or samples of the phase-locking information at times when the frequency is close to its extreme values. When a sinusoid is frequency modulated at a 10-Hz rate, the time during which the frequency is within, say, 10% of the extremes of frequency is rather short—about 14 ms. The ability to discriminate differences in frequency of steady tones is known to worsen with decreasing duration (Moore, 1973). Hence, the ability to detect FM by taking snapshots of the frequency at times close to frequency extremes may be limited by the short time spent close to the extremes.

The worsening of pulsed-tones frequency discrimination with decreasing duration is more rapid at 125 than a 1000 Hz (Moore, 1973). If this depends on the way phase-locking information is processed, for example by measurement of interspike intervals (Goldstein and Srulovicz, 1977), one might expect that the transition from detection of FM by phase locking to detection of FM by changes in excitation level would take place at lower modulation rates. Consistent with this, the discrimination of AM from FM was consistently worse at 5 than at 2 Hz for the 125-Hz carrier, but this difference was less marked for the 1000-Hz carrier.

II. EXPERIMENT 2: COMPARISON OF MODULATION DETECTION FOR SINUSOIDAL AND TRAPEZOIDAL MODULATION

A. Rationale

To test the idea that the use of phase locking to detect FM depends on the amount of time spent at frequency ex-
tremes, we conducted an experiment using patterns of amplitude and frequency change that were approximately trapezoidal; carriers modulated in this way spend more time at frequency or amplitude extremes than for a sinusoidal modulator with the same period. One might expect some benefit from this for a mechanism based purely on detection of changes in excitation level. However, if the measured benefit is greater for FM than for AM, this would support the idea of an extra, sluggish mechanism for FM. Psychometric functions for the detection of AM and FM were compared for sinusoidal modulation and quasitrapezoidal modulation.

B. Method

The carrier frequency was 250, 1000, or 6000 Hz. The modulation rate was five periods per second, chosen to be in the range where phase-locking information was probably only marginally useful for sinusoidal modulation. The pattern of frequency or amplitude change over time was either sinusoidal or had the following form: Within each modulation period of 200 ms, 60 ms was spent at each extreme of frequency or amplitude. The transitions between the extremes had the form of a half-cycle of a cosine function, each transition lasting 40 ms. For such a pattern of modulation, the frequency or amplitude is within 10% of its extreme values for 72 ms around each maximum and minimum. The corresponding duration for sinusoidal modulation with the same period is only 28 ms. Modulation depths for the AM and FM stimuli are specified in terms of the peak deviations from the mean values. Thus, for the AM stimuli, equal m implies equal peak amplitude deviation from the mean amplitude.

Other aspects of the stimuli, including the method of stimulus generation, were the same as for experiment 1, and the procedure was also the same. One of the subjects from experiment 1 was used (AS), together with two new subjects (CH and CM) who had extensive previous experience in similar tasks. The data for sinusoidal modulation of 1000- and 6000-Hz carriers for subject AS were taken from experiment 1.

C. Results

As before, the percent correct scores were converted to d' values. The results for the quasitrapezoidal modulator are shown by the triangles in Figs. 7 (250-Hz carrier), 8 (1000-Hz carrier), and 9 (6000-Hz carrier). The results obtained using the sinusoidal modulator are shown by open circles. For the carrier frequencies of 250 and 1000 Hz, the quasitrapezoidal patterns of frequency or amplitude change generally led to better performance than the sinusoidal changes, for both FM and AM. The effect of modulation waveform was small for the 6000-Hz carrier, although generally in the same direction.

As before, straight lines were fitted to the values of d' as a function of the square of the modulation depth; the slopes of these lines are indicated in Figs. 7–9. The ratios of the slopes for the two types of modulator are given in Table I; these ratios give a quantitative measure of the benefit obtained from spending more time at frequency or amplitude extremes. The procedure used to fit the straight lines to the data also gave standard errors (s.e.'s) of the slope estimates. The s.e.'s were used to estimate the s.e.'s of the ratios of slopes given in Table I. These s.e.'s are shown in parentheses after each ratio.

