The critical modulation frequency and its relationship to auditory filtering at low frequencies

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If the thresholds for detecting sinusoidal amplitude or frequency modulation of a sinusoidal carrier with frequency \( f_c \) are expressed in terms of the respective modulation indices, \( m \) and \( \beta \), the ratio \( \beta/m \) decreases as the modulation frequency increases, and approaches an asymptotic value of unity. The modulation frequency at which the ratio first becomes unity is called the critical modulation frequency (CMF). It has been suggested that the CMF is reached when the spectral sidebands in the stimulus first become detectable and that the CMF corresponds to half the value of the critical bandwidth (CB) at \( f_c \). In this paper it is demonstrated that the CMF is confounded as a measure of frequency selectivity at low frequencies, since, for modulation frequencies around the CMF, the sideband that is most detectable changes with \( f_c \). For values of \( f_c \) above 250 Hz, the lower sideband is most detectable. For values of \( f_c \) below 200 Hz, the upper sideband is most detectable. These findings can account for the fact that the CMF flattens off at low carrier frequencies, reaching an asymptotic value of about 40 Hz, whereas the auditory filter bandwidth continues to decrease down to very low center frequencies.

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INTRODUCTION

The critical bandwidth (CB) is a measure of the frequency resolution of the auditory system that can be derived using many different tasks. It can be defined empirically as "that bandwidth at which subjective responses change rather abruptly" (Scharf, 1970). It is generally assumed that the CB reflects the operation of an array of bandpass filters (the "auditory filters") in the auditory system, and Scharf's definition has sometimes been taken to imply that the filters have rectangular or near-rectangular shapes. However, on close examination, most of the tasks that have been used to estimate the CB do not reveal any abrupt changes as a function of bandwidth. Rather, performance tends to change smoothly and progressively as bandwidth is altered (Moore and Glasberg, 1986; Patterson and Moore, 1986). This is not consistent with the idea that the auditory filters are rectangular in shape.

Recent methods for estimating the shape of the auditory filter have been based largely on the use of rippled-noise (Houtgast, 1977; Pick, 1980; Glasberg et al., 1984) or notched-noise (Swets et al., 1962; Patterson, 1976; Patterson and Moore, 1986) maskers. These measurements have revealed that the auditory filter has a rounded top and sloping edges. A popular measure of the bandwidth of the auditory filter as estimated in these experiments is its equivalent rectangular bandwidth (ERB) (Patterson and Moore, 1986). In the remainder of this paper, "ERB" will be used to refer to the auditory filter bandwidth measured in this way.

It is generally assumed that the CB should be related to the ERB. Indeed, for some methods that have been used to estimate the CB, it is possible to derive a theoretical relationship between the empirical value of the CB and the ERB. This has been done in the case of Fletcher's (1940) classical band-widening experiment (Patterson and Hennig, 1977; Patterson and Moore, 1986), measurements of the threshold of a narrow-band signal centered in a two-tone masker (Glasberg et al., 1984), and measurements of loudness as a function of bandwidth (Moore and Glasberg, 1986). These analyses have shown that the empirically measured CB (as defined by Scharf, 1970) is not necessarily numerically equal to the ERB. For example, using an extension of the model for loudness proposed by Zwicker and Scharf (1965), Moore and Glasberg (1986) showed that an assumed ERB of 130 Hz at a center frequency of 1000 Hz led to a predicted CB for loudness of about 165 Hz, which is close to the empirically obtained value (Zwicker et al., 1957). In general, the relationship between the ERB and the CB will depend both on the type of experiment used to estimate the CB (e.g., loudness summation or masking) and on the method used to derive CB values from the data. However, for any given method, the CB and the ERB would be expected to vary with frequency in a similar way.

The "traditional" function relating the CB to center frequency (Zwicker, 1961; Scharf, 1970; Zwicker and Terhardt, 1980) is similar in form to the function relating the ERB to center frequency (Moore and Glasberg, 1983, 1987; Glasberg and Moore, 1990) for center frequencies above 1000 Hz. However, at low center frequencies the "traditional" CB function flattens off, reaching an asymptotic value of about 100 Hz, whereas the ERB function continues to decrease down to very low center frequencies (Moore et al., 1990; Peters and Moore, 1992). Early estimates of the CB at low center frequencies were strongly influenced by measurements of the critical modulation fre-
This paper is especially concerned with the discrepancy between the ERB and the CMF at low frequencies, and so we present next a more detailed description of the measurement of the CMF.

