Psychological Bulletin
1961, Vol. 58, No. 3, 205–217

COMPLEX SOUNDS AND CRITICAL BANDS[1]

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Studies of the responses of human observers to bands of noise and other complex sounds have led to the measure of what appears to be a basic unit of hearing, the critical band. When the frequency spectrum of a stimulating sound is narrower than the critical band, the ear reacts one way; when the spectrum is wider, it reacts another way. For example, experiments show that at values less than the critical bandwidth, both loudness and absolute threshold are independent of bandwidth; only when the critical bandwidth is exceeded do the loudness and the absolute threshold increase with the width (Gässler, 1954; Zwicker & Feldtkeller, 1955; Zwicker, Flottorp, & Stevens, 1957).

The critical band has also been measured in experiments on auditory discriminations that seem to depend upon phase (Zwicker, 1952) and in experiments on the masking of a narrow band of noise by two tones (Zwicker, 1954). In all four types of experiment—loudness, threshold, sensitivity to phase, and two-tone masking—the value of the critical band is the same function of its center frequency. The values of the critical band, as a function of the frequency at the center of the band, are given by the top curve in Figure 1. The ordinate gives the width (ΔF), in cycles per second, of the critical band; the abscissa gives the center frequency. As the frequency at the center of a complex sound increases, the critical band that is measured around the center frequency becomes wider.

Not only does the critical band have the same values when measured for several kinds of auditory response, it is also independent of such stimulus parameters as the number of components in the complex (Scharf, 1959b) and the sound pressure level (Feldtkeller, 1955; Feldtkeller & Zwicker, 1956).

Prior to the experimental measures of the critical band, Fletcher (1940) had hypothesized the existence of a critical band for masking. He suggested that when a white noise just masks a tone, only a relatively narrow band of frequencies surrounding the tone does the masking, energy outside the band contributing little or nothing. Although attempts to test this hypothesis remain inconclusive, investigators (Bilger & Hirsh, 1956; Hawkins & Stevens, 1950) have been able to calculate values for the width of these hypothetical masking bands by assuming that the masking band and the just-masked tone have the same intensity. The calculated values, which are labeled "critical ratios" in Figure 1, are smaller for the masking band than for the critical band as measured in the experiments cited above. As we shall see, this discrepancy is more apparent than real.

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[1] This paper was completed while the author held a research grant, B2223, from the National Institute of Health, United States Public Health Service. The author wishes to thank S. S. Stevens for detailed criticism and advice in the final preparation of the manuscript. A. B. Warren and H. S. Zamansky are also thanked for reading and making suggestions about the final draft.

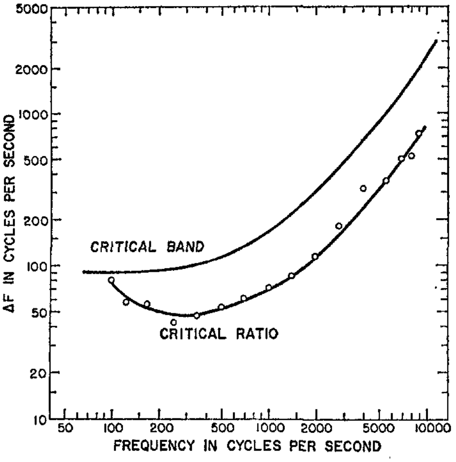

FIG. 1. The width, ΔF, of the critical band and of the critical ratio as a function of the frequency at the center of the band. (The ordinate gives the width, in cycles per second, of the critical band—and of the critical ratio—for the center frequencies shown on the abscissa. The top curve gives the values for the critical band which are based upon direct measurements in four types of experiment; the bottom curve gives the values for the critical ratio which are calculated from measurements of the masked threshold for pure tones in white noise. The points on the bottom curve are from Hawkins and Stevens—1950. This figure is adapted from an article by Zwicker, Flottorp, and Stevens—1957, p. 556—which contains also a table of critical-band values.) (Adapted with permission of the *Journal of the Acoustical Society of America*)

EXPERIMENTAL MEASURES OF THE CRITICAL BAND

Four types of experiment in which critical bands have been measured are reviewed: absolute threshold of complex sounds, masking of a band of noise by two tones, sensitivity to phase differences, and loudness.