For carriers of 250 and 1000 Hz, the ratios are consistently greater for FM than for AM. This is consistent with the idea of an extra, sluggish mechanism for FM detection, based upon phase locking. This mechanism benefits considerably from more time spent at frequency extremes. Hartmann and Klein (1980), using an 800-Hz carrier and a 4-Hz modulation rate, found somewhat smaller differences in detectability between sinusoidal and trapezoidal modulation than us. However, they used a modulator for which the time spent at frequency extremes was only 50%, as compared to 60% for our stimuli.

For the 6000-Hz carrier the ratios of slopes for AM and FM are similar and are close to unity. The fact that the ratios
are similar for AM and FM is consistent with the idea that phase locking does not play a role in FM detection for high carrier frequencies. In this case, common mechanisms are probably used to detect AM and FM.

It is curious that trapezoidal modulation was of less benefit for AM detection at 6000 than at 250 or 1000 Hz. We have no explanation for this. One possibility is that AM detection at the two lower carrier frequencies was influenced to a small extent by phase-locking information. However, the precision of phase locking changes only slightly with level except at very low levels, so this seems unlikely.

III. DISCUSSION

We have argued that our results suggest the existence of two mechanisms for FM detection. One is similar to the mechanism used for AM detection and appears to operate most effectively at rates above 5 Hz. The other, which is probably based on phase-locking information, is most effective at low modulation rates. Edwards and Viemeister (1994) also argued that AM and FM were partly coded by the same mechanism, but that there was a second mechanism for the coding of FM; this allowed AM to be discriminated from FM. However, they argued that the second mechanism for FM only operated at suprathreshold values of FM. This conclusion was largely based on their observation that equally detectable amounts of AM and FM could only be discriminated when the detectability of the AM and FM was high.

Our results show that equally detectable amounts of AM and FM can be discriminated when the detectability is low, but only when the modulation rate is also low; for a 2-Hz modulation rate the discriminability of AM from FM was sometimes as good as the detectability of the AM or FM, for $d'$ values up to about 1.7. The lowest modulation rate used by Edwards and Viemeister was 4 Hz, and at that rate one

<table>
<thead>
<tr>
<th>Subject</th>
<th>250 Hz</th>
<th>1000 Hz</th>
<th>6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>2.5 (0.2)</td>
<td>1.7 (0.2)</td>
<td>8.8 (0.8)</td>
</tr>
<tr>
<td>CM</td>
<td>3.4 (0.5)</td>
<td>1.9 (0.2)</td>
<td>4.6 (0.3)</td>
</tr>
<tr>
<td>AS</td>
<td>2.4 (0.2)</td>
<td>2.1 (0.2)</td>
<td>2.4 (0.3)</td>
</tr>
</tbody>
</table>
subject showed discrimination performance almost as good as detection performance, while the other two subjects showed poorer discrimination performance. In their experiment 2, described in the Introduction, the modulation rate was 16 Hz, well above the rate where the second mechanism proposed by us would operate optimally. It is possible that the second mechanism for coding FM can play some role at modulation rates above 5 Hz, but only when the modulation is highly detectable. Viewed in this way, our interpretation is compatible with the results of Edwards and Viemeister.

The results of our first experiment showed that, for carrier frequencies of 125 and 1000 Hz, FM detection was generally best at the lowest modulation rate used (2 Hz), while for a carrier frequency of 6000 Hz, FM detection was poorest for the 2-Hz rate. We have obtained a similar pattern of results in an experiment that measured thresholds for the detection of FM, called FMDLs (Sek and Moore, 1995). FMDLs were measured for a wide range of center frequencies (0.25–8 kHz) and for modulation rates of 2, 5, or 10 Hz. At 2 kHz and below, FMDLs usually worsened with increasing modulation rate. Above 4 kHz, FMDLs improved with increasing modulation rate. For the 10-Hz modulation rate, the FMDLs at each center frequency were, to a good approximation, a constant proportion of the equivalent rectangular bandwidth (ERB) of the auditory filter at that center frequency (Glasberg and Moore, 1990). This is consistent with the idea that, for a 10-Hz modulation rate, FM detection is based mainly on changes in the excitation pattern. For the 2- and 5-Hz modulation rates, the FMDLs were a smaller proportion of the ERB at low center frequencies than at high frequencies, suggesting that some other mechanism plays a role.

