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The Discernibility of Changes in Program Band Width*

By D. K. GANNETT and IDEN KERNEY

One of the factors that should be considered in determining how wide a transmission band is required for high fidelity broadcasting is the ability of people to perceive the effects of restricting the band to various limits, when listening to typical radio programs. Tests are described in which this was directly measured. The tests were concerned only with the physical ability to hear the differences in band width and disregarded the question of the enjoyment or aesthetic appreciation of wider bands. It is concluded that changes in band width are detectable about twice as readily with music as with speech; that one must go from 8 to 15 kc. to obtain a change as readily detected as a change from 5 to 8 kc.; and that both these changes, for speech, are just sufficient to have an even chance of being detected by listeners having experience in such tests.

THE question of how wide a frequency band it is necessary to transmit to provide high fidelity broadcasting involves consideration of a number of factors. Among these are the limits of hearing of the human ear, the spectra of program material, the aesthetic sensibilities of listeners, the effect of room noise in studios and homes, and the acoustic properties of rooms. A true engineering solution of the problem would attempt to assign numerical values to each of these factors, and then to combine them in some way to obtain a figure of merit versus band width. Sufficient information to do this in a complete and satisfactory manner is not available, however, and in practice the final answer is usually obtained by the exercise of judgment, bolstered by such technical data as can be found on the component factors.

The first two of the above factors, the limits of hearing and the spectra of program material, have been separately investigated and the results published in the technical literature by a number of experimenters. Because of the intangibles involved, however, even these two sets of data cannot readily be combined, forgetting the other factors, with complete assurance that their contribution to the answer is established. The authors, therefore, undertook a series of tests to measure directly their combined effect.

* This paper is a publication, substantially without change, of a report prepared some time ago before work non-productive to the war effort was suspended.

These experiments tested the ability of critical listeners to hear changes in band width on direct comparison when listening to representative program material. The purpose of this paper is to present the data from these tests. Similar experiments have of course been done before. The excuse for this paper is that the experiments represent a complete set of data and the analysis of the data is believed to be in such form as to be useful in further consideration of the requirements of program fidelity.

The circuit arrangements used for the tests are shown schematically in Fig. 1. The essential features are a source of program, a switch for connecting into the circuit either of two low-pass filters, and a high-quality loudspeaker. Controls for adjusting levels, volume indicators, etc., are omitted from the diagram. The arrangements included a signal visible to the

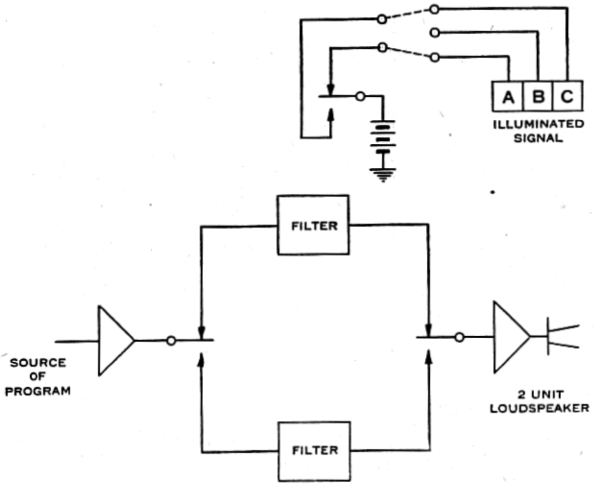

Fig. 1—Arrangement for testing program band widths.

listeners in which one of the letters, A, B, or C, could be illuminated. On a given test two of these letters were associated with the switch so that one letter was illuminated for one position and the other letter for the other position. The choice of letters among the three was varied more or less at random for different tests. Low pass filters were available to provide cut-offs of 3, 5, 8, 11 and 13 kc. When no filter was inserted the band was considered to extend to 15 kc. as this was about the upper limit of transmission of the testing circuits and loud speaker. The lower limit of the transmitted band for all conditions was approximately 40 cycles.