Threshold of Complex Sounds

When two tones, whose frequencies are not too far apart, are presented simultaneously, a subject may report hearing a sound even though either tone by itself is below threshold. Gässler (1954) made careful measures of this phenomenon, using many tones and systematically varying the difference in frequency, ΔF, between the lowest and highest components of the complex sounds.[2] He varied the ΔF by varying the number of equally intense tones, which were spaced at intervals of 20 cps. The number of tones was increased from 1 to 40 or until ΔF was equal to 780 cps. Each time a tone was added, the threshold for the whole complex was measured by a "tracking" method (Stevens, 1958). It was necessary, of course, that all the tones in the complex have the same threshold when heard singly, for otherwise it would have been impossible to determine the precise cause of a change in the threshold for a complex whose ΔF had been increased by the addition of a tone. Thus measurements were restricted to portions of the frequency spectrum over which a subject's threshold curve was flat. In order to study other portions of the spectrum, the multitone complexes were presented against a background of white noise that had been tailored to raise the threshold for tones at all the audible frequencies to the same level, thus artificially flattening a subject's threshold curve.

Whether the background was quiet, or consisted of a noise at 0 db. SPL, at 20 db., or at 40 db., the same effect was noted: as soon as ΔF exceeded a particular value whose size depended upon the frequency at the center of the complex, the threshold for the multitone complex began to increase. Similar data were reported when bands of white noise were substituted for the multitone

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[2] Two or more tones constitute a complex sound, i.e., a sound with energy at more than one frequency in contrast to a single or pure tone with most of its energy concentrated at a single frequency.

complexes. The results indicate that the *total* energy necessary for a sound to be heard remains constant so long as the energy is contained within a limiting bandwidth. Although differences between the two observers in these experiments were sometimes of the order of 40%, the average size of the limiting bandwidths for both multitone complexes and bands of noise is approximated by the critical-band curve of Figure 1.[3]

Two-Tone Masking

The masking of a narrow-band noise by two tones provided a second measure of the critical band. Using a tracking method, Zwicker (1954) measured the threshold of a narrow-band noise in the presence of two tones, one on either side of the noise. Increasing the difference in frequency, ΔF, between the two tones left the masked threshold for the noise unchanged until a critical ΔF was reached, whereupon the threshold fell sharply and, in general, continued to fall as ΔF was increased further. The two subjects who served in this experiment showed the same drop in threshold at approximately the same ΔF for a given center frequency regardless of the SPL of the masking tones. The critical-band curve of Figure 1 gives the approximate values of ΔF at which the masking effect of two tones is sharply reduced.

Sensitivity to Phase

The critical band is also relevant to phase sensitivity, measured by a comparison between the ear's ability to detect amplitude modulation (AM) and its ability to detect frequency modulation (FM). This procedure requires some explanation.

When the *amplitude* of a tone is modulated—i.e., alternately increased and decreased—a three-tone complex is produced with the original tone (the "carrier") at the center of the complex and a tone on either side (side bands). When the *frequency* of a tone is modulated over a narrow range, a three-tone complex is also produced.[4] The only important difference between the three-tone complex that is produced under AM and the complex that is produced under FM concerns the phase relations among the components. Consequently, any difference in the ear's sensitivity to AM and FM would presumably depend upon these phase relations.

Zwicker (1952) found, indeed, that in order for a subject to just hear a difference between a modulated and a pure, unmodulated tone, a smaller amount of AM is required than FM. The ear is more sensitive to AM than to FM, however, only at low rates of modulation. As the rate of modulation is increased, the difference in sensitivity to AM and FM gradually disappears. How do these results pertain to the critical band? The rate at which a tone is modulated determines the frequency separation, ΔF, between the side bands of the three-tone complex produced under the modulation. It turns out that the rate of modulation at which AM and

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[3] Gässler (1954) measured a critical band of 165 cps at 1000 cps. Garner (1947) had written earlier that "the best estimate . . . is that a band of frequencies no wider than 175 cps around 1000 cps is necessary if temporal integration of acoustic energy is to be perfect" (p. 813). His estimate was based upon measurements of the threshold changes for a wide-band noise, an unfiltered 1000-cycle tone, and a filtered 1000-cycle tone as a function of bandwidth which was varied by varying the duration of the signal.