An amplitude-modulated (AM) sine wave with modulation index $m$, and a frequency-modulated (FM) sine wave with modulation index $\beta$, may each be considered as composed of three sinusoidal components, corresponding to the carrier frequency and two sidebands (an FM wave actually contains many sidebands but, for small modulation indices, the amplitudes of all but the first two sidebands are negligible). When the modulation indices are numerically equal ($m = \beta$), and when the carrier frequencies and modulation frequencies are the same, the components of an AM wave and an FM wave are identical in frequency and amplitude, the only difference between them being in the relative phase of the components. If, then, the two types of wave are perceived differently, the difference is likely to arise from a sensitivity to the relative phase of the components, which affects the temporal structure of the sound.

Zwicker (1952), Schorer (1986), and Sek (1994) measured the just-detectable amounts of amplitude or frequency modulation, for various rates of modulation. They found that for high rates of modulation, where the frequency components were widely spaced, the detectability of FM and AM was equal when the components in each type of wave were of equal amplitude ($m = \beta$). However, for low rates of modulation, when all three components fell within a narrow frequency range, AM could be detected when the relative levels of the sidebands were lower than for a wave with a just-detectable amount of FM ($m < \beta$). This is illustrated in the upper panel of Fig. 1 (data from Sek, 1994). Thus, for small frequency separations of the components, subjects appear to be sensitive to the relative phases of the components, while for wide frequency separations they are not.

If the threshold for detecting modulation is expressed in terms of the modulation index, $m$ or $\beta$, the ratio $\beta/m$ decreases as the modulation frequency increases, and approaches an asymptotic value of unity (or zero if the value of $\log(m/\beta)$ is used). This is illustrated in the lower panel of Fig. 1. The modulation frequency at which the ratio first becomes unity is the CMF. Zwicker (1952) and Schorer (1986) suggested that the CMF is reached when the spectral sidebands in the stimulus first become detectable. Once the modulation is detected in this way, the relative phases of the components do not play a role. Zwicker (1952) and Schorer (1986) suggested further that the CMF corresponded to half the value of the CB; essentially, the CMF was assumed to be reached when the overall stimulus bandwidth reached the CB. If this is correct, then the CMF may be regarded as providing an estimate of the CB at the carrier frequency.

Schorer (1986) argued that the CMF was one of the best ways of estimating the CB, especially at low center frequencies. He gave several reasons supporting this argument:

1. The whole stimulus falls within a very restricted spectral region; at the CMF, only one critical band is excited.
2. Variations in absolute threshold with frequency have only a small influence on the results, because of the small stimulus bandwidth.
3. Problems with off-frequency listening should be minimal.
4. Combination tones do not appear to influence the results, so the method can be used over a wide range of sound pressure levels of the stimuli.

Further analysis, elaborated below, suggests that reasons (1)–(3) may not be entirely valid. Furthermore, the interpretation of the CMF proposed by Zwicker (1952) and by Schorer (1986) may not be completely correct. Hartmann and Hnath (1982) suggested that the CMF corresponds to the point where the lower sideband in the spectrum first becomes detectable. The threshold for detecting the lower sideband depends more on the selectivity of auditory filters centered close to the frequency of the sideband than on the selectivity of the auditory filter centered on the carrier frequency. Furthermore, the level of the sideband relative to that of the carrier may be altered by transmission through the middle ear, especially at low frequencies, where the efficiency of transmission may change markedly with frequency (Zwislocki, 1975; Rosowski, 1991).
Perhaps a more serious problem comes from the possibility that, at the CMF, detection is not always based on the lower sideband. The results of several experiments support the idea that, at medium to high center frequencies, the lower sideband is more detectable than the upper sideband (Hartmann and Hnath, 1982; Ozimek and Sek, 1987; Moore and Sek, 1992). However, this may not be the case at low center frequencies. If detection were based on the upper sideband at low carrier frequencies, then the CMF would not provide a good estimate of the CB, or the ERB of the auditory filter, since the sideband on which detection is based would change as the center frequency was changed.

The main purpose of the experiments reported here was to explore the mechanism of modulation detection for low carrier frequencies and for modulation frequencies around the CMF; more specifically, we wished to determine whether the detection of AM and FM for modulation frequencies at and above the CMF depended on detection of the lower sideband, the upper sideband or both, and whether this changed with carrier frequency. To establish this, the results from two experiments were compared. In the first experiment, thresholds were measured for the detection of AM and FM, using several different (low) carrier frequencies and a range of modulation rates around the CMF. The thresholds were expressed in terms of the levels of the sidebands at threshold. In the second experiment, thresholds were measured for detecting a single sinusoid, corresponding to either the upper or lower sideband of the modulated sounds in experiment 1, in the presence of a sinusoidal masker corresponding to the carrier frequency. If a component corresponding to a given sideband, say the upper one, has a lower threshold than a component corresponding to the other sideband, then the given sideband should be more detectable in a situation where both sidebands are present (as in the modulation-detection task). Furthermore, if modulation detection thresholds are determined by the threshold for the most-detectable sideband, then the thresholds determined for that sideband in experiment 2 should correspond with those determined in experiment 1.

