EWT

RESEARCH DEPARTMENT

Stereophony: the effect of crosstalk between left and right channels

RESEARCH REPORT No. L·049/2
1964/1

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

STEREOPHONY:
THE EFFECT OF CROSSTALK BETWEEN LEFT AND RIGHT CHANNELS

Research Report No. L-049/2

(1964/1)

H.D. Harwood, B.Sc., A.Inst.P., A.M.I.E.E.
D.E.L. Shorter, B.Sc.(Eng.), A.M.I.E.E.

W. Proctor Wilson

(W. Proctor Wilson)

This Report is the property of the British Broadcasting Corporation and may not be reproduced in any form without the written permission of the Corporation.

Report No. L-049/2

STEREOPHONY

THE EFFECT OF CROSSTALK BETWEEN LEFT AND RIGHT CHANNELS

January 1964

Research
Report No. L-049/2

(1964/1)

STEREOPHONY:

THE EFFECT OF CROSSTALK BETWEEN LEFT AND RIGHT CHANNELS

SUMMARY

The investigation of the effect of interchannel crosstalk in a stereophonic system, of which the first results were given in Research Report L-049, has been continued. The experiments have covered crosstalk in different regions of the audio-frequency band. The influence of acoustic environment and of the observer's position in relation to the loudspeakers has been investigated, as well as the effect of restricting the frequency range of the programme. Comparisons are made with published work.

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, which in stereophony can produce a displacement or blurring of the acoustic images, it is usual to borrow from the vocabulary of the telephone engineer the term 'crosstalk'. This crosstalk can arise from a variety of causes, and presents a particularly serious problem in disk recording; of particular interest for the present purpose, however, is the crosstalk which may appear in a stereophonic broadcast transmission system.

In an earlier report[1] an account was given of experiments to determine subjectively the effect, on a stereophonic image, of crosstalk between left- and right-hand channels. These tests, carried out in the A.F. Section listening room, were confined to crosstalk increasing with frequency at the rate of 6 dB/octave, a condition which may occur in multiplex transmission systems. The present report describes two further series of experiments on the subjective effect of crosstalk. In the first of these, the original tests were repeated under different listening conditions, and the effect of restricting the frequency range of the programme material, which in the earlier tests extended to 13 kc/s, was also investigated. In the second, similar methods were employed to determine the effect of crosstalk increasing progressively at low frequencies, and of crosstalk independent of frequency; both conditions can occur in multiplex systems - the former through faulty design and the latter through faulty adjustment.

2. EXPERIMENTAL DETAILS

2.1. General

The listening room and equipment, the layout of which is shown in Fig. 1, were the same as in the original crosstalk experiments,[1] and the same twelve observers took part in the tests.

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 crosstalk increasing at high and low frequencies respectively, the axial frequency characteristics lay within ± ½ 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 crossover region (800 c/s to 1600 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 crosstalk channels interchanged, the two results being subsequently averaged.

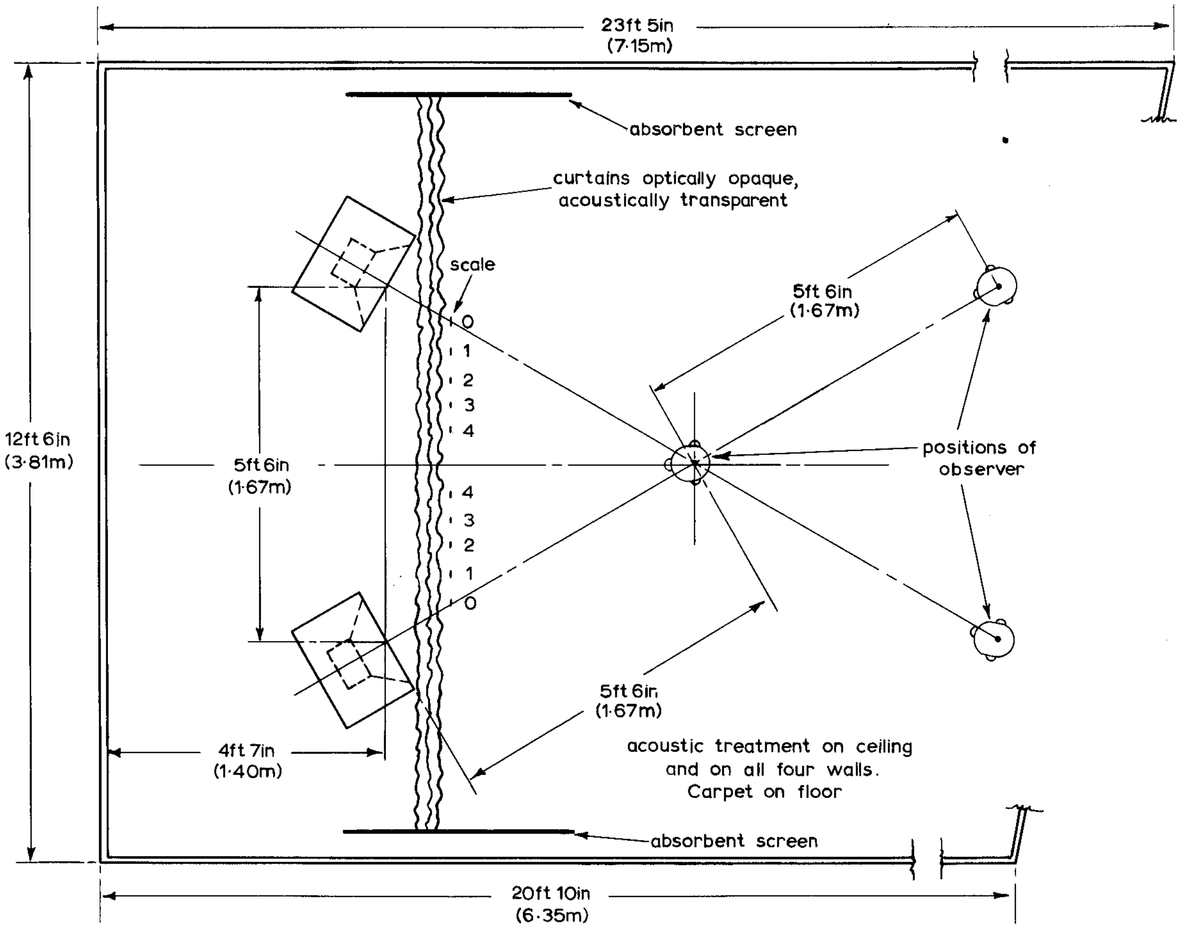


Fig. 1 - Plan of Listening Room

To discover how far the subjective effect of crosstalk depends on the acoustic environment, most of the experiments were repeated in a dead room, normally employed for measurements on microphones and loudspeakers, in which the reflexion coefficient of the walls at frequencies above 80 c/s was less than 10%. These dead surroundings represent an extreme acoustic condition and have the advantage that they can be duplicated in other laboratories.

2.2. 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 crosstalk and further from that reproducing the programme, the alteration in the relative levels, coupled with the precedence effect, would make the result of the crosstalk more noticeable. The more critical tests were therefore repeated with the observer placed, as shown in Fig. 1, in a position to one side of a hypothetical triangular seating layout and facing towards the centre of the stage.

2.3. Crosstalk increasing at High Frequencies

In these experiments the method of introducing the crosstalk was similar to that adopted in the earlier tests, the signal from one channel reaching the other being proportional to frequency and leading 90° in phase; the same test passage - an excerpt from a recording of Latin American music - was also used. The bandwidth was, however, restricted in some of the tests to a nominal upper limit of 6 kc/s or 10 kc/s by low-pass filters having the frequency response shown in Fig. 2(a); the rate of

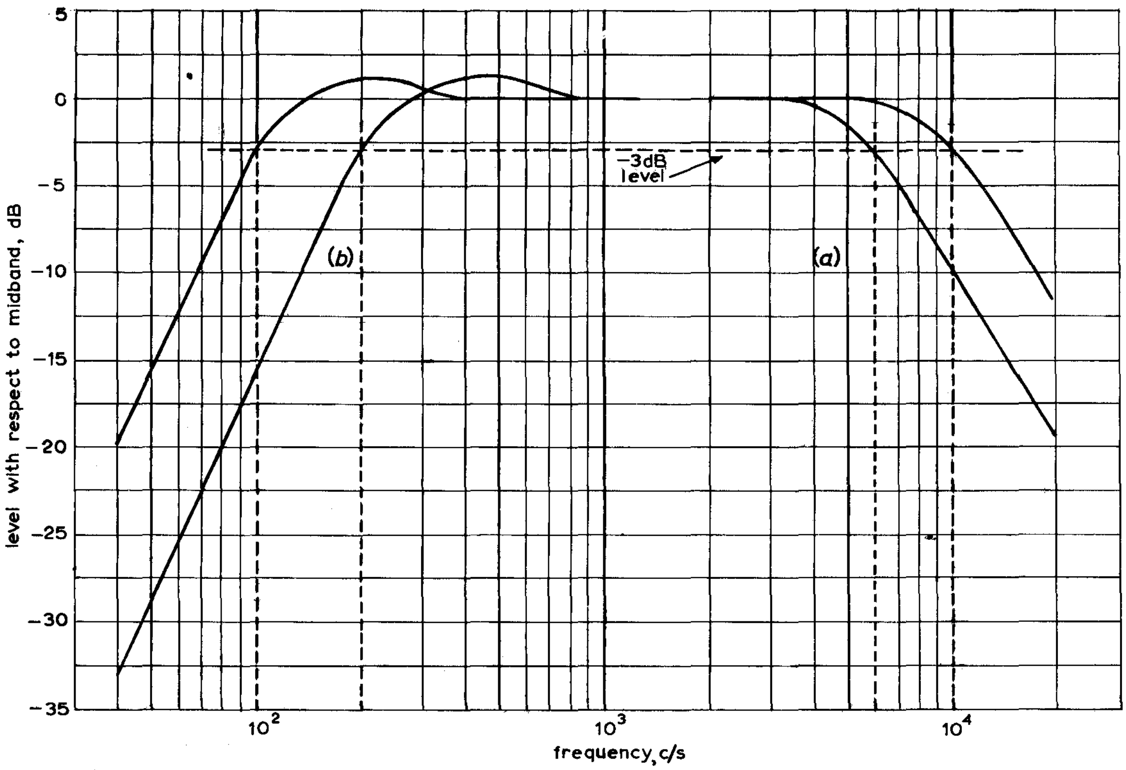


Fig. 2 - Frequency response of filters used for limiting programme bandwidth
(a) Low Pass (b) High Pass

cut-off was deliberately restricted to 12 dB/octave to avoid ringing at the cut-off frequency. The nominal limit of the band was taken as the frequency at which the filter attenuation exceeded the mid-band value by 3 dB. The filters were inserted in the common signal channel and did not therefore introduce any additional phase difference between the programme and crosstalk. In the absence of the filters, the upper frequency range of the programme material was restricted to 13 kc/s by the characteristics of the loudspeakers used and this condition will therefore be referred to for convenience as the 13 kc/s limit.

2.4. Crosstalk increasing at Low Frequencies

For these experiments, the test circuit was modified so that the signal from one channel reaching the other was inversely proportional to frequency and lagging 90° in phase. As in the earlier experiments, no attempt was made to compensate for phase shift, since this would normally appear in practice. The programme material consisted of separate recordings of organ, bass drum and plucked double-bass; the spectrum extended down to 40 c/s in each case, and this figure will therefore be used for convenience in referring to the lower limit of the unrestricted frequency range.

Fig. 2(b) shows the frequency characteristics of the filters, in this case of the high-pass type, employed in some of the tests to restrict the low-frequency range of the programme.

2.5. Crosstalk Independent of Frequency

For the experiments with crosstalk independent of frequency the programme material employed consisted of male speech, and no attempt was made to restrict the frequency range. 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 crosstalk increasing at high and low frequencies respectively, to produce tolerance figures for the whole audio-frequency range.

The crosstalk signal was transferred from one channel to the other without change of phase.

2.6. Programme Loudness

As in the previous experiments, the maximum sound level for most of the tests was set at 74 dB on an unweighted sound-level meter, the preferred listening level for the general public.[2] A few additional tests were carried out on crosstalk at low frequencies for levels 6 dB above and below this figure; the effect of such level changes on the results was no greater than that already found[1] with crosstalk at high frequencies.

2.7. Presentation of Test Material

The degree of crosstalk was controlled by the observer, who was asked to adjust an attenuator until the position of the inner edge of the image coincided with one of the divisions on the scale shown in Fig. 1. At a later stage in each test, the observer was 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 crosstalk. 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.