In conducting a test, a group of observers listened to comparisons between two of the available band widths, the conditions being switched every few seconds until a sufficient number of comparisons had been made. The conditions were unknown to the observers, being designated to them only by the letters in the signal. At the conclusion of the test the observers were asked to mark on a ballot which letter appeared to coincide with the wider band (not which they preferred). A series of tests consisted of comparisons between substantially all of the possible band widths among those available. There were also included in some of the series as a check, one or two tests in which the band width was the same for both positions of the switch. Ten complete series of tests were carried out, two on each of five different programs.

The programs consisted of a dance orchestra, two large symphony orchestras, speech from a male speaker repeating a test sentence, and a radio dramatic sketch. The programs, except for the spoken test sentences, were obtained by special arrangement over direct wire lines from the studio or theater in which the performance took place. The entire system from microphones to and including the loud-speaker had a substantially flat transmission characteristic from 40 to 15,000 cycles, with no filters in the circuit. The loud-speaker was of the two-unit type and was one of a number built for the demonstration of auditory perspective in 1933. The tests were conducted in the program laboratory of the Bell Telephone Laboratories where the acoustic noise level was about +30 decibels. The noise contributed by the electrical parts of the system was considerably below the acoustic noise. The loudness of the programs was adjusted to about unity reproduction, that is, to the volume that would be heard by listeners in a favorable position at the original performance.

The observers were engineers having a considerable experience in tests of program quality. They were doubtless therefore considerably more critical than the average radio listener. The number of observers varied somewhat during the tests but averaged about sixteen. The ages of the observers were in the 30's and 40's so that neither very young nor very old ears were represented.

The immediate outcome of the tests was some 2,000 ballots which were meaningless until analyzed. Before the analysis could be made, however, it was necessary to decide how to express the results.

There are no familiar units to express fidelity or program quality. It was decided therefore to employ the very useful concept of the limen and the liminal unit. These terms have occasionally been applied to other subjective data and may be roughly defined as the least change in a quantity which is detectable. In the present case, if the band widths being compared differ greatly, there will be a nearly unanimous agreement among the observers as to which is the wider. If they differ only slightly, however, many of the observers will vote wrongly for the narrower band and on successive repetitions of the test many will reverse themselves. An average of a large number of votes will show a plurality for the wider band, the margin of choice increasing as the difference in band width is made greater. A significant measure of the detectable difference in band width will be taken to be that difference such that 75% of the observers correctly select the wider band and 25% wrongly select the narrower band. This difference in band widths will be designated one "difference limen." The sensory effect of a change of one difference limen will be called one "liminal unit".

The significance of the vote of 75 to 25% is assumed to be as follows: On a particular test some of the observers can detect the difference between the conditions while the remainder will guess. Of the latter, half are likely to guess right and half wrong. When 25% vote wrongly they are assumed to be guessing and must be paired with another 25% who also guessed but happened to guess right. Therefore a vote of 75 to 25% is taken to indicate that 50% of the observers were guessing and the remainder could actually detect the difference. The difference limen may now be more specifically defined as that difference in band widths which is detectable to half the observers.

It may be commented that this attempt to explain the definition of "liminal unit" is perhaps over-simple. The observers themselves are frequently uncertain whether they are guessing or are influenced in their choice by some minute difference. The test could be done with a single observer, repeated many times to obtain the same number of observations as with a group. When the conditions are nearly equal he will vote about as often one way as the other, but as the difference between the conditions is increased he will vote a larger per cent of the time correctly for the wider band, just as did the group. When the two conditions are separated by one difference limen he will vote correctly 75% of the time and wrongly 25% of the time, which may be said, in line with the argument given earlier, to indicate that he is guessing half the time and can discern the difference half the time. The difference limen could therefore be defined as that threshold difference for which there is an even chance of its discernment by a listener.

