An analysis of quasi-frequency-modulated noise and random-sideband noise as comparisons for amplitude-modulated noise

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(Received 31 August 1999; revised 5 January 2000; accepted 23 April 2000)

Experiments were performed to determine under what conditions quasi-frequency-modulated (QFM) noise and random-sideband noise are suitable comparisons for AM noise in measuring a temporal modulation transfer function (TMTF). Thresholds were measured for discrimination of QFM from random-sideband noise and AM from QFM noise as a function of sideband separation. In the first experiment, the upper spectral edge of the noise stimuli was at 2400 Hz and the bandwidth was 1600 Hz. For sideband separations up to 256 Hz, at threshold sideband levels for discriminating AM from QFM noise, QFM was indiscriminable from random-sideband noise. For the largest sideband separation used (512 Hz), listeners may have used within-stimulus envelope correlation in the QFM noise to discriminate it from the random-sideband noise. Results when stimulus bandwidth was varied suggest that listeners were able to use this cue when the carrier was wider than a critical band, and the sideband separation approached the carrier bandwidth. Within-stimulus envelope correlation was also present in AM noise, and thus QFM noise was a suitable comparison because it made this cue unusable and forced listeners to use across-stimulus envelope differences. When the carrier bandwidth was less than a critical band or was wideband, QFM noise and random-sideband noise were equally suitable comparisons for AM noise. When discrimination thresholds for QFM and random-sideband noise were converted to modulation depth and modulation frequency, they were nearly identical to those for discrimination of AM from QFM noise, suggesting that listeners were using amplitude modulation cues in both cases. [S0001-4966(00)01208-X]

PACS numbers: 43.66.Mk, 43.66.Nm [DWG]

INTRODUCTION

Most of the complex sounds of interest to us, such as speech, music, and environmental sounds, are identifiable by patterns of amplitude change over time. A systematic method of measuring the perception of dynamic amplitude changes has been to measure threshold modulation depth for detection of sinusoidal amplitude modulation of a carrier. Modulation thresholds as a function of modulation frequency have been called the temporal modulation transfer function (TMTF). For noise carriers with bandwidths of at least twice the highest modulation frequency, the resulting function has the form of a low-pass filter (Viemeister, 1979; Dau *et al.*, 1997). The TMTF has the advantage of separating the effects of temporal resolution from intensity resolution, which may be confounded in other temporal measures such as gap detection. At low modulation frequencies, the system can easily follow the temporal fluctuations, and thus these thresholds reflect the intensity resolution of the system. As the modulation frequency increases, the system cannot follow the amplitude changes faithfully, and the frequency at which the function begins to roll off reflects the temporal resolution of the system.

The bandwidth of the carrier must be restricted when the goal is to examine the effects of frequency region or bandwidth on temporal processing. It is critical to find stimuli that are discriminable only on the basis of envelope cues. In the case of tonal carriers, sinusoidal amplitude modulation adds sideband components at plus and minus the modulation frequency, as shown in Eq. (1):

$$\mathrm{AM}(t)=\cos(2\pi f_c t)+\frac{m}{2}(\cos(2\pi(f_c-f_s)t)+\cos(2\pi(f_c+f_s)t)), \quad (1)$$

where f_c is the carrier frequency, and f_s is the modulation frequency. If this is used as the signal stimulus, and a tone at the carrier frequency is used as the comparison, listeners may be able to discriminate them either on the basis of the envelope modulation or on the basis of the long-term spectrum. In order to eliminate the spectral cue, a quasi-frequency-modulated (QFM) tone may be used as the comparison, as shown in Eq. (2):

$$\mathrm{QFM}(t)=\cos(2\pi f_c t)+\frac{m}{2}\left(\cos\left(2\pi(f_c-f_s)t+\frac{\pi}{2}\right)+\cos\left(2\pi(f_c+f_s)t+\frac{\pi}{2}\right)\right). \quad (2)$$

The long-term amplitude spectrum is identical to that of the AM tone, and thus this is no longer a cue. However, changing the phase of the sidebands introduces other differences from the AM tone. The instantaneous frequency of a QFM tone is modulated at a rate of f_s. A QFM tone is amplitude modulated at a frequency of 2^*f_s. For the same value of *m*, the modulation depth is smaller for the QFM stimulus than that of an AM tone. In addition, the difference in phases of the components may introduce differences in the long-term spectra within the ear, due to distortion products. In a previous paper (Strickland and Viemeister, 1997), it was argued that the presence of these multiple cues makes it unclear whether thresholds for discriminating an AM from a QFM tone are based solely on envelope cues when f_s is high.

In that paper, the approach taken was to use narrow-band noise carriers instead of tones. It was argued that this might eliminate the above-mentioned frequency modulation cue in the QFM stimulus, because the pitch of a noise is less salient than that of a tone. Differences in internal long-term spectra might also be unusable, due to the nondeterministic nature of the stimuli. Indeed, TMTFs with a low-pass filter shape can be obtained when QFM noise is used as the comparison, but the detectability of other cues in QFM noise was not measured. In addition, once the carrier is broadened to a noise band, it would be possible to simply add sidebands in random phase. The goal of this paper is to determine what noise is the most suitable comparison for AM noise in measuring a TMTF.