[4] For a lucid discussion of the intricacies of modulation, consult Stevens and Davis (1938, pp. 225–231).

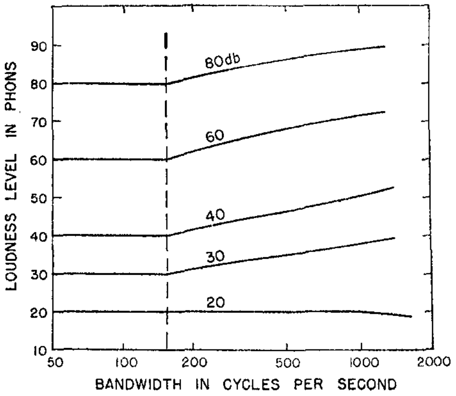

FIG. 2. The loudness level of a band of noise centered at 1000 cps measured as a function of the width of the band. (The parameter is the effective SPL of the noise. The dashed line shows that the bandwidth at which loudness begins to increase is the same at all the levels tested. This figure is adapted from the book, *Das Ohr als Nachrichtenempfänger,* by Feldtkeller and Zwicker—1956, p. 82.) (Adapted with permission of S. Hirzel Verlag)

FM become equally difficult to detect corresponds to values of ΔF that are essentially the same as the critical-band values given in Figure 1. Zwicker's investigation showed, moreover, that the critical band determined by phase sensitivity is independent of the SPL of the modulated tone and varies only as a function of the frequency of the "carrier" which lies, of course, at the center of the band.

Since the complexes produced under AM and those produced under FM differ primarily with respect to phase relations, the ear may be able to detect AM more easily than FM at low rates of modulation because it is more sensitive to the kind of phase relations that occur under AM. The ear seems to be sensitive to the phase relations, however, only when the ΔF of the complex is less than a critical band. When ΔF is greater than a critical band, there is no difference in sensitivity to AM and FM, implying that, beyond the critical band, the phase relations within the complex no longer serve as a significant cue in the detection of modulation.

Loudness of Complex Sounds

The critical band has been measured most thoroughly in studies of the loudness of complex sounds as a function of bandwidth. Zwicker and Feldtkeller (1955) demonstrated that the loudness of a white noise is independent of bandwidth until the critical band is exceeded, whereupon the loudness begins to increase. Their procedure was straightforward. They presented a band of filtered white noise and a comparison tone alternately through a single earphone. The subject adjusted the intensity of the tone until the tone and the noise sounded equally loud. The overall SPL of the noise was held constant; only the bandwidth was varied from judgment to judgment. (Zwicker and Feldtkeller did not report the number of subjects or the amount of variability; probably only a few, well-trained subjects were used and the variability was small.) Figure 2 shows what happens to the loudness of a band of noise when its width is increased. These curves are for bands centered at 1000 cps, which was the geometric mean of the two half-power points. At all the SPLs tested, from 30 to 80 db., the loudness of the noise remains constant and the curve is flat up to a bandwidth of about 160 cps, whereupon the loudness begins to increase. Within the critical band, the noises are as loud as a tone of equal intensity, having the same frequency as the center of the band. Functions similar in shape to those in Figure 2 were generated for bands centered at

500, 2000, and 4000 cps. The bandwidth at which loudness begins to increase defines the critical band for loudness, which was found to have approximately the same values as had been measured for threshold, two-tone masking, and phase sensitivity (see Figure 1).

Zwicker and Feldtkeller studied continuous spectra, i.e., noises that have energy at every frequency between the cutoff points. Bauch (1956) studied line spectra, i.e., sounds that have energy at two or more separate frequencies. He measured the loudness of three-tone complexes, produced by amplitude modulation, as a function of the difference, ΔF, in cps between the lowest and highest components of the complex. Bauch obtained the same results with three-tone complexes centered at various frequencies as Zwicker and Feldtkeller had obtained with bands of noise. For values of ΔF less than a critical band, loudness is constant except when ΔF is so small that beats are heard. The loudness begins to increase as a function of ΔF only when ΔF exceeds the critical band.

