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Stereophony: the effect of cross-talk between left and right channels

by

H. D. HARWOOD, B.Sc., A.Inst.P., A.M.I.E.E.

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D. E. L. SHORTER, B.Sc.(Eng.), A.M.I.E.E.

(Research Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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FOREWORD

This is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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STEREOPHONY: THE EFFECT OF CROSS-TALK BETWEEN LEFT AND RIGHT CHANNELS

SUMMARY

In a stereophonic transmission system, excessive cross-talk between the left- and right-hand channels leads to displacement or blurring of the reproduced sound images. Subjective tests have established quantitative relationships between cross-talk attenuation and the resulting impairment of the stereophonic presentation. The experiments covered cross-talk increasing at high frequencies or at low frequencies as well as cross-talk independent of frequency. The effect of restricting the bandwidth of the programme material has been investigated, together with the influence of acoustic environment and of the observer's position in relation to the loudspeakers. Comparisons are made with previously published data.

1. Introduction

One of the technical defects which may appear in a stereophonic sound system is the unintentional transference of a portion of the signal in one of the channels to the other channel; to describe this phenomenon it is usual to borrow from the vocabulary of the telephone engineer the term 'cross-talk'. The effect of this cross-talk is to displace the position of the images,* thus altering the scale of width.* If the cross-talk is in phase with the direct signal and is independent of frequency, the effect is to alter the scale of width by a constant factor, the images remaining sharp; it is then fairly simple to recover the original width at a later stage by introducing cross-talk of opposite sign. When, however, cross-talk is dependent on frequency, the change in scale of width is also dependent on frequency; the different components of a complex sound are displaced in varying degrees and blurring and anomalous movement of the images may then be experienced, an effect which is somewhat analogous to that of chromatic aberration in optics.

Cross-talk may be accidentally produced in several ways, such as by capacitative coupling in amplifiers, magnetic coupling in tape recording machines or by mechanical coupling in disc-recording and reproducing equipment. Of particular interest for the present purpose, however, is the cross-talk which may appear in a stereophonic broadcast transmission system. In multiplex systems for broadcasting two-channel stereophony from a single station, the programme is transmitted in the form of a pair of signals, usually designated M and S respectively, which are proportional to the sum and the difference of the original left- and right-hand signals. It can readily be shown that if, in the process of transmission and reception, the ratio of the amplitudes or the difference in phase of the M and S signals is altered, then the reconstituted left- and right-hand signals applied to the listener's two loudspeakers will each contain a component derived from the other, i.e. cross-talk will be introduced. A case of considerable practical importance arises in radio transmission where the M and S signals may be subject to unequal time delays in the course of modulation or demodulation; the cross-talk then increases with frequency at a rate of 6 dB per octave over a considerable range. A similar situation can arise in the M–S microphone system,[2] in which the sum and difference signals are produced respectively by two microphones, of appropriate directional characteristics, with their axes at right angles. The M and S microphones are nominally coincident but are in fact mounted at a small but finite distance one above the other; any sound wave whose direction of propagation is not horizontal will therefore generate M and S signals separated by a slight time interval.

In the design of equipment for originating, transmitting, or receiving stereophonic programmes, it is important to know what degree of interchannel cross-talk may be permitted without modifying the stereophonic presentation as observed by the listener; it is also useful to be able to express quantitatively the effects observed when this threshold value is exceeded. To obtain such information, the tests to be described were carried out in the BBC Research Department; the work formed part of a series of experiments undertaken as a contribution to an international study of stereophony organized by the European Broadcasting Union (E.B.U.).

* Definitions of these and other special terms used in stereophony are given in an earlier Monograph.[1]

2. Experimental Details

2.1 *General*

It is known that the apparent position of one stereophonically reproduced sound can be influenced to some extent by the presence of another occurring concurrently or even preceding it by a short time interval.[3] It is not possible, therefore, by employing pure tones or isolated bands of noise to obtain data directly applicable to the reproduction of complex and rapidly fluctuating sounds. For this reason the tests were carried out with selected magnetic-tape recordings of speech and music. However, in order to assess the contributions to the phenomena under investigation made by the extreme high- and low-frequency components of the sound, some of the experiments were repeated with the bandwidth of the programme restricted by low- and high-pass filters respectively. Fig. 1 shows the characteristics of the filters employed; the rate of cut-off was restricted to 12 dB per octave to avoid audible ringing at the cut-off frequency. The nominal limit of the band was taken as the frequency at which the attenuation exceeded the mid-band value by 3 dB; the cut-off fre-

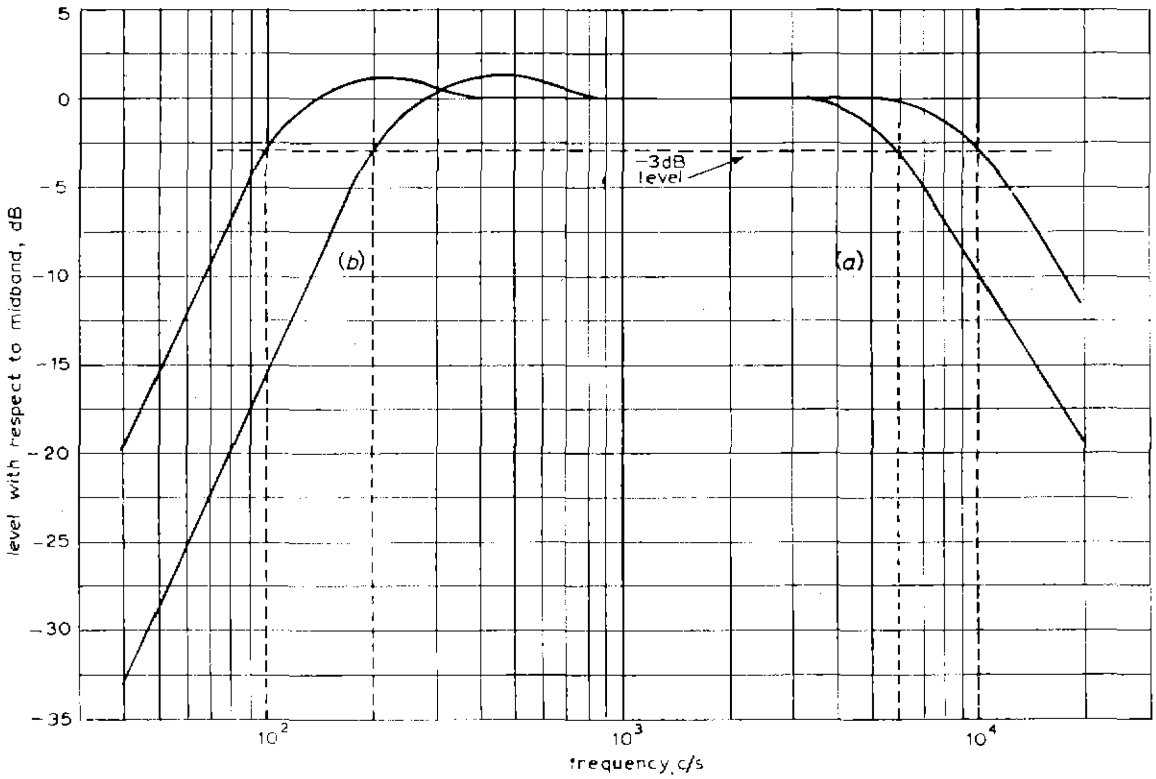

Fig. 1 — Frequency response of filters used for limiting programme bandwidth.
(a) Low Pass
(b) High Pass

quencies thus defined were 6 kc/s and 10 kc/s for the low-pass filters, 100 c/s and 200 c/s for the high-pass filters. In the absence of the filters, the bandwidth of the reproducing system was restricted to the range 40 c/s to 13 kc/s by the characteristics of the loudspeakers employed.

The effect of interchannel cross-talk on the stereophonic presentation depends on the position of the sound sources which make up the programme. Thus, when the signals in the left-hand and right-hand channels are identical—i.e. when the image is intended to be central—the existence of a cross-talk path between the two channels may slightly change the level of these signals but will leave them still equal, so that the position of the image is not disturbed. On the other hand, the effects of cross-talk are most pronounced when a signal is transmitted in one channel only; in this case, the existence of a cross-talk path will allow an unwanted signal to reach the loudspeaker which should be silent. Excessive cross-talk will then cause an image which should be located, say, at the left-hand loudspeaker to be displaced towards the right.

The effects of cross-talk may also depend on the spectrum of the programme material. If, as is likely in practice, the degree of cross-talk increases at the two extremes of the audio-frequency band, displacement or blurring of images will be most noticeable with sounds having strong components at high or low frequencies.

To reduce this potentially complex situation to its simplest terms, it was decided in the present experiments to deal only with the extreme cases. The programme signal was accordingly applied to one loudspeaker only, a known fraction of this signal being applied to the other loudspeaker as cross-talk, and the spread of the image across the stage was observed. By this procedure it was possible to utilize a monophonic source of programme with a single set of filters for restricting the frequency range. Separate experiments were carried out for cross-talk increasing at high frequencies, cross-talk increasing at low frequencies, and cross-talk independent of frequency, using programme material appropriate to each case. The team of observers, twelve in number, was chosen from individuals experienced in the subjective assessment of high-quality reproduction. The results of these experiments thus represent to the system designer the limits beyond which it is unnecessary to go.

2.2 *Layout of Equipment*

Fig. 2 shows the layout of the equipment. The two loudspeakers were concealed behind an acoustically transparent curtain. A series of vertical black tapes hung immediately in front of the curtain formed two scales, each divided in equal angular increments and numbered 0 to 4 from the outside towards the centre. Fig. 3 shows an observer seated in the central position. The observers were asked to face the centre of the stage throughout the tests;

a neck rest was provided to locate the observer in a reproducible position without interfering with those small movements of the head which are known[4] to play an essential part in directional hearing.

2.3 *Position of Observer*

Most of the experiments were carried out with the observer in the central position. It was thought, however, that if the listening position were located nearer to the loudspeaker reproducing the cross-talk and farther from that reproducing the programme, the alteration in the relative levels, coupled with the precedence effect, would make the result of the cross-talk more noticeable. The more critical tests were therefore repeated with the observer placed, as shown in Fig. 2, in a position to one side of a hypothetical triangular seating layout but still facing towards the centre of the stage.

2.4 *Loudspeakers*

Fig. 4 shows free-field frequency characteristics of one of the loudspeakers used, taken on the nominal axis and at 45° to the axis in the horizontal plane. The loudspeakers were of the two-unit type; the nominal axis—taken for the purpose of the experiment to be midway between the low- and high-frequency units—was at approximately the same height as the ears of a seated observer.