An AM noise may be created by using the Rice model (Rice, 1944) to extend Eq. (1) for a noise. A carrier band is created, and sidebands are added at plus and minus f_s from each component, as shown in Eq. (3):

$$\mathrm{AM}(t)=\sum_{f_c=f_l+f_s}^{f_h-f_s} A_c\Big[\cos(2\pi f_c t+\phi_c) + \frac{m}{2}(\cos(2\pi(f_c-f_s)t+\pi+\phi_c) + \cos(2\pi(f_c+f_s)t-\pi+\phi_c))\Big], \quad (3)$$

where A_c is a Rayleigh-distributed amplitude, ϕ_c is a random phase rectangularly distributed from 0 to 2π radians, and m is the modulation index (0 to 1). For the frequency terms, f_c is the frequency of each carrier component, f_l and f_h are the lower and upper spectral edges of the whole noise, including the sidebands, and f_s is the sideband separation from the carrier frequency in Hz. AM can be created by any phase relationship between the sidebands such that one is in positive phase and the other is in negative phase by the same amount relative to the carrier phase. In this experiment, the phases were chosen so that the modulation would start and end in a valley. AM noise is sinusoidally amplitude modulated at frequency f_s, at a modulation depth of m, from 0 to 1.

QFM noise may be created by extending Eq. (2) in the same manner, as shown in Eq. (4):

$$\mathrm{QFM}(t)=\sum_{f_c=f_l+f_s}^{f_h-f_s} A_c\Big[\cos(2\pi f_c t+\phi_c) + \frac{m}{2}\Big(\cos\Big(2\pi(f_c-f_s)t-\frac{\pi}{2}+\phi_c\Big) + \cos\Big(2\pi(f_c+f_s)t-\frac{\pi}{2}+\phi_c\Big)\Big)\Big], \quad (4)$$

which differs from Eq. (3) in that the sideband phases are shifted by minus $\pi/2$ radians from the carrier phase rather than plus and minus π radians. QFM noise has the same frequency and amplitude modulation characteristics as a QFM tone. The amplitude modulation comes from interaction between the two sidebands and the carrier, and has the form of a fully rectified sine wave at high modulation depths, and is nearly sinusoidal at lower modulation depths.

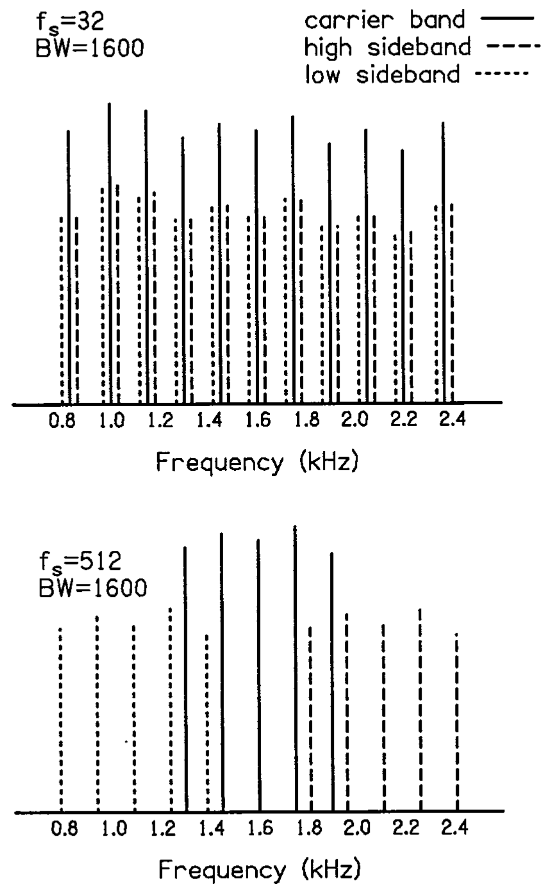

FIG. 1. Schematic depiction of the carrier band and sidebands for $f_s=32$ (top panel) and 512 Hz (bottom panel), for $m=1.0$. Component separation is 150 Hz, for clarity. In the experiments, the component separation was 2 Hz. The bandwidth is 1600 Hz in both panels.

As noted above, it would also be possible to create a noise with the same long-term average power spectrum as AM noise simply by adding the sidebands in random phase, as shown in Eq. (5):

$$\text{Random-sideband}(t)=\sum_{f_c=f_l+f_s}^{f_h-f_s} A_c\Big[\cos(2\pi f_c t+\phi_c) + \frac{m}{2}(\cos(2\pi(f_c-f_s)t+\phi_{c1}) + \cos(2\pi(f_c+f_s)t+\phi_{c2}))\Big], \quad (5)$$

where ϕ_{c1} and ϕ_{c2} are phases randomly selected for each sideband. Thus, the phase of these sidebands is random relative to the carrier phase, in contrast to the AM and QFM noise, where there is a specified phase relationship between the sidebands and the carriers.