Having chosen a method of expressing the results, the analysis can now be attacked. The first step is to group together all tests on similar types of program material, and to determine for each band width comparison the per cent of votes for the wider and narrower band, respectively. The data thus obtained for music and speech are shown by the solid curves of Figs. 2 and 3. A curve labeled 8 kc., for example, shows the per cent of the total votes which selected as the wider each of the other band widths to which 8 kc. was compared. The points, although somewhat irregular, fell systematically enough to permit drawing the smooth curves with the application of some judgment and having due regard to the necessary symmetry between them. (For example, the 8 kc. curve at an abscissa of 5 kc. must agree with the 5 kc. curve at an abscissa of 8 kc.) A much larger volume of data would be needed to obtain points falling accurately on a smooth curve. To facilitate obtaining the best approximations, the curves were plotted on several kinds of coordinates, including rectangular, semi-logarithmic (shown in the illustrations), probability and logarithmic probability.

The dotted curves were interpolated between the solid curves and progress in steps of 1 kc. The interpolation was readily accomplished with consider-

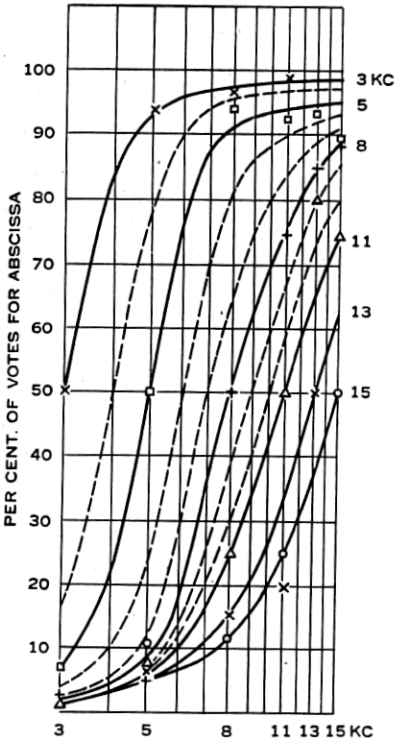

Fig. 2—Music

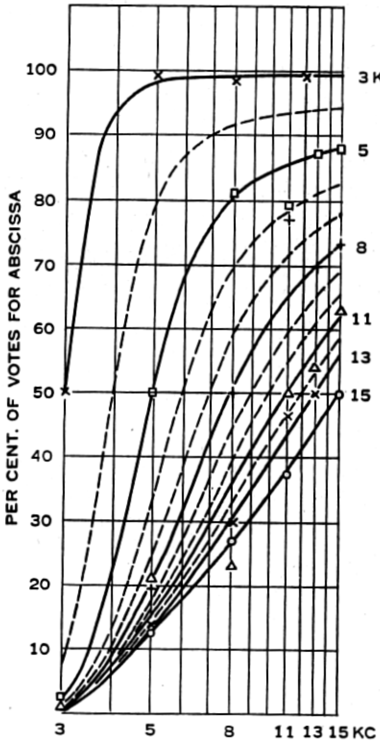

Fig. 3—Speech

Figs. 2 & 3—Detectability of changes in band width.

able accuracy. For example, points for the 10 kc. curve are obtained from the values of each of the solid curves corresponding to an abscissa of 10 kc.

From these curves, the difference limens for each band width were determined by reading directly the bands corresponding to votes of 25% and 75%. The bands at which these votes occur therefore by definition differ from the reference band by one limen. The following table gives the intervals of one limen as thus derived from the curves.

Differences in Upper Limit of Program Band in KC, Corresponding to One Limen

Music	Speech
3— 3.6	3— 3.3
3.3— 4— 4.8	3.4— 4— 4.8
4.1— 5— 6	4.1— 5— 6.9
5 — 6— 7.4	4.6— 6— 9.4
5.8— 7— 9.3	5.1— 7—12.8
6.4— 8—11	5.5— 8
6.9— 9—12.2	5.8— 9
7.4—10—13.4	6.2—10
8 —11—15	6.4—11
9.8—13	7 —13
11 —15	7.6—15

The difference limens are seen to vary with the frequency of cut-off, increasing as the frequency increases. Since each difference limen corresponds to a sensory effect of one liminal unit, it is obvious that the reciprocal