The two loudspeakers employed were well matched. Over the range 3 kc/s to 13 kc/s and 40 c/s to 250 c/s, which contain most of the components of interest in the experiments on cross-talk increasing at high and low frequencies respectively, the axial frequency characteristics lay within $\pm\frac{1}{2}$ dB of one another; within the middle frequency band (250 c/s to 3 kc/s) the differences were less than ± 1 dB except in the cross-over region (800 c/s to 1,600 c/s), where local deviations up to ± 2 dB existed. To minimize the effects of residual asymmetry of the loudspeaker system, of the acoustic environment, and of the observer's directional sense, all tests were repeated with the programme and cross-talk channels interchanged, the two results being subsequently averaged.

2.5 *Acoustic Environment*

Experiments were carried out in a listening room having a volume of 85 m^3 and a reverberation time characteristic shown in Fig. 5. To discover how far the subjective effects of cross-talk depend upon the acoustics of the surroundings in which the sound is reproduced, most of the tests were repeated in a dead room, normally employed for

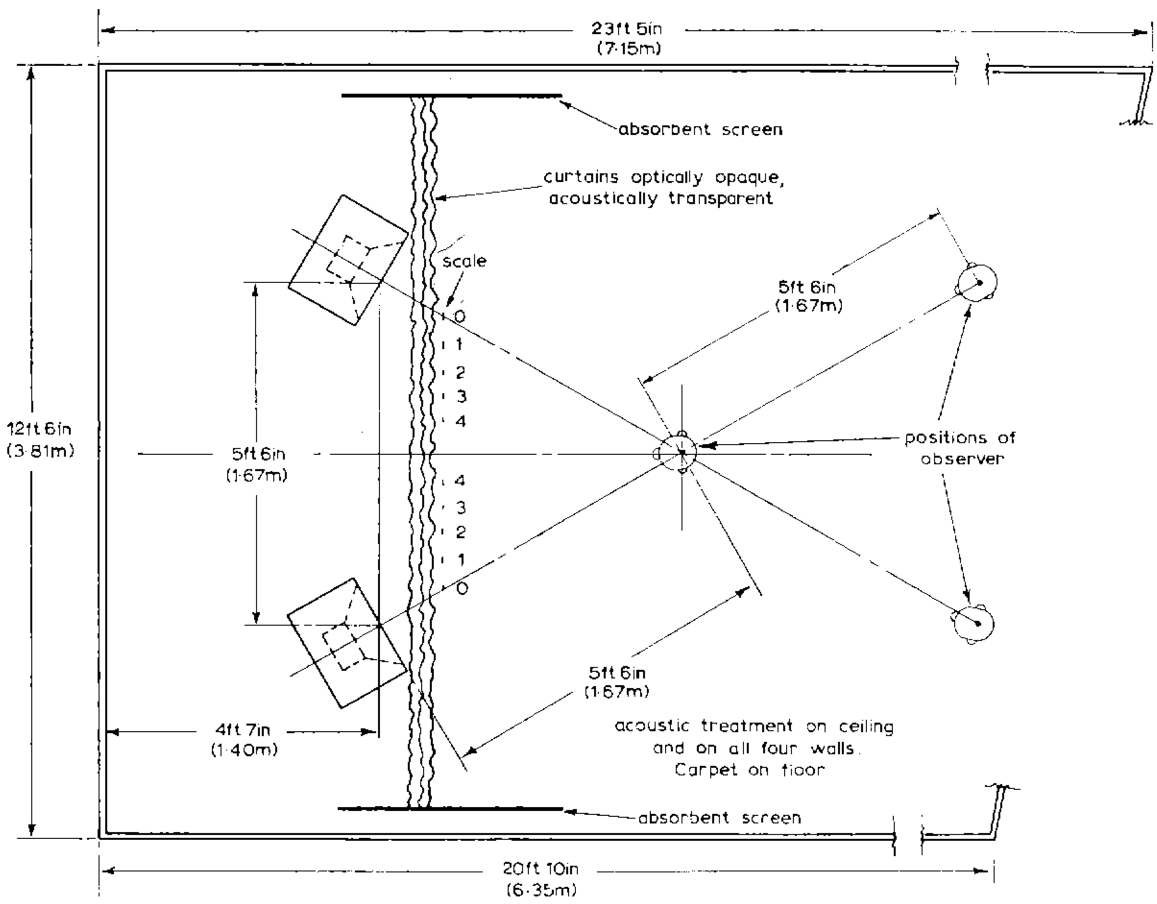

Fig. 2 — Plan of Listening Room.

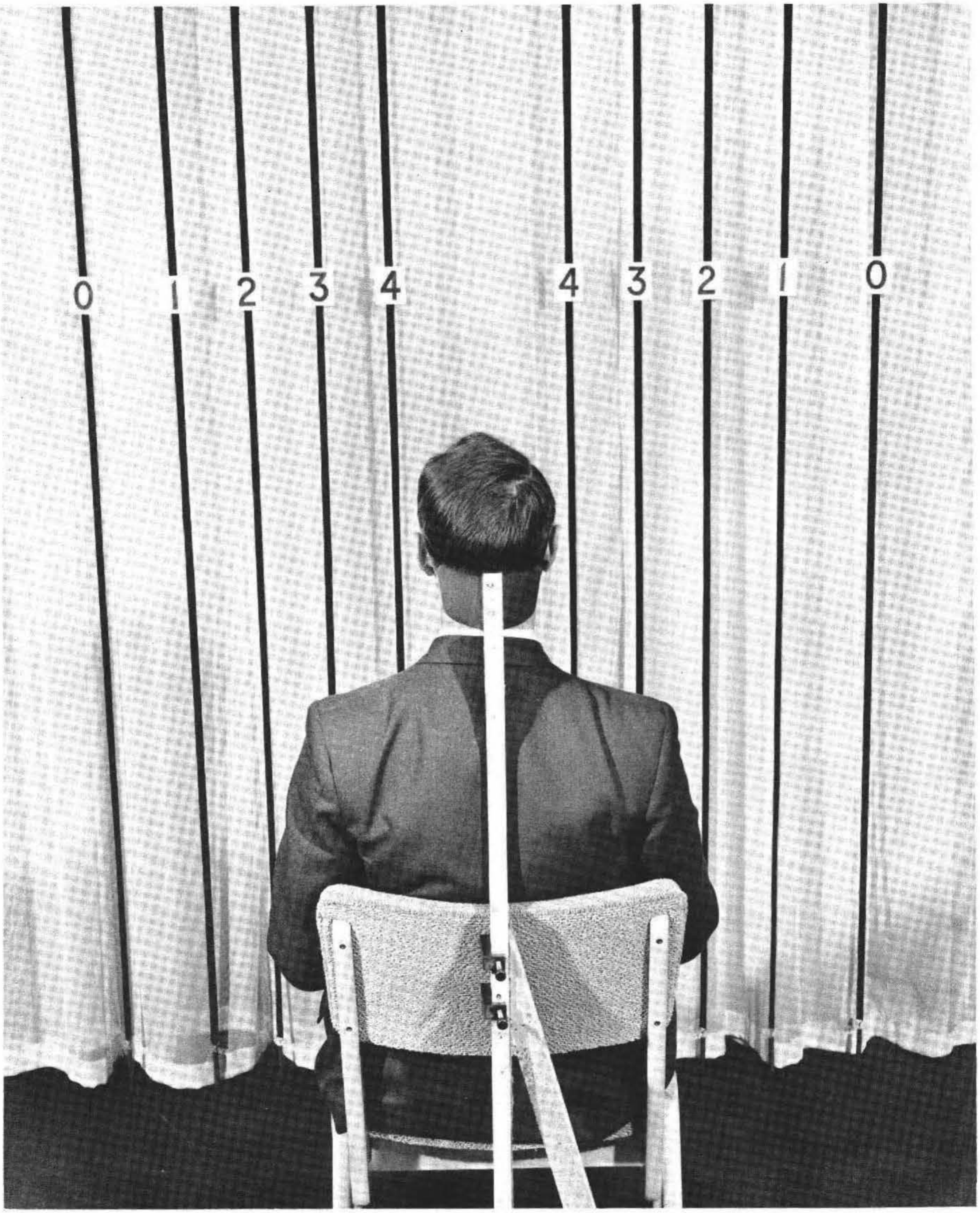

Fig. 3 — View of subject in listening room.

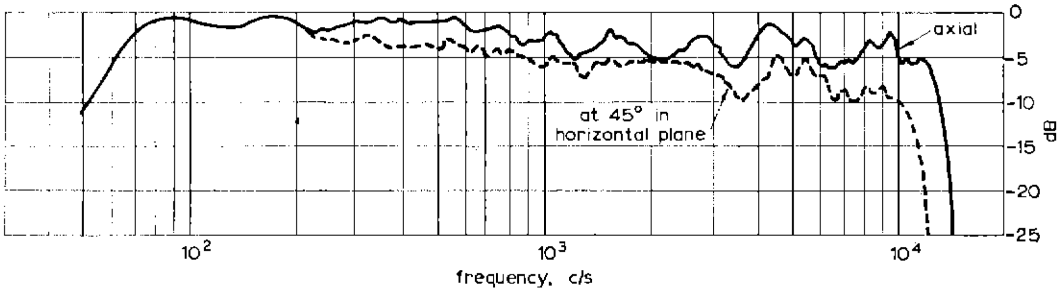

Fig. 4 — Frequency response of loudspeaker measured at 1·5 m in dead room.

measurements on microphones and loudspeakers, having a wall-reflexion coefficient of less than 10% at all frequencies above 80 c/s. The former location was taken to simulate the environment for domestic listening, while the latter represents a limiting condition and has the advantage of being reproducible in other acoustic laboratories.

2.6 *Loudness Level of Programme*

In a preliminary test, each observer was asked to adjust a volume control to give the most comfortable listening level. The mean listening level for the team was found to correspond to a maximum reading, in the loud passages of programme, of 74 dB on an unweighted sound level meter placed at the listening point. This figure of 74 dB agrees with the preferred listening level arrived at some years ago[5] by tests on a representative sample of the general population; the scatter of the results was such that 75 per cent of the population was estimated to have a preferred listening level within the range 74 dB$\pm$6 dB.

The first experiments were carried out with the level of the reproduced programme adjusted to reach a maximum of 74 dB and then repeated at levels 6 dB above and 6 dB below this figure; the cross-talk attenuation associated with a particular degree of image displacement was found to vary with level by less than 2 dB. Since the effect of cross-talk was not critically dependent on listening level, it was decided to carry out the remainder of the experiments at a maximum sound level of 74 dB, and all the results given in Section 3 relate to this condition.

2.7 *Circuit Arrangements*

The channel carrying the programme was connected to the second channel of the stereophonic system through a simulated cross-talk path including a buffer amplifier, an attenuator, and, where required, a reactive element arranged to make the cross-talk vary with frequency.

For the experiments on cross-talk increasing with frequency a small series capacitance was inserted in the cross-talk circuit, so that the signal from one channel reaching the other was proportional to frequency—i.e. rising 6 dB per octave—and leading 90° in phase up to the highest frequency of interest. It can be shown (see Appendix) that this form of cross-talk coupling gives, to a good approximation, the same effect as a time delay between the M and S channels of a multiplex system. For convenience, the degree of cross-talk was specified by giving the cross-talk attenuation at 10 kc/s.