These three types of noises have identical long-term average amplitude spectra. As shown schematically in Fig. 1, the amplitude spectra of these stimuli have a central flat area, composed of carriers and sidebands, and a lower amplitude region flanking the central area, composed only of sidebands. Figure 1 is structured to make the relationship between each carrier and its sidebands clear, so the frequency spacing of the components is 150 Hz, in contrast to the spacing of 2 Hz in the actual stimuli. Of course, sidebands would add with carrier components in the central area, so they would not be separately visible as they are in the figure. In this experiment, the total bandwidth of the stimuli stays constant at $f_h - f_l$, and thus the width of the central area decreases and the width of the sidebands increases with f_s. Thus, in the top panel the central area is 1536 Hz wide, and the sidebands extend out 32 Hz to either side, while in the bottom panel the central area is only 576 Hz wide, and the sidebands extend out 512 Hz. The phases in which the sidebands are added relative to the carrier components create different dynamic characteristics in each type of noise.

Both QFM and random-sideband noise have average long-term amplitude spectra that are identical to AM noise. Random-sideband noise might appear to be a better comparison for AM noise, because it does not have other cues that could make it discriminable from AM noise, while QFM noise may have cues such as frequency modulation. Calculations done using an envelope detector model for a previous paper (Strickland and Viemeister, 1997), however, made it apparent that QFM noise might be a more suitable comparison for AM noise under certain conditions. For AM noise, the orderly relationship between modulation depth and sideband level relative to the carrier only holds true if the carrier and both sidebands interact. In the auditory system, the stimuli are filtered by the cochlea. When the modulation frequency is high, as shown in the bottom panel of Fig. 1, the sidebands overlap very little with the carrier. If the listener monitored a filter which passed the carrier band and one sideband, the output of the filter would have the form of a fully rectified sine wave (known as ''beats'') with a frequency equal to f_s. Goldstein (1967) has shown that for a sinusoidally AM signal, the modulation depth will be maximal when the carrier and one sideband are equal in level. If random-sideband noise were the comparison, a listener could attend to the filter that maximized beats in the AM noise. If the comparison were QFM noise, monitoring the filter that produced beats in the AM noise would also produce beats in the QFM noise, and therefore this would no longer be a usable cue for discrimination.

From the above discussion it is apparent that the structure of QFM noise may make it a better comparison for AM noise than random-sideband noise under some conditions. In previous studies, the detection of a specific cue in AM noise, amplitude modulation, has been measured by adapting on modulation index m, that is, the level of the sidebands relative to the carrier band (Strickland and Viemeister, 1997; Strickland, 2000; Eddins, 1999). The comparison used has been QFM noise. As the sideband level increases, the modulation depth of QFM noise also increases and the frequency sweeps in the QFM become less sinusoidal. The aim of this experiment is to determine under what conditions QFM noise and random-sideband noise are suitable comparisons for AM noise, in that the sinusoidal AM in the AM noise is the only cue for discrimination. The first experiment was conducted to determine at what values of m QFM noise is discriminable from random-sideband noise, as a function of f_s. These threshold values of m will be compared to those for discriminating AM noise from QFM noise. If threshold values of m for discriminating QFM from random-sideband noise are reliably well above those for discriminating AM from QFM noise, then QFM noise is a suitable comparison for AM noise.

I. METHODS

A. Stimuli

AM, QFM, and random-sideband noises were generated according to the above equations. The test stimuli had an upper spectral edge of 2400 Hz and a bandwidth of 1600 Hz. This condition was chosen because it was the largest bandwidth used in a previous paper (Strickland and Viemeister, 1997). The rate and extent of the frequency sweeps in the QFM noise increase with f_s, but f_s cannot be more than half of the bandwidth of the test stimulus. Using the widest bandwidth from the previous study maximizes f_s, and thus the chances that QFM might be discriminable from random-sideband noise on the basis of frequency sweeps.

The sideband frequency separation, f_s, was set from 4 to 512 Hz in equal log steps. Test stimuli were presented at a spectrum level of 40 dB. A low-frequency band of masking noise extending from 100 to 600 Hz was presented at a spectrum level of 30 dB, in order to mask detection of low-frequency distortion products that have been noted in other studies (Strickland and Viemeister, 1997; Eddins, 1999). Discrimination functions for QFM and random-sideband noise were measured with and without a high-frequency band of masking noise. This noise had a bandwidth of 1600 Hz and had a lower spectral edge of 2450 Hz. A previous study (Strickland and Viemeister, 1997) showed that adding such a masking noise above the test stimulus increased the modulation detection threshold for modulation frequencies of 64 Hz and below. These results suggested that when no masking noise was present, listeners might attend to the frequency region above the test stimulus, where the modulation depth might be magnified by nonlinear spread of excitation. It was of interest to determine the effects of such a noise on discrimination of QFM from random-sideband noise, where different cues may be used. Discrimination of AM from QFM noise was only measured with the high-frequency masking noise present.

The test stimuli and masking noises were 500 ms in duration, including 10-ms raised-cosine ramps. The test stimuli and masking noises were digitally generated by a computer and output through separate digital-to-analog channels (TDT DA1) at a rate of 16 384 Hz. They were low-pass filtered at 6 kHz (Kemo VBF/23). The levels were adjusted by programmable attenuators (TDT PA4). Stimuli were presented through one earphone of Sennheiser HD450 headphones to a listener seated in a double-walled sound-attenuating booth.