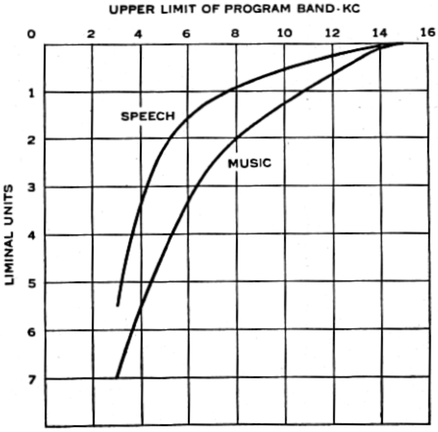

Fig. 4—Ability to detect changes in program band width.

of the difference limen gives the rate of change of liminal units with changes of program band width in terms of liminal units per kilocycle. Therefore, curves of liminal units versus the upper limit of the program band may be constructed from the figures in the table. Such curves are plotted in Fig. 4. The actual mechanics of the process used to plot the curves was as follows, taking the data for "music" for illustration. The lowest frequency occurring in the table is 3 kc., and it is seen that raising the band width to 3.6 kc. will bring about a subjective increase of one liminal unit. Therefore, on an arbitrary scale, 3 kc. was plotted at 0 and 3.6 kc. at one liminal unit. Next a smooth curve was drawn through these points and the location of 3.3 kc. (next line of table) was determined by interpolation. Since 4 kc. is one liminal unit above 3.3 kc., and 4.8 is one liminal unit above 4 kc., these points were plotted and the curve extended through them. By a similar process the curve was extended step by step up to 15 kc. Finally, the origin was shifted so as to express the liminal curve with respect to 15 kc. instead of 3 kc.

It was mentioned above that a number of tests were introduced without the knowledge of the observers in which the conditions were not changed, the band width remaining constant while the illuminated letters were switched. This produced the most interesting psychological result that observers voted nearly two to one for the letter appearing in the right-hand position in the signal, on each of the six tests of this kind. This raises the question as to whether this effect impaired the results on the other tests.

In the course of the tests, comparisons between each pair of band widths were presented 10 times, 6 times with music and 4 times with speech. The letters corresponding to the two conditions were assigned more or less at random from the three letters A, B, and C. Taking 11 of these groups of tests in which the narrower band was represented about as often by the right hand as by the left hand of the pair of letters chosen, the average vote for the right-hand letter was 51.1% and for the left-hand letter was 48.9%. The difference between these two figures is too small to be significant. It is therefore concluded that when there was a real difference, the observers were not measurably influenced by their slight subconscious predilection for the right-hand letter. It would be interesting to correlate this phenomenon with the right or left-handedness of the observers. This point illustrates the extreme care that must be taken in conducting judgment tests of this sort to insure that no irrelevant factors affect the statistical result.

The curves of Fig. 4 permit drawing the following conclusions:

1. Increases in band width can be detected up to 15 kc. for both music and speech. The fact that this is true for speech is rather surprising. However, above about 5 kc., changes in band width are twice as readily detectable on music as on speech.
2. It requires an increase in band width from 8 to 15 kc. to be as readily detected as an increase from 5 to 8 kc., for both speech and music.
3. The following intervals correspond to one liminal unit and are therefore just discernible half of the time to the observers:
   Speech: 5 to 8 kc.; 8 to 15 kc.
   Music: 5 to $6\frac{1}{2}$ kc.; $6\frac{1}{2}$ to 8 kc.; 8 to 11 kc.; 11 to 15 kc.

In considering these conclusions, the fundamental assumption and limitations of the data should be borne in mind. First, the data were obtained from tests with a certain group of observers and on certain program material. Curves of somewhat different slope would doubtless be obtained with observers of different average age, experience, musical appreciation, etc. It is likely, however, that this would affect the absolute importance of the different intervals in liminal units rather than the relative values. As noted earlier, the observers in these tests were considerably more experienced and critical than average radio audiences. The program material tested was representative of most of the programs on the air, but different results would be obtained with material markedly different in nature. This would probably be particularly true of selected sound effects. Secondly, it should not be forgotten that the results are based only on the ability of the ear to detect the changes, with no weighting for factors such as aesthetic values or personal preferences, or for the effects of room noise and other factors present in the practical case. Thirdly, it should be appreciated that comparison tests such as these are very sensitive tests, showing up differences that could not be detected under usual home listening conditions.