To simulate cross-talk rising at low frequencies a corresponding shunt capacitance arrangement was used; the circuit values were such that the signal from one channel reaching the other was inversely proportional to frequency —i.e. falling off 6 dB per octave—and lagging 90° in phase down to the lowest frequency of interest. As before, the degree of cross-talk was specified by giving the cross-talk attenuation at a convenient reference frequency, in this case 50 c/s.

No attempt was made to compensate for the phase shift introduced in the cross-talk circuit, since this would normally appear in practice.

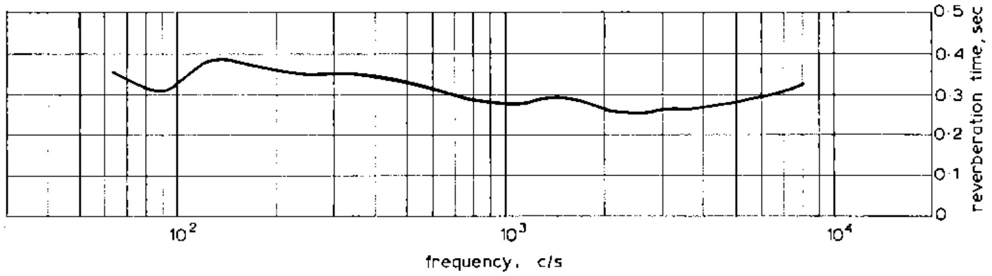

Fig. 5 — Reverberation time of listening room.

2.8 *Programme Material*

For the experiments on cross-talk increasing at high frequencies a piece of Latin American music was chosen; this type of programme, with its maraccas and similar percussion instruments, is among the most sensitive to the effects of high-frequency cross-talk.

For the experiments on cross-talk increasing at low frequencies it was not possible to find any single representative piece of programme, and the tests were carried out with passages on the organ, the bass drum, and the double bass played *pizzicato*; the spectrum extended down to 40 c/s in each case.

Experiments on cross-talk independent of frequency were made with male speech as programme material. Since the spectrum of speech contains no strong components at the extremes of the audio-frequency band, this test is principally representative of the middle of the band; the resulting data can therefore be combined with that obtained with cross-talk increasing at high and low frequencies respectively to produce tolerance figures for the whole audio-frequency range.

2.9 *Presentation of Test Material*

In the early experiments two types of presentation were tried. In the first type, in which the test sequence was prerecorded, the programme alone was presented from one loudspeaker for 7 seconds so that the observer could assess the position of the image. After a pause of 2 seconds this

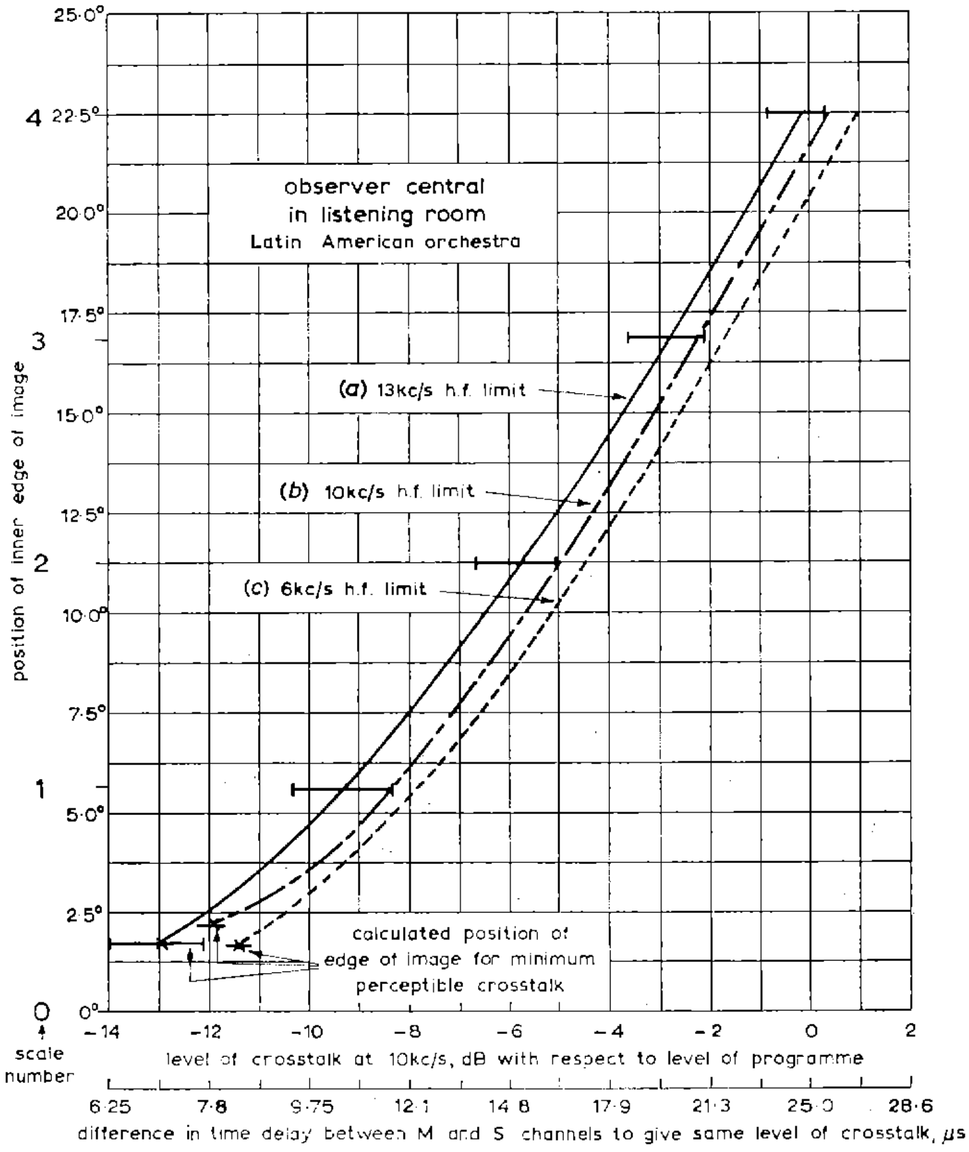

Fig. 6 — Position of inner edge of image as a function of cross-talk increasing at high frequencies. Observer central in listening room.

Standard error shown thus ⊢⊣.

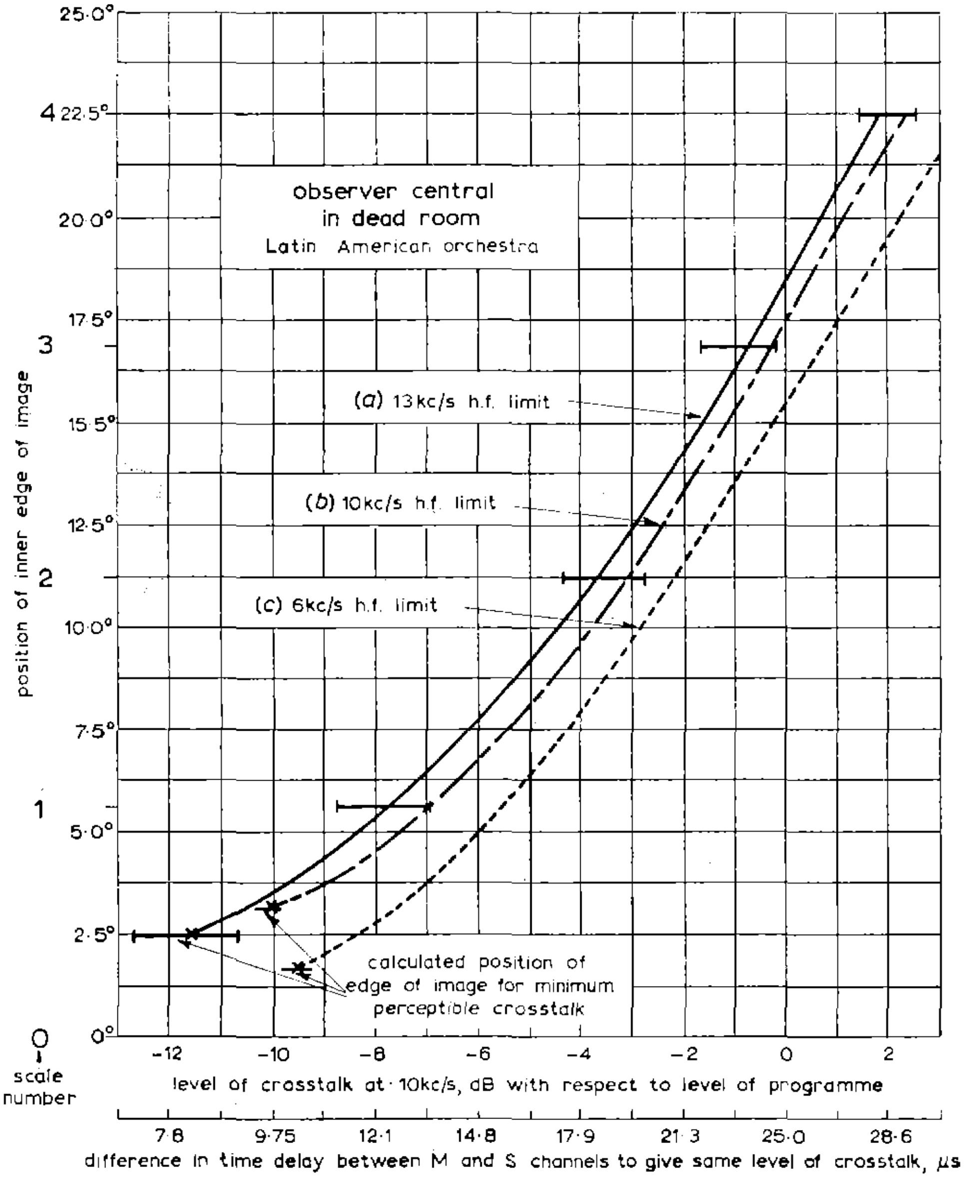

Fig. 7 — Position of inner edge of image as a function of cross-talk increasing at high frequencies. Observer central in dead room. Standard error shown thus ⊢—⊣.

was followed by 7 seconds of programme mixed with a predetermined level of cross-talk coming from the other loudspeaker; an interval of 3 seconds followed, after which the sequence was repeated. The observer was then required to indicate the position of the inner edge of the image in terms of the numbered scale shown in Fig. 3. Six levels of cross-talk, one of them zero, were presented in a random order, each level being given twice during the period of test. The experiment was repeated later with programme from the right-hand loudspeaker and cross-talk on the left; the time taken for each side was 8 minutes.