B. Procedure

Sideband separation, f_s, was fixed within a run, and $20\log(m)$ was adjusted in an adaptive two-interval forced-choice (2IFC) procedure with a two-down, one-up stepping rule, to track 71% correct (Levitt, 1971). Fifty trials were presented in each block, and feedback was given after each trial. The initial step size was 3, and was reduced to 1 after the first two reversals. The threshold estimate for each block was calculated from the average of the last even number of reversals at the smaller step size. When measuring discrimination of AM from QFM, initial values of $20\log(m)$ ranged from -9 at low modulation frequencies to -6 at high modulation frequencies, and if $20\log(m)$ would have exceeded zero the track was terminated and was not included in threshold estimates. This was done because for AM, when $20\log(m)$ exceeds zero, the modulation frequency doubles and the modulation is no longer sinusoidal. When the discrimination was between QFM and random-sideband noise, $20\log(m)$ was allowed to exceed zero, and initial values ranged from 5 at low modulation frequencies to 15 at high modulation frequencies. Threshold values are based on the average of at least three blocks.

C. Subjects

Three females and one male were tested. The age range was from 23 to 41 years, with a mean of 29 years. All listeners had thresholds within laboratory norms for pure tones at octave frequencies from 250–8000 Hz in the ear tested. S1, S2, and S3 had at least 10 h of experience with psychoacoustic tasks before testing, while S4 was a naive listener. S1 was not tested in the AM vs QFM condition due to time constraints.

II. RESULTS

A. Thresholds for QFM vs random-sideband noise

Thresholds in units of $20\log(m)$ (left axis) or m (right axis) as a function of f_s are shown in Fig. 2. Thresholds increase *downward* on these figures, as that has been the convention often used in plotting AM thresholds. Note also that in contrast to AM thresholds, where m is always less than 1, m in this task generally exceeded 1. Thresholds with no high-frequency masking noise are shown by the filled circles, while those with high-frequency masking noise are shown by the open triangles. Error bars are one standard deviation about the mean. With no masking noise, thresholds were fairly constant and variability was low at low f_s. At higher f_s, thresholds increased and variability increased markedly. This variability was seen even if tracks with high standard deviations were excluded. For two subjects (S2 and S4) threshold decreased again for $f_s=512$. The addition of the high-frequency masking noise had a similar effect across subjects. Thresholds increased by about 2 units for f_s of 64 Hz and below. At higher f_s, thresholds increased markedly and were quite variable within and across subjects.

In Fig. 3, the average thresholds for discrimination of QFM from random-sideband noise are shown compared to thresholds for discrimination of AM from QFM noise, using

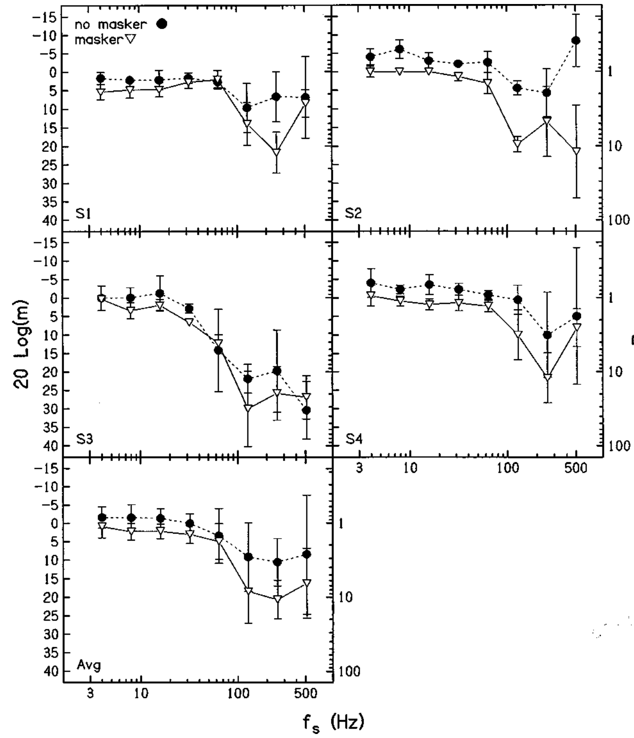

FIG. 2. Thresholds for discriminating QFM from random-sideband noise, either with (open triangles) or without (filled circles) a high-frequency masker. Error bars in all figures are one standard deviation about the mean.

test stimuli with the same bandwidth, upper cutoff frequency, and level as the QFM and random-sideband noises. For $f_s=512$ Hz, when AM was being compared to QFM noise, only one of the three subjects tested in this condition could achieve a threshold without terminating the track. Thresholds for the other two subjects were averaged in as $20\log(m)=0$. Thresholds for discrimination of AM from QFM noise were well below those (higher on the figure) for discrimination of QFM from random-sideband noise when $f_s=256$ Hz and below. This indicates that QFM noise is a suitable comparison for AM noise when $f_s=256$ Hz or less, for the particular stimulus conditions used here. However, it is not clear that this is true when $f_s=512$ Hz, due to the variability of the thresholds for discriminating QFM from