At the time that the critical band was being mapped out in Germany at the Technischen Hochschule Stuttgart (Bauch, 1956; Gässler, 1954; Zwicker, 1952, 1954; Zwicker & Feldtkeller, 1955) some of us at the Psycho-Acoustic Laboratory at Harvard were puzzled by our failure to find an increase in the loudness of a four-tone complex as a function of ΔF. We had assumed that loudness summation begins as soon as ΔF is increased. We were, however, studying four-tone complexes whose ΔFs were smaller than a critical band. When reports of the critical band came from Germany, our results began to make sense and, indeed, agreed well with those being obtained across the sea. The experiments were continued at Harvard by S. S. Stevens with G. Flottorp from Norway and E. Zwicker from Germany (Zwicker et al., 1957). Four-tone complexes and bands of white noise, at various center frequencies and various SPLs, were studied. In these experiments, 16 to 22 untrained subjects sometimes adjusted the complex sound and sometimes adjusted the comparison until the two were equally loud. Figure 3 shows a typical set of results, those for four-tone complexes centered at 1000 cps. Each point is the median of 20 loudness matches. Although the

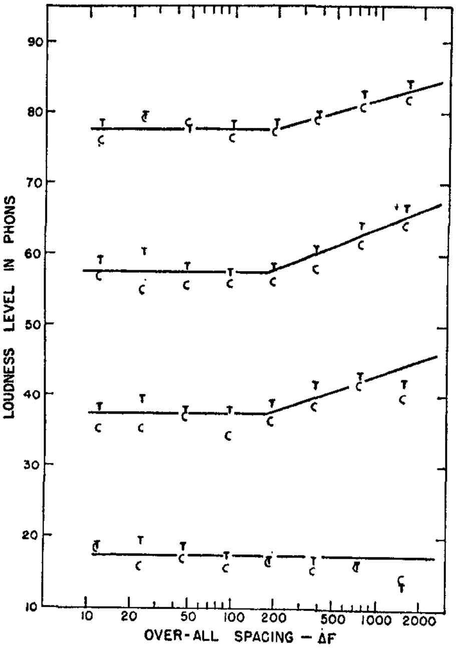

FIG. 3. The dependence of the loudness of a four-tone complex, centered at 1000 cps, on spacing and level. (Each point represents the median of two judgments by each of 10 listeners. The symbol T means the comparison tone was adjusted; C means the complex was adjusted. This figure is from Zwicker, Flottorp and Stevens—1957, p. 550.) (Reproduced with permission of the *Journal of the Acoustical Society of America*)

subjects were somewhat variable in their judgments, the medians are orderly and the lines through the data show a break at approximately the same value of ΔF that had been measured in Germany. The critical band made the transatlantic journey safely and invariantly.

Another investigation carried out at Harvard (Scharf, 1959a) showed that at low levels, between 5 and 35 db. above threshold, where the loudness of a complex sound increases more slowly with bandwidth than at higher levels, the critical band must be exceeded before loudness begins to change as a function of bandwidth.

Niese (1960), in Dresden, has also studied loudness summation and the critical band. He presented the sound stimuli not only through earphones (as in all the previous experiments) but also through a loudspeaker in a free field, i.e., in an anechoic room where sounds are almost completely absorbed by specially constructed walls. The results for free-field listening are similar to those for earphone listening; the loudness of a band of white noise begins to increase with bandwidth when the critical band is exceeded. Niese found, however, that the loudness did not continue to increase indefinitely with bandwidth, but increased about 8 db. and then remained constant for bandwidths greater than 1000 to 5000 cps depending upon the center frequency. It may be that the loudness did not increase further because the available energy was spread to very low and very high frequencies which contributed little to the total loudness.