In the second type of presentation the degree of cross-talk was controlled by the observer, who was asked to adjust the attenuator until the position of the inner edge of the image coincided with one of the divisions on the scale. It was necessary to avoid the possibility of an observer's decision in one test being affected by his recollection of the setting obtained in another; the experimenter was therefore provided with a preset attenuator connected in tandem with that controlled by the observer, the amount of additional attenuation thereby introduced being varied between tests. It was noted that during the early experiments the results obtained from the two types of presentation were indistinguishable, and as the second method was quicker and was preferred by the subject, the remainder of the tests were carried out in this way.

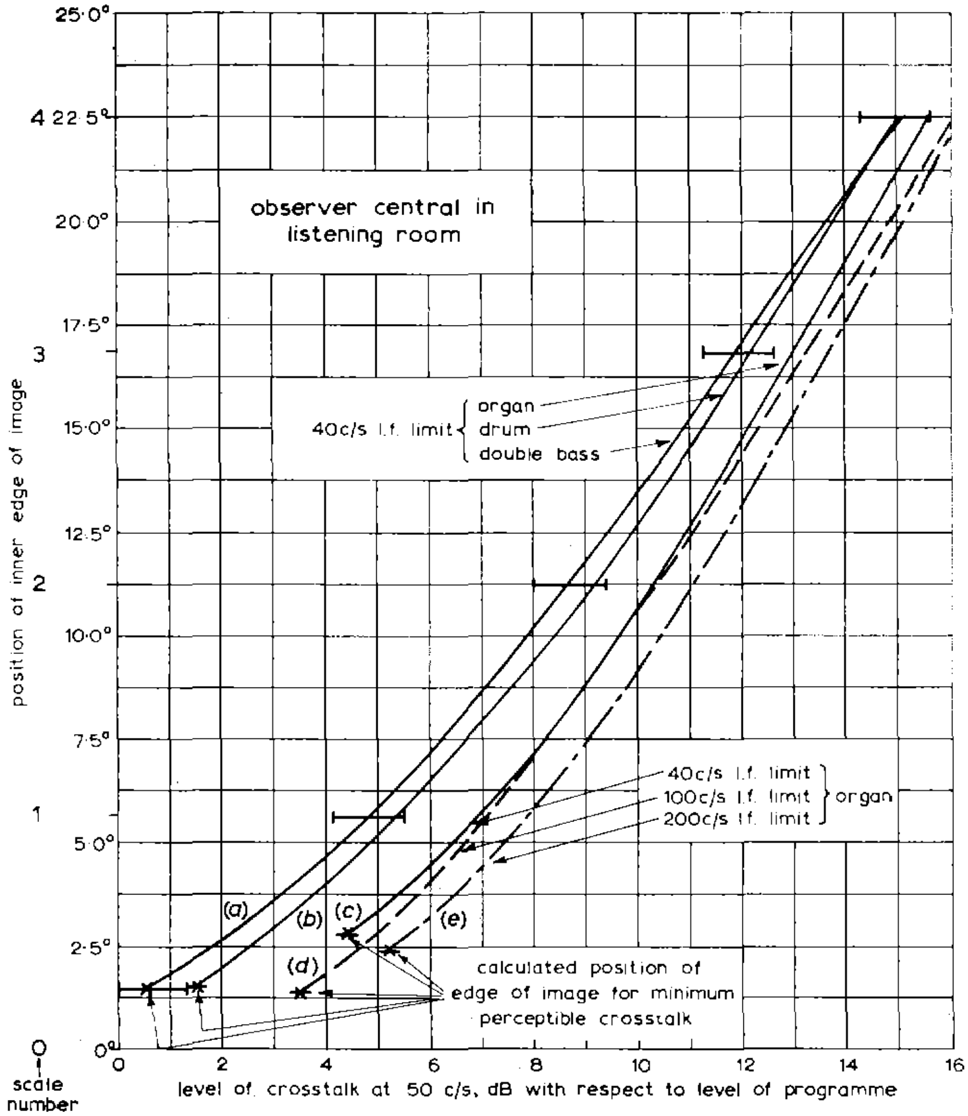

Fig. 8 — Position of inner edge of image as a function of cross-talk increasing at low frequencies. Observer central in listening room. Standard error shown thus ⊢—⊣.

At a later stage in each test the observer was also asked to find the setting of the attenuator corresponding to the minimum perceptible displacement of the edge of the image from its position with no cross-talk.

In each test the programme material was repeated until the observer had arrived at a decision. In preliminary experiments the test passage was recorded on an endless loop of tape; this method had to be abandoned, however, because excessive tape wear resulted in a loss of the high-frequency components. A recording consisting of many repetitions of the same passage was therefore employed. There is always a possibility with subjective measurements of this kind that learning or adaptation by the observers will occur during the period of the tests and so lead to inconsistencies in the results. To avoid this effect all observers were given a period in which to accustom themselves to the signals before the tests were commenced.

3. Results

3.1 *Observer in Central Position*

Figs. 6 and 7 show the relationship between cross-talk and image displacement for observers in the listening room and dead room respectively for cross-talk increasing at high frequencies; curves (a), (b), and (c) are for the three different bandwidths. As indicated earlier, the cross-talk is specified by its level, with respect to the level of the programme, at 10 kc/s. A supplementary scale is provided to show the degree of time displacement between the sum and difference channels (usually known as the M and S chan-

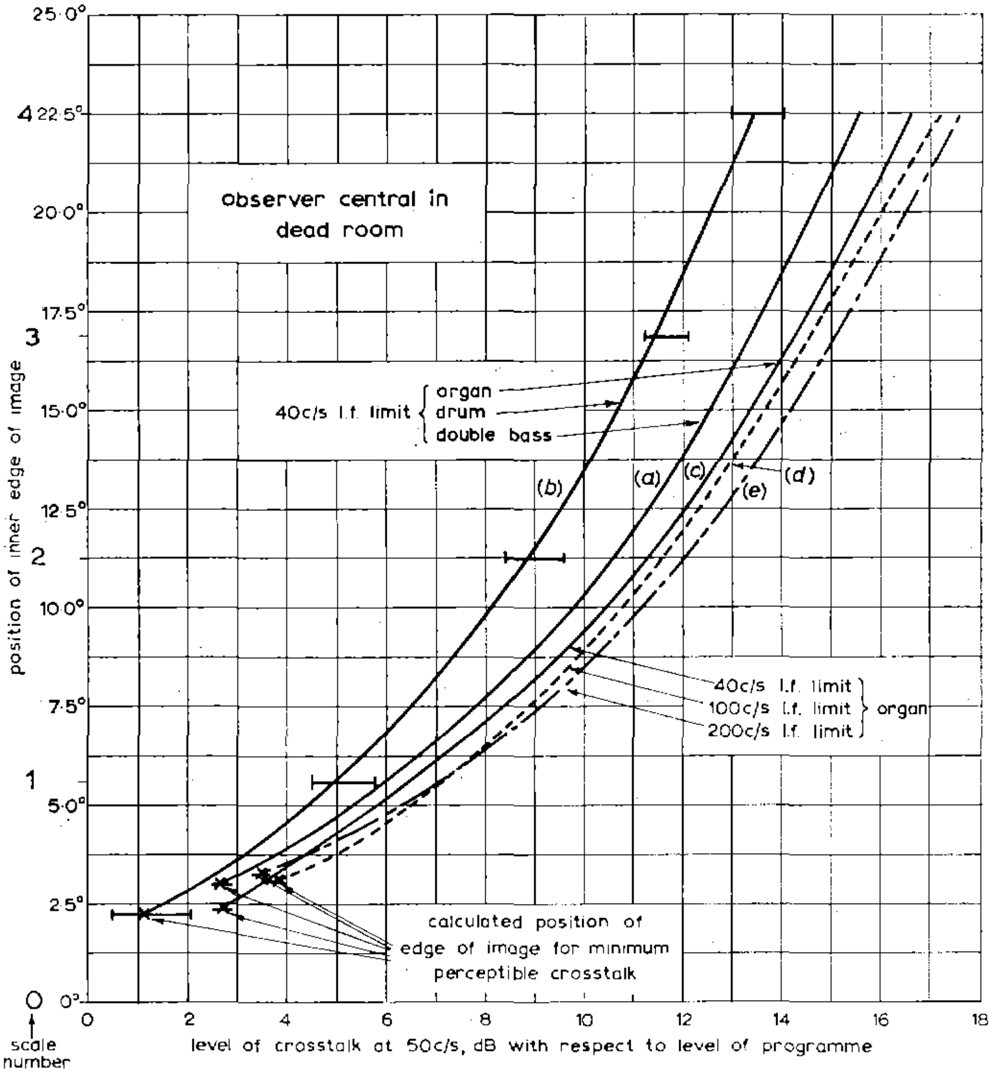

Fig. 9 — Position of inner edge of image as a function of cross-talk increasing at low frequencies. Observer central in dead room. Standard error shown thus ⊢⊣.

nels respectively) of a multiplex transmission system which would produce the same effect. The results represent the mean of all the observations; to indicate the order of experimental accuracy involved the standard error is shown, but for the sake of clarity this is in general marked on one curve only. Figs. 8 and 9 show the corresponding results for cross-talk increasing at low frequencies, the level of cross-talk with reference to programme being taken for reference purposes at 50 c/s; the experiments with restricted bandwidth were confined to organ music. Fig. 10 shows the image displacement produced in the listening room by cross-talk independent of frequency, with male speech as the programme material. In Figs. 6 to 10 the lowest figure of cross-talk to be plotted was the 'minimum perceptible' value, and the question arose as to the degree of displacement to be assigned to this. Direct estimation of the displacement by the observer in this case was found too difficult, and an attempt was therefore made to arrive at an appropriate figure by indirect means. To this end the 'probable error',* calculated from the spread of the minimum perceptible cross-talk figures for an individual observer, was taken as a measure of angular acuity. This figure was then multiplied by the slope of the cross-talk-displacement curve at its lowest point, to give the equivalent angular displacement; the result, averaged over the team, was used to provide the ordinate value corresponding to 'minimum perceptible cross-talk'. It will be seen that the figure thus obtained is not very different from that which would be arrived at by extrapolation of the curve.

Some of these cross-talk-displacement curves extend into the region of positive abscissae, in which the level of

* The probable error is the deviation which includes 50 per cent of the judgements; it is approximately two-thirds of the standard deviation.