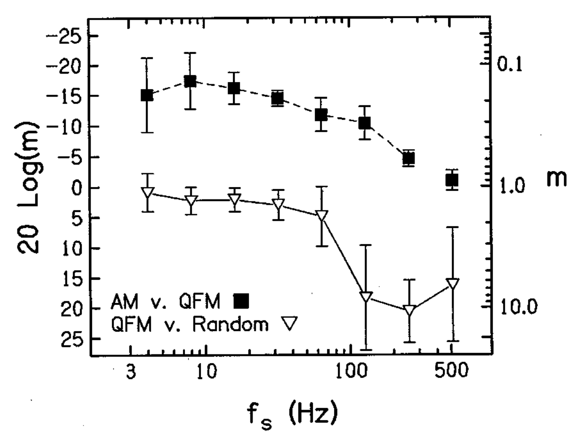

FIG. 3. Average thresholds for discriminating QFM from random-sideband noise (open triangles, replotted from Fig. 2) and AM from QFM noise (filled squares).

random-sideband noise, and the fact that no threshold could be obtained for discriminating AM from QFM noise for two of the subjects. Even though the average thresholds were clearly separated, the variability within subjects made it impossible to be certain that other cues in the QFM noise were unusable in discriminating AM from QFM.

B. Psychometric functions

Thresholds for discrimination of QFM from random-sideband noise for $f_s = 128$ Hz and above were quite variable both within and across subjects, and were more affected by the addition of the high-frequency masking noise than thresholds for lower f_s. These thresholds were also at higher values of m. The gross similarity between the two functions in Fig. 3 suggested that listeners might be using modulation depth as a cue in discriminating QFM noise from random-sideband noise. For AM noise, m corresponds directly to amplitude modulation depth. The envelope is shown in Eq. (6):

$$E(t) = 1 + m\cos(f_s t). \tag{6}$$

For QFM noise, the envelope is related to m in a more complex manner, as shown by Eq. (7):

$$E(t) = \sqrt{1 + m^2\cos^2(f_s t)}, \tag{7}$$

which was modified from the relationship derived by Edwards and Viemeister [1994a, Eq. (2)]. If listeners were using modulation depth as a cue, this complex relationship between m and modulation depth for QFM noise might account for the change in variability at different values of m.

For the same four subjects, psychometric functions were measured for high f_s (64 Hz and above) to investigate the higher variability at these frequencies. A two-cue 2IFC procedure (Bernstein and Trahiotis, 1982) was used. Intervals one and four were random samples of the random-sideband noise, and the QFM noise could occur with equal probability in interval two or three. This was done so that subjects only had to discriminate between the two types of noise, not identify them. Subjects also began each run by listening to a sample interval in which $20\log(m)$ was fixed at 27, and the QFM noise was always in the first interval. The value of $20\log(m)$ was fixed for a block of 50 trials, and randomized across blocks. Thresholds for $f_s = 64$ Hz were also measured, using a 2IFC procedure with no cues. The high-frequency masking noise was present in all conditions. The results are shown in Fig. 4. For $f_s = 64$ Hz, performance increased with $20\log(m)$ and plateaued at approximately 100% correct. For higher f_s, however, performance plateaued at a lower percent correct or was even nonmonotonic. This explains the extreme variability, both within and between subjects, seen in the thresholds for discrimination of QFM from random-sideband noise at high f_s in Figs. 2 and 3. Because percent correct may change little with large changes in $20\log(m)$, the adaptive tracking procedure does not converge on a consistent value.

To see what the psychometric functions would look like if subjects were using amplitude modulation depth as a cue, modulation depth (mod) was calculated for each value of m by creating a QFM tone in MATLAB and calculating (max −min)/(max+min). These functions are shown in Fig. 5. The psychometric functions for $f_s = 64$ and 128 Hz were monotonic, and the form was similar to that found by Eddins (1993) for AM noise for similar modulation frequencies (125 and 250 Hz, which would be close to the modulation frequencies of 128 and 256 Hz for the QFM noise), shown as asterisks in Fig. 5. Subject behavior was ambiguous when $f_s = 256$ Hz. One of the four subjects was at chance (50%); two others were above chance but showed almost no change in performance as a function of modulation depth. The fourth subject showed a monotonically increasing psychometric function. For $f_s = 512$ Hz, however, the functions clearly plateaued below 100%, and some were nonmonotonic. This suggests that up to $f_s = 128$ Hz, for most subjects, modulation depth was the cue used to discriminate QFM noise from random-sideband noise. For $f_s = 512$ Hz, however, Fig. 4

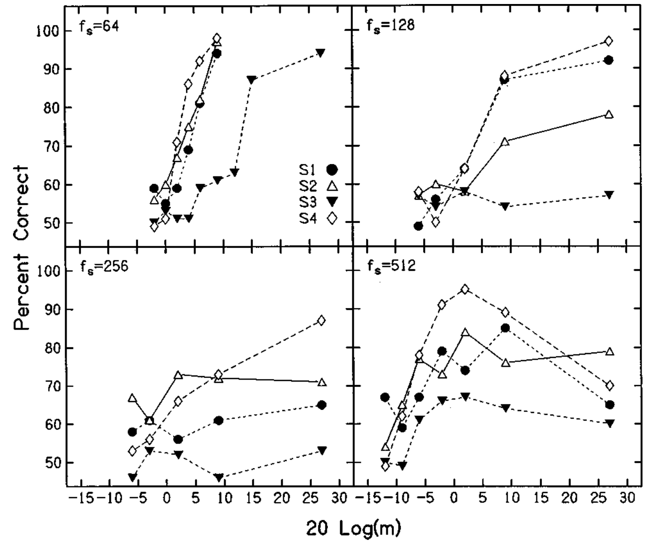

FIG. 4. Psychometric functions for discriminating QFM from random-sideband noise for four subjects.