In a third experiment we examined the question of which sideband is most detectable by studying the detection of combined AM and FM (mixed modulation, MM) as a function of relative modulator phase.

I. EXPERIMENTS 1 AND 2

A. Stimuli

In experiment 1 (modulation detection), the carrier was a sinusoid with frequency $f_c = 125, 160, 200, \text{ or } 250$ Hz, and with a level of 70 dB SPL. The carrier was sinusoidally modulated in amplitude or frequency, using modulation frequencies from 20 to 70 Hz in 10-Hz steps. These modulation frequencies were chosen to encompass the CMF, which is typically about 40 Hz for low carrier frequencies (Zwicker, 1952; Schorer, 1986; Sek, 1993). Signals were generated using a Masscomp 5400 computer system via a 16-bit digital-to-analog converter (DAC, Masscomp model DA04H) at a sampling frequency of 10 kHz. The output of the DAC was low-pass filtered (Kemo VBF8/04, 90-dB/oct slope) with a cutoff frequency of 4 kHz, passed through a manual attenuator and delivered via one earpiece of a Sennheiser HD 414 headset.

In experiment 2 (masking), the masker had the same frequencies as the carrier in the modulation-detection experiment; the masker was a sinusoid with frequency $f_c = 125, 160, 200, \text{ or } 250$ Hz, and with a level of 70 dB SPL. Each signal had a frequency corresponding to one of the sidebands of the modulated sounds in experiment 1. For example, with $f_c = 200$ Hz, the signal frequencies were 130, 140, 150, 160, 170, 180, 220, 230, 240, 250, 260, and 270 Hz. So, for each masker frequency, 12 signal frequencies were used. For this experiment, the masker and signal were each generated by a Farnell DSG1 signal generator. Thus the relative starting phase of the signal and masker varied randomly across trials. The timing of the stimuli was controlled by a Texas Instruments 990/4 computer. Analog multipliers (AD534L) were used as gates, gating voltages being derived from two 12-bit digital-to-analog converters. Two multipliers were used in series to give an on-off ratio exceeding 100 dB. The computer varied the signal level via a Charybdis model D programmable attenuator; the level of the masker was adjusted by means of a manual attenuator (Hatfield 2125). The signal and masker were combined in an adder (Analog Devices 507) before being passed to a sound-attenuating chamber and a final manual attenuator. The earphone was the same as for experiment 1.

In both experiments, two successive sounds were presented on each trial. One of them was a sinusoid with frequency $f_c$ and the other one was either a modulated sinusoid with carrier frequency equal to $f_c$ (experiment 1) or that same sinusoid together with a single sinusoidal signal (experiment 2). The order of the sounds in a pair was random. Each sound had a duration of 500 ms including raised-cosine rise/fall times of 50 ms. The interstimulus interval was 500 ms.

B. Procedure

An adaptive two-alternative forced-choice (2AFC) procedure was used. Subjects were required to indicate the interval containing the modulated carrier (experiment 1) or the masker plus signal (experiment 2). Observation intervals were marked by lights on the response box and correct-answer feedback was provided by illuminating the light corresponding to the correct interval. The modulation index ($\alpha$ or $\beta$) in experiment 1 or the level of the signal in experiment 2 was increased after one incorrect response and decreased after three successive correct responses. This procedure tracks the point on the psychometric function corresponding to 79.4% correct (Levitt, 1971). In experiment 1, the modulation index was changed by a factor of 1.5 until four reversals had occurred, and by a factor of 1.26 for the rest of the run. In experiment 2, the initial step size of 5 dB was changed to 2 dB after the fourth reversal. For each threshold measurement twelve reversals were obtained. Threshold was calculated as the geometric mean
value at the last eight reversals (for the modulation index—experiment 1) or as the arithmetic mean of the levels at the last eight reversals (experiment 2). Thresholds presented in this paper are the average of at least five single threshold determinations. The variability of the thresholds was reasonably constant across conditions, but tended to increase with decreasing carrier frequency. Subjects were tested in a double-walled sound-attenuating chamber.