In other experiments, Niese (1960) tested the assumption that loudness summation is a peripheral process occurring independently in each ear. In one procedure, a band of white noise was divided in half at its center frequency; the upper half was presented through an earphone to one ear and the lower half to the other ear. The loudness of the noise in both ears did not begin to increase with bandwidth until the *overall* width exceeded a value approximately *twice* the critical band, i.e., until the noise in each ear was wider than a single critical band. In a second procedure, two narrow bands, each 100 cycles wide, were first presented together to one ear and later separately to each ear. When presented together to a single ear, the loudness of the two bands increased with the frequency separation between them. When, on the other hand, one band was presented to each ear, the loudness did not increase with the frequency separation, no matter how great it was. The loudness did not increase because the band of noise presented to each ear was never wider than a critical band; it was always 100 cycles wide. Loudness summation thus seems to depend only upon the distribution of energy in one ear, suggesting that summation takes place not at some higher level in the auditory system where nerve impulses from the two ears join, but at the periphery, probably in the inner ear.

Still another aspect of loudness summation has been recently investigated (Scharf, 1959b). The results indicate that the loudness of a complex sound remains essentially unchanged when only the number of components in the complex is varied. The loudness of the complex increases with ΔF when ΔF is greater than a critical band, but at any given value of ΔF the loudness is approximately invariant with the number of components, provided the overall sound pressure remains invariant.

The several experiments in loudness summation, along with those on threshold, two-tone masking, and phase sensitivity provide a firm body of evidence for the critical band. There remains, however, the question of the role of the critical band in the masking of pure tones by white noise.

MASKING BANDS

Although the empirical measures of the critical band are quite recent, the concept of a critical band was expounded some 20 years ago by Fletcher (1940) when he hypothesized that: (*a*) a pure tone that is masked by a white noise is in effect masked only by a narrow band of frequencies surrounding the tone, and (*b*) the intensity of the part of the band that does the masking is equal to the intensity of the tone.

Fletcher (1940) presented some preliminary experimental results to support his thesis, but the projected full-scale experiment has apparently not been reported. Nonetheless the concept of a critical band has become important in theories about masking. Moreover, the acceptance of Fletcher's hypotheses permits the calculation of values for the masking band from the measurement of the masking of pure tones by white noise (Hawkins & Stevens, 1950). The calculated values for the masking band turn out to be about two-and-one-half times smaller than the empirical values for the critical band, as measured in experiments on loudness, two-tone masking, etc. This discrepancy, however, may be resolved either by a modification of Fletcher's second hypothesis, or, better, by direct measurements of the masking band. Let us turn first to the indirect measurements of the masking band and the assumptions underlying them.

Indirect Measures of the Masking Band

If both Fletcher's hypotheses about the existence of a masking band and about the equality of the intensities of the tone and noise are accepted, it is possible to calculate the size of the masking band from the masked thresholds for pure tones in white noise. Only one empirical operation is necessary. The threshold for a tone is measured in the presence of a white noise. From the intensity of the just-masked tone and the intensity of the masking noise, it is fairly simple to calculate how large a band within the noise contains the same energy as the tone. The width of this band is, *by definition*, the masking band. Its width is calculated by taking the ratio of the intensity of the tone to the intensity per cycle of the noise. (Since a white noise contains all audible frequencies at equal intensity, the intensity per cycle is uniform throughout.) For example, Hawkins and Stevens (1950) found that the ratio between the intensity of a 1000-cycle tone (at its masked threshold) and the intensity per cycle of the masking noise is 63:1 or 18 db. Since the intensity in each one-cycle band of noise is 1/63 the intensity of the masked tone, a band of frequencies 63 cps wide will have an *overall* intensity equal to that of the tone. Therefore, according to the second hypothesis, the masking band is taken to be 63 cps wide for a tone of 1000 cps. Values for the masking band that are calculated in the foregoing manner will be called "critical ratios," as suggested by S. S. Stevens (see Zwicker et al., 1957).

Hawkins and Stevens measured the masked thresholds at many frequencies from 100 to 9000 cps in the presence of white noise at levels from 20 to 90 db. They found that the ratio of the intensity of a just-masked tone to the intensity per cycle of the masking noise remains constant at all noise levels except the very lowest. In other words, the critical ratio does not change as a function of the level of the masking noise. The critical ratio is, however, different at different center frequencies, as shown in Figure 1. The results of these experiments agree with similar measurements that Fletcher and Munson (1937) had made of the critical ratio for tones masked by a uniform masking noise.