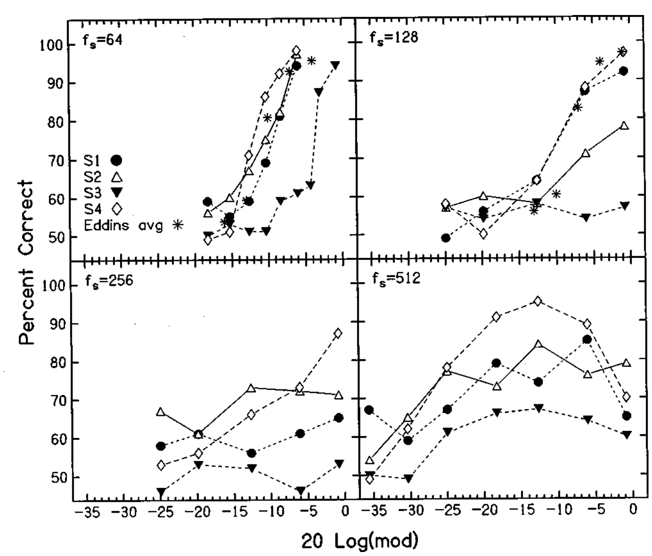

FIG. 5. The data from Fig. 4 plotted in terms of calculated modulation depth. The asterisks are average data from Eddins (1993), for a modulation frequency of 125 Hz in the upper-left panel, and 250 Hz in the upper-right panel.

shows that there was a different cue that became more salient with increases in 20 log(m) up to approximately -5 or 0, and then plateaued or decreased again. The value of 20 log(m) is 6 dB higher than the level of the sidebands relative to the carrier. In Fig. 4, whatever cue the subjects were using was most salient when 20 log(m) was 2, or the sidebands were just 4 dB below the level of the carrier.

C. Possible cues at $f_s = 512$ Hz

The psychometric function for $f_s = 512$ Hz suggests that subjects are able to detect other cues that are available within these noises. To understand one possible cue, it is necessary to think about the structure of QFM noise, which was shown schematically in Fig. 1. It consists of a carrier band of noise, and sidebands that are the same bandwidth, whose outer spectral edges extend out from the carrier band by f_s. The total bandwidth of the test stimulus is held constant. When f_s is low, the carrier band and the sidebands overlap almost entirely, as shown schematically in the top panel for $f_s = 32$ Hz. At high f_s, however, the sidebands overlap with the carrier band less and less. This leads to three nearly separate bands of noise that have the same power spectrum, except that the sidebands may be shifted in level by a constant, as shown in the bottom panel of Fig. 1 for $f_s = 512$ Hz. If each of these bands of noise were passed through a separate filter, the envelopes would be exactly correlated. This is true because the sideband components have exactly the same phases, and the phases of the carrier components are all shifted by a constant phase. In reality some of the carrier components overlap the sideband components, but the envelopes would still be highly correlated. Random-sideband noise would have the same amplitude spectrum, but because the phases of the components are randomized, the envelopes of the carrier and the two sidebands would be less correlated. Richards (1988) has shown that subjects can discriminate with a high degree of accuracy between the equivalent of the random carrier and sidebands, which have identical power spectra but different envelopes, and the QFM carrier and sidebands, which have identical power spectra and envelopes.

Although listeners could conceivably compare any of the bands, data from Richards (1987) suggest it is likely that they are using the carrier band and the upper sideband. In that study, performance improved as the center frequencies of the noise bands were increased. The fact that some subjects show a decline in performance as the sideband level is increased relative to the carrier (see Fig. 4) is probably due to masking of one band by another. When the carriers are more separated in frequency, it is possible for subjects to make envelope judgments even when carrier levels are unequal (Goldstein, 1965; Strickland *et al.*, 1989).

In order to test the theory that listeners were detecting envelope correlation when $f_s = 512$, QFM versus random-sideband discrimination was tested when the total extent of the test stimulus was 10 to 6000 Hz. In this case the situation would be closer to the top panel of Fig. 1, and the carrier band and sidebands would always overlap to a large extent. Even when the sidebands extend out by 512 Hz, the carrier is approximately 5000-Hz wide, and the upper sideband would be related to the high-frequency end of the carrier while the lower sideband would be related to the low-frequency end of the carrier. Thus, the sidebands would not be highly correlated with each other. Thresholds measured using the broadband stimulus are shown in Fig. 6. It can be seen that thresholds now fell off monotonically as f_s increased. This suggests that listeners were forced to use the temporal cue at the modulation frequency, 2^*f_s, and now have no envelope correlation cue.