Absolute thresholds were measured for signal frequencies of 55, 65, 75, 85, 100, 120, 150, 190, 230, 290, and 330 Hz, using the same procedure as for experiment 2.

C. Subjects

Three subjects with normal hearing at all audiometric frequencies were used. One was the author AS. The other two subjects were paid for their services. All subjects were trained for about 10 h, after which their performance appeared to be stable.

D. Results

The results for both experiments are presented in Figs. 2-5 for \( f_c = 125, 160, 200, \) and 250 Hz, respectively. Each panel shows results for one subject, and the value of \( f_c \) is indicated by an arrow. Dashed lines show absolute thresholds. The open symbols show the results of experiment 1; the level of each sideband at the modulation detection threshold is plotted as a function of the frequency of the sideband. Since the upper and lower sidebands were always equal in level, each measured threshold is presented twice, giving a pattern of thresholds symmetrical about \( f_c \). For the higher modulation frequencies used, the AM and FM thresholds coincide, whereas for the lower values used (sidebands closest to \( f_c \)), the FM thresholds are higher than the AM thresholds. This reflects the fact that the modulation frequencies were chosen to span the CMF. These results are consistent with earlier results showing that the CMF for low carrier frequencies is typically about 40 Hz (Zwicker, 1952; Schorer, 1986; Sek, 1993).

The filled symbols show the results of experiment 2, where thresholds were measured for single sinusoids corresponding to the upper and lower sidebands in experiment 1. For the three lowest values of \( f_c \) (Figs. 2-4), the thresholds obtained for signals with frequencies below \( f_c \) (filled circles) were generally higher than those for signals with frequencies above \( f_c \). This suggests that, when both sidebands were present simultaneously (as in experiment 1),
detection was based on the upper sideband rather than the lower sideband.

For the two lowest values of \( f_c \), the thresholds for signals with frequencies below \( f_c \) tended to increase as the frequency separation between the signal and masker increased. This effect is opposite to what would be expected on the basis of frequency selectivity alone; reasons for it are discussed later in this paper.

Comparing the results of experiments 1 and 2, it is clear that for the lowest carrier frequency (125 Hz, Fig. 2) the thresholds for the lower sideband alone (filled circles) are markedly higher than the levels of the lower sideband at the modulation detection threshold (open symbols). This indicates that, at the modulation detection threshold, the lower sideband would have been undetectable. Indeed, for the highest modulator frequency used, the lower sideband (at 55 Hz) would have been below absolute threshold. In contrast, for modulation rates above the CMF, the levels of the upper sideband at the modulation detection threshold are almost identical with the detection thresholds of the upper sideband when presented alone (filled squares). Taken together, these results indicate that modulation detection thresholds for modulation rates above the CMF were determined by the threshold for detection of the upper sideband.

The results for a carrier frequency of 160 Hz (Fig. 3) are similar to those for a carrier frequency of 125 Hz, except that the discrepancies between the thresholds for the lower sideband presented alone (filled circles) and the levels of the lower sideband at the modulation detection threshold (open symbols) are smaller. Again, however, the results show that modulation detection thresholds for modulation rates above the CMF were determined by the threshold for detection of the upper sideband.

The results for a carrier frequency of 200 Hz (Fig. 4) are somewhat less clear cut. For subjects CL and AS, thresholds for the lower sideband alone (filled circles) are clearly above those for the upper sideband alone (filled squares) and are also above the levels of the lower sideband at the modulation detection threshold. This suggests that, for these subjects, modulation detection thresholds were determined by the threshold for detecting the upper sideband. However, for subject SB, the thresholds for the upper sideband alone and the lower sideband alone are almost equal. In both cases, thresholds are very slightly above the levels of the sidebands at the modulation detection threshold for modulation rates above the CMF. The results for SB suggest that modulation detection thresholds for modulation rates above the CMF were based about equally on detection of the upper and lower sidebands; the presence of both sidebands simultaneously led to slightly lower thresholds than obtained for each sideband separately. On average, the thresholds for single sinusoids at 130, 140, 260, and 270 Hz were 2 dB above the levels of the
corresponding sidebands at the modulation detection threshold.

For $f_c=250$ Hz (Fig. 5), the thresholds for the upper sideband alone and the lower sideband alone are almost equal for SB and AS. The thresholds are generally very slightly (but not significantly) above the levels of the sidebands at the modulation detection threshold for modulation rates above the CMF. These results suggest that modulation detection thresholds for modulation rates above the CMF were based about equally on detection of the upper and lower sidebands. For CL, thresholds for the lower sideband alone were slightly higher than those for the upper sideband alone, suggesting that modulation detection for rates above the CMF was determined mainly by the threshold for the upper sideband.