3. RESULTS

3.1. Observer in Central Position

Figs. 3 and 4 show the relationship between crosstalk and image displacement

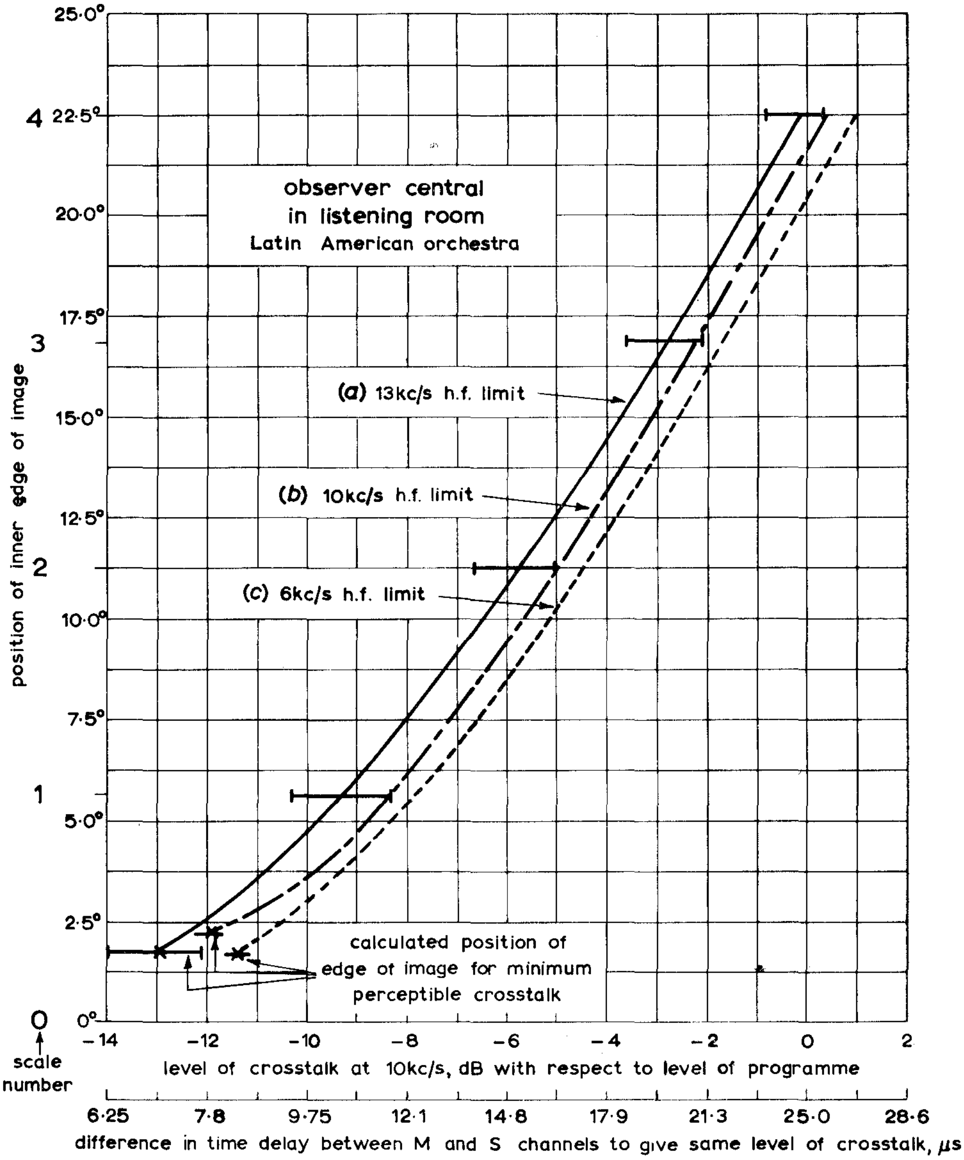


Fig. 3 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer central in Listening Room

Standard error shown thus ⊢—⊣

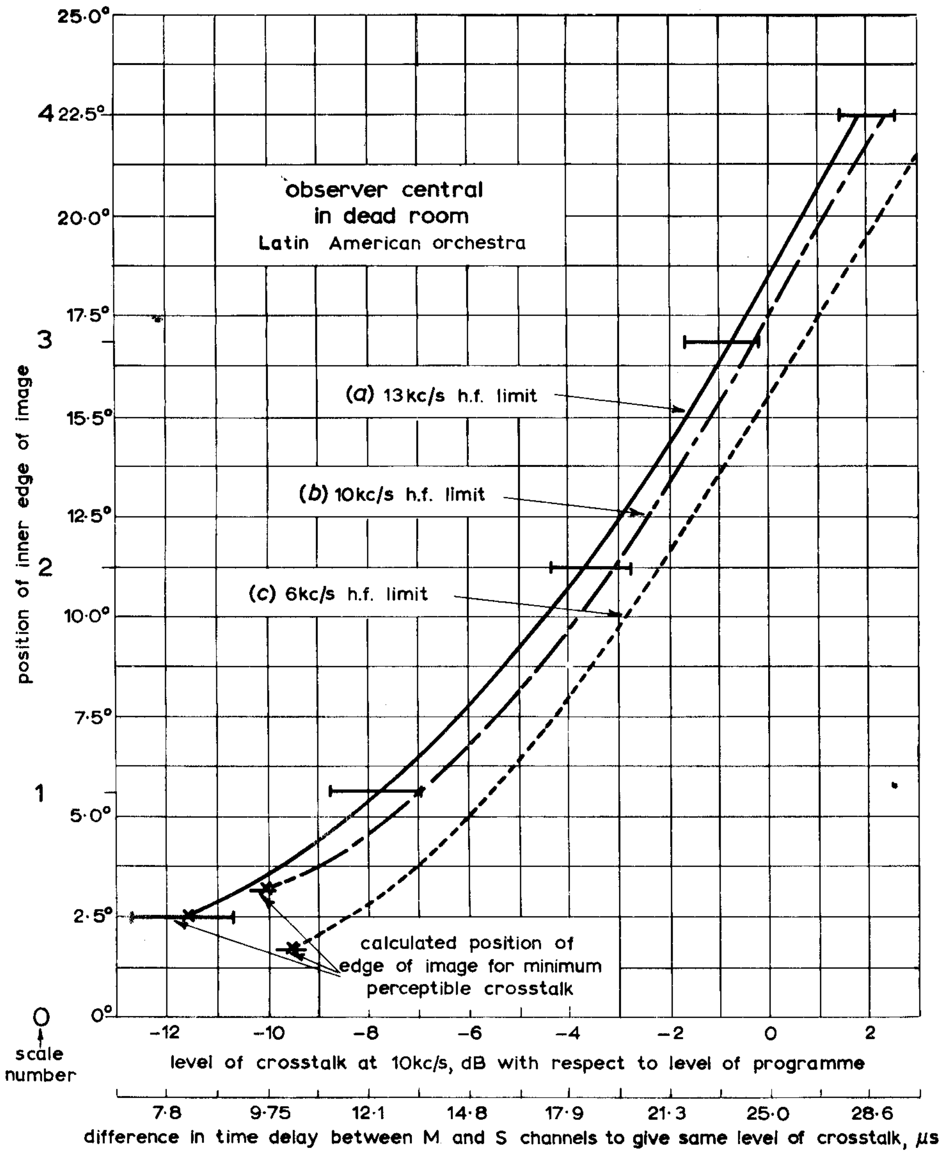


Fig. 4 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer central in Dead Room

Standard error shown thus

for observers in the listening room and dead room respectively for crosstalk increasing at high frequencies; curves (a), (b) and (c) are for the three different bandwidths. As in the earlier experiments, the crosstalk is specified by its level, with respect to the level of the programme, at 10 kc/s, and 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 channels respectively) of a multiplex transmission system[1] 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. 5 and 6 show the corresponding results for crosstalk increasing at

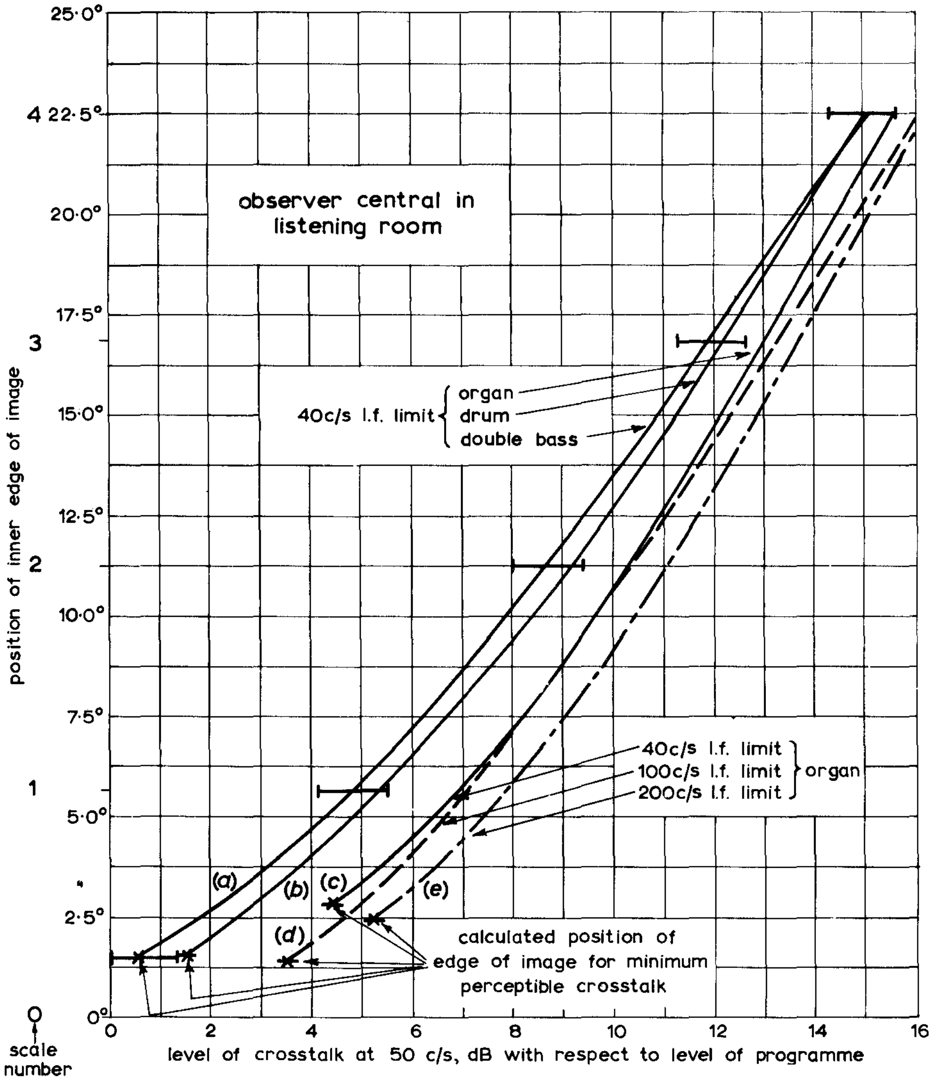


Fig. 5 - Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer central in Listening Room

Standard error shown thus

low frequencies, the level of crosstalk with reference to programme being taken for reference purposes at 50 c/s; the experiments with restricted bandwidth were confined to organ music. In each case the position assigned to the inner edge of the image for the minimum perceptible value of crosstalk was estimated, as explained in the earlier report,[1] from the probable error of the data from individual observers; the figure thus obtained is not very different from that which would have been arrived at by extrapolation of the curve.

Some of these curves extend into the region of positive abscissae, in which the level of crosstalk 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[1] at high frequencies on account of differences in time delay between the sum and difference channels; at low frequencies such a situation is less

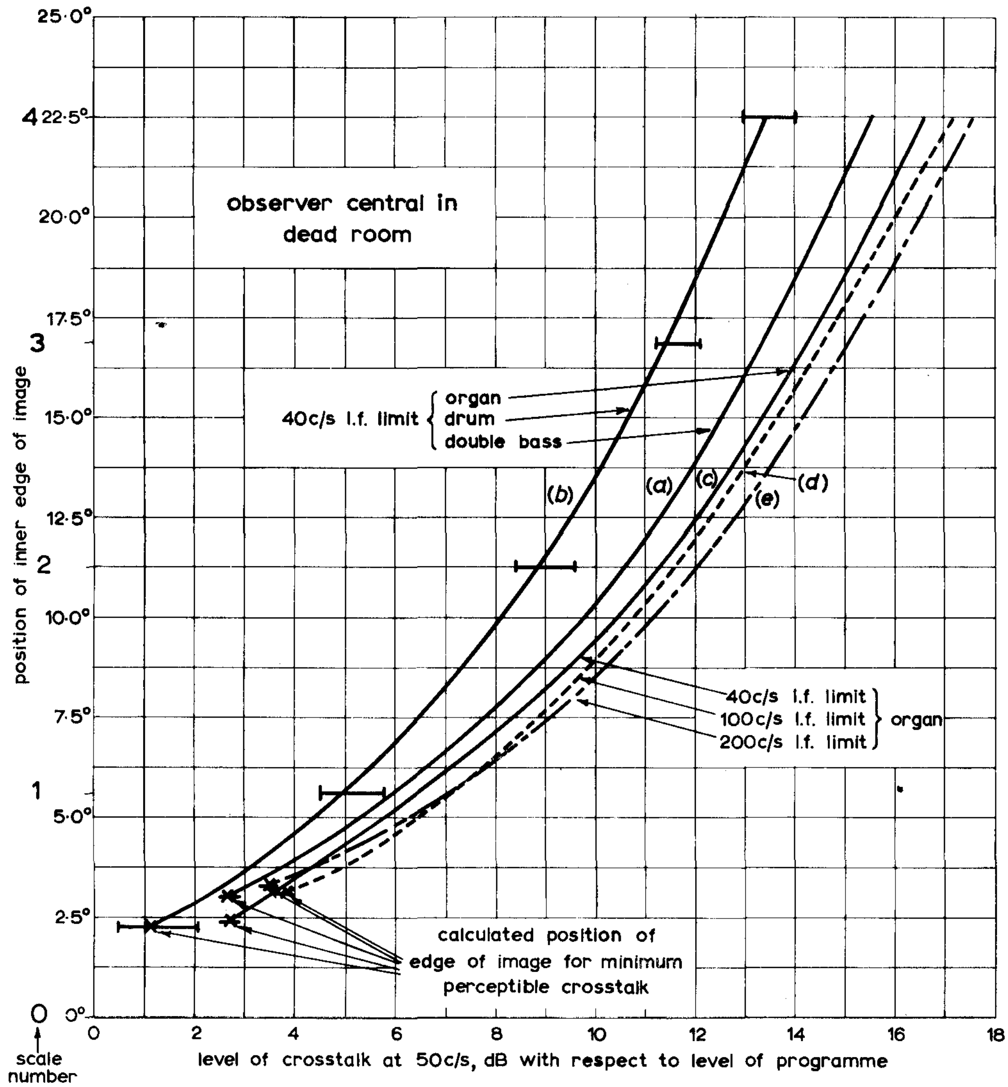


Fig. 6.-Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer central in Dead Room

Standard error shown thus ⊢—⊣

likely, but could arise if a high-pass filter were used to restrict the bandwidth of the difference channel.

It will be observed in Figs. 3 to 6 that the subjective effect of crosstalk 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 crosstalk 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. 4 with Fig. 3, it will be seen that for the 13 kc/s and 10 kc/s frequency range, the results obtained with crosstalk near to the minimum perceptible level were not significantly affected by the change in acoustic environment; at higher levels of crosstalk 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. 5 and 6 shows that the change in acoustic environment had no great effect on the perceptibility of crosstalk at low frequencies.

Fig. 7 shows the image displacement produced in the listening room by crosstalk independent of frequency, with male speech as the programme material.