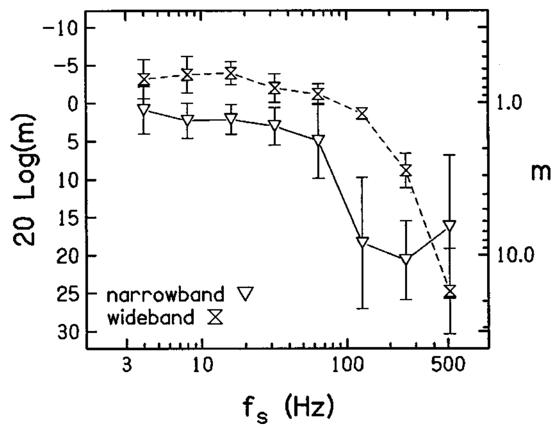

FIG. 6. Average thresholds for discrimination of QFM from random-sideband noise with a test stimulus bandwidth of 1600 Hz (open triangles, replotted from Fig. 2) or 6000 Hz (hourglasses).

D. Comparison to AM

The psychometric functions in Fig. 5 suggest that listeners are discriminating QFM from random-sideband noise on the basis of amplitude modulation depth for $f_s = 128$ Hz and below. To examine this, the thresholds from Fig. 6 were converted to modulation depths and plotted at their amplitude modulation frequencies, 2^*f_s. These are shown in Fig. 7 along with AM vs QFM noise thresholds, also plotted in terms of modulation depth of the AM signal. In the top panel, the bandwidth of the test stimuli was 1600 Hz. In the bottom panel, it was 6000 Hz, and the AM vs QFM data are from a previous study (Strickland, 2000). The large error bars are due to variability between subjects. Although not significant, there was a tendency for thresholds to be higher for QFM vs random-sideband noise than for AM vs QFM noise at the lowest modulation frequencies. This was also noted by Edwards and Viemeister (1994b) when comparing thresholds for tonal carriers for AM versus tone and for QFM vs FM. Following their suggestion, there may have been enough frequency modulation in the QFM noise to make detection of the amplitude modulation slightly more difficult. Above a modulation frequency of 16 Hz, thresholds were nearly identical up to a modulation frequency of 256 Hz in the top panel and 1024 Hz in the bottom panel, supporting the idea that listeners were basing their judgments on modulation depth in both cases.

E. AM vs QFM compared to AM vs random sideband

The data suggest that for low f_s, QFM noise is indiscriminable from random-sideband noise at values of m at

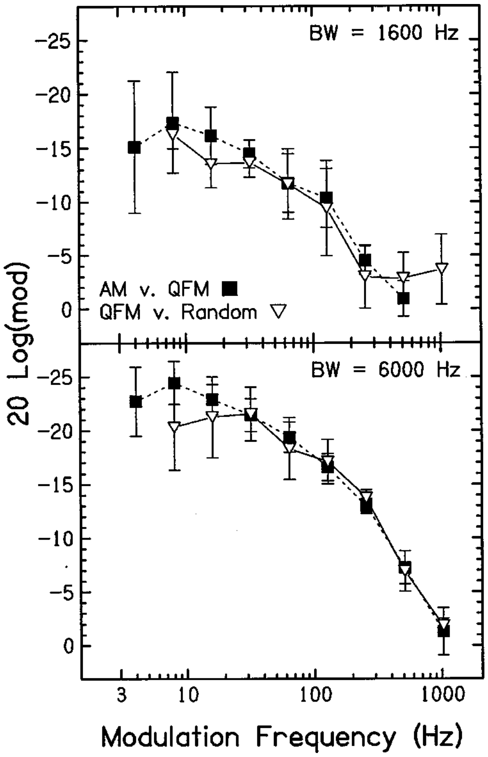

FIG. 7. Average thresholds for discrimination of QFM from random-sideband noise (open triangles) and AM from QFM noise (filled squares) with a test stimulus bandwidth of 1600 Hz (top panel) or 6000 Hz (bottom panel). The data are plotted in terms of modulation frequency and calculated modulation depth.

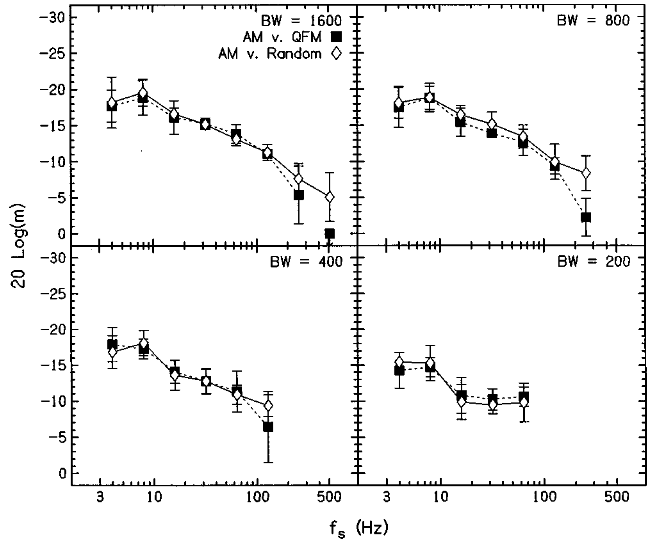

FIG. 8. Average thresholds for four subjects for discrimination of AM from QFM noise (filled squares) and AM from random-sideband noise (open diamonds) as a function of test stimulus bandwidth.