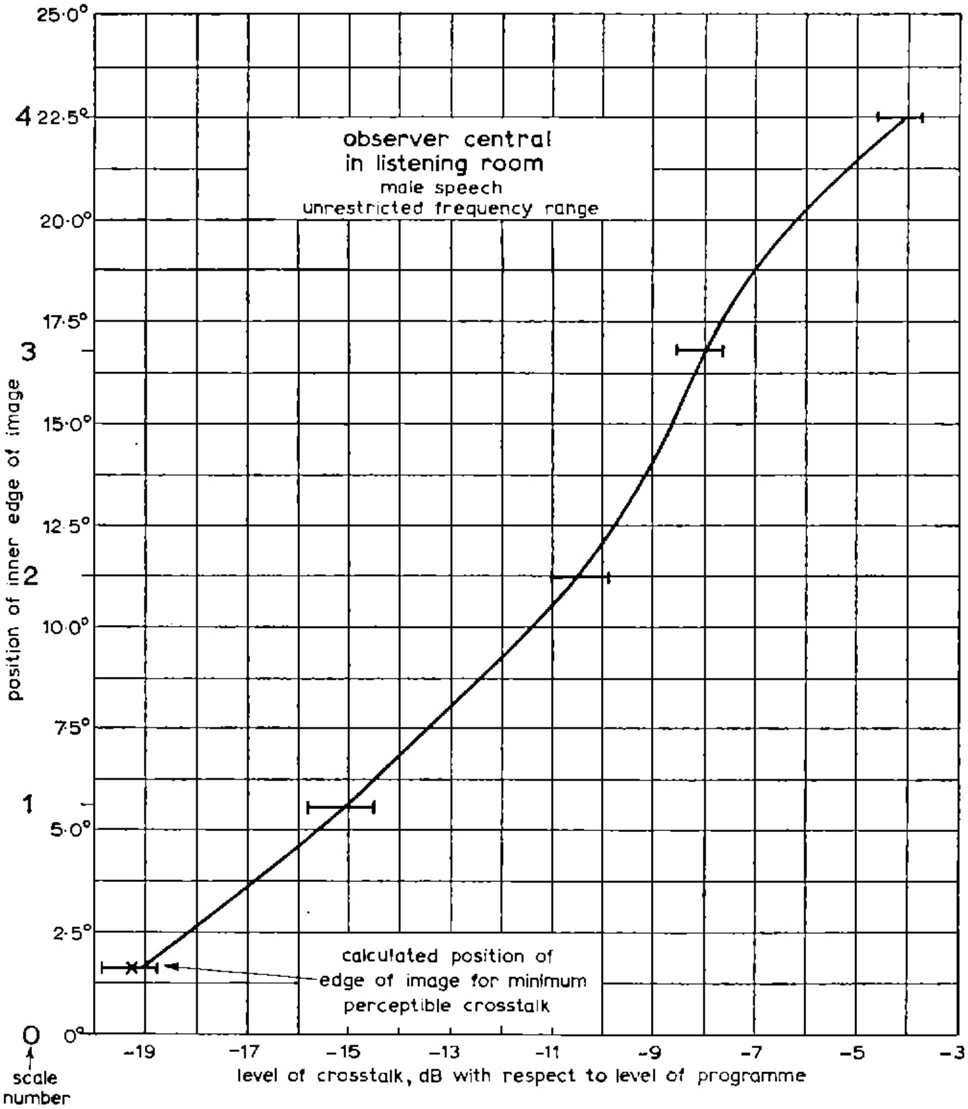

Fig. 10 — Position of inner edge of image as a function of cross-talk independent of frequency. Observer central in listening room. Standard error shown thus ⊢—⊣.

cross-talk produced by a signal at 10 kc/s or 50 c/s respectively is greater than that of the programme. This condition could easily occur in a multiplex transmission system at high frequencies on account of differences in time delay between the sum and difference channels; at low frequencies such a situation is less likely, but could arise if a high-pass filter without phase compensation were used to restrict the bandwidth of the difference channel.

It will be observed that the subjective effect of cross-talk is only slightly reduced by restricting the frequency range of the programme. This result was confirmed by an independent experiment in the listening room for the case of cross-talk increasing at high frequencies; each observer was asked to set the inner edge of the image to division 4 on the scale for the 13 kc/s frequency range and to note the change in position of the edge when the high-frequency range was suddenly restricted to 6 kc/s by switching in the appropriate filter. Although the change in tonal quality was very marked, the image displacement was found to be small and in the direction indicated by the curves. That restriction of the frequency band should have so little effect suggests that components of the sound lying well inside the audio-frequency band may tend to obscure the position of those at the extremes of the frequency range. It would not, however, be safe to assume that further restriction of the programme bandwidth would have no effect on the image displacement.

Comparing Fig. 7 with Fig. 6, it will be seen that for the 13 kc/s and 10 kc/s frequency range the results obtained with cross-talk near to the minimum perceptible level were not significantly affected by the change in acoustic environment; at higher levels of cross-talk and with the frequency range restricted to 6 kc/s, the image displacements observed were only slightly less in dead surroundings. Similarly, comparison between Figs. 8 and 9 shows that the change in acoustic environment had no great effect on the perceptibility of cross-talk at low frequencies.

3.2 *Observer in Off-centre Position*

Figs. 11 and 12 show the relationship between cross-talk and image displacement with cross-talk increasing at high and low frequencies respectively, for an observer in the off-centre positions shown in Fig. 2. In these tests the full frequency range of the system was employed; for the case of cross-talk increasing at low frequencies only the double bass recording was used. Fig. 13 shows the corresponding results for male speech with cross-talk independent of frequency. In Figs. 11, 12, and 13, curve (a) in each case refers to the listening room and curve (b) to the dead room.

By comparing these data with the corresponding results already given for the central position, it will be seen that the effect of moving the observer to the off-centre position depended on the part of the frequency range concerned. In the listening room the minimum perceptible level of cross-

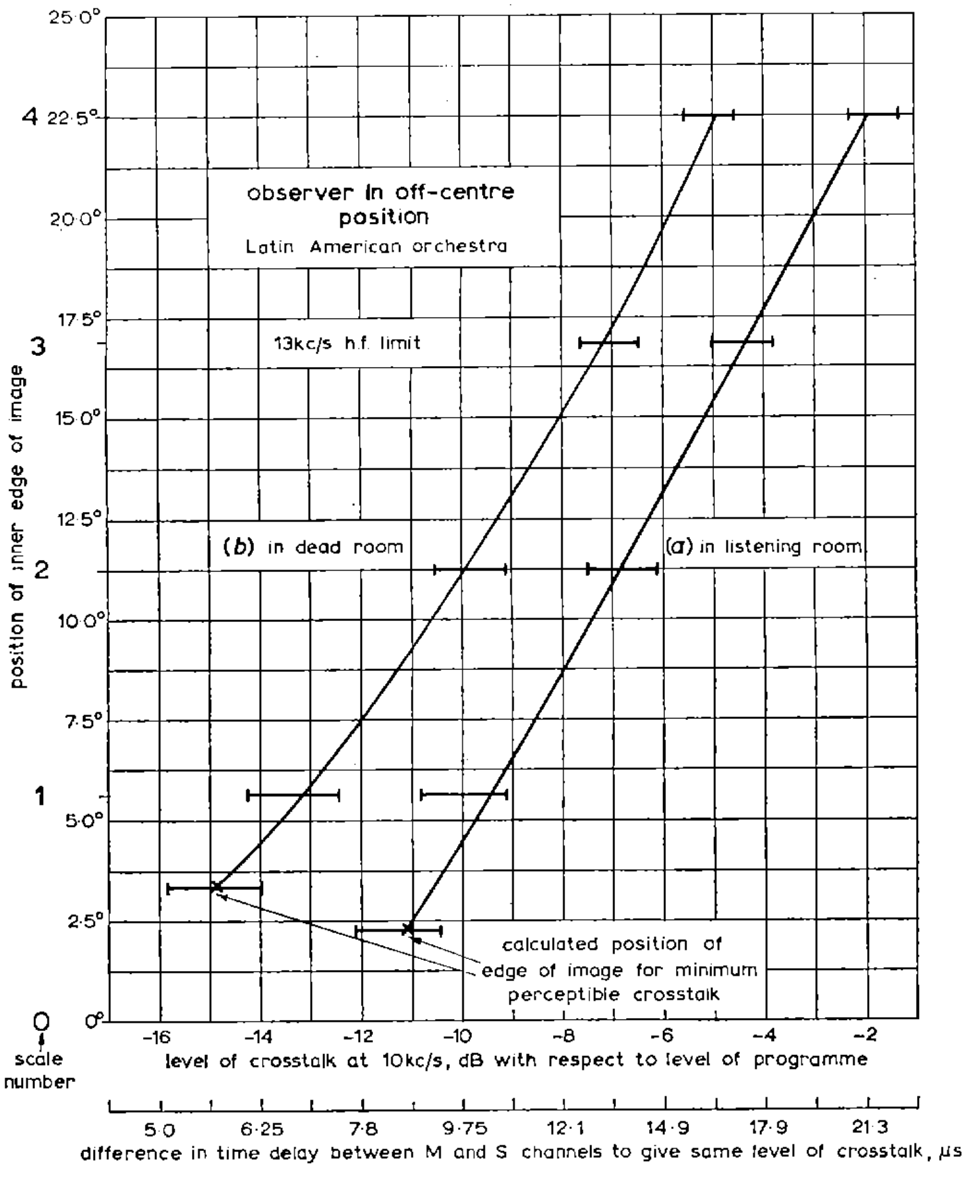

Fig. 11 — *Position of inner edge of image as a function of cross-talk increasing at high frequencies. Observer off-centre in listening room and dead room.*

Standard error shown thus ├─┤.

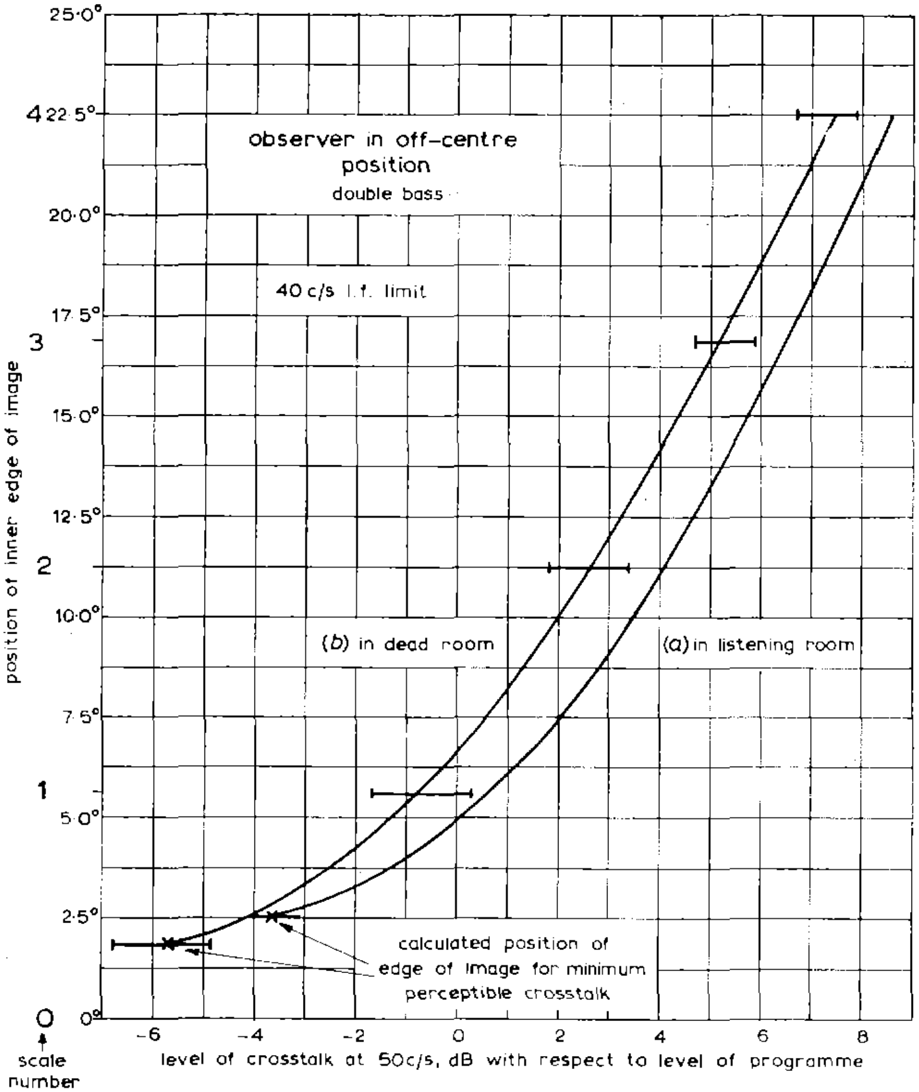

Fig. 12 — Position of inner edge of image as a function of cross-talk increasing at low frequencies. Observer off-centre in listening room and dead room. Standard error shown thus ⊢⊣.