Bilger and Hirsh (1956) also calculated critical ratios from masking data obtained with bands of white noise 250 mels wide. (The mel is a unit of pitch.) The substitution of a 250-mel band, which is about five times as wide as the critical ratios measured by Hawkins and Stevens, is consistent with the assumption that the energy outside the masking band contributes nothing to the masking effect. If this, Fletcher's fundamental assumption, is true the critical ratio should be the same in both experiments. The results of the two independent experiments were, in fact, in close agreement.

In all these experiments the calculated value of the critical ratio depends upon the measured value of the masked threshold which may not be very reliable. Blackwell (1953) has shown, for example, that the value obtained for a threshold depends upon the psychophysical method employed in its measurement. The congruence of the results of the several experiments tends, however, to negate this criticism. Using the reported threshold measurements, we can modify Fletcher's second asumption so that the masking band has the same values as the critical band.

Instead of assuming, quite arbitrarily, that the intensities of the masked tone and of the masking band are equal, we can just as well assume that the intensity of the masking band is two-and-one-half times as great as that of the masked tone. Over most of the frequency range, this simple modification of Fletcher's second hypothesis yields values for the masking band that are equal to the measured values of the critical band. A simple modification succeeds because, as Figure 1 shows, except for very low frequencies, the critical band and the critical ratio are the same functions of center frequency. Since this new assumption is ad hoc and arbitrary, it will probably have little appeal. What we need is a more direct and straightforward type of evidence of the existence of the masking band.

Direct Measures of the Masking Band

The direct measurement of the masking band requires the sampling of the masked threshold for tones in the presence of bands of noise of different widths. If a masking band exists, the tone should become more difficult to detect as the bandwidth of the noise is increased up to the value of the masking band. Increasing the bandwith beyond the masking band should not raise the threshold for the tone any further. (In such experiments, energy is added to the noise as the bandwidth is increased, unlike experiments on loudness summation where a constant amount of noise energy is spread over a wider frequency range in order to increase the bandwidth.) Direct measurements of this type have been reported by Fletcher (1940), Hamilton (1957), and Schafer, Gales, Shewmaker, and Thompson (1950). Some of the recent experiments suggest that the masking band is larger than the critical ratio and may approximate the critical band as measured for other auditory phenomena.

In the first and most famous of these experiments, Fletcher (1940) measured the threshold for tones of seven different frequencies ranging from 125 to 8000 cps in the presence of bands of noise of various widths. No information about subjects, apparatus, or procedure was given. The results of this admittedly preliminary experiment provided some evidence for the masking-band hypothesis; the masked threshold tended first to increase and then to remain constant as the bandwidth of the masking noise was increased. The results seemed also to justify the assumption that, within the masking band, the intensity of the noise and the just-masked tone are equal: a band of noise, 30 cps wide, just masked a tone lying at its center frequency and having the same intensity. Precise determinations of the width of the masking band were not possible, however, because the data were highly variable and only a few bandwidths had been sampled. Of bandwidths having values in the vicinity of those for the masking band, only one, 200 cps wide, was adequately sampled. Nevertheless, relying heavily upon the assumption that the masking band and the just-masked tone are equally intense and upon the threshold measurements made in the presence of wide-band noise, Fletcher suggested values for the width of the masking band. These values, which Fletcher cautioned might be wrong by a factor of two, turned out to be approximately the same as the critical ratios calculated in 1950 by Hawkins and Stevens (see Figure 1). This similarity is not surprising, for the values recommended by Fletcher were, in effect, critical ratios. While suggestive, Fletcher's results provided neither conclusive support for his hypotheses nor a solid basis for the direct measurement of the width of the masking band.

Hamilton's (1957) more recent work provides a direct and precise measure of the masking band. Measuring the masked threshold for an 800-cycle tone in the presence of bands of noise that were centered at 800 cps and that varied in width from 19 to 1100 cps, he found that up to a bandwidth of 145 cps the masked threshold increased as the width of the masking noise increased. Beyond 145 cps the threshold remained constant, indicating that the masking band at 800 cps is 145 cps wide. The critical band measured in four other types of experiment is also about 145 cycles wide at 800 cps (see Figure 1). This coincidence of values is remarkable in view of the variability inherent in these experiments and Hamilton's apparent unfamiliarity with the other measures of the critical band.