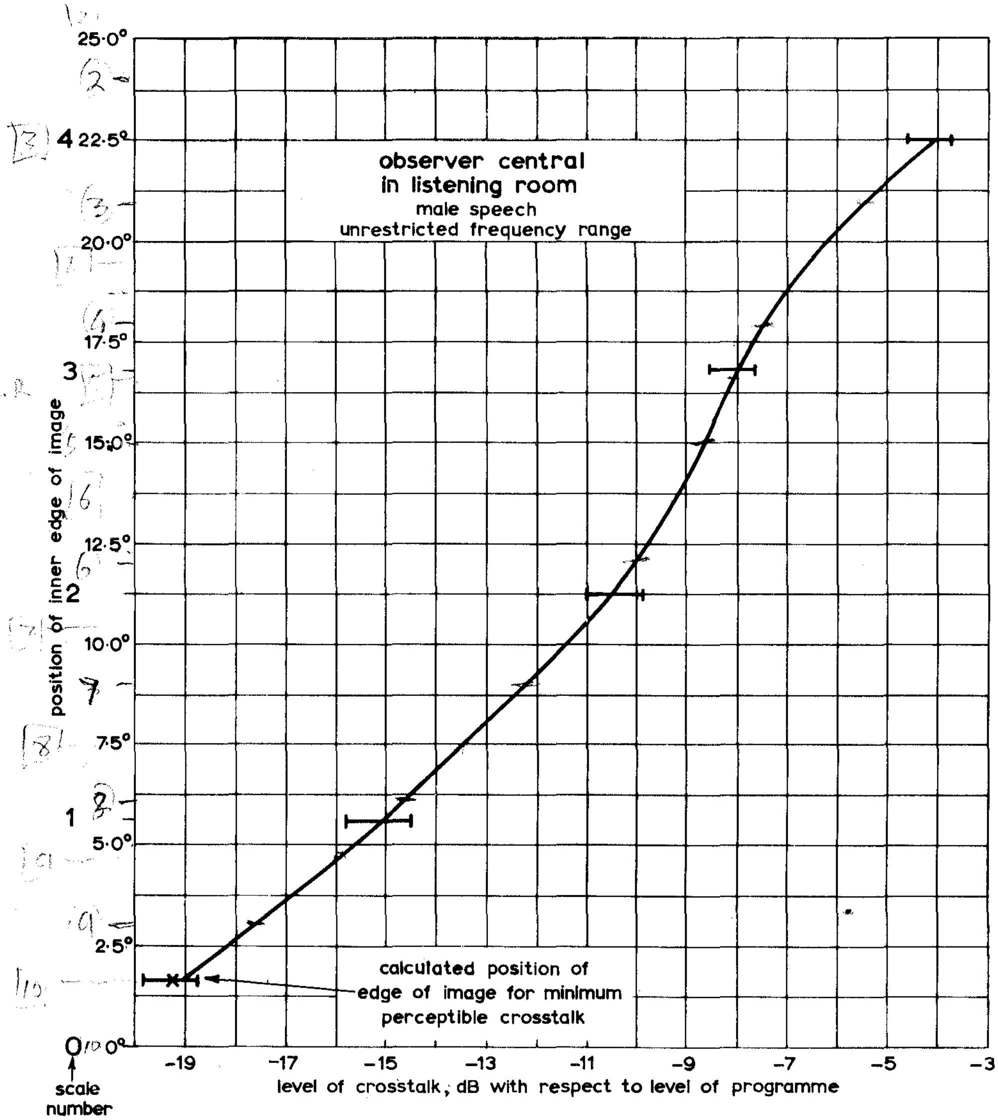


Fig. 7 - Position of inner edge of image as a function of crosstalk independent of frequency. Observer central in Listening Room

Standard error shown thus

3.2. Observer in Off-Centre Position

Figs. 8 and 9 show the relationship between crosstalk and image displacement with crosstalk increasing at high and low frequencies respectively, for an observer in the off-centre positions shown in Fig. 1. In these tests the full frequency range of the system was employed; for the case of crosstalk increasing at low frequencies, only the double-bass recording was used. Fig. 10 shows the corresponding results for male speech with crosstalk independent of frequency. In Figs. 8, 9 and 10, curve (a) in each case refers to the listening room and curve (b) to the dead room.

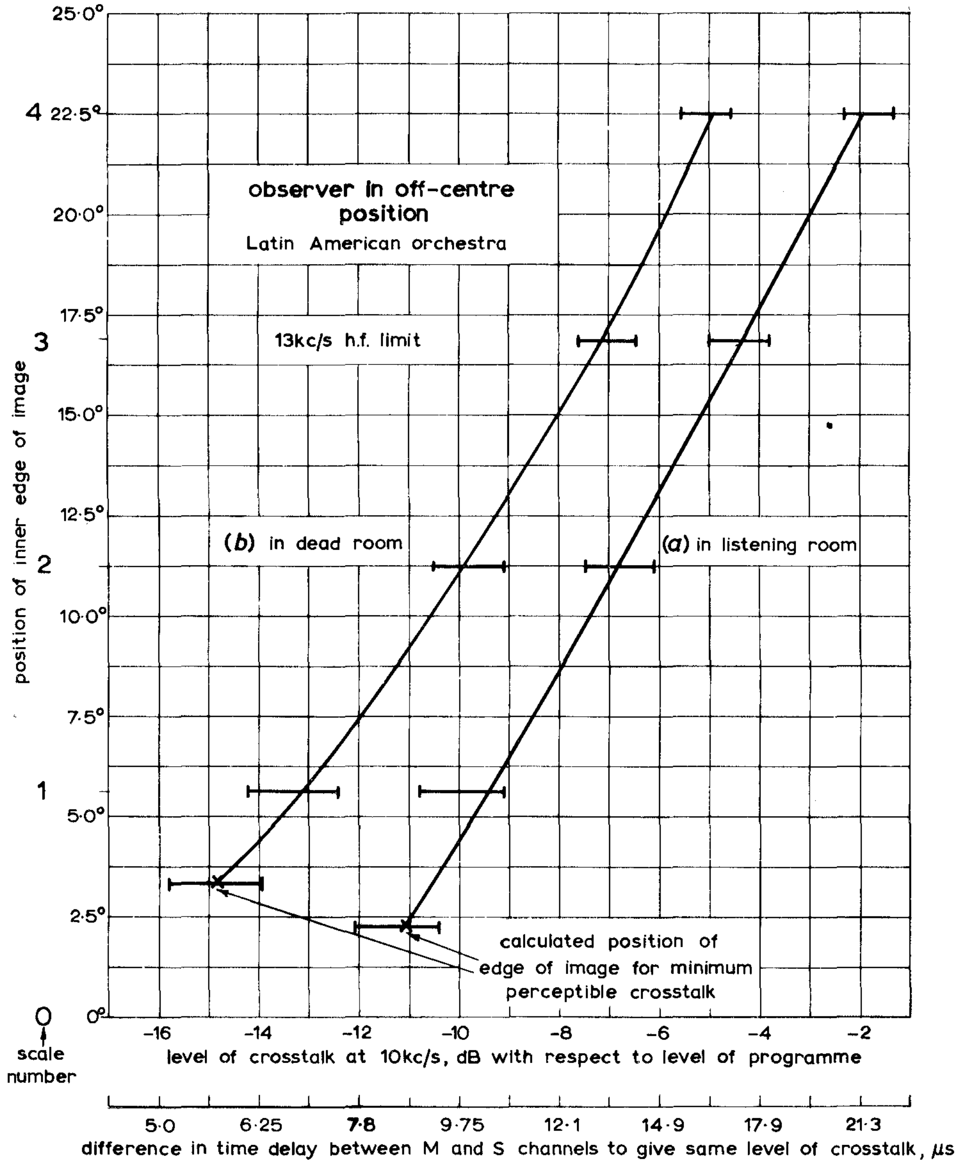


Fig. 8 - Position of inner edge of image as a function of crosstalk increasing at high frequencies. Observer off-centre in Listening Room and Dead Room

Standard error shown thus

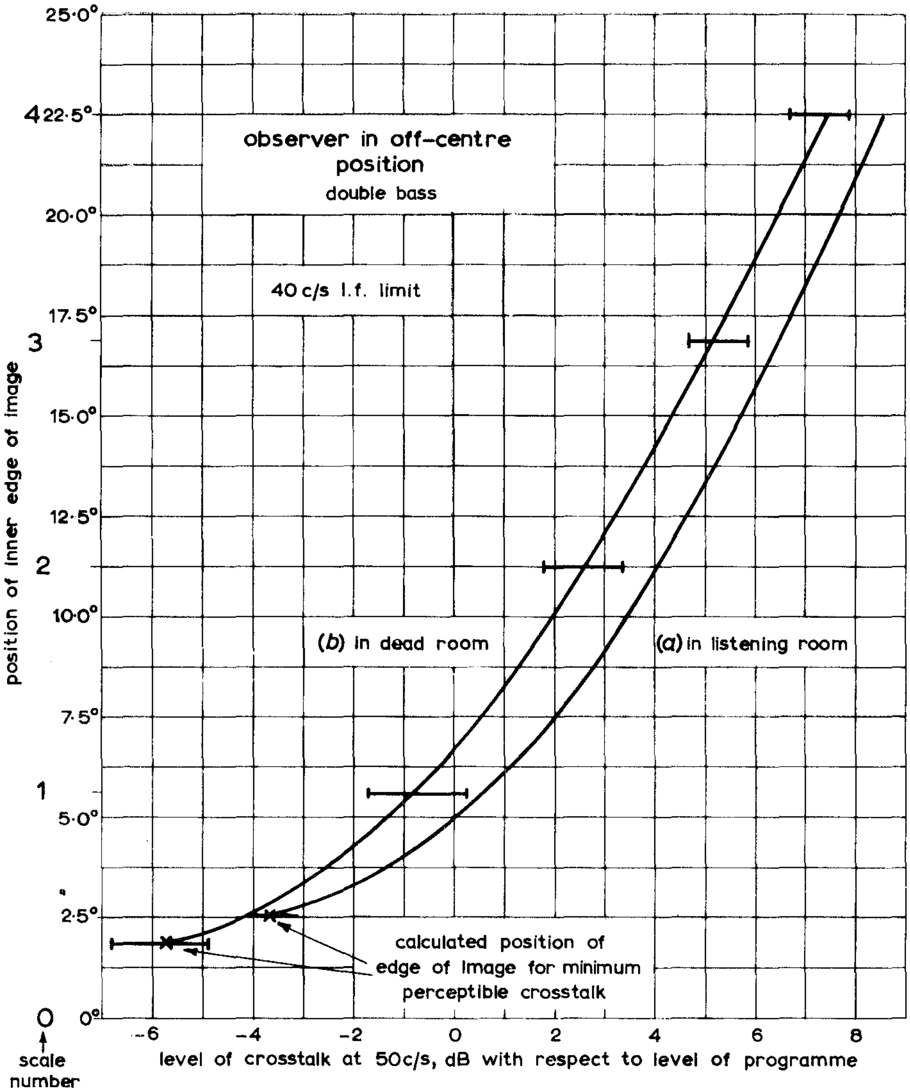


Fig. 9 - Position of inner edge of image as a function of crosstalk increasing at low frequencies. Observer off-centre in Listening Room and Dead Room

Standard error shown thus

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 crosstalk increasing at low frequencies was lowered by 4 dB. For crosstalk increasing at high frequencies and crosstalk 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 crosstalk increasing at high frequencies was 3 dB lower for the off-centre position than for the central position; for crosstalk 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.

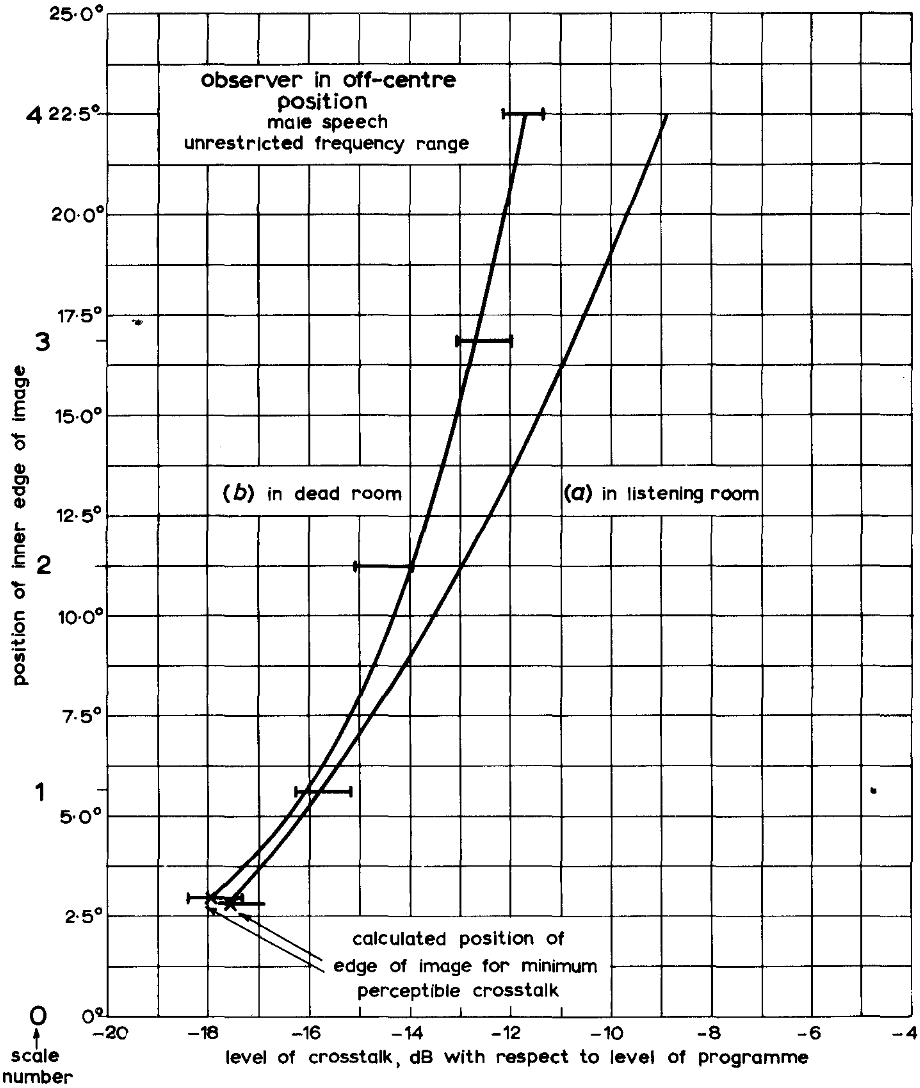


Fig. 10 - Position of inner edge of image as a function of crosstalk independent of frequency. Observer off-centre in Listening Room and Dead Room

Standard error shown thus

3.3. Crosstalk as Function of Frequency

Fig. 11 shows the crosstalk/frequency relationship existing in the test circuit when the subjective effect of the crosstalk was just perceptible. Most of the data relate to a central observer but corresponding curves for the off-centre position are also shown for cases in which the 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 crosstalk rising 6 dB/octave at high frequencies. Curves (b_1) and (b_2) give the corresponding characteristics for crosstalk rising 6 dB/octave at low frequencies, taking the most critical type of programme material in each case; curve (b_1) is for a central observer and curve (b_2) for an observer in the off-centre position. Fig. 11(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 crosstalk independent of frequency. It must be emphasized that these curves give the characteristics of a system in which the effect of crosstalk is just perceptible on programme; they should not be taken to represent the minimum perceptible crosstalk for any one frequency considered separately.