It appears that carrier frequencies from 200 to 250 Hz lie in a transition region. For carriers below that region, modulation detection thresholds for rates above the CMF are determined by the threshold for detecting the upper sideband. For carriers above that region, previous work suggests that detection is based mainly on the threshold for detecting the lower sideband (Hartmann and Hnath, 1982; Ozimek and Sek, 1987; Moore and Sek, 1992). Within that region, both sidebands may contribute to detection of the modulation.

It should be emphasized that the conclusions stated above apply for modulation rates greater than the CMF (about 40 Hz). For modulation rates less than this, thresholds for detecting AM were typically lower than those for detecting FM. Furthermore, in the case of AM, the level of the most detectable sideband at threshold was usually slightly lower than the threshold for that sideband when presented alone. For example, in Fig. 3, the open squares at 180 Hz (level of the upper sideband at modulation detection threshold) are below the filled squares (threshold for a 180-Hz sinusoid). This indicates that detection of AM was probably not based on detection of individual sidebands. Rather, at these low modulation rates, it appears that the auditory system is able to follow the temporal structure of the modulated stimuli as determined by the interaction of the carrier and both sidebands. The modulation is heard as loudness (AM) or pitch (FM) changes or as roughness (Terhardt, 1974; Kemp, 1982). Similarly, in experiment 2, when the stimulus in the signal interval consisted of two sinusoids separated by 20 or 30 Hz, subjects reported hearing a rapid loudness fluctuation, corresponding to beats. However, the peak-to-valley modulation depth (in dB) produced by two sidebands (modulation detection) is about twice that produced by a single sideband (experiment 2) at the same relative level. This can explain why the levels of the sidebands at the AM modulation detection threshold were usually lower than the thresholds for the single most detectable sideband, for modulation rates less than the CMF.

Even for modulation rates above the CMF, the primary detection cue may have been a temporal fluctuation (beat). However, in this case auditory filtering would have played a significant role. The pattern of beating would have differed at the outputs of different auditory filters (Goldstein, 1967). The strongest beats would have occurred at the outputs of filters tuned around the frequencies of the sidebands, rather than the frequency of the carrier.

In summary, the results need to be considered separately for modulation rates below and above the CMF. For modulation rates below the CMF, modulation detection thresholds appear to depend on following the temporal structure of the entire signal. Both sidebands influence this temporal structure, and the relative phases of the sidebands play an important role. For modulation rates above the CMF, the relative phases of the sidebands do not influence the results; threshold for detecting AM and FM are equal. For carrier frequencies below 200 Hz, modulation detection thresholds correspond to the threshold for detecting the upper sideband in the spectrum. For carrier frequencies above 250 Hz, modulation detection thresholds correspond to the threshold for detecting the lower sideband in the spectrum. For carrier frequencies in the range 200 to 250 Hz, both sidebands may contribute to the detection of modulation, although this depends somewhat on the individual subject.

II. EXPERIMENT 3

In this experiment, we used a different method for assessing which sideband in the spectrum of a modulated sound is most important in determining the threshold for detecting modulation at rates above the CMF. The method depends on the measurement of thresholds for detecting combinations of AM and FM, i.e., mixed modulation (MM). Hartmann and Hnath (1982), Ozimek and Sek (1987), and Moore and Sek (1992) have shown that thresholds for detecting MM, for modulation rates higher than the CMF, depend strongly on the relative phase of the AM and FM modulators. The pattern of results, for the 1-kHz carrier frequency used in all of these studies, was consistent with predictions based on the assumption that performance depended on detection of the lower sideband. The present experiment repeats these experiments with lower carrier frequencies, to establish which sideband of the modulated signal’s spectrum is decisive for modulation detection.

A. Theory and predictions

The spectrum of a MM signal depends strongly on the relative phase of the AM and FM modulators. A general formula describing the waveform of a MM sinewave, following Moore and Sek (1992), is

$$A(t) = A_0 [1 + m \cos(\omega_m t + \Phi)]$$

$$\times \cos[\omega_c t + \beta \sin(\omega_m t + \theta)],$$

where $t$ is time, $A_0$ is the envelope amplitude of the unmodulated signal, $m$ and $\beta$ are the modulation indices for AM and FM, respectively, $\omega_m$ is the modulation frequency, $\omega_c$ is the carrier frequency, and $\Phi$ and $\theta$ are terms representing the phases of the two modulators. The phase difference between the modulating signals, $\Delta \phi = \Phi - \theta$. When $\Delta \phi = 0$, a maximum in frequency coincides with a maximum in amplitude. In our experiments, we used values for
Δφ of 0, π/2, π, and 3π/2. It may be shown that the spectrum of a MM signal consists primarily of three components of which the middle one corresponds to the carrier, while the two sidebands are the result of the modulation process. The relative amplitudes, $A_U$ and $A_L$, of the upper and lower sidebands depend on the value of Δφ:

for $Δφ=0$,

\[
A_U = (A_0/2) |m+β|, \quad (2)
\]

\[
A_L = (A_0/2) |m-β|, \quad (3)
\]

for $Δφ=π$,

\[
A_U = (A_0/2) |m-β|, \quad (4)
\]

\[
A_L = (A_0/2) |m+β|, \quad (5)
\]

for $Δφ=π/2$ and $3π/2$,

\[
A_U = A_L = (A_0/2) \sqrt{(m^2+β^2)}. \quad (6)
\]

In this experiment, we initially determined thresholds for detecting AM alone and FM alone. The threshold modulation index for AM will be denoted by $m_{th}$ and that for FM by $β_{th}$. Next, thresholds were measured for detecting FM, when that FM was combined with "subthreshold" amounts of AM ($m < m_{th}$) at the same modulation frequency. Equations (2) to (6) can be rewritten to apply to this situation on the assumption that the threshold for detecting the MM corresponds to a fixed level of the most-detectable sideband. If the amounts of modulation are expressed relative to the threshold values for AM and FM alone (i.e., as $m/m_{th}$ and $β/β_{th}$), the equations become particularly simple. If the lower sideband is most detectable, then the FM modulation index required for threshold, $β_{th}$, is

for $Δφ=0$,

\[
β/β_{th} = 1 + m/m_{th}, \quad (7)
\]

for $Δφ=π$,

\[
β/β_{th} = 1 - m/m_{th}, \quad (8)
\]

for $Δφ=π/2$ and $3π/2$,

\[
β/β_{th} = \sqrt{1-(m/m_{th})^2}. \quad (9)
\]

If the upper sideband is most detectable, then

for $Δφ=0$,

\[
β/β_{th} = 1 - m/m_{th}, \quad (10)
\]

for $Δφ=π$,

\[
β/β_{th} = 1 + m/m_{th}, \quad (11)
\]

for $Δφ=π/2$ and $3π/2$,

\[
β/β_{th} = \sqrt{1-(m/m_{th})^2}. \quad (12)
\]

Hence the pattern of results for $Δφ=0$ and $Δφ=π$ is completely different depending on whether threshold is determined by the upper or lower sideband. The expected pattern of results for these two cases is illustrated in Fig. 6.

**B. Method**

The carrier signal was always a sinusoid with $f_c = 125$, 250, or 500 Hz and level = 70 dB SPL. The modulation frequency was chosen to be about 1.5 times the value of the CMF determined by Sek (1994). Values used were 60, 70, and 80 Hz for carrier frequencies of 125, 250, and 500 Hz, respectively. 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. The timing of the stimuli, the method of signal generation and the procedure were the same as for experiment 1.

Initially, thresholds for detecting AM alone and FM alone were determined for each modulation frequency. Next, thresholds were measured for detecting FM, when that FM was combined with "subthreshold" amounts of AM ($m < m_{th}$) at the same modulation frequency. In this stage of the experiment, the stimulus in the signal interval was both amplitude and frequency modulated, while the other stimulus was unmodulated. Within a block of trials, the amount of AM ($m$) was held constant, and the amount of FM ($β$) was varied to determine threshold. Values of $m$ used were 0.25$m_{th}$, 0.5$m_{th}$, and 0.75$m_{th}$. Four values of $Δφ$, the phase shift between the modulators for AM and FM, were used, namely 0, $π/2$, $π$, and $3π/2$.

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 were trained for about 10 h, after which their performance appeared to be stable.

**C. Results**

Thresholds for detecting AM alone and FM alone are given in Table I. Subject CL tended to have slightly higher thresholds than the other subjects. All subjects showed slightly worse performance at $f_c = 125$ Hz than at the two higher carrier frequencies. For each subject at each $f_c$, the
TABLE I. Modulation indices at threshold for the detection of AM alone (m) and FM alone (\( \beta \)), for each carrier frequency and each subject.