which AM is just discriminable from QFM noise. It would be expected then that thresholds for discriminating AM noise from QFM noise should be the same as those for discriminating AM noise from random-sideband noise for these sideband separations. For $f_s = 512$ Hz, envelope correlation cues should be present for the AM noise just as they are for QFM noise, and these may be usable when the comparison is random-sideband noise. As part of a previous study, thresholds for these two cases were measured for S2 and three additional subjects. Subjects were two males and two females, with an average age of 24.8 years, and a range of 18 to 36 years. Each subject had thresholds for pure tones within laboratory norms for the ear tested, which was the left ear for all subjects. The methods and stimuli were the same as those used above. In addition to a test stimulus bandwidth of 1600 Hz, bandwidths of 800, 400, and 200 Hz were used, with the upper spectral edge fixed at 2400 Hz. Figure 8 shows threshold modulation depths for discrimination of AM from QFM noise, and AM from random-sideband noise. Data points are the average of the four subjects. For bandwidths of 800 and 1600 Hz, thresholds were clearly lower (higher on the figure) for the highest f_s when random-sideband noise was the comparison. The same trend was seen when the bandwidth was 400 Hz. For the 200-Hz bandwidth, thresholds were nearly identical for all f_s. A filter centered on the 200-Hz bandwidth stimulus would have a center frequency of 2.3 kHz. According to the formula of Glasberg and Moore (1990), the equivalent rectangular bandwidth would be 273 Hz. This suggests that when the carrier bandwidth is larger than a critical band, an envelope correlation cue may be usable when the sidebands only minimally overlap the carrier band and the comparison is random-sideband noise. When QFM noise is the comparison, both of the test stimuli have correlation between the carrier and the sideband envelopes. Thus, this is not a usable cue and thresholds are higher.

III. DISCUSSION

The results indicate that if the goal is to measure detection of the temporal fluctuations in the AM noise, QFM is a suitable comparison in all conditions, while random-sideband noise is not suitable in some conditions. When the carrier is wider than a critical band, and the sideband separation approaches the carrier bandwidth, it appears that listeners can discriminate QFM noise from random-sideband noise using envelope correlation between sidebands and the carrier. This would also be true for AM noise, and thus in these conditions QFM noise is a better comparison than random-sideband noise, because it eliminates this as a cue for discrimination. Both QFM and random-sideband noise are good comparisons in all other conditions.

As noted in the Introduction, the first author originally chose QFM over random-sideband noise as the comparison noise for AM noise due to concern about detection of beats between the sidebands and the carrier (see also Strickland and Viemeister, 1997, footnote 1). Thus, that study and others that have used the technique for creating noises used in this paper have used QFM noise as the comparison (Strickland, 2000; Eddins, 1999). Other studies using bandlimited stimuli have filtered after modulation (Formby and Muir, 1988; Rodenburg, 1977; van Zanten, 1980; Viemeister, 1979; Bacon and Viemeister, 1985; Dau *et al.*, 1997; Eddins, 1993) or restricted the frequency region with notched noise (Patterson *et al.*, 1978), so envelope correlation cues would not be available. Detection of envelope correlation should only be a possibility when the sideband separation approaches or exceeds the carrier bandwidth, and the carrier is wider than a critical band. Under these conditions, it is important that QFM noise be used as the comparison.

When a QFM tone is being discriminated from a pure tone, sideband level at threshold decreases with sideband separation for small sideband separations (Edwards and Viemeister, 1994b). This is consistent with the idea that listeners use the size of the instantaneous frequency sweeps, which would increase with sideband separation. Figure 2 shows that thresholds do not decrease with sideband separation when QFM noise is compared to random-sideband noise, and thus that frequency sweeps are not a usable cue. This is further supported by the fact that the data in Fig. 2 are very similar to data from Edwards and Viemeister (1994b, Fig. 2) for discrimination of QFM and FM tones, when the sideband separation is 64 Hz or less. This is consistent with the idea that temporal envelope cues are used in both cases. When the sideband separation is greater than 64 Hz, thresholds for QFM vs FM become lower than those for QFM versus random-sideband noise, due to detection of sideband differences. The use of noise allows comparison of the QFM tone to be extended to higher sideband separations, and shows that envelope fluctuations are the only cue under these conditions.

IV. CONCLUSIONS

(1) When QFM noise is compared to random-sideband noise, listeners use amplitude modulation cues when sideband separations are well below the carrier bandwidth. As sideband separation approaches the carrier bandwidth, they may use correlation between carrier and sideband envelopes as a cue.

(2) Frequency modulation is not a usable cue in QFM noise with a bandwidth of 1600 Hz.

(3) When measuring modulation depth thresholds with narrow-band noise carriers, QFM noise is a suitable comparison for AM noise. When sideband separations are well below the carrier bandwidth, the amplitude modulation cues in QFM noise are below threshold at threshold sideband levels for discriminating AM from QFM. When the sideband separation approaches the carrier bandwidth, and the carrier bandwidth is greater than a critical band, AM and QFM noise have correlations between the carrier and sideband envelopes, and thus listeners are forced to use the amplitude modulation cue.

ACKNOWLEDGMENTS

The authors thank Tamara Scott for assistance in data collection, and John Madden and two anonymous reviewers for constructive comments on an earlier version of the paper.

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