In comparing curve 11(c) with curves 11(a), (b_1) and (b_2), the effect of the different phase relationships between crosstalk and programme has to be borne in mind. The 90° phase lead associated with the crosstalk 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,[3] 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 crosstalk coming from the programme in the other channel, the phase relationship between crosstalk and programme must influence the subjective effect. For this reason, the 90° phase lag associated with the increase of crosstalk at low frequencies prevents direct comparison with the

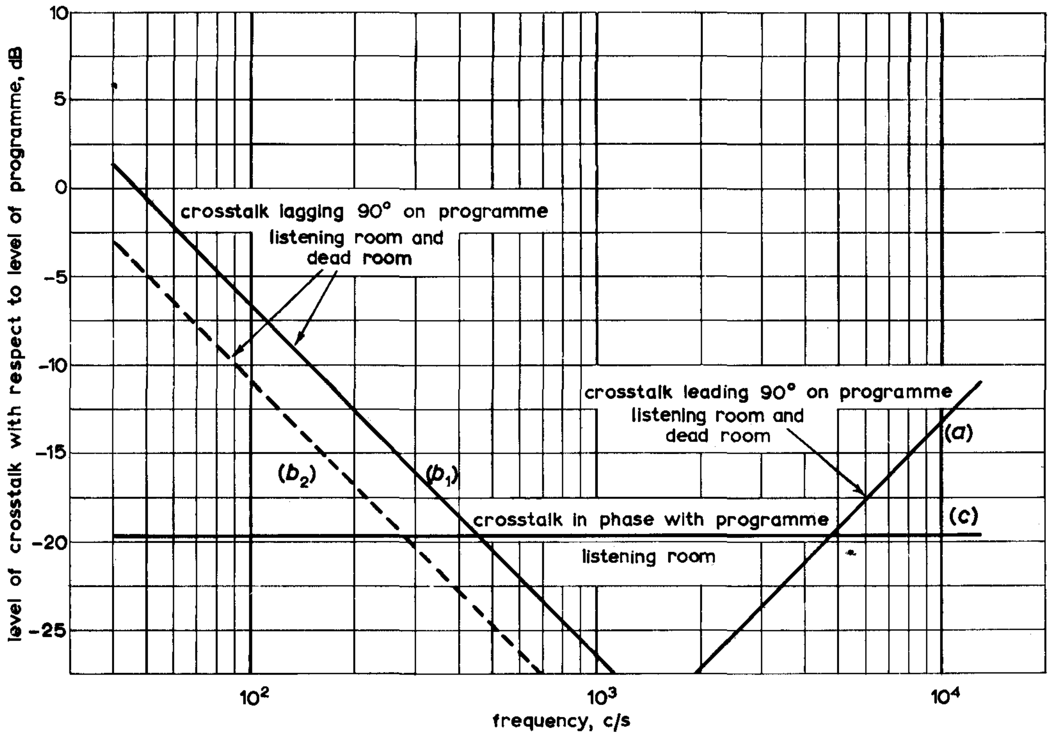


Fig. 11 - Crosstalk/frequency characteristic of test circuit for minimum perceptible subjective effect (mean of all observations). Frequency range 40 c/s to 13 kc/s

—— Observer central
---- Observer in off-centre position (see Fig. 1)

data on crosstalk independent of frequency, for which there is no phase shift. With this reservation, Fig. 11 can be taken as a rough overall picture of the kind of tolerances which might be imposed on a stereophonic system where the crosstalk increases gradually towards the extremes of the frequency band.

3.4. Spread of Results

The data presented in Figs. 3 to 11 relate to the mean of all the values given by the team of observers; thus, in 50% of the observations, a lower level of crosstalk than that shown as 'minimum perceptible' was detectable while in the remaining 50% a higher level went undetected. It is, however, of interest to consider the variation of opinions within the team. Fig. 12, which applies to the minimum perceptible crosstalk for a central observer in the listening room with unrestricted frequency range, shows the statistical distributions for the three cases: (a) crosstalk increasing at high frequencies, (b) crosstalk increasing at low frequencies and (c) crosstalk 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. 13, in which the same data are replotted on a Gaussian probability scale, the minimum crosstalk 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 described in Sections 2.4. and 2.5. and the collected results for the dead room and listening room tests respectively are plotted

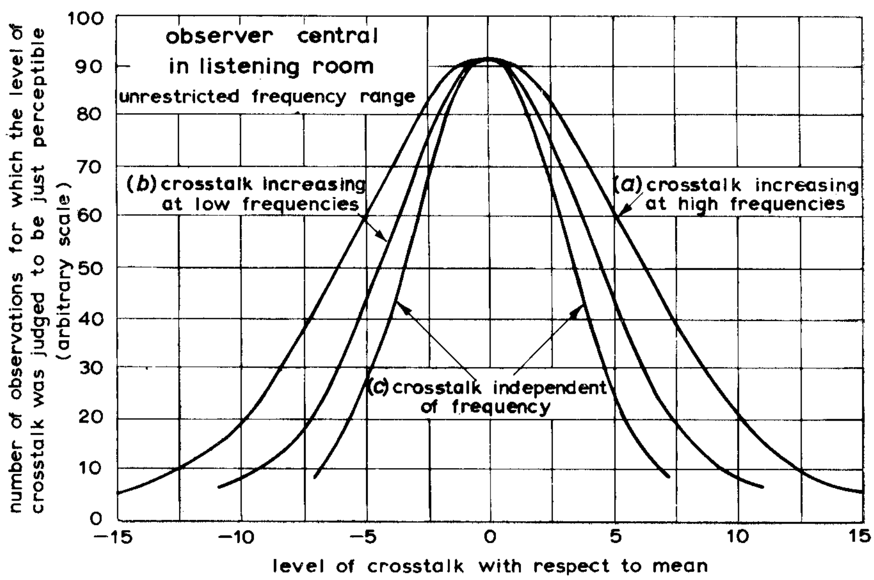


Fig. 12 - Distribution of levels given by team for minimum perceptible crosstalk. Observer central in Listening Room

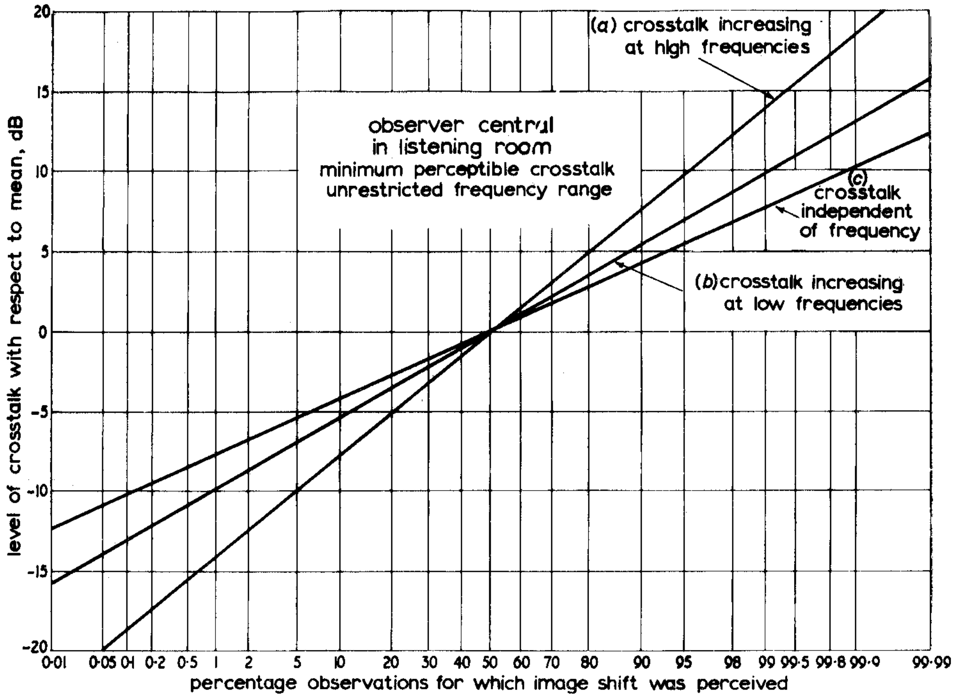


Fig. 13 - Distribution of levels given by team for minimum perceptible crosstalk. (Probability scale) Observer central in Listening Room

in Fig. 14 on a Gaussian probability scale showing the distribution of the values obtained. Although the data apply to a variety of experimental conditions - crosstalk 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 image displacement, as distinct from the minimum perceptible crosstalk 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 2.1., every test carried out with the programme on the left channel and crosstalk 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 crosstalk

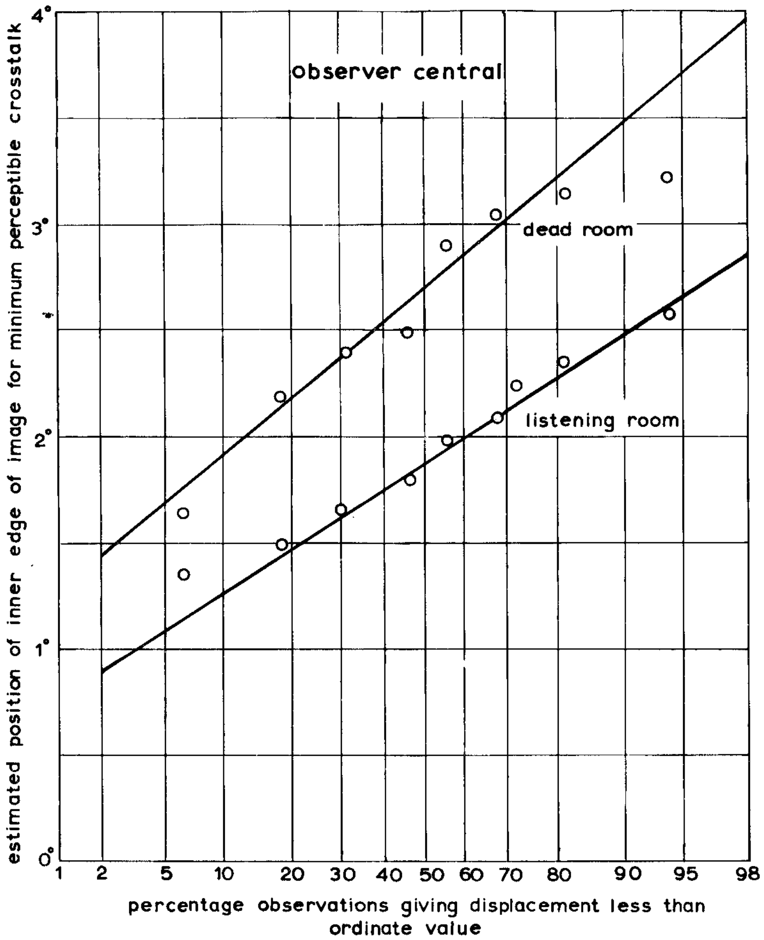


Fig. 14 - Distribution of values of displacement assigned to inner edge of image for minimum perceptible crosstalk. Observer central in Dead Room and Listening Room

from one side than from the other. Fig. 15 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 ± 2•3 dB about the crosstalk figure averaged for all the tests.

4. COMPARISON WITH EARLIER WORK

Little is to be found in the literature on the subject of interchannel crosstalk, and the only work of immediate interest for purposes of comparison appears in papers by Harvey and Schroeder of the Bell Telephone Laboratories[4] and McCoy of the R.C.A. Laboratories.[5]

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 crosstalk varying in amount but independent of frequency.

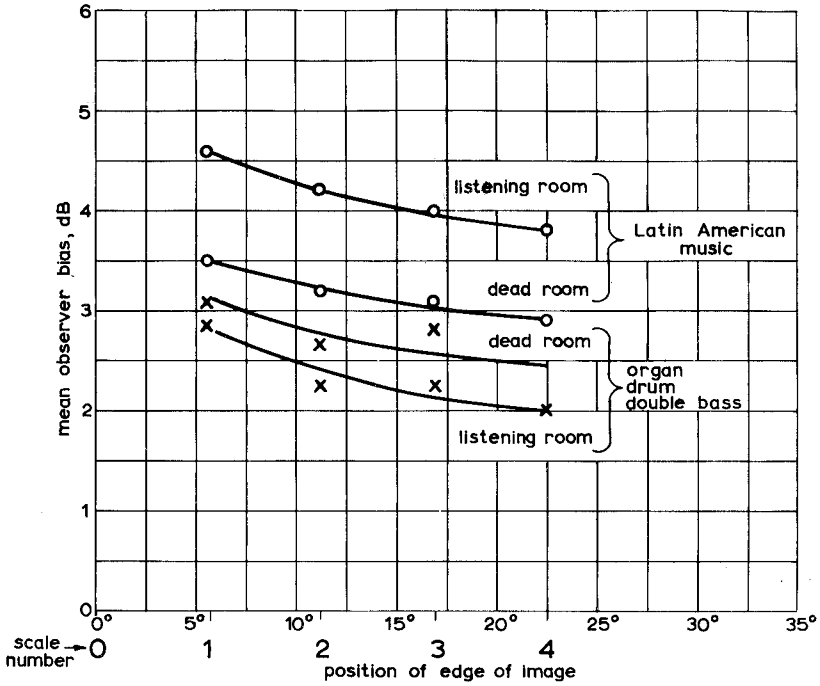


Fig. 15 - Left or Right Bias of individual observers as a function of image position. Observer central in Dead Room and Listening Room

The programme material consisted of stereophonic recordings and the assessment was based on the proportion of observers who noticed the impairment produced by the crosstalk. It was concluded that in setting commercial standards for stereophonic transmission, the crosstalk 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 crosstalk level shown in Fig. 7 for male speech. Apart from this, however, direct comparison between Harvey and Schroeder's results and those given in this report is not possible because the increase in crosstalk 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 crosstalk at low frequencies is to be expected when the phase of the crosstalk lags 90° with respect to that of the programme.

In McCoy's experiments, crosstalk 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 crosstalk varying with frequency in a manner depending on the characteristics of the filter. As in the experiments described in this report, 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 crosstalk 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 report. In other tests, however, the filter consisted of a simple resistance-capacity network, so that the rate of change of crosstalk 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. 16, curves (a) and (b) are computed from the data obtained by McCoy with a resistance-capacity filter, using phase compensation; in this case the crosstalk was in phase with the programme. Curve 16(a) applies to crosstalk increasing with frequency; it shows the crosstalk/frequency characteristic which in McCoy's experiments produced on average an image 'spread' of 1/10th stage width. Curve 16(b), obtained in a similar fashion, applies to crosstalk increasing at low frequencies. For comparison, the corresponding curves 16(c) and 16(d) are derived from the data already given in Figs. 3(a) and 5(a) respectively. It will be seen that curves (a) and (b) show a somewhat lower degree of crosstalk 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.

