XVI. SIGNAL DETECTION BY HUMAN OBSERVERS[*]

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A. MASKING WITH TWO CONTINUOUS TONES

One of the earliest studies in the modern era of psychoacoustics was the paper of Wegel and Lane.[1] Their data show how a single continuous pure tone at some fixed frequency masks[2] other pure tones. One of the main findings reported by Wegel and Lane was that a masking sinusoid of low intensity influences the detectability of the other tone
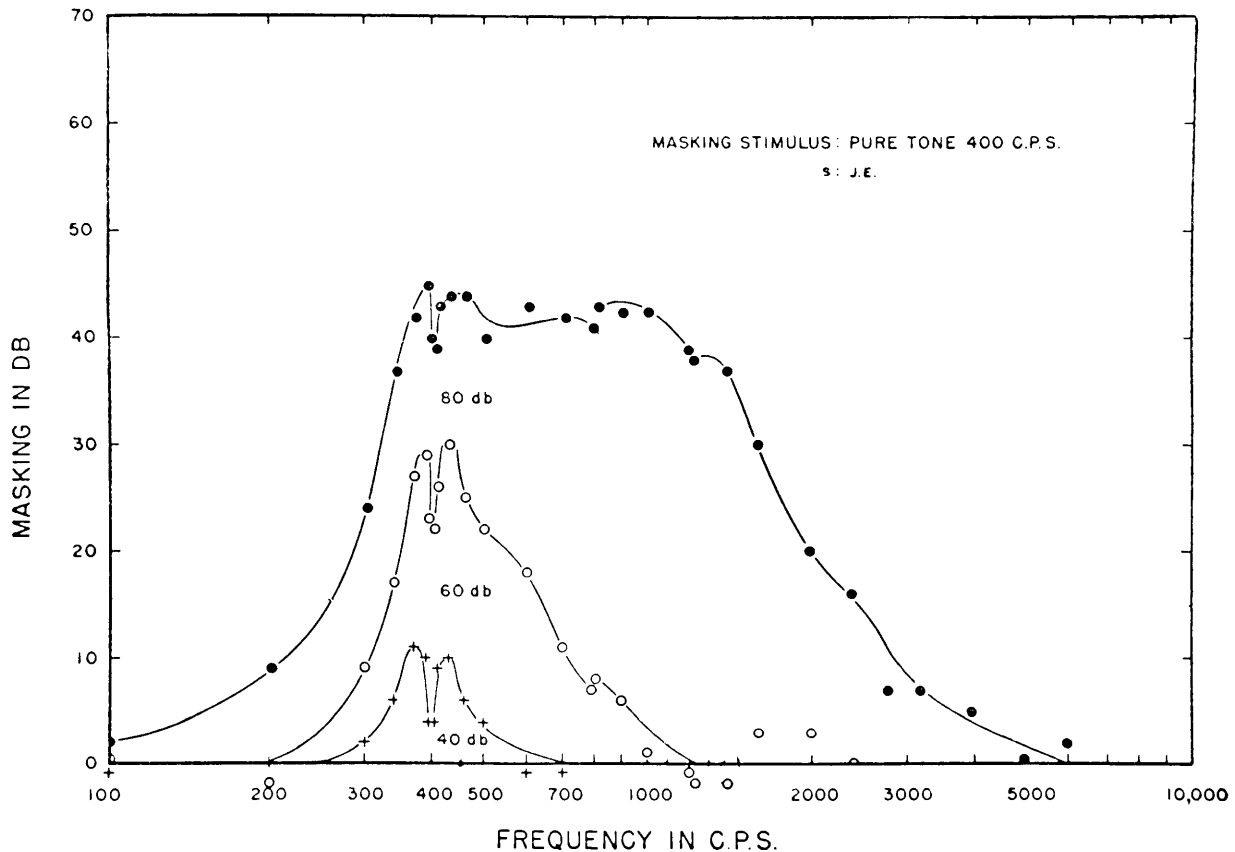

Fig. 1. The curves are masking audiograms of a pure tone of 400 c.p.s. The number under each curve is the sound-pressure level (decibels re 0.0002 dyne/cm²) of the masking tone (0 db sensation level corresponds to 15 db S.P.L. at 400 c.p.s.). The abscissa represents the frequency of the masked tone and the ordinate represents the shift in decibels of its absolute threshold. Note how asymmetrical the curves become as the intensity of the masking stimulus is increased.