talk increasing at low frequencies was lowered by 4 dB. For cross-talk increasing at high frequencies and cross-talk independent of frequency the figure was raised 2 dB; however, as the standard error in the measurements was about 2 dB, the change was hardly statistically significant.

In the dead room the minimum perceptible level of cross-talk increasing at high frequencies was 3 dB lower for the off-centre position than for the central position; for cross-talk increasing at low frequencies the figure obtained in the off-centre position was lower by 7 dB. In both cases the change was in the direction to be expected, but the 3 dB figure is barely significant statistically. It should be noted that, with the layout shown in Fig. 2, the directivity of the loudspeakers at high frequencies will tend to reduce the effects peculiar to the off-centre position.

3.3 *Cross-talk as Function of Frequency*

Fig. 14 shows the cross-talk/frequency relationship existing in the test circuit when the subjective effect of the cross-talk was just perceptible. Most of the data relate to a central observer but a corresponding curve for the off-centre position is also shown for cross-talk rising at low frequencies, since these results were significantly different. All curves refer to the unrestricted frequency range 40 c/s to 13 kc/s; as already shown in Section 3.1, restriction of the frequency band by an octave at high frequencies and two and a half octaves at low frequencies has only a slight influence on the subjective result. Curve (a) relates to cross-talk rising 6 dB/octave at high frequencies. Curves (b_1) and (b_2) give the corresponding characteristics for cross-talk rising 6 dB/octave at low frequencies, taking the most critical type of programme material in each case; curve (b_1)

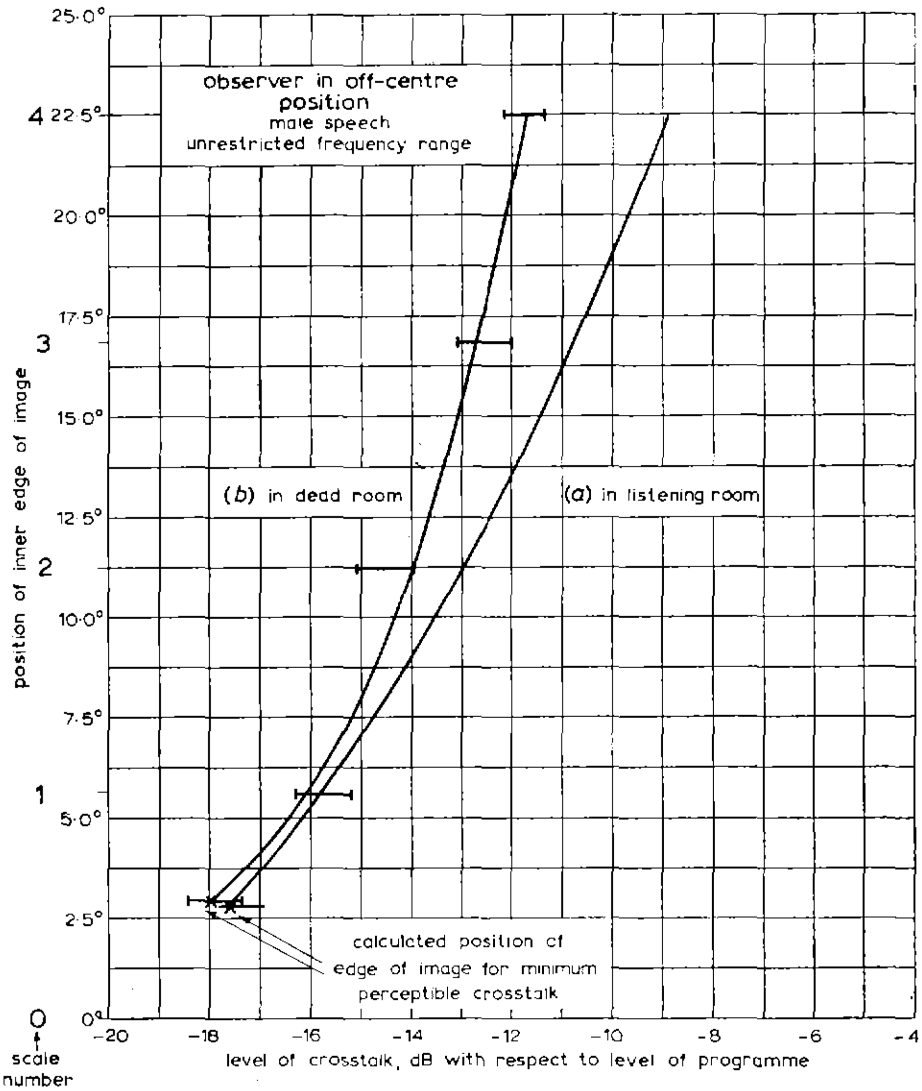

Fig. 13 — Position of inner edge of image as a function of cross-talk independent of frequency. Observer off-centre in listening room and dead room. Standard error shown thus ⊢—⊣.

is for a central observer and curve (b_2) for an observer in the off-centre position. Fig. 14 (a), (b_1), and (b_2) all apply, with sufficient accuracy, to both listening room and dead room, as the differences between the results in these two conditions are not statistically significant. The horizontal straight line (c) refers to the tests in the listening room on cross-talk independent of frequency. It must be emphasized that these curves give the characteristics of a system in which the effect of cross-talk is just perceptible on programme; they should not be taken to represent the minimum perceptible cross-talk for any one frequency considered separately.

In comparing curve 14 (c) with curves 14 (a), (b_1), and (b_2), the effect of the different phase relationships between cross-talk and programme has to be borne in mind. The 90° phase lead associated with the cross-talk increasing at high frequencies may for the purpose of this comparison be ignored, since in the region above 3 kc/s the image position is determined by differences in time of arrival, rather than differences in phase,[2] between the signals applied to the two loudspeakers. On the other hand, at middle and low frequencies the image position is a function of the relative phases of the signals applied to the two loudspeakers. Thus, in the particular case where the signal in one channel consists of cross-talk coming from the programme in the other channel, the phase relationship between cross-talk and programme must influence the subjective effect. For this reason the 90° phase lag associated with the increase of cross-talk at low frequencies prevents direct comparison with the data on cross-talk independent of frequency, for which there is no phase shift. With this reservation Fig. 14 can be taken as a rough overall picture of the kind of toler-

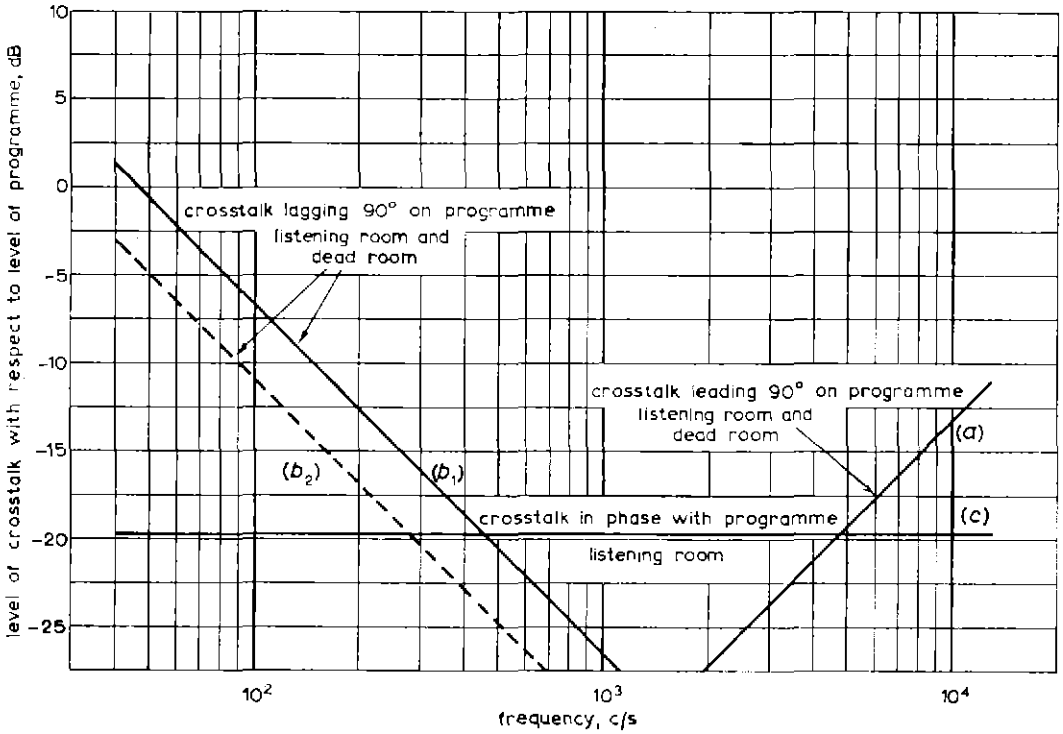

Fig. 14 — Cross-talk/frequency characteristic of test circuit for minimum perceptible subjective effect (mean of all observations). Frequency range 40 c/s to 13 kc/s.