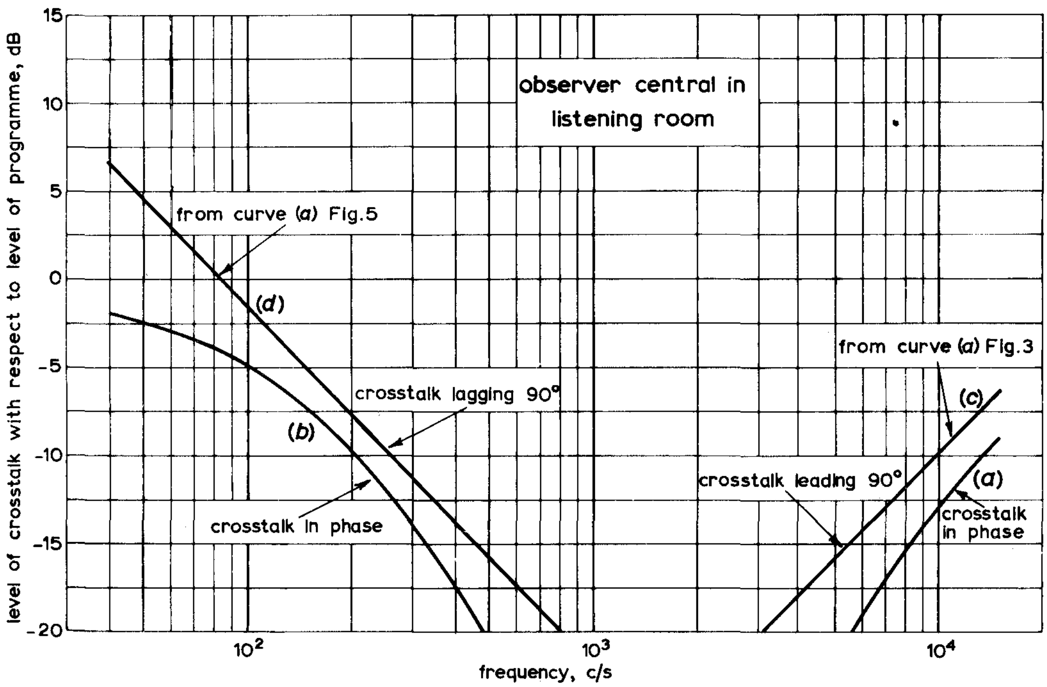


Fig. 16 - Crosstalk/frequency characteristics which produce, on average, an image spread of 1/10th stage width

(a) and (b) calculated from McCoy's data (1961)

(c) and (d) calculated from Figs. 3(a) and 5(a) respectively of present report

5. CONCLUSIONS

Data have been obtained on the impairment of a stereophonic image through various forms of interchannel crosstalk which may occur in practice. The minimum perceptible degree of crosstalk 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. REFERENCES

1. 'The Effect of Crosstalk at High Frequencies Between Left and Right Channels on Stereophonic Reproduction', Research Department Report No. L-049, Serial No. 1961/17.

2. Somerville, T. and Brownless, S.F., 'Listeners' Absolute Loudness Preferences', BBC Quarterly, January 1949, Vol. III, No. 4, pp. 11 - 16.

3. Leakey, D.M., 'Further Thoughts on Stereophonic Sound Systems', Wireless World, April and May 1960, Vol. 66, Nos. 4 and 5, pp. 154 - 160 and 238 - 240.

4. Harvey, F.K. and Schroeder, M.R., 'Subjective Evaluation of Factors Affecting Two-Channel Stereophony', Journal of the Audio Engineering Society, January 1961, Vol. 9, No. 1, pp. 19 - 28.

5. McCoy, D.S., 'Distortion of Auditory Perspective Produced by Interchannel Mixing at High and Low Audio Frequencies', Journal of the Audio Engineering Society, January 1961, Vol. 9, No. 1, pp. 13 - 18.

RESEARCH DEPARTMENT

Stereophony: The effect of differences between the amplitude/frequency characteristics of left and right channels

RESEARCH REPORT No. L-049/4

1964/67

THE BRITISH BROADCASTING CORPORATION

ENGINEERING DIVISION

RESEARCH DEPARTMENT

STEREOPHONY: THE EFFECT OF DIFFERENCES BETWEEN THE AMPLITUDE/FREQUENCY CHARACTERISTICS OF LEFT AND RIGHT CHANNELS

Research Report No. L-049/4

(1964/67)

D.E.L. Shorter, B.Sc.(Eng.), A.M.I.E.E.
H.D. Harwood, B.Sc., A.Inst.P., A.M.I.E.E.
W.I. Manson, B.Sc.(Eng.)

D. Maurice

(R.D.A. Maurice)

This Report is the property of the British Broadcasting Corporation and may not be reproduced in any form without the written permission of the Corporation.

Research Report No. L-049/4

STEREOPHONY: THE EFFECT OF DIFFERENCES BETWEEN THE AMPLITUDE/FREQUENCY CHARACTERISTICS OF LEFT AND RIGHT CHANNELS

Research Report No. L-049/4

October, 1964 (1964/67)

STEREOPHONY: THE EFFECT OF DIFFERENCES BETWEEN THE AMPLITUDE/FREQUENCY CHARACTERISTICS OF LEFT AND RIGHT CHANNELS

SUMMARY

In a stereophonic transmission system, differences between the amplitude/frequency characteristics of the left- and right-hand channels may result in displacement or dispersion of the sound images across the stage.

These effects have been subjectively assessed for such differences in channel characteristics as might be expected to occur in the S.B. system, and tentative suggestions made for the tolerances to be allowed on a pair of channels used for transmitting a stereophonic programme. The experiments were carried out as a contribution to the work of the E.B.U. in establishing performance limits for stereophonic transmission systems.

1. INTRODUCTION

The two channels necessary for the transmission of the left- and right-hand signals in stereophony should ideally have identical amplitude/frequency and phase/frequency characteristics. Failure to meet these requirements may lead to displacement of the reproduced sound images from their intended positions; where such displacement depends on frequency, the image of a complex sound source may be blurred through the dispersion of its individual components.

A previous report[1] in this series described an investigation into the effect, on the stereophonic presentation, of differences between the phase/frequency characteristics of left- and right-hand channels having amplitude/frequency characteristics identical within the working frequency band. The present report is concerned with the effect of differences between the amplitude/frequency characteristics of left- and right-hand channels containing only minimum phase-shift networks; in this case there can be no interchannel difference in phase/frequency characteristics save that which is unavoidably associated with the difference in amplitude/frequency characteristics. For the purpose of this report, the term 'interchannel amplitude differences' will be used for brevity to denote unintentional differences arising from lack of similarity between the channels, as distinct from intentional differences in amplitude between the original left- and right-hand signals to be transmitted.

In practice, the gains or losses in the two stereophonic channels are adjusted at the receiving point to be equal at mid-band, and it is therefore sufficient to consider only the divergence between the amplitude/frequency characteristics at higher and lower frequencies. In the tests to be described, the upper and lower ends of the audio-frequency range were investigated separately, using programme material appropriate to each case.

The widest divergencies between the characteristics of the left- and right-hand stereophonic channels are likely to occur in the lines from studio to transmitter, the more so because it may be desirable, as an insurance against total loss of programme through a line fault, to utilise lines following two different routes rather than two pairs in the same cable. The maximum degree of interchannel amplitude difference to be considered in the experiments was therefore based on the performance of the S.B. system. The upper and lower limits shown in Fig. 1, reproduced from a Designs Department report[2], embrace the frequency characteristics of 90% of the S.B. lines in use in 1948, and these were taken to represent the worst case which need be considered.

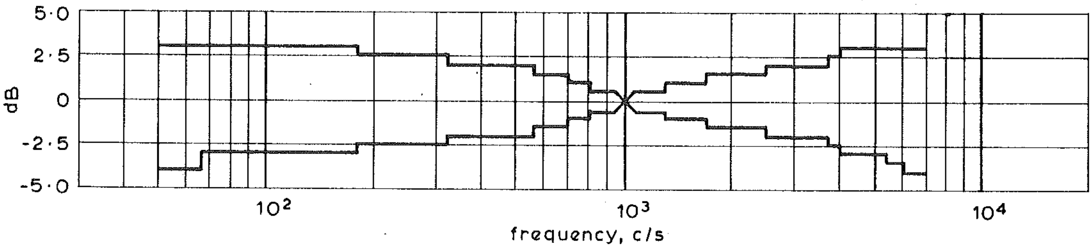


Fig. 1 - Amplitude/frequency response limits met by more than 90% of S.B. chains in 1948. (From data given in Designs Department Report No. 2.13 (51)).

2. GENERAL

Most of the tests were carried out in the same listening room and with the same equipment as in the experiments on the effect of interchannel crosstalk described in an earlier report in this series.[3] However, in accordance with more recent practice, all image displacements were specified as a proportion of the stage width rather than as an angle subtended at the observer's head. The numbered scale used to designate the position of the sound image was marked off in tenths of a stage width on either side of a centre zero. As in the previous investigation, some of the tests were repeated in a 'dead' room for which the reflexion coefficient of the walls, floor and ceiling was less than 10% at frequencies above 80 c/s.

Thirteen observers, all experienced in subjective judgments of this kind, took part in the experiments on interchannel amplitude differences at high frequencies and twelve in the corresponding experiments on differences at low frequencies.

The observer was situated equidistant from the two loudspeakers, thus avoiding any degradation in the image through differences in time of arrival of the sound from the two sides. In these circumstances, the image displacement produced by a small change in the amplitude ratio of the left- and right-hand signals is greatest[4] when the two signals are nearly equal, i.e. when the image is near the centre of the stage. To simulate this condition in the experiment, the left- and right-hand channels were supplied from a common programme source, the difference in the amplitude/frequency characteristics being introduced by networks designed to increase the high or low frequency response of one channel while reducing the response of the other.

The limits shown in Fig. 1 embrace an infinite variety of amplitude/frequency characteristics, and for the present purpose it was necessary to make an arbitrary selection. Fig. 2 shows diagrammatically the form of characteristic, produced by

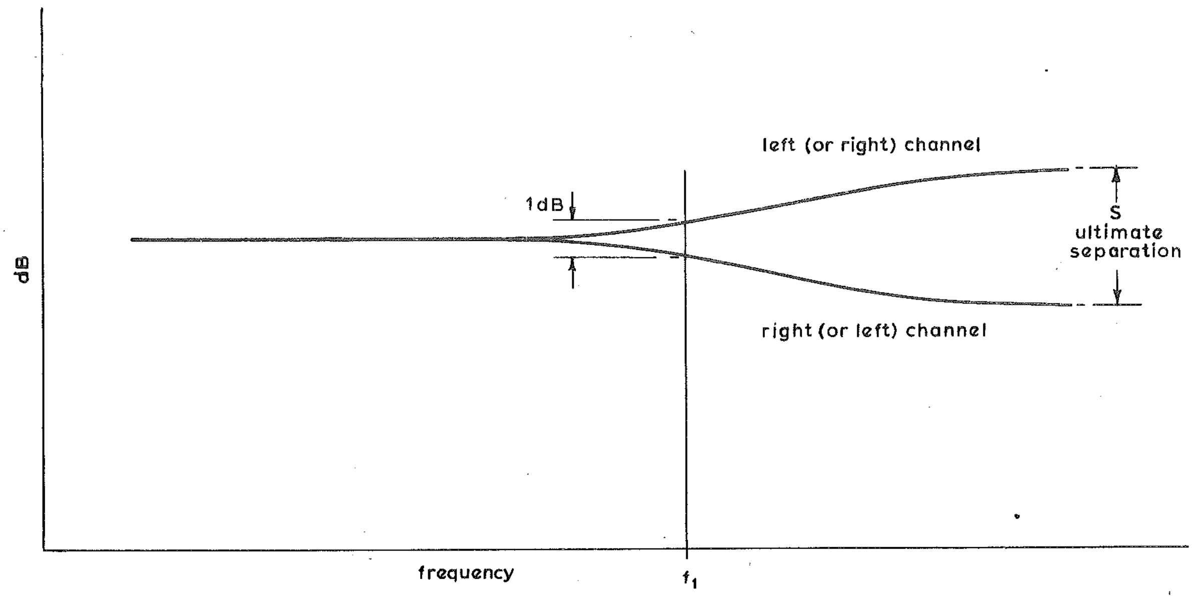


Fig. 2 - Method of specifying degree of interchannel amplitude difference at high frequencies

resistance-capacitance networks, chosen for the experiments on interchannel amplitude differences increasing at high frequencies. In one series of experiments, all the pairs of curves had the same ultimate separation S, the degree of impairment of the transmission being varied by altering the circuit capacitances, thus displacing the characteristics along the frequency scale without changing the form of the curves; for reference purposes, each condition was arbitrarily designated by the frequency f_1 at which the characteristics of the left- and right-hand channels diverged by 1 dB. In a second series, the degree of impairment was controlled by varying the circuit resistances, thus altering S; the value of the latter quantity was then used for reference. In both cases, the networks producing the desired amplitude/frequency characteristics were adjusted in steps by means of ganged rotary switches so arranged that an increase in response of one channel at any frequency was accompanied by a substantially equal decrease (on a dB scale) in the response of the other.

In the case of interchannel amplitude differences increasing at low frequencies, the characteristics of the two channels took the form shown in Fig. 3, which is a mirror image of Fig. 2; from the results of a pilot experiment, however,

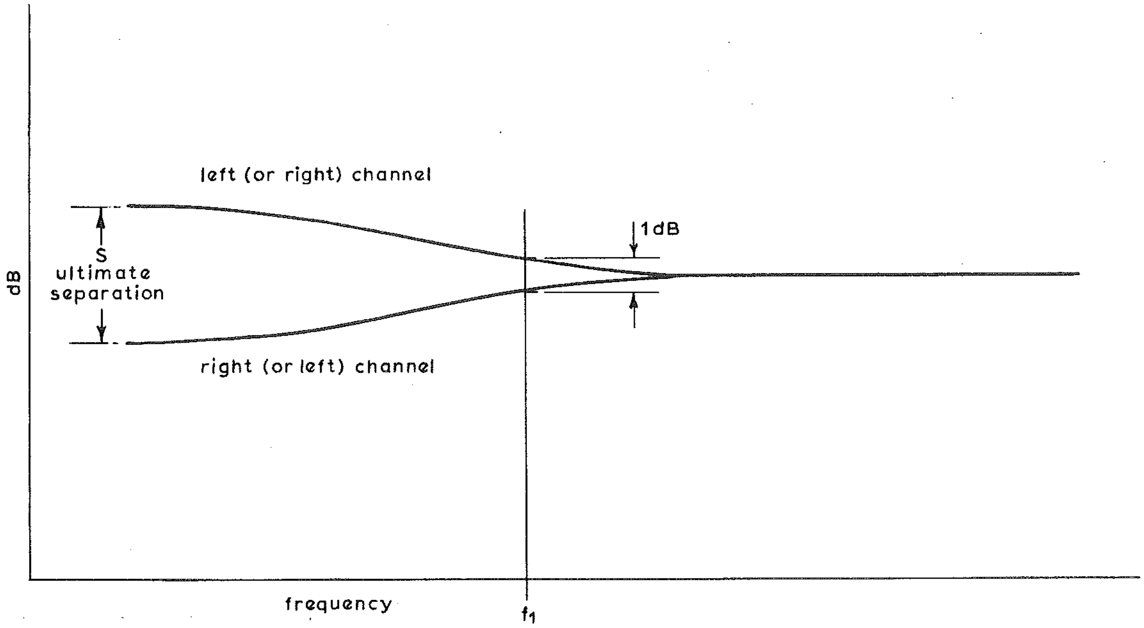


Fig. 3 - Method of specifying degree of interchannel amplitude difference at low frequencies

it was considered unnecessary to carry out a second set of tests with S as the independent variable and the investigation was therefore confined to the effect of varying f_1.