A second important result in Hamilton's experiment shows that the difference (the signal/noise ratio) between the intensity of the 800-cycle tone at its masked threshold and the overall intensity of the masking noise is not constant, even when the width of the masking noise is less than a critical band. The signal/noise ratio decreases from about 0 db. for a band 30 cps wide to almost −4 db. for the critical width of 145 cps. (Hamilton reports similar results by Bauman, Dieter, Lieberman, and Finney, 1953.) Fletcher had also found that a band 30 cps wide just masks a tone at its center when the signal/noise ratio is 0 db., i.e., when the intensities of the tone and the noise are equal. This equality at a width of 30 cps suggested that at the critical bandwidth also, the tone and noise have the same intensity. Hamilton showed, however, that at the critical bandwidth the signal/noise ratio is not the same as at 30 cps. Accordingly, Fletcher's threshold measurements for a tone in a 30-cps-wide band of noise probably lend no support to the critical-ratio hypothesis; they are, however, consistent with critical-band values for the masking band.

Although Hamilton studied only one frequency, his results provide valuable information because they are orderly and self-consistent. Probably the use of a forced-choice procedure with well-trained subjects contributed to the preciseness of the results. In contrast, Schafer et al. (1950) report a more extensive experiment whose results are difficult to interpret. They measured the masked threshold for tones in three frequency regions as a function of the bandwidth of the surrounding noise. Instead of the usual white noise, they used bands of synthetic noise composed of tones one cycle apart. Preliminary experiments indicated no important difference between these bands of synthetic noise and bands of white noise. Twenty-five subjects served in the main experiments in which a random method of limits was used to measure the masked threshold for a tone that had been matched in pitch to the masking noise. The results suggest the presence of a masking band, but since no sharp change in the masked threshold was observed as the bandwidth was increased, the width of the masking band can be estimated only approximately. In the three frequency regions that were tested, the results suggest a masking band that is larger than that given by the critical ratio, and one that could well be as large as a critical band.

Schafer et al. (1950) interpreted their results to indicate no change in the signal/noise ratio within the masking band. Hamilton (1957), on the other hand, did find a small but consistent change in the signal/noise ratio within the masking band. Since, however, Schafer's observers were too variable to permit a precise measurement of changes in the signal/noise ratio, the small difference between the results of the two experiments is probably not significant. There is also some question about what Schafer et al. measured. Their use of a tone "matched in pitch to the masking noise" may account for some of the disparity between their results and Hamilton's.

These two experiments, by Hamilton and by Schafer, seem to be the only direct tests of the masking-band hypothesis since Fletcher's original attempt. One related experiment (Webster, Miller, Thompson, & Davenport, 1952) deserves mention. A white noise with octave gaps was used to mask tones at frequencies corresponding to those in and near the gaps. The measurements of the masked thresholds seem to suggest that Fletcher's values for the masking bands are too small.

The lack of extensive tests of the masking-band hypothesis prevents a definitive statement about the validity of the hypothesis, and even less may be said about the size of the bands. Nevertheless the net impression one obtains from the literature is that a masking band does exist and that it may well be the same width as the critical band.[5]

Other Correlates of the Critical Band

We have seen that the function relating the critical band to the frequency at the center of the band is derived from four types of experiment and that the width of the masking band may be the same as that of the critical band. Of interest, also, is the resemblance that the critical-band function bears to several other functions of frequency: the place of maximal displacement on the basilar membrane, the difference limen for frequency, and the mel scale of subjective pitch. These similarities have been noted elsewhere with respect to the critical band (Zwicker et al., 1957) and also with respect to the critical ratio (Fletcher, 1940, 1953; von Békésy & Rosenblith, 1951).

Perhaps the most interesting fact about the critical band is that it seems to correspond to a constant distance of about 1.3 millimeters along the basilar membrane. The first line in Figure 4 is a slightly idealized schematization of the frequency representation on the basilar membrane. The second line shows that 24 or 25 critical bands may be represented by equal-sized segments of the membrane. The boundaries of the critical bands are not fixed, of course, since a critical band may take shape around any frequency.