Fig. XVI-1. Results of Egan and Hake using a single sinusoidal masker [reprinted with permission from J. Acoust. Soc. Am. 22, 622 (1950)].

only in a narrow range of frequencies centered about the frequency of the masking tone. Figure XVI-1, taken from a paper by Egan and Hake[3] shows one of these typical masking patterns.

Presumably, the dip in the function in the region of 400 cps arises because of beats between the masking tone and the signal. The asymmetry seen at the high level for the masking stimulus was presumed to represent, in part, distortion of the middle ear and the generation of harmonics of the masking frequency. Except for the dip in the curve when the signal and masking frequency are very nearly the same, the general shape of the curve, especially at low masking levels, is reminiscent of frequency response of a bandpass filter. Fletcher[4] pursued this same thought when he introduced the concept of a critical band. The critical band was, in effect, a hypothetical auditory filter. Fletcher's estimates of the width of this critical band, based on other experiments in which noise was used as a masker, are listed in column 2 of Table XVI-1.

Recent studies[5,6] have reported data repeating parts of the old Wegel and Lane data. While, in general, these studies confirm the earlier findings, two exceptions should be noted in detail. While both Ehmer's and Small's data show irregularities in the masking curves obtained at high masking levels, these irregularities are not at the harmonics of the masking frequency. This result is at variance with the nonlinear distortion hypothesis. More important for our purpose is Small's result that the masking patterns, obtained at different frequencies and low intensity levels of the masking stimulus, are all very similar if one plots the ratio of the masking frequency to the signal frequency. Thus, if one tries to estimate "critical bandwidth" from Small's data, whether one uses a 3-, 6-, or 10-db definition of bandwidth, one still will conclude that the critical bandwidth is proportional to center frequency. This variation of bandwidth with center frequency is quite different from the estimates suggested by Fletcher (see Table XVI-1).

Table XVI-1. Estimates of the width of critical band in cps based on several different experiments.

Center Frequency	Fletcher[4]	Zwicker[8] Flottorp Stevens	Békésy[11]	Present Experiment
250	51	95	190	200
500	51	110	350	
1000	63	160	760	600
2000	98	295	1500	
3000	141	450	2400	
4000	204	680	3000	2200

Fletcher's estimates come from experiments in which noise, rather than a sinusoid, is used as the masker. A variety of experiments have employed noise, or noiselike stimuli as the masker. Stated briefly, the plan of these experiments is to measure the detectability of a sinusoidal signal located in the center of a noise band. The noise band is made progressively narrower until a point is reached at which the detectability of the signal is first influenced. This point is taken as the critical bandwidth. It is clearly important to use noise bands that are very sharp so that the width of the critical band is clearly defined.

Greenwood[7] has used a heterodyne technique to achieve very sharp frequency response characteristics for his noise signal. Greenwood also estimates critical bandwidths, and these estimates of critical bandwidth are in general agreement with a recent paper[8] in which a variety of experiments is summarized. It can be seen from Table XVI-1 that Zwicker, Flottorp, and Stevens' estimates of critical bandwidths are larger than Fletcher's estimates by almost a factor of three.

The present experiment used two continuous sinusoidal signals as the masking stimuli. The width between the two sinusoids is varied and a critical band is inferred from the amount of masking that such a complex produces on a third sinusoid, the signal, which is located in frequency midway between the two maskers. By comparing the amount of masking produced by the two sinusoids in combination and separately, the experiment also provided a means of assessing the masking effectiveness of combinations of sinusoidal stimuli.

Procedure

Two continuous sinusoids, each of 77-db sound pressure level, (SPL) were the masking stimuli. The two sine waves were separated in frequency by an amount denoted Δf. Midway between these two sinusoids, $\Delta f/2$ above the frequency of the lower masker, a gated sinusoid is presented as the signal. The signal duration was 100 msec with a 25-msec rise and fall to the signal to minimize switching transients. A two-alternative temporal forced-choice procedure was used to measure the detectability of the signal. The signal occurred at random in one or the other of two temporal intervals, marked by lights, for the observer. The intensity of the signal needed by the observer to detect the signal 75 per cent of the time was the dependent variable of the experiment.