<table>
<thead>
<tr>
<th>Carrier frequency (Hz)</th>
<th>Subject</th>
<th>125</th>
<th>250</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CL</td>
<td>CL</td>
<td>CL</td>
<td>CL</td>
</tr>
<tr>
<td></td>
<td>( m )</td>
<td>0.110</td>
<td>0.059</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>0.118</td>
<td>0.069</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
<td>LB</td>
</tr>
<tr>
<td></td>
<td>( m )</td>
<td>0.076</td>
<td>0.053</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>0.063</td>
<td>0.045</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>AS</td>
<td>AS</td>
<td>AS</td>
</tr>
<tr>
<td></td>
<td>( m )</td>
<td>0.057</td>
<td>0.040</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>( \beta )</td>
<td>0.067</td>
<td>0.041</td>
<td>0.044</td>
</tr>
</tbody>
</table>

values of \( m \) and \( \beta \) at threshold were similar, as would be expected for a modulation rate above the CMF.

The thresholds for detecting FM in the presence of fixed “subthreshold” amounts of AM are shown in Figs. 7–9; each figure shows results for one carrier frequency. The abscissa shows the fixed amount of AM as a proportion of the “threshold” value (as given in Table I) for each subject, and the ordinate shows the amount of FM required for threshold with the MM stimulus, plotted as a percentage of the threshold for FM alone. The parameter is the phase shift between the AM and FM, \( \Delta \phi \). Each panel shows results for one subject.

Consider first the results for \( f_c = 125 \) Hz. For \( \Delta \phi = 0 \), i.e., when the maxima in amplitude and frequency were coincident, an increase in AM depth caused a decrease in the FM index required for threshold. In other words, the coexisting AM made the FM easier to detect. An opposite effect was observed for \( \Delta \phi = \pi \); an increase in \( m \) produced a large increase in the value of \( \beta \) required for threshold. For \( \Delta \phi = \pi/2 \) or \( 3\pi/2 \), the values of \( \beta \) required for threshold decreased with increasing \( m \), but did not decrease as much as when \( \Delta \phi = 0 \). This pattern of results is almost exactly as predicted on the assumption that thresholds are based on detection of the upper sideband in the spectrum of the MM signal (see Fig. 6, left panel).

For \( f_c = 250 \) Hz (Fig. 8), the pattern of results is different from that for \( f_c = 125 \) Hz, and it also varies across subjects. For subject CL, the FM thresholds tend to be highest for \( \Delta \phi = \pi \), as was the case for \( f_c = 125 \) Hz. However, for the other two subjects, thresholds tend to be highest for \( \Delta \phi = 0 \). It appears that, for \( f_c = 250 \) Hz, neither one sideband nor the other dominates overall in determining the threshold. In all probability, the sideband that is dominant varies with the relative levels of the sidebands and with the exact characteristics of the auditory filters of the individual subjects.

For \( f_c = 500 \) Hz (Fig. 9), the pattern of results for \( \Delta \phi = 0 \) and \( \Delta \phi = \pi \) is almost opposite to that for \( f_c = 125 \) Hz (Fig. 7). For \( \Delta \phi = 0 \), an increase in \( m \) caused an increase in the value of \( \beta \) required for threshold. For \( \Delta \phi = \pi \), an increase in \( m \) produced a decrease in the value of \( \beta \) required for threshold. The results for \( f_c = 500 \) Hz are of the general form predicted on the assumption that the thresholds are based on detection of the lower sideband in the spectrum of the MM signal (see Fig. 6, right panel).

However, the changes in threshold with changes in the value of $m$ are somewhat less than predicted.

III. DISCUSSION

The results presented above indicate that the CMF does not provide a direct measure of frequency selectivity at the carrier frequency, at least for low carrier frequencies. Contrary to the claim of Schorer (1986), the CMF is affected by off-frequency listening, in the sense that modulation threshold at the CMF depends on detection of one or the other of the sidebands. For example, at a carrier frequency of 125 Hz, the modulation detection threshold at the CMF is primarily determined by the threshold for the sideband at 165 Hz; that sideband would be detected using the output of an auditory filter centered at or slightly above 165 Hz, rather than a filter centered at 125 Hz. The fact that the most detectable sideband switches from the lower one to the upper one as the carrier frequency decreases means that the CMF is confounded as a measure of frequency selectivity, since the auditory filter centered on the upper sideband will have a greater bandwidth than the auditory filter centered on the lower sideband.

The data show that, for masker frequencies below 200 Hz, the threshold for detection of a single sinusoidal signal is greater for a signal below the masker frequency than for a signal an equivalent amount above the masker frequency. Indeed, for the lowest masker frequency used (125 Hz), the signal threshold actually increased as the signal frequency was decreased from 105 to 55 Hz. There may be several reasons for these effects:

1. The transfer function of the middle ear would result in an attenuation of low-frequency signals relative to the level of a higher-frequency masker (Zwislocki, 1975; Rosowski, 1991); conversely, the level of signals above the masker in frequency would be boosted relative to the masker level.