No attempt was made to phase-compensate the circuits used to vary the amplitude/frequency characteristics of the two channels, any interchannel phase differences thereby introduced being accepted as a natural attribute of the system under investigation. In the event, these phase differences were found in the most extreme conditions to be less than 25° and could not therefore[1] have contributed appreciably to the subjective effect.

At the commencement of each group of tests, the rotary switch controlling the difference between the amplitude/frequency characteristics of the two channels was set at one end of its travel; in this condition identical signals were applied to the left- and right-hand channels, and the resulting image will be described for convenience as 'unimpaired'. The observer was asked to adjust a trimming attenuator controlling the relative levels of sound from the two loudspeakers until he judged the image to be central. He was then asked to operate the rotary switch controlling the interchannel difference in amplitude/frequency characteristic and to find (a) the first position for which a displacement of the image became perceptible, and (b) the setting for which the edge of the image coincided with some designated position on the numbered scale extending across the stage. Equal numbers of tests were carried out with the image displacement to the left and to the right; the various experimental conditions were presented in random order to avoid any recognizable sequence which might influence the observer's judgment.

Even when the left- and right-hand channels have identical amplitude/frequency characteristics, the resulting unimpaired image possesses a finite width which is a function, partly of any residual asymmetry in the sound reproducing system, and partly of the listener's own resolving powers. In a supplementary experiment, carried out with the same programme material and the same bandwidth restrictions as in the main experiment, each observer was asked to estimate the width of a central unimpaired image.

3. INTERCHANNEL AMPLITUDE DIFFERENCES INCREASING AT HIGH FREQUENCIES

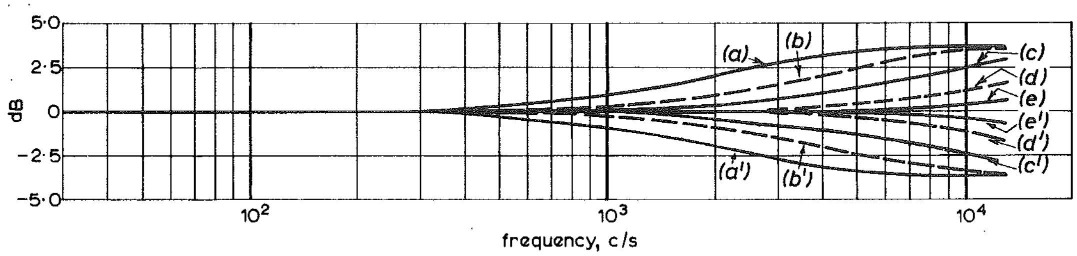
3.1. Experimental Details

The programme material used for these tests was a recorded excerpt of Latin American music, repeated as many times as was necessary for the observer to reach a decision.

The susceptibility of a stereophonic presentation to changes in the relationship between the left- and right-hand signals at high frequencies is known from earlier experiments[4] to be little affected by a reduction in the normal amount of reverberation. It was therefore considered unnecessary to repeat any of the tests in the dead room.

As in previous experiments in this series, an attempt was made to assess the part played by components in the upper part of the audio-frequency range. To this end, some of the tests were carried out with the bandwidth of the system limited to 10 kc/s or 6·8 kc/s by low-pass filters; in the absence of the filters, the upper frequency limit was set at 13 kc/s by the characteristics of the loudspeakers employed.

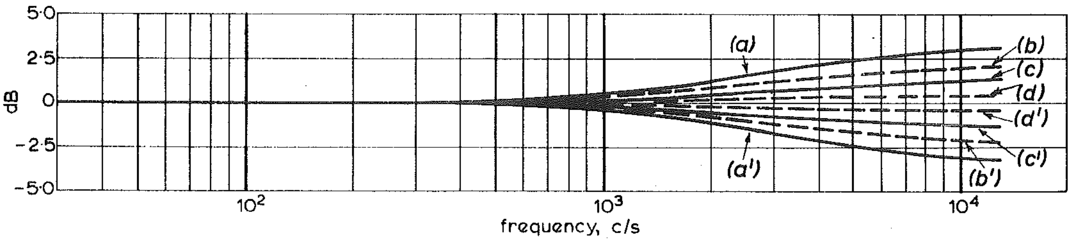
The amplitude/frequency characteristics of the left- and right-hand channels obtained by varying f_1 are indicated in Fig. 4; the observer's control switch



LEFT (OR RIGHT) CHANNEL	RIGHT (OR LEFT) CHANNEL	f_1 kc/s
a	*a'*	0·7
b	*b'*	1·4
c	*c'*	2·8
d	*d'*	5·6
e	*e'*	11·0

Fig. 4 - Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at high frequencies. (Alternate steps shown). f_1 *variable*

operated in eleven steps, but for clarity the characteristics for alternate steps only are given in the figure. Fig. 5 shows corresponding pairs of characteristics obtained by varying S; in this case, the characteristics are given for every third step. The pairs of characteristics in Fig. 4 were obtained by altering the reactances in the circuit, the ultimate separation S remaining constant at 7·5 dB; in Fig. 5, the reactances were kept constant at such values that with S = 6 dB, f_1 = 1 kc/s.



LEFT (OR RIGHT) CHANNEL	RIGHT (OR LEFT) CHANNEL	ULTIMATE SEPARATION S dB
a	*a'*	6
b	*b'*	4·2
c	*c'*	2·4
d	*d'*	0·6

Fig. 5 - Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at high frequencies. (Every third step shown). S *variable*

3.2. Results

Figs. 6(a), 6(b) and 6(c) show the results obtained with the upper frequency range restricted to 13 kc/s, 10 kc/s and 6·8 kc/s respectively, when the interchannel amplitude difference was varied, as shown in Fig. 4, by altering f_1; values of f_1 are plotted as abscissae to a logarithmic frequency scale so arranged that the degree of impairment of the system increases from left to right; the ordinates are plotted to a Gaussian probability scale. Curve (i) in each case shows the percentage of observations in which there was no perceptible image displacement; curve (ii) shows the percentage of observations in which the edge of the image was less than 0·1 of the stage width from the centre and curve (iii), the corresponding data for 0·2 of the stage width from the centre.

In most of the experiments, the points fall nearly on a straight line* indicating a Gaussian distribution. However, in these and similar figures given later, the lines representing different degrees of image impairment are in some cases not parallel and would therefore intersect if extrapolated; evidently the Gaussian distribution holds only over a limited range. The difference in slope between the lines, which, whenever it is statistically significant, indicates a decrease in standard deviation with decreasing image impairment, may be due partly to the finite width of the image.

Table 1 is derived from Figs. 6(a), 6(b) and 6(c). It shows the values of f_1 for which, in 50% of the observations, the subjective impairment of the image

* The line of best fit was arrived at in each case by the method described in Research Report A-037.

TABLE 1

Tests in Listening Room

SUBJECTIVE IMPAIRMENT OF NOMINALLY CENTRAL IMAGE IN 50% OF OBSERVATIONS	FREQUENCY RANGE RESTRICTED TO 13 kc/s		FREQUENCY RANGE RESTRICTED TO 10 kc/s		FREQUENCY RANGE RESTRICTED TO 6·8 kc/s	
	f_1 kc/s	S.E. (octave)	f_1 kc/s	S.E. (octave)	f_1 kc/s	S.E. (octave)
Imperceptible	10·5	0·15	9·3	0·15	5·4	0·1
Edge of image off-centre by less than 0·1 stage width	5·1	0·3	4·3	0·25	2·9	0·2
Edge of image off-centre by less than 0·2 stage width	1·7	0·25	1·6	0·25	1·2	0·25

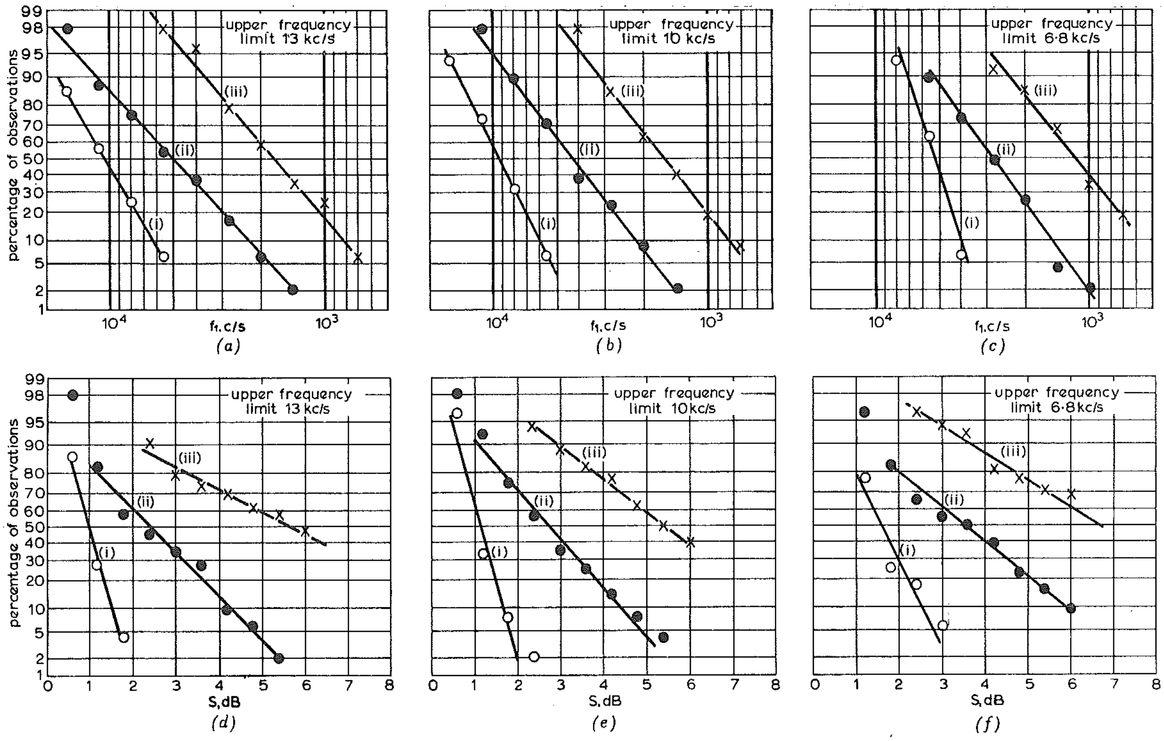


Fig. 6 - Subjective effect of difference between amplitude/frequency characteristics of left and right channels at high frequencies. Divergence of channels expressed in (a), (b) and (c) in terms of f_1, *in (d), (e) and (f) in terms of* S

Numbering of curves:-

(i) Percentage of observations in which there was no perceptible image displacement
(ii) Percentage of observations in which the edge of the image was less than 0·1 stage width from the centre
(iii) Percentage of observations in which the edge of the image was less than 0·2 stage width from the centre

caused by the interchannel amplitude difference can be classified as 'imperceptible', 'edge of image off-centre by less than 0·1 of stage width' and 'edge of image off-centre by less than 0·2 of stage width' respectively. The standard error of the mean (S.E.) is given in each case to the nearest 0·05 octave.

Figs. 6(d), 6(e) and 6(f) show the results obtained with the upper frequency range restricted to 13 kc/s, 10 kc/s and 6·8 kc/s respectively when the interchannel amplitude difference was varied, as shown in Fig. 5, by altering S. Apart from the change in the independent variable, the remarks already made with regard to Figs. 6(a), 6(b) and 6(c) apply here also. However, since there can be no impairment of the image when the interchannel amplitude difference is zero, there is an inevitable departure from Gaussian distribution as the curves approach S = 0.

Table 2, derived from Figs. 6(d), 6(e) and 6(f), shows the values of S, in dB, for which, in 50% of the observations, the effect of the interchannel amplitude difference can be classified as 'imperceptible', 'edge of image off-centre by less than 0·1 of stage width' and 'edge of image off-centre by less than 0·2 of stage width' respectively. The standard error of the mean is given in each case to the nearest 0·1 dB.

TABLE 2

Tests in Listening Room

SUBJECTIVE IMPAIRMENT OF NOMINALLY CENTRAL IMAGE IN 50% OF OBSERVATIONS	FREQUENCY RANGE RESTRICTED TO 13 kc/s		FREQUENCY RANGE RESTRICTED TO 10 kc/s		FREQUENCY RANGE RESTRICTED TO 6·8 kc/s	
	S dB	S.E. dB	S dB	S.E. dB	S dB	S.E. dB
Imperceptible	1	0·1	1·2	0·1	1·6	0·2
Edge of image off-centre by less than 0·1 stage width	2·4	0·4	2·7	0·4	3·5	0·6
Edge of image off-centre by less than 0·2 stage width	5·6	0·8	5·4	0·6	6·7	0·7

As already stated in Section 2, a supplementary experiment was carried out to find the width of a central image produced with identical left- and right-hand channels. For the Latin American music referred to above, the mean image width was found in this experiment to be 0·1 of the stage width (S.E. 0·01) with no significant difference between the results for the three bandwidths. This means that the unimpaired image was regarded by the observers as extending, on average, 0·05 of the stage width on either side of the centre. It follows that if the image is spread towards either side as a result of some system impairment and extends, for example, to 0·2 on the numbered scale, the edge of the image must have been displaced by only 0·15.

So far, the impairment in the stereophonic transmission system has for convenience been expressed in terms of the arbitrary quantities f_1 and S. It is now necessary to reverse the process and to consider what differences between the amplitude/frequency characteristics of the left- and right-hand channels are associated with a particular subjective grading. The result is shown in Figs. 7, 8 and 9, which are derived from Fig. 6 by interpolation. Fig. 7 shows the amplitude/frequency characteristics of the two channels for which the displacement of the image would in 50% of the tests be imperceptible. The data is given for the three bandwidths; the full line and dashed curves relate respectively to the results obtained by varying f_1 and S. Fig. 8 shows the amplitude/frequency characteristics of the two channels for which, in 50% of the observations, the edge of the image would be off-centre by less than 0·1 of the stage width, and Fig. 9 the corresponding data for 0·2 of the stage width.