This signal level was estimated by presenting the signal at five different intensities and estimating the percentage of correct detections at each level. The resulting function relating the percentage of correct detections to the level of the signal is called a psychometric function. Two hundred observations were used to estimate each point on the psychometric function. The 75 per cent point was determined by visual interpolation after graphing the results.[9]

Three center frequencies were used for the signal: 250, 1000, and 4000 cps. At each center frequency the separation in frequency between the maskers was varied from a minimum width of 4 cps to a separation large enough to either drive the lower frequency masker to near zero frequency or until a complete curve relating Δf to signal level was obtained. In Fig. XVI-2 the experimental data are presented.

Let us first discuss the data for Δf in the range 4-100 cps. It appears that the amount of masking produced by two sinusoids symmetrically located in frequency about the gated signal is independent of the center frequency of the complex. This is a peculiar and unexpected result for two reasons. First, it is unlike the data on the detection of gated sinusoids in wideband noise. Data from Green, Licklider, and McKey[10] show that from 250 cps to 4000 cps the signal level must be changed by 8 db in order to maintain some constant level of detectability. The Fletcher estimates of the critical bandwidth as a function of center frequency reflect, in part, exactly this variation.

Second, such independence of center frequency is unexpected from data on single-sinusoid masking or from an experiment measuring the detectability of an increment in
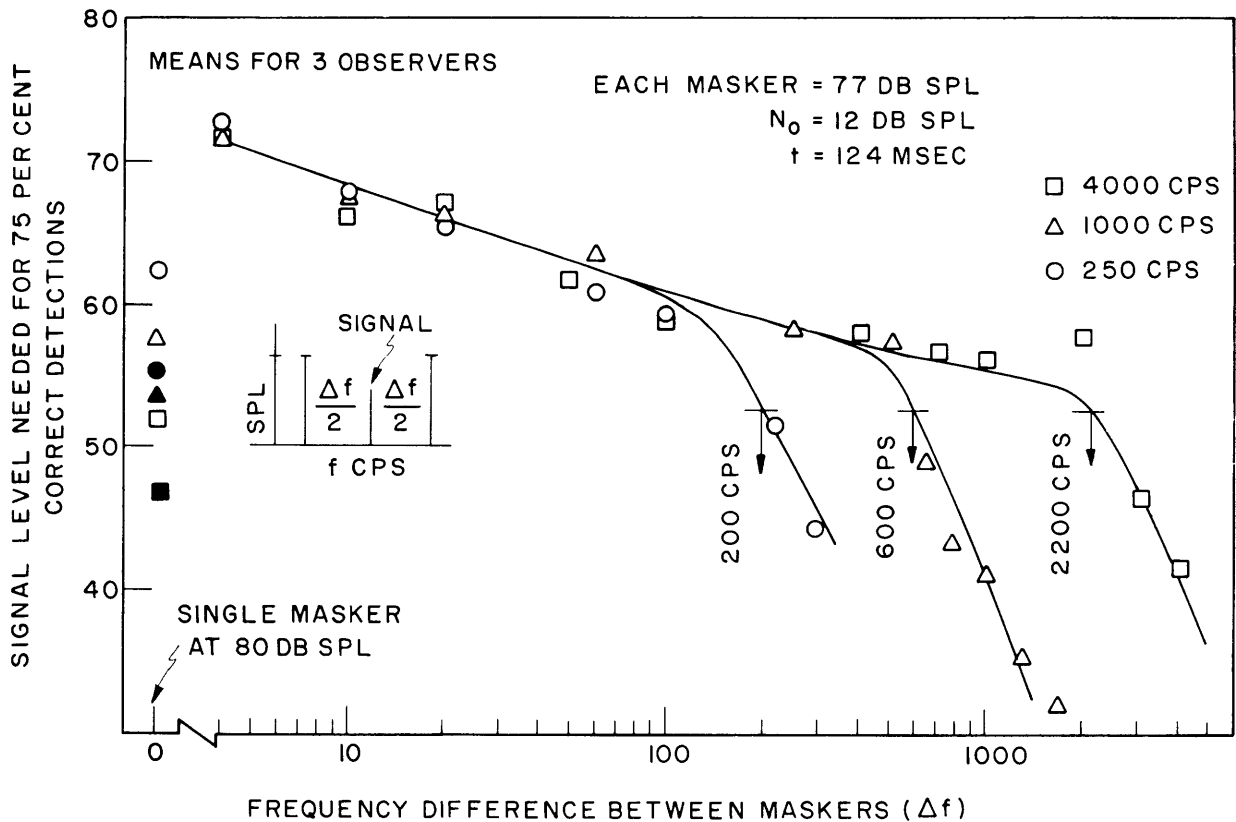

Fig. XVI-2. Results of the experiment using two sinusoidal maskers. Open points indicate results with incoherent relation between masker and signal. Solid points indicate results when signal was added in phase to masker.

the intensity of a sinusoid. At the left-hand side of Fig. XVI-2, above the abscissa value of zero, we have plotted the intensity of the gated sine wave that is needed for 75 per cent correct detection in the presence of a single sinusoidal masker. The results obtained for the single masker are obviously dependent on the frequency region tested.