——— *Observer central.*

- - - - - *Observer in off-centre position (see Fig. 2).*

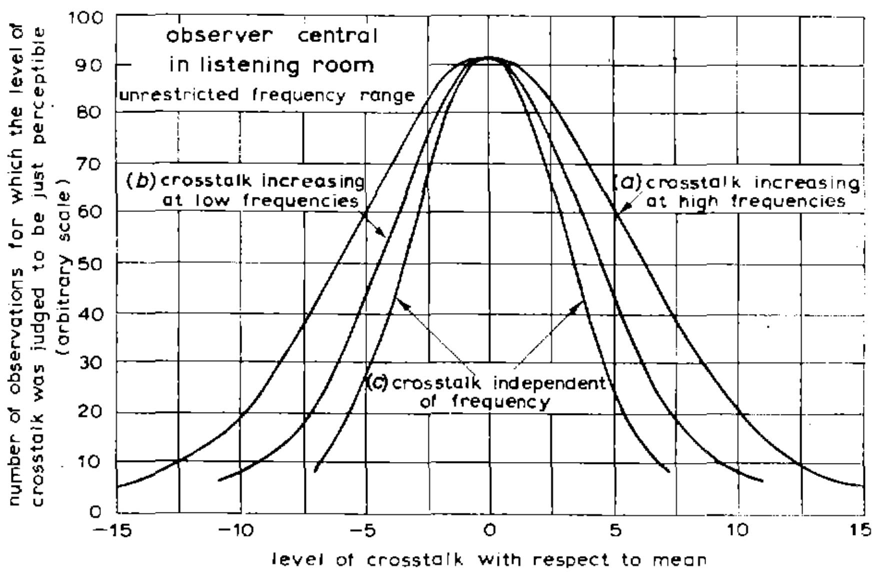

Fig. 15 — Distribution of levels given by team for minimum perceptible cross-talk. Observer central in listening room.

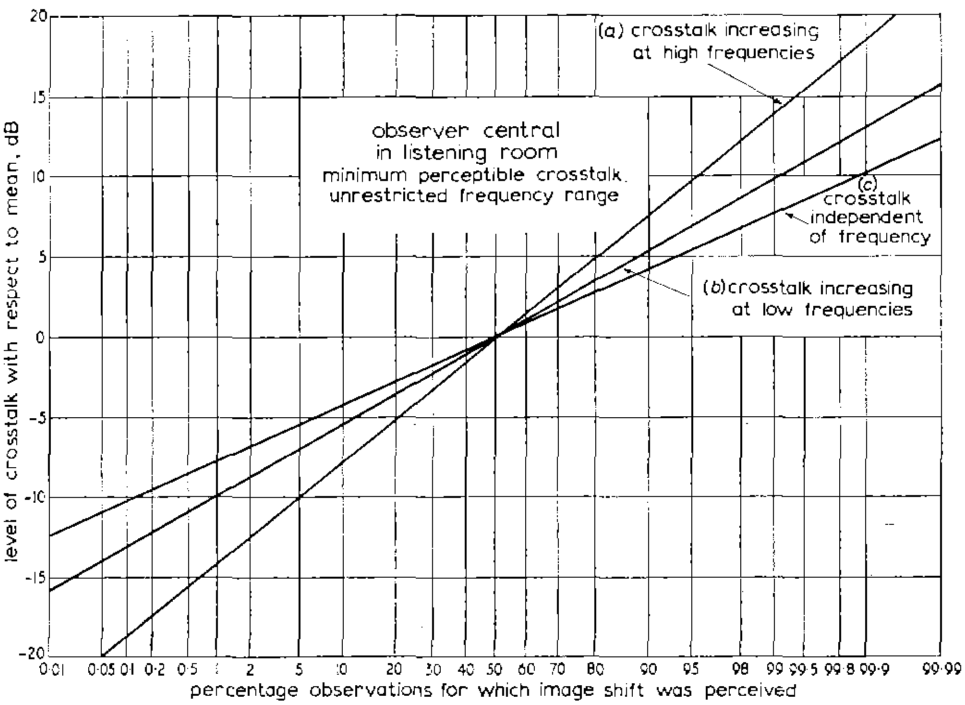

Fig. 16 — Distribution of levels given by team for minimum perceptible cross-talk. (Probability scale.) Observer central in listening room.

ances which might be imposed on a stereophonic system where the cross-talk increases gradually towards the extremes of the frequency band.

In Section 1 reference was made to the special case in which cross-talk is produced by a difference in time delay between channels carrying the sum and difference signals M and S. It will be seen from Figs. 6, 7, and 11 that the difference in delay corresponding to minimum perceptible cross-talk in a system having an upper frequency limit of 10 kc/s or more is less than 10 μs and may be as little as 6 μs. In 10 μs the distance travelled by sound in air is only ⅛ in. (0·3 cm), while in an M–S microphone system the two microphones have necessarily a vertical separation of at least 1 in. (2·5 cm). From these two figures it follows that sounds arriving from the extreme left or right of the pick-up area at an angle greater than 8° above or below the horizontal can give rise to audible cross-talk.

3.4 *Spread of Results*

The data presented in Figs. 6 to 14 relate to the mean of all the values given by the team of observers; thus, in 50 per cent of the observations, a lower level of cross-talk than that shown as 'minimum perceptible' was detectable, while in the remaining 50 per cent a higher level went undetected. It is, however, of interest to consider the variation of opinions within the team. Fig. 15, which applies to the minimum perceptible cross-talk for a central observer in the listening room with unrestricted frequency range, shows the statistical distributions for the three cases: (*a*) cross-talk increasing at high frequencies, (*b*) cross-talk increasing at low frequencies, and (*c*) cross-talk independent of frequency. The smallest divergence of opinion appears in case (*c*) in which, as already noted, the programme material contains no very strong components at the extremes of the frequency range. From Fig. 16, in which the same data are replotted on a Gaussian probability scale, the minimum cross-talk detectable by any percentage of the observers can be determined.

In addition to the variation of opinion between different observers, it is also of interest to know the degree of consistency with which each observer can repeat his performance under the same conditions. As indicated in Section 3.1, the average of the probable errors of the individual observer, expressed in terms of equivalent angular displacement across the stage, has been taken as a measure of the observer's acuity and also of the minimum perceptible image displacement. One such figure has been derived for each of the experiments on cross-talk increasing at high and low frequencies, and the collected results for the dead room and listening room tests respectively are plotted in Fig. 17 on a Gaussian probability scale showing the distribution of the values obtained. Although the data apply to a variety of experimental conditions—cross-talk increasing at low frequencies and at high frequencies respectively, with three different bandwidths in each case—all the points derived from dead room tests are found to lie nearly on one straight line and all the points derived from listening room tests on another. For the listening room the mean value of the ordinate is 1·9° and for the dead room 2·7°, a significant difference since the standard errors in the two cases are only 0·17° and 0·25° respectively. Thus, the observer's acuity, expressed in terms of

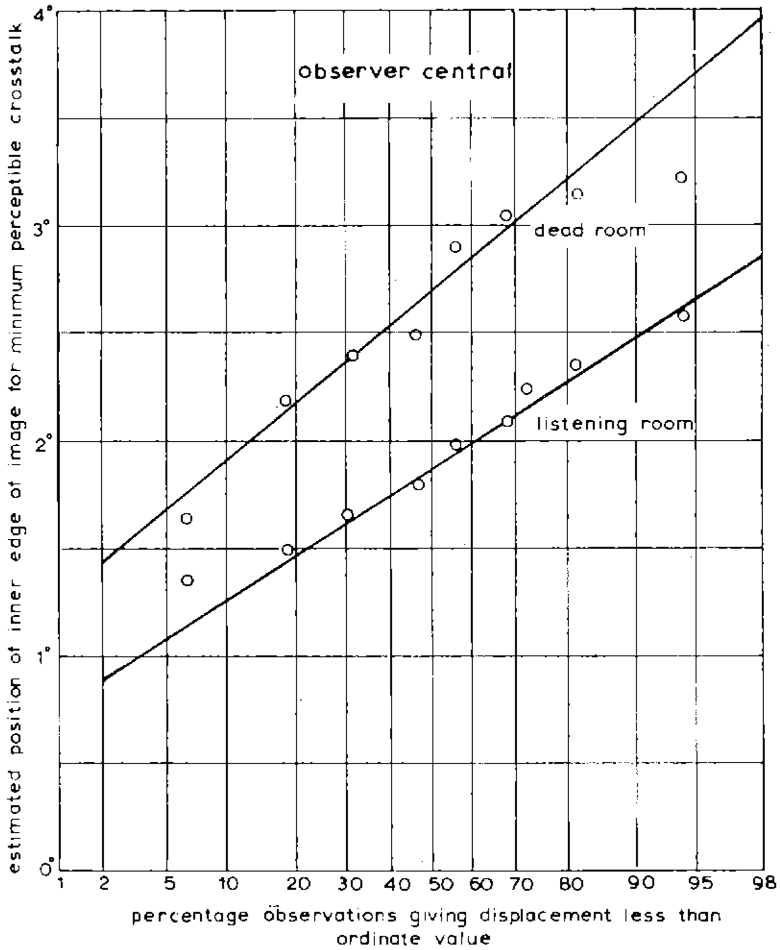

Fig. 17 — *Distribution of values of displacement assigned to inner edge of image for minimum perceptible cross-talk. Observer central in dead room and listening room.*

image displacement as distinct from the minimum perceptible cross-talk referred to in Section 3.1, was greater in the listening room than in the dead room. No explanation has so far been found for this effect, but it is conceivable that the first reflexion from the floor or ceiling of the listening room may contribute additional directional information to the ear.

3.5 *Lateral Bias of Observers*

As already indicated in 2.4, every test carried out with the programme on the left channel and cross-talk on the right was repeated with the positions of the channels interchanged. Analysis of the differences between the results obtained in the two cases, together with evidence from additional tests carried out with the loudspeakers interchanged, failed to reveal any significant degree of asymmetry in the experimental arrangements. Most of the observers, however, were found to exhibit a left or right bias, being in some cases as much as 10 dB more sensitive to cross-talk from one side than from the other. Fig. 18 shows the mean bias for the team—taken without regard to sign—as a function of image displacement, for various experimental conditions; the values range from 2 dB to 4·6 dB, representing deviations of ± 1 dB to $\pm 2 \cdot 3$ dB about the cross-talk figure averaged for all the tests.