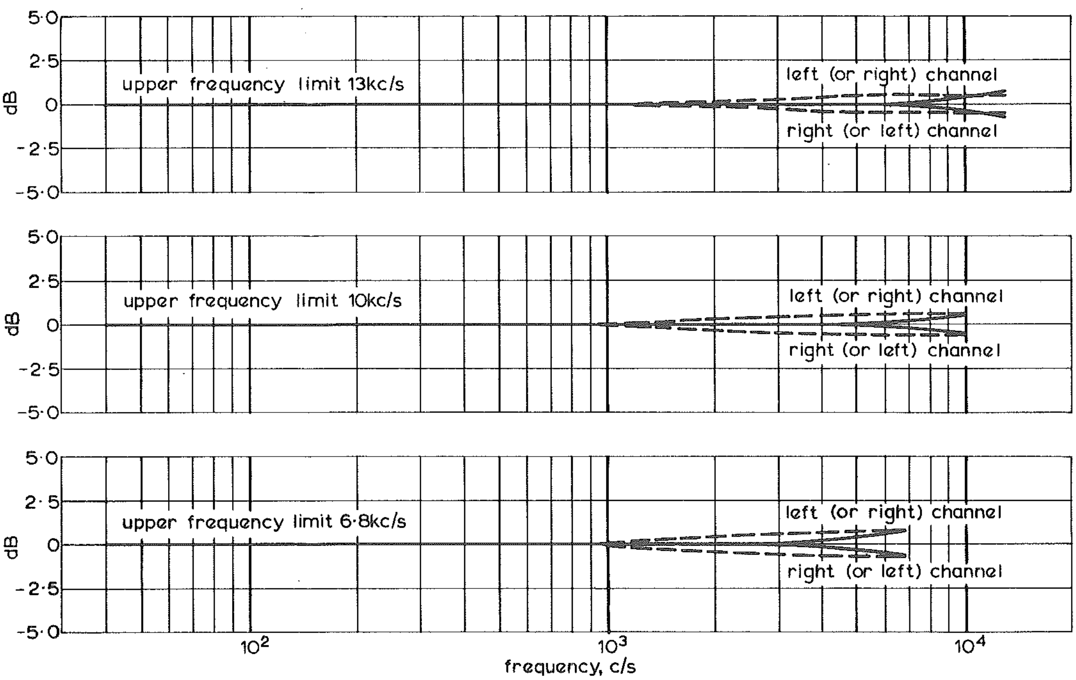


Fig. 7 - Amplitude/frequency characteristics of left and right channels at high frequencies for which there was no perceptible image displacement in 50% of observations

——— f_1 variable　　　— — — S variable

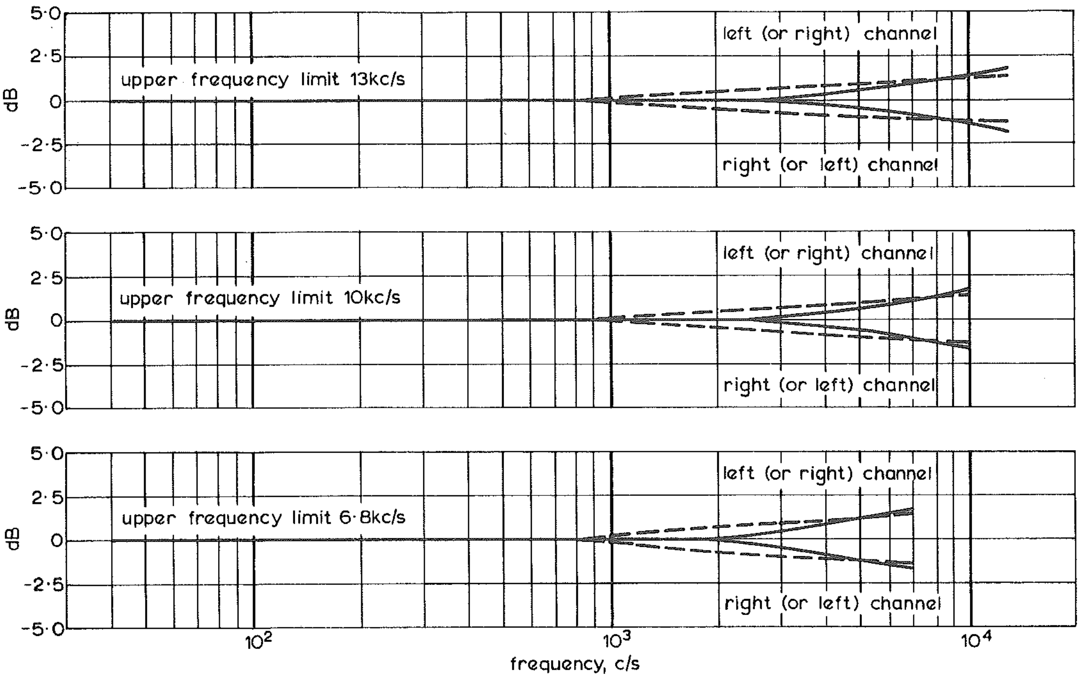


Fig. 8 - Amplitude/frequency characteristics of left and right channels at high frequencies for which the edge of the image was less than 0·1 stage width from centre in 50% of observations

——— f_1 variable ---- S variable

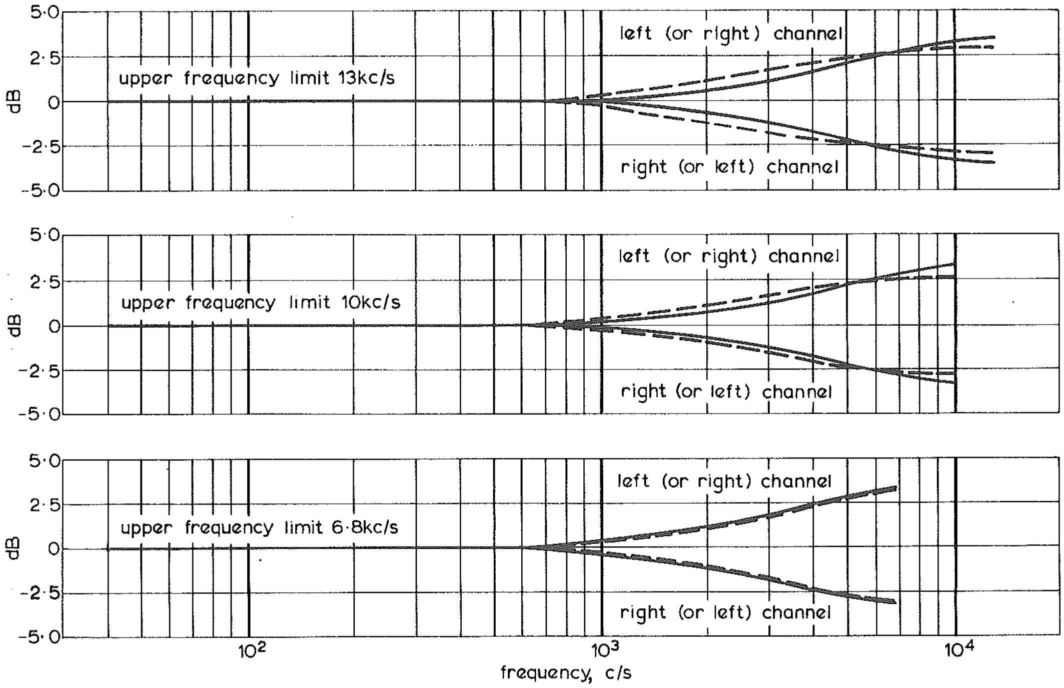


Fig. 9 - Amplitude/frequency characteristics of left and right channels at high frequencies for which the edge of the image was less than 0·2 stage width from centre in 50% of observations

——— f_1 variable ---- S variable

It will be seen that in Figs. 7, 8 and 9, each curve relating to variation in S intersects the corresponding curve relating to variation in f_1; it seems likely that the subjective assessment in each case was influenced largely by components having frequencies in the region of intersection.

It will also be noticed that for each subjective grading, the degree of divergence between the amplitude/frequency characteristics of the left- and right-hand channels at the upper end of the band is nearly independent of the bandwidth.

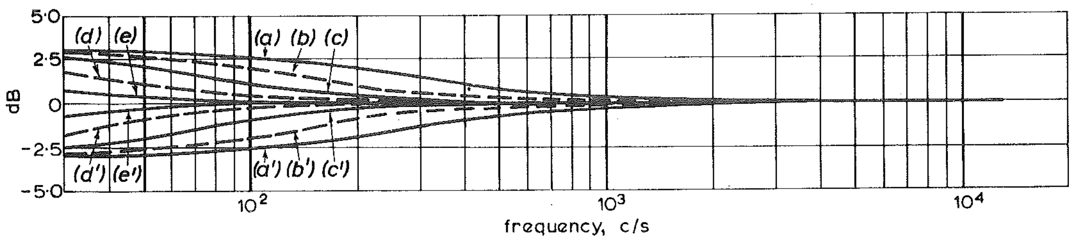
4. INTERCHANNEL AMPLITUDE DIFFERENCES INCREASING AT LOW FREQUENCIES

4.1. Experimental Details

The programme material consisted of excerpts from recorded solos on organ, bass drum and double bass played pizzicato; the test passages were repeated until the observer had come to a decision.

From previous experience[4] it was thought possible that the results of this part of the experiment might be significantly affected by a reduction in the amount of reverberation in the listening area. Tests were therefore carried out both in the listening room and in the dead room.

As long as the interchannel amplitude differences below 1 kc/s did not exceed the limits given in Fig. 1, the maximum impairment of the stereophonic presentation was not large enough to justify closer analysis by the introduction of filters to restrict the frequency band; tests were therefore made only with the full frequency range, limited at its lower end to approximately 40 c/s by the nature of the programme material and the characteristics of the loudspeakers. For the same reason it was thought sufficient to control the difference between the amplitude/frequency characteristics of the left- and right-hand channels by varying the frequency f_1 at which the curves diverge by 1 dB, the value of S being held constant at 6 dB. Fig. 10 shows the form of characteristic obtained by this means; as in the corresponding curves in Fig. 4, eleven different pairs of characteristics could be produced, but for clarity, only alternate steps are shown.



LEFT (OR RIGHT) CHANNEL	RIGHT (OR LEFT) CHANNEL	f_1 c/s
a	*a'*	720
b	*b'*	360
c	*c'*	180
d	*d'*	90
e	*e'*	45

Fig. 10 - Amplitude/frequency response curves of networks used to introduce interchannel amplitude differences at low frequencies. (Alternate steps shown). f_1 variable

4.2. Results

Figs. 11(a), 11(b) and 11(c) show the results of the tests in the listening room for organ, drum and double bass respectively. Curve (i) in each case shows the percentage of observations in which there was no perceptible image displacement, and curve (ii) the percentage of observations in which the edge of the image was less than 0·1 stage width from the centre. Even with the maximum interchannel difference between amplitude/frequency characteristics indicated in Fig. 10, the image rarely extended as far as 0·2 on the scale and the data was therefore insufficient to allow a reliable curve to be drawn for this condition. As in the corresponding curves in Fig. 6, the abscissae are plotted to a Gaussian probability scale, and the curves of best fit approximate to straight lines. It will be noted that whereas Fig. 6 covers three different bandwidths, Fig. 11 relates to three different musical instruments.

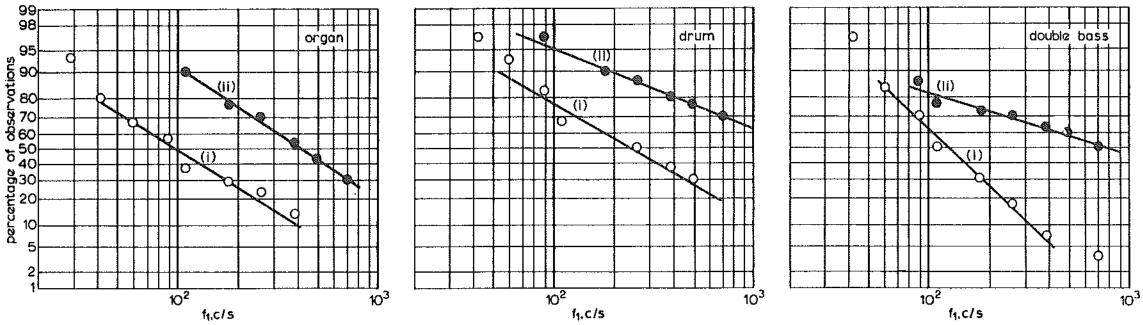


Fig. 11 - Subjective effect of difference between amplitude/frequency characteristics of left and right channels at low frequencies. Divergence of channels expressed in terms of f_1

Numbering of curves:-

(i) Percentage of observations in which there was no perceptible image displacement
(ii) Percentage of observations in which the edge of the image was less than 0·1 stage width from centre

Table 3, derived from Figs. 11(a), 11(b) and 11(c), shows the values of f_1 for which, in 50% or more of the observations, the effect of the interchannel amplitude difference can be classified as 'imperceptible', and 'edge of image off-centre by less than 0·1 of stage width' respectively. The standard error of the mean is given in each case to the nearest 0·05 octave.

TABLE 3

Tests in Listening Room

SUBJECTIVE IMPAIRMENT OF NOMINALLY CENTRAL IMAGE IN 50% OF OBSERVATIONS	ORGAN		DRUM		DOUBLE BASS	
	f_1 c/s	S.E. (octave)	f_1 c/s	S.E. (octave)	f_1 c/s	S.E. (octave)
Imperceptible	96	0·4	240	0·45	124	0·3
Edge of image off-centre by less than 0·1 stage width	406	0·4	1700	0·65	760	0·85

In the dead room, the values of f_1 obtained were nearly the same as those shown in Table 3 and are not therefore reproduced here. Such small differences as existed between the two sets of figures, though barely significant statistically, suggested that the effects of interchannel amplitude differences were, if anything, less noticeable in the dead room than in the listening room.

The supplementary experiment carried out to determine the width of an unimpaired central image yielded results which were in some cases significantly larger than those given in Section 3.2. The average image width in the listening room was 0·14, 0·13 and 0·09 of the stage width for the organ, drum and double bass respectively, the standard error being about 0·013 of the stage width in each case. In the dead room, the image width was slightly less for the drum and double bass, though for the organ, which has a greater middle frequency content, no significant difference was observed. In some later experiments with male speech (which contains no very low-frequency components) the image was found to be narrower in the listening room than in the dead room; it appears, therefore, that at low frequencies the effect of the acoustic environment on the width of a central image depends to some extent on the part of the spectrum involved.