Experiment 2 of the current paper showed that, for carrier frequencies of 250 and 1000 Hz, changing from sinusoidal to trapezoidal modulation resulted in a greater improvement in detectability for FM than for AM. This was not the case for a carrier of 6000 Hz. We argued that this was consistent with the idea of an extra, sluggish mechanism for FM detection based on the use of phase locking; this mechanism benefits from the greater time spent at frequency extremes for the trapezoidal modulator, but it operates weakly if at all for very high carrier frequencies.

The correlated-differencing model of Hartmann and Klein (1980) also predicts better FM detection for trapezoidal than for sinusoidal modulation, and it does this without specifying a specific coding mechanism for FM (e.g., neural synchrony or changes in the excitation pattern). However, the correlated-differencing model does not explain why trapezoidal modulation is beneficial at 250 and 1000 Hz but not at 6000 Hz. Furthermore, the slope ratios for trapezoidal and sinusoidal patterns of FM given in Table I are markedly greater than predicted by the correlated-differencing model, except for the 6000-Hz carrier. The ratios are also greater than predicted by two other models considered by Hartmann and Klein (1980, p. 943). Hence we believe that the mechanism proposed by us provides a more satisfactory account of the results.

V. CONCLUSIONS

(1) For carrier frequencies of 125 and 1000 Hz, FM detection tended to be better for a 2-Hz modulation rate than for a 5- or 10-Hz rate. In contrast, AM detection was best at the 10-Hz rate.

(2) For a 6000-Hz carrier, both AM and FM detection tended to be poorest at the 2-Hz modulation rate.

(3) For carrier frequencies of 125 and 1000 Hz, the ability to discriminate AM from FM was always poorest at the highest modulation rate (10 Hz); at this rate some subjects were essentially unable to discriminate AM from FM when the detectability of the modulation was relatively low (d' of 1.16 and below). For a modulation rate of 2 Hz, and when the detectability of the modulation was moderate (d' up to about 2), some subjects discriminated the type of modulation about as well as they detected the modulation.

(4) For a carrier frequency of 6000 Hz, the effect of modulation rate varied across subjects, but there was still a trend for poorer discrimination of the type of modulation at the highest modulation rate.

(5) The results are consistent with the interpretation that FM detection at a 10-Hz modulation rate is based largely on changes in excitation level for all carrier frequencies. For the 2-Hz modulation rate, and for the two lowest carrier frequencies, an extra mechanism, possibly based on phase locking to the carrier, may play a role. This mechanism appears to be sluggish, and only operates effectively when the stimuli spend sufficient time at frequency extremes.

(6) For a modulation rate of five periods per second and carriers of 250, 1000, and 6000 Hz, quasitrapezoidal patterns of amplitude or frequency change generally led to better performance than sinusoidal patterns. For carriers of 250 and 1000 Hz, the benefit of the difference in modulation pattern was much greater for FM than for AM. This is consistent with the idea of an extra, sluggish mechanism for FM detection, based on phase locking, that benefits considerably from more time spent at frequency extremes. For the 6000-Hz carrier, the benefit was small and was similar for FM and AM. This is consistent with the loss of phase-locking information at high carrier frequencies.

ACKNOWLEDGMENTS

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1 We chose to plot the results in terms of $\Delta f$ rather than the modulation index $\beta$, to allow comparison across modulation rates (for a fixed $\Delta f$, $\beta$ is proportional to the reciprocal of modulation rate). When plotted in terms of modulation indices, the results show consistently better performance for AM than for FM, consistent with earlier work at low modulation rates.