2. The cochlea may be characterized by a relatively high level of internal noise at low frequencies (Nedzel-nitsky, 1980). It has been argued that this noise is partly responsible for the marked increase in absolute threshold at very low frequencies (Glasberg and Moore, 1990; Zwicker and Fastl, 1990). The internal noise would make it more difficult to detect a low-frequency sinusoidal signal in the presence of a higher-frequency sinusoidal masker, both by exerting a direct masking effect and by restricting off-frequency listening (Patterson and Moore, 1986).

3. The signal-to-masker ratio required for threshold may increase at low frequencies. It seems likely that the main cue used for signal detection when a single sideband was present was the beating produced by the interaction of the signal and masker. The higher the level of the signal relative to the masker, the greater is the beat "depth" (the peak-to-valley ratio in dB). Riesz (1928) and Harris (1963) showed that the beat depth required for the detection of beats increased markedly at low frequencies. In addition, the detectability of beats decreases with increasing beat rate (above 3–4 Hz) and with decreasing sensation level (Riesz, 1928; Harris, 1963).

These reasons provide further justification for our claim that the CMF is confounded as a measure of frequency selectivity; none of the reasons (1)–(3) above is directly connected with frequency selectivity, yet all may influence the value of the CMF for low carrier frequencies.

To determine whether the values of the CMF at low frequencies could be reconciled with the estimates of auditory filter bandwidth and shape summarized by Glasberg and Moore (1990), we used the CMF data of Sek (1994), obtained with carriers at the same level as used in the present experiments. His data indicate that the CMF is about 36.5 at 125 Hz and about 42.5 at 250 Hz. For each of these carrier frequencies, we calculated excitation patterns using the program published by Glasberg and Moore (1990) for two stimuli: The carrier alone, and the carrier plus the most-detectable sideband when that sideband was at the threshold determined at the CMF. The sideband for the 125-Hz carrier had a frequency of 161.5 Hz and a level of 45 dB. The sideband for the 250-Hz carrier had a frequency of 207.5 Hz and a level of 40 dB. A "correction" based on absolute thresholds as a function of frequency was applied (see Glasberg and Moore, 1990, for the rationale for using a "correction"). The difference in excitation level for the carrier alone and the carrier-plus-sideband was used to calculate the beat depth (the peak to valley ratio in dB) at each center frequency on the excitation pattern.

For the 125-Hz carrier, the maximal beat depth was about 4.6 dB, and it occurred for an auditory filter centered around 173 Hz; the mean excitation level at the output of that filter was about 38 dB. Such a beat depth is reasonably consistent with the threshold values published by Riesz (1928), taking into account the low carrier frequency and relatively high beat rate, although he did not present results for the exact combination of center frequency and beat rate relevant here. For the 250-Hz carrier, the beat depth increased monotonically with decreasing center frequency below about 200 Hz. However, the excitation level decreased monotonically over this range, and the detectability of beats decreases markedly at sensation levels below about 20 dB (Riesz, 1928; Harris, 1963). Over the region of the excitation pattern where the mean excitation level was between 20 and 30 dB (center frequencies from about 142–161 Hz), the beat depth was between 5.9 and 4.5 dB. This is of the same order as the maximal beat depth for the 125-Hz carrier and 161.5-Hz sideband. Thus the values of the CMF for the two carrier frequencies, 125 and 250 Hz, can be reconciled, at least to a first approximation, with the estimates of auditory filter bandwidth and shape summarized by Glasberg and Moore (1990).

IV. CONCLUSIONS

The CMF is confounded as a measure of frequency selectivity for several reasons. First, for modulation frequencies around the CMF, the sideband that is most detectable changes with $f_c$. For carrier frequencies below 200 Hz, modulation detection thresholds correspond to the threshold for detecting the upper sideband in the spectrum. For carrier frequencies above 250 Hz, modulation detec-
tion thresholds correspond to the threshold for detecting the lower sideband in the spectrum. For carrier frequencies in the range 200 to 250 Hz, both sidebands may contribute to the detection of modulation, although this depends somewhat on the individual subject. Second, the CMF is probably influenced by changes in effective sound spectrum produced by middle ear transmission, by internal noise at low frequencies, and by changes in the detectability of beats with frequency, sensation level, and beat rate.

Taken together, these factors can account for the fact that the CMF flattens off at low carrier frequencies, whereas the auditory filter bandwidth continues to decrease down to very low center frequencies.

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