When only one sine wave is used as the masker, the level was set at 80 db to equal in power the intensity of the pair of sinusoids used in the main experimental condition. The signal was either added coherently, in phase, to the continuous background signal or the signal was derived from an independent oscillator and gated on without regard to the phase of the continuous masker. This later arrangement is denoted as the incoherent condition in the legend of Fig. XVI-2. Note again that the results are clearly frequency-dependent; the highest frequency signals are easier to hear than the low frequency signals. The difference between the coherent and incoherent conditions are about the same at all three frequencies, namely 5.5 db. This difference is presumably explained on the simple basis that in one case (coherent conditions) the signal always causes an increment in the power of the sound, whereas in the other case (incoherent condition) the sound may increase, decrease, or stay roughly the same in power.

The difference in masking effectiveness between a single sine wave and two sine waves, 4 cycles apart and of the same power, is approximately 10 db at 250 cps, 15 db at 1000 cps, and 20 db at 4000 cps. It has long been known that noise is a much more effective masking agent than a sinusoidal stimulus. This difference in effectiveness on a power basis is ~12-20 db, the difference depending on the exact circumstances and conditions of the experiment. The difference just cited between single and double sinusoidal maskers would suggest that there is little if any difference in the masking effectiveness of noise and two closely spaced sinusoidal maskers. As this experiment shows, masking with two sinusoids is independent of signal frequency, whereas masking with noise is not; thus any more rigorous pursuit of this comparison would appear to be impossible.

Finally, let us consider the data obtained with large frequency separations of the two maskers. We have arbitrarily chosen a drop in masking effectiveness of approximately 20 db from the maximum masking, at $\Delta f = 4$, to use as our estimates of our critical band.

Were we to change our arbitrary 20 db to some lower figure, our estimates of critical band would be independent of center frequency.

Were we to increase the figure to 30 db, all of the estimated bands would increase roughly by the same fractional amount. These estimates are extremely large for any critical-band estimate based on psychoacoustic data. They are not far different from the width of the envelope of the travel wave as reported by von Békésy.[11]

It would appear that two general mechanisms are involved in these results. One, the extent to which the basilar membrane is vibrated by a sinusoid, is probably

responsible for the rapid fall in masking at the very large frequency separations (Δf). The other mechanism appears to be a temporal one that is clearly place- or frequency-independent, and probably is basically the same type of mechanism investigated by those interested in periodicity pitch.

We are at present trying to develop a more quantitative theory to explain the data. These results and their interpretation also suggest a reevaluation of some of the older masking data.

<div style="text-align: right">D. M. Green</div>

References

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2. Masking is defined as "the amount by which the threshold of audibility of a sound is raised by the presence of another sound" (Z24.1, 1951) American Standard Acoustic Terminology (American Standards Association, New York, 1951).

3. J. P. Egan and H. W. Hake, J. Acoust. Soc. Am. 22, 622 (1950).

4. H. Fletcher, Revs. Modern Phys. 22, 47-65 (1940).

5. R. H. Ehmer, J. Acoust. Soc. Am. 31, 115 (1959).

6. A. Small, Pure tone masking, J. Acoust. Soc. Am. 31, 1619 (1959).

7. Greenwood reports an off-band attenuation of 200 db per octave. (See D. D. Greenwood, J. Acoust. Soc. Am. 33, 484-502 (1961).)

8. E. Zwicker, G. Flottorp, and S. S. Stevens, J. Acoust. Soc. Am. 29, 548 (1957).

9. More sophisticated analysis is now being made.

10. D. M. Green, J. C. R. Licklider, and M. J. McKey, J. Acoust. Soc. Am. 31, 1446-1452 (1959).

11. G. von Békésy, Experiments in Hearing (McGraw-Hill Book Company, Inc., New York, 1960).