TABLE I

	Upper Frequency Limit Versus Unrestricted Band, Corresponding to One Liminal Unit
Musical Instruments	
1. Flute	13,500 cycles
2. Snare Drum	13,000
3. Violin	13,000
4. Soprano Saxophone	12,700
5. Oboe	12,700
6. 14 in. Cymbals	12,000
7. Bass Clarinet	10,500
9. Piccolo	10,200
9. Bassoon	10,000
10. Cello	9,800
11. Bass Saxophone	8,600
12. Clarinet	8,500
13. Trumpet	8,300
14. Bass Viol	7,800
15. Trombone	7,200
16. Bass Tuba	6,300
17. French Horn	6,100
18. Piano	5,600
19. Bass Drum	4,300
20. Timpani	3,500
Speech	
Male	7,300
Female	9,200
Sound Effects	
Footsteps	12,000
Handclapping	15,000
Key Jingling	15,000

It is of interest to compare the above results with previously published data. In a paper "Audible Frequency Ranges of Music, Speech and Noise,"[1] W. B. Snow gave data for 20 musical instruments, certain noises, and

[1] Jour. Acous. Soc. Amer., July 1931; *Bell Sys. Tech. Jour.*, Oct. 1931.

speech. The data showed the frequency limitations as compared with unlimited bands (about 15 kc.) which yielded a vote of 60 to 40%, and 80 to 20% among a considerable number of observations. In Table I these data have been interpolated to determine the limits that would correspond to a vote of 75 to 25%, in line with the criterion assumed in this paper. In making the interpolation, it was assumed that the curve of per cent of observers voting correctly for the wider band versus logarithm of the frequency is a straight line in the range of interest.

TABLE II

	Lower Frequency Limit Versus Unrestricted Band, Corresponding to One Liminal Unit
Musical Instruments	
1. Bass Viol	53 cycles
2. Bass Tuba	55
3. Timpani	60
4. Bass Drum	72
5. Bass Saxophone	72
6. Bassoon	74
7. Bass Clarinet	80
8. Cello	83
9. Snare Drum	87
10. Piano	95
11. Trombone	110
12. French Horn	125
13. Clarinet	140
14. Trumpet	160
15. Soprano Saxophone	210
16. Violin	230
17. Oboe	240
18. Flute	250
19. 14 in. Cymbals	370
20. Piccolo	510
Speech	
Male	115
Female	190
Sound Effects	
Footsteps	95
Handclapping	135
Key Jingling	915

It is difficult to interpret these data from individual instruments in terms of results to be expected from whole orchestras and other music as usually heard. However, comparing Table I with Fig. 4, it will be seen that the frequency limit determined from the present tests as corresponding to one liminal unit for music falls about one third the way down the list of instruments in the table, and the limit corresponding to two liminal units falls about two thirds down the table, which seems reasonable. Also the frequency limit found in the present tests to correspond to one liminal unit for speech lies between the figures given in the table for male and female speech, which is a good check.

The present tests did not include measurements on the lower end of the frequency band. However, some clue to the results that would be expected may be obtained from Mr. Snow's paper. Table II, derived from Mr. Snow's data in a manner similar to that just described, gives the lower limit of the frequency band corresponding to a degradation of one liminal unit compared with transmitting a much lower frequency.

The frequency corresponding to one liminal unit for speech may be taken as the mean of the figures for male and female speech, or about 150 cycles. In the case of music, it may be expected that at the lower as well as the upper end of the frequency range one liminal unit for an orchestra should fall about one third the way down the list of individual instruments, and two liminal units about two thirds the way down the list. This would make one liminal unit for music correspond to about 80 cycles and two liminal units to about 150 cycles. This speculation leads to the interesting hypothesis that the relations are probably the same at the lower as at the upper end of the frequency scale, that is, changes in band widths are twice as readily detected for music as for speech, and that the frequency limit corresponding to one liminal unit for speech corresponds to two liminal units for music.