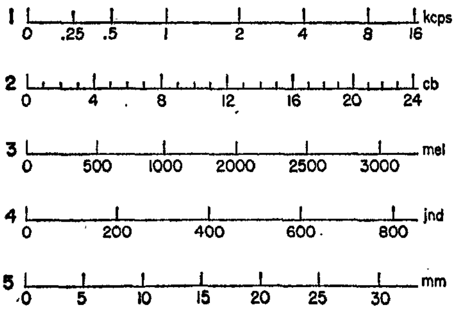

FIG. 4. Representation on the basilar membrane of (1) frequency in kilocycles, (2) critical bands, (3) pitch (Stevens & Volkmann, 1940), (4) just noticeable differences for frequency, the fifth line marks off distance in millimeters on the basilar membrane. (This figure is adapted from the book, *Das Ohr als Nachrichtenempfänger*, by Feldtkeller and Zwicker—1956, p. 60.) (Adapted with permission of S. Hirzel Verlag)

The mel and the jnd for frequency also correspond to constant distances on the basilar membrane (see the third and fourth lines in Figure 4). It is, therefore, not surprising that the critical-band function looks very much like the functions for the mel scale and the jnd scale. Measured in mels, the size of the critical band varies little, from 100 mels at low center frequencies to 180 mels at high frequencies. The mel scale is not accurate enough, however, to distinguish 100 from 180 mels at opposite ends of the scale, so that the pitch range of the critical band may, in fact, be fairly constant, perhaps approximating 150 mels.

The width of the critical band on the basilar membrane is determined from the map relating the frequency of pure tones to the position of maximal stimulation on the membrane (von Békésy, 1949). Although no di-

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[5] Since the preparation of this article, Greenwood (1960) has reported an extensive study that confirms the suggestion that there is a masking band and that it is the same size as the critical band. Greenwood measured the threshold for pure tones presented in bands of white noise. He varied not only the width of the bands of noise around a given center frequency, but also the sensation level of the noise and the frequency of the masked tone. Investigating bands of noise in five regions of the spectrum, he found consistent evidence for the existence of a fairly sharp masking band approximately the same size as the critical band.

rect physiological measures of the critical band have been reported, the fact that throughout the frequency spectrum the critical band corresponds to a constant length of the basilar membrane lends support to the notion that this band may be regarded as a fundamental unit of hearing.

FUTURE PROSPECTS

With the experimental basis for the critical band reasonably well established, investigators are beginning to consider the relevance of the critical band to the loudness of pure tones, to temporal integration, to deafness, to speech perception, and to other auditory processes.

Zwicker (1956, 1958), for example, has argued that the loudness of an intense pure tone is a composite loudness because the displacement of the basilar membrane is spread over many critical bands. Zwicker assumes that the "loudnesses" corresponding to these critical bands summate to give the total loudness of the tone. Similar assumptions underlie Zwicker's (1958) system for the objective calculation of the loudness of a complex noise. The loudness of a noise is assumed to equal the sum of the individual loudnesses of the component critical bands after allowance for mutual masking effects among the bands.

Other investigators are studying temporal integration for short tone pulses (cf. Plomp & Bouman, 1959). Since short tone pulses are in effect multicomponent complexes whose bandwidth varies with time, the integration of energy at threshold would be expected to occur within the critical band.

Clinical use of the critical band has been attempted by deBoer (1960) in the diagnosis of hearing loss. His results suggest that the critical-band mechanism may be disturbed in certain kinds of deafness. The related problem of individual differences for the critical band has remained essentially uninvestigated except for some observations by Niese (1960) and indications from earlier data (e.g., Gässler, 1954) that the size of the critical band may vary from person to person, just as thresholds do.

Although no answers have yet come forth, phoneticists are beginning to ask about the role of the critical band in the perception of speech. Musicians may soon add their problems. The quest has begun in earnest. Now that a fundamental unit of hearing has been identified, it remains to discover its role in all the many processes called hearing.

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(Received January 7, 1960)