4. Comparison with Earlier Work

Little is to be found in the literature on the subject of inter-channel cross-talk, and the only work of immediate interest for purposes of comparison appears in papers by Harvey and Schroeder of the Bell Telephone Laboratories[6] and McCoy of the R.C.A. Laboratories.[7]

Harvey and Schroeder employed a system of split-band filters so arranged that above or below a predetermined frequency the left- and right-hand channels were in effect connected in parallel; in the transition region the channel separation changed, within half an octave, from less than 1 dB to greater than 20 dB. Tests were also carried out with cross-talk varying in amount but independent of frequency. The programme material consisted of stereophonic recordings and the assessment was based on the proportion of observers who noticed the impairment produced by the cross-talk. It was concluded that, in setting

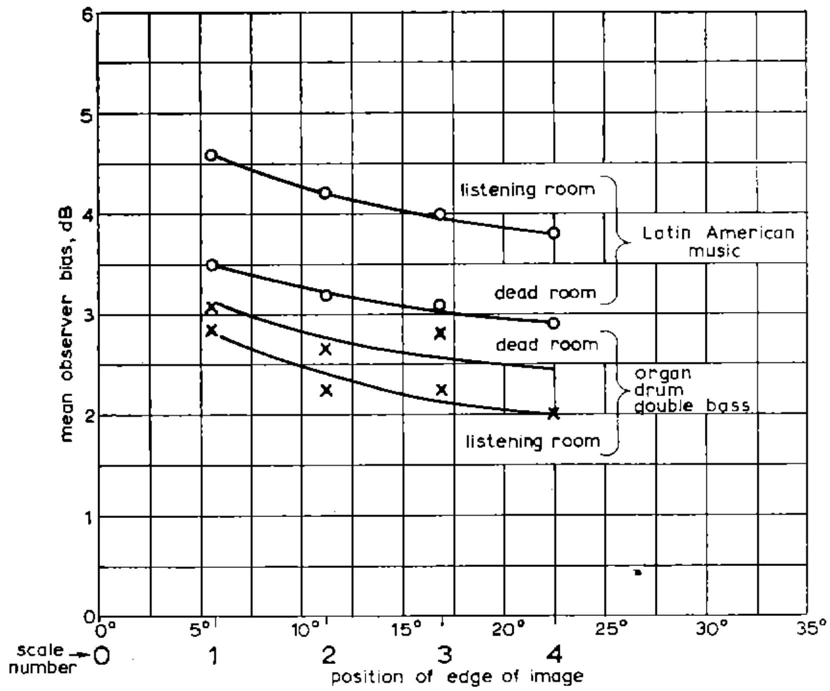

Fig. 18 — Left or right bias of individual observers as a function of image position. Observer central in dead room and listening room.

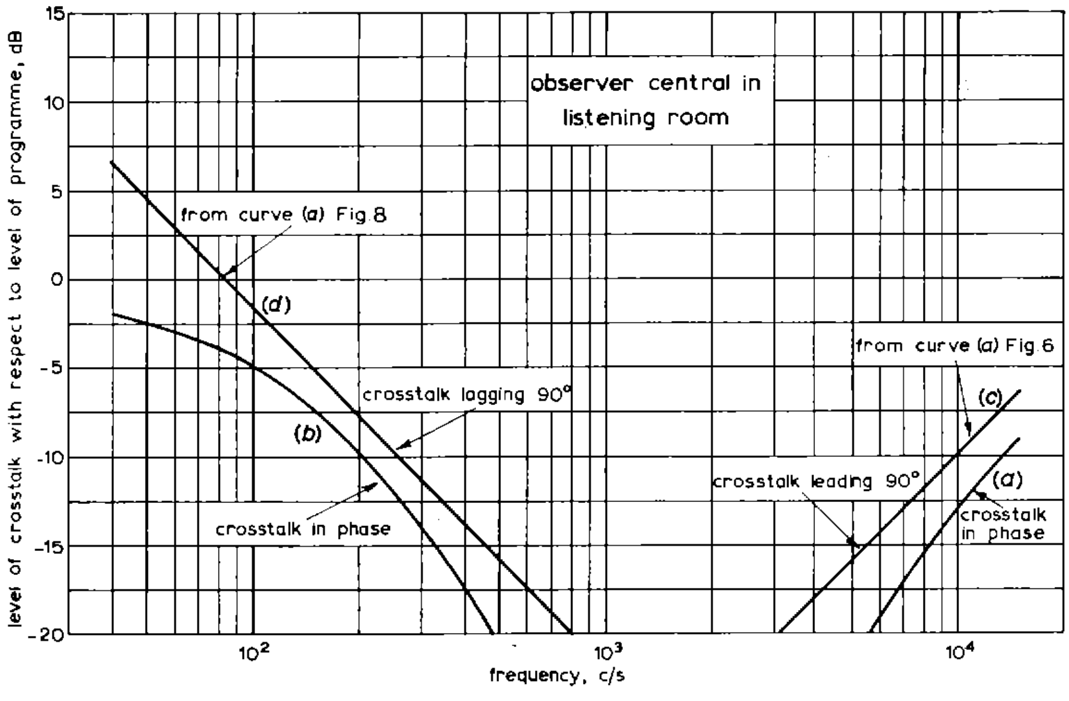

Fig. 19 — Cross-talk/frequency characteristics which produce, on average, an image spread of 1/10*th stage width.*
(a) and (b) calculated from McCoy's data (1961).
(c) and (d) calculated from Figs. 6 *(a) and* 8 *(a) respectively of present monograph.*

commercial standards for stereophonic transmission, the cross-talk level should be at least 20 dB below the programme level for the frequency range 100 c/s to 8 kc/s. This limit of 20 dB agrees closely with the minimum perceptible cross-talk level shown in Fig. 10 for male speech. Apart from this, however, direct comparison between Harvey and Schroeder's results and those given in this monograph is not possible because the increase in cross-talk with frequency at the ends of the band was in the former case abrupt, but in the latter gradual; moreover, an increase in the tolerable amount of cross-talk at low frequencies is to be expected when the phase of the cross-talk lags 90° with respect to that of the programme.

In McCoy's experiments, cross-talk was introduced at low and high frequencies respectively by temporarily converting the left- and right-hand stereophonic signals to the equivalent sum and difference signals and inserting a high- or low-pass filter in the difference channel; in some of the tests the phase shift introduced by the filter in the pass band was compensated by an all-pass network inserted in the sum channel. The sum and difference signals were then added and subtracted, producing left- and right-hand signals together with cross-talk varying with frequency in a manner depending on the characteristics of the filter. As in the experiments described in this monograph, the incoming programme was applied to one channel only, thus producing an image whose intended position was on the extreme left or right of the stage, and the effect of the cross-talk was expressed in terms of lateral spread of the sound. In some of McCoy's tests filters with a sharp cut-off were used and, as in the case of the Harvey and Schroeder experiments, the results cannot be directly compared with those given in this monograph. In other tests, however, the filter consisted of a simple resistance-capacity network, so that the rate of change of cross-talk with frequency was more gradual and in these cases some comparisons can be made. The programme items in the two sets of experiments are also comparable, the *pizzicato* double-bass and Latin American music in this investigation having a rough parallel in the jazz-band recording used by McCoy and described as 'strong strummed bass viol with celeste and other moderate level medium- and high-frequency percussion'. In Fig. 19 curves (a) and (b) are computed from the data obtained by McCoy with a resistance-capacity filter, using phase compensation; in this case the cross-talk was in phase with the programme. Curve 19 (a) applies to cross-talk increasing with frequency; it shows the cross-talk/frequency characteristic which in McCoy's experiments produced on average an image 'spread' of one-tenth stage width. Curve 19 (b), obtained in a similar fashion, applies to cross-talk increasing at low frequencies. For comparison, the corresponding curves 19 (c) and 19 (d) are derived from the data already given in Figs. 6 (a) and 8 (a) respectively. It will be seen that curves (a) and (b) show a somewhat lower degree of cross-talk than curves (c) and (d) for the same degree of image displacement; in the low-frequency range, curves (b) and (d), some of this difference can be accounted for by the 90° phase lag referred to earlier.

5. Conclusions

Data have been obtained on the impairment of a stereophonic image caused by various forms of interchannel cross-talk which may occur in practice. The minimum perceptible degree of cross-talk is influenced to some extent by the position of the observer in the listening room but is largely independent of the acoustics of the room and of the bandwidth of the system. For reasons not yet clear, the acuity of the observer's directional sense, as measured by the ability to repeat results, was greater in an acoustic environment similar to that of an average living room than in free-space conditions.

6. Acknowledgments

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APPENDIX

In a two-channel system for the transmission of stereophonic sound let the signals in the left- and right-hand channels be designated A and B respectively. At some stage in transmission the two signals may be combined to form a sum signal $(A+B)$ known as the M signal and a difference signal $(A-B)$ known as the S signal. At a later stage the original signals are then recovered by further addition and subtraction thus:

$$\tfrac{1}{2}[(A+B)+(A-B)]=A$$
$$\tfrac{1}{2}[(A+B)-(A-B)]=B$$

In a system as described above consider the case where $A=A_0 \sin \omega t$ and $B=0$. The M and S signals are now identical with the A signal.

If now the S signal be delayed in time with respect to the M signal the phase angle between them will be proportional to frequency. Let this angle be θ and assume S to lag in respect to M by a time τ. Then, if

$$M=A_0 \sin \omega t,$$
$$S=A_0 \sin(\omega t-\theta)=A_0 \sin \omega(t-\tau), \text{ since } \theta=\omega\tau$$

Recombination of the sum and difference signals now yields new left- and right-hand signals

$$A'=\tfrac{1}{2}(M+S)=\tfrac{1}{2}A_0[\sin \omega t+\sin(\omega t-\theta)]$$
$$=A_0 \cos \tfrac{1}{2}\theta \,.\, \sin(\omega t-\tfrac{1}{2}\theta)$$

and $$B'=\tfrac{1}{2}(M-S)=\tfrac{1}{2}A_0[\sin \omega t-\sin(\omega t-\theta)]$$
$$=A_0 \sin \tfrac{1}{2}\theta \,.\, \cos(\omega t-\tfrac{1}{2}\theta)$$

in which A' and B' are in quadrature, and have peak values $A_0 \cos \frac{1}{2}\theta$, $A_0 \sin \frac{1}{2}\theta$ in the ratio $1 : \tan \frac{1}{2}\theta$.

If, instead of time delay in the S signal, capacitive cross-talk is introduced between the left and right channels, for example by the method shown in Fig. 20, then a similar effect is produced. If the capacitance is small enough, the component injected from one channel to the other is in quadrature with the signal from which it is derived and its amplitude is proportional to frequency. By suitable choice of constants the two arrangements can be made to yield substantially equal values of A'/B' as long as $\frac{1}{2}\theta \simeq \tan \frac{1}{2}\theta$. This approximation holds good to within 10 per cent for values of θ less than 64°, i.e. when $\tan \frac{1}{2}\theta$ is less than 0·62, or B' lies more than 4 dB below A'. For a frequency band extending to 10 kc/s this ratio corresponds to a time difference between the $A+B$ and $A-B$ signals of 18 μs. For greater time delays the degree of cross-talk required to displace the edge of the image by the same amount can be calculated, but in these circumstances those components of the image which are displaced to a lesser degree will have a different distribution across the stage. It will be seen from curve (a) of Fig. 6 that the -4 dB point referred to above corresponds to an image spread extending to 2·5 on the scale (14°).

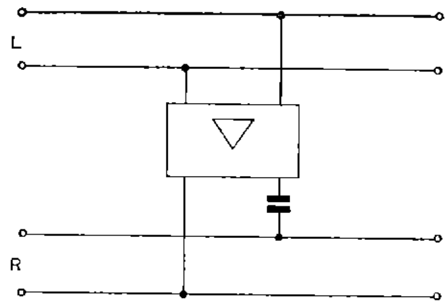

Fig. 20 — Schematic circuit showing method of introducing cross-talk.

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