As explained in Section 3.2, the distance by which the edge of the image was displaced in reaching a particular position on the numbered scale can be estimated by subtracting from the scale reading one half the width of the unimpaired central image.

Figs. 12 and 13, derived from Fig. 11 by interpolation, show the amplitude/ frequency characteristics of the left- and right-hand channels for which, in 50% or

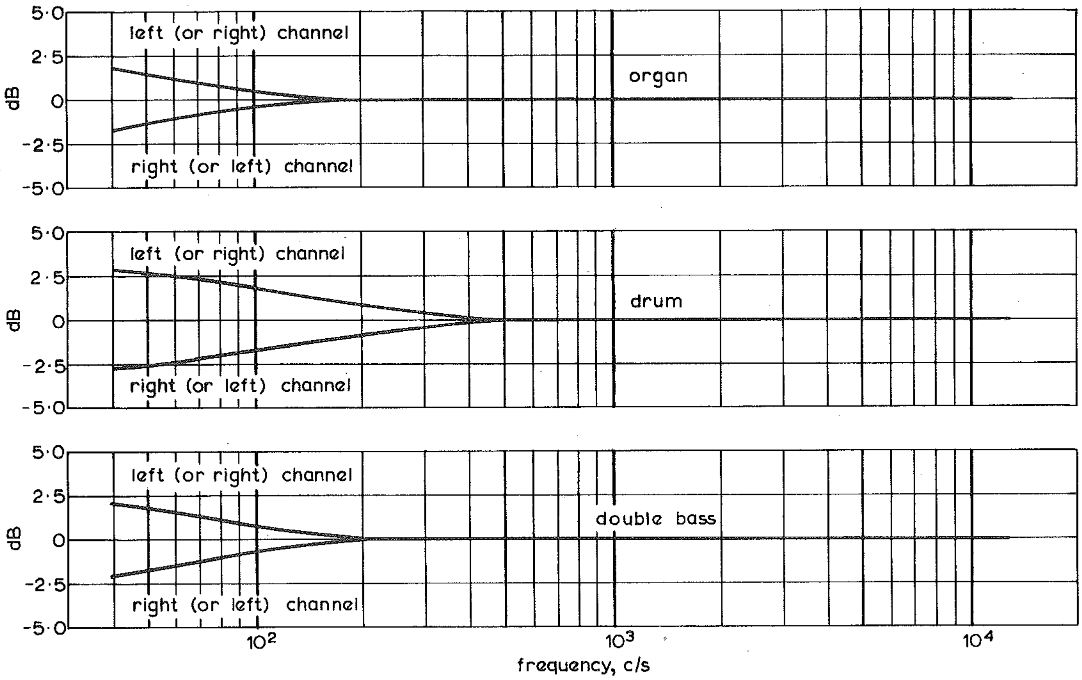


Fig. 12 - Amplitude/frequency characteristics of left and right channels at low frequencies for which there was no perceptible image displacement in 50% of observations

——— f_1 variable

more of the observations, the subjective impairment would be classified respectively as 'imperceptible' and 'edge of image off-centre by less than 0·1 of stage width'. It will be seen that for the same degree of image impairment, a much greater divergence between the channel characteristics could be permitted at low than at high frequencies.

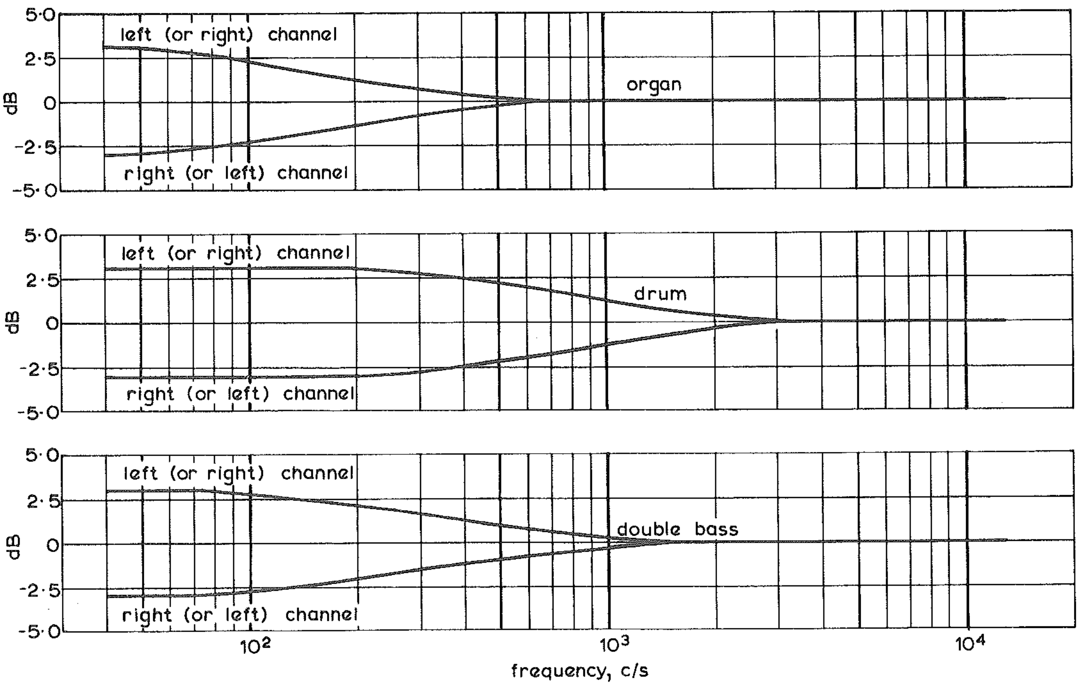


Fig. 13 - Amplitude/frequency characteristics of left and right channels at low frequencies for which the edge of the image was less than 0·1 stage width from centre in 50% of observations

——— f_1 variable

5. CONCLUSIONS

From the foregoing information it is now possible to consider the tolerances which might be imposed in practice on the matching of the amplitude/frequency characteristics of the left- and right-hand channels of a stereophonic system. To this end, it is convenient to replot the curves of Figs. 7, 8, 9, 12 and 13 to show, instead of the actual amplitude/frequency characteristics of the two channels, the difference between the two; the resulting data is presented in Figs. 14, 15 and 16 for the high-frequency range and in Figs. 17 and 18 for the low-frequency range.

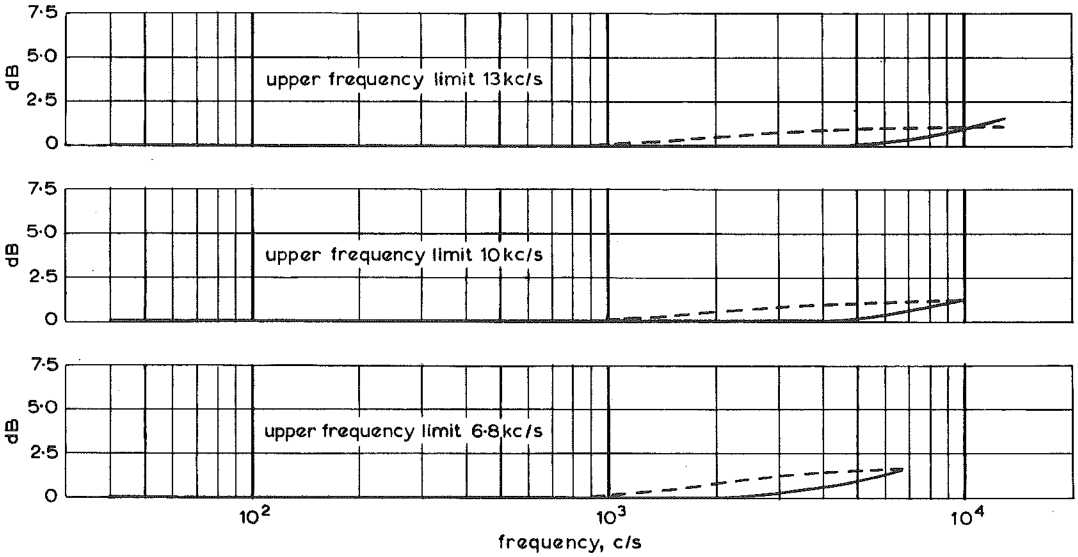


Fig. 14 - Difference between amplitude/frequency characteristics of left and right channels for which there was no perceptible image displacement in 50% of observations

Frequency characteristics of left and right channels diverging at high frequencies

——— f_1 variable ---- S variable

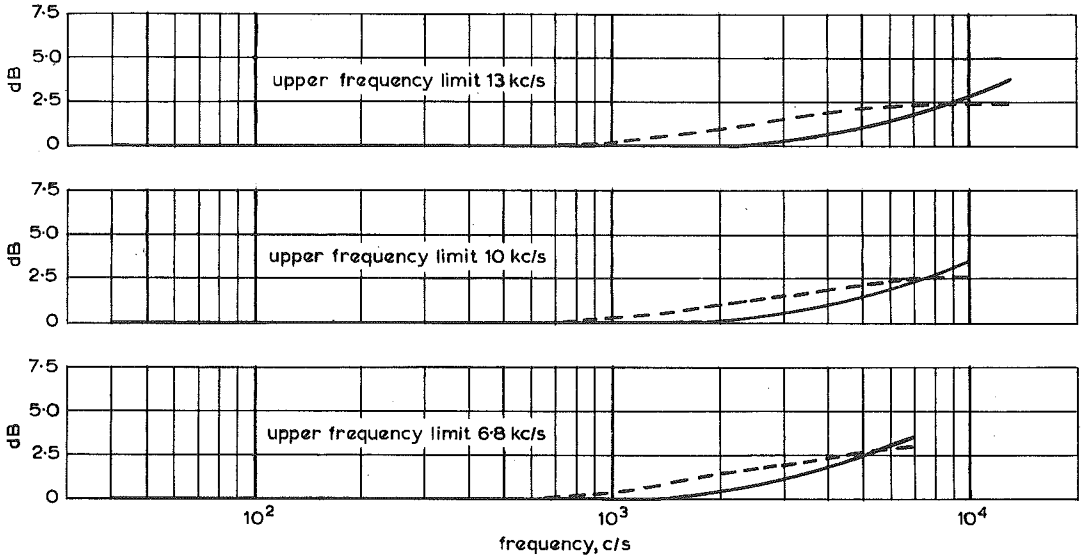


Fig. 15 - Difference between amplitude/frequency characteristics of left and right channels for which the edge of the image was less than 0·1 stage width from centre in 50% of observations

Frequency characteristics of left and right channels diverging at high frequencues

——— f_1 variable ---- S variable

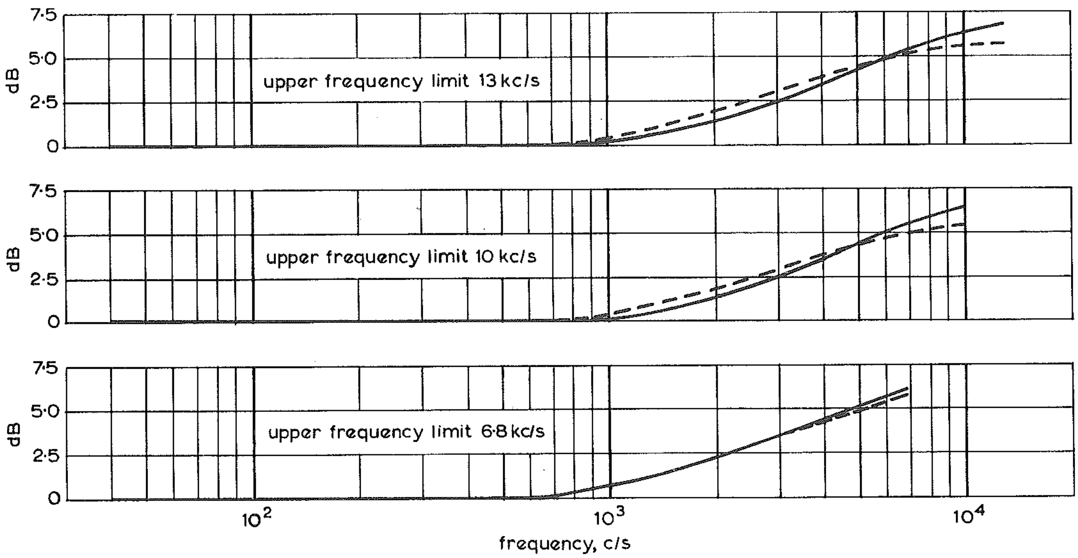


Fig. 16 - Difference between amplitude-frequency characteristics of left and right channels for which the edge of the image was less than 0·2 stage width from centre in 50% of observations

Frequency characteristics of left and right channels diverging at high frequencies

——— f_1 variable ---- S variable

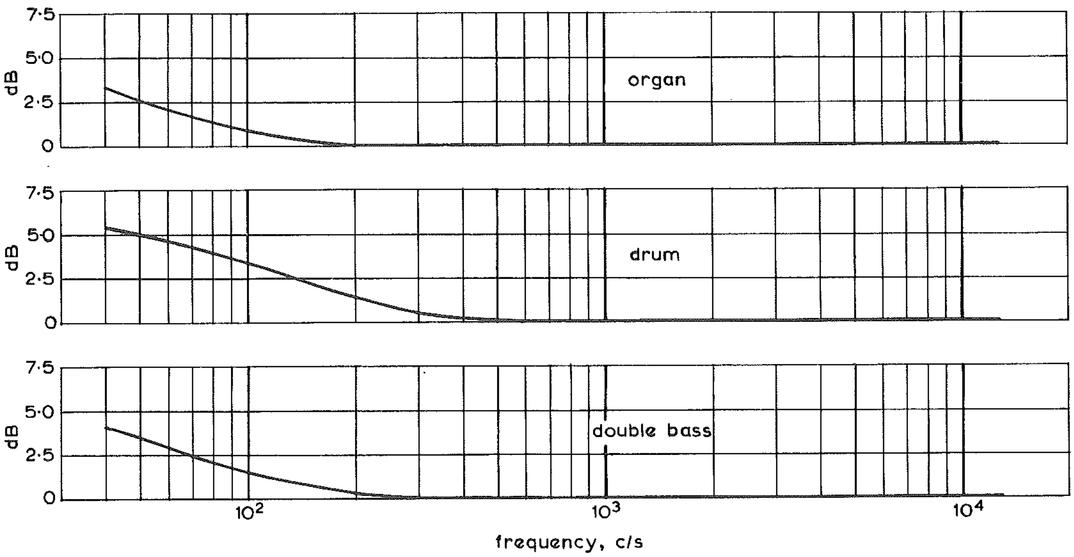


Fig. 17 - Difference between amplitude/frequency characteristics of left and right channels for which there was no perceptible image displacement in 50% of observations

Frequency characteristics of left and right channels diverging at low frequencies

——— f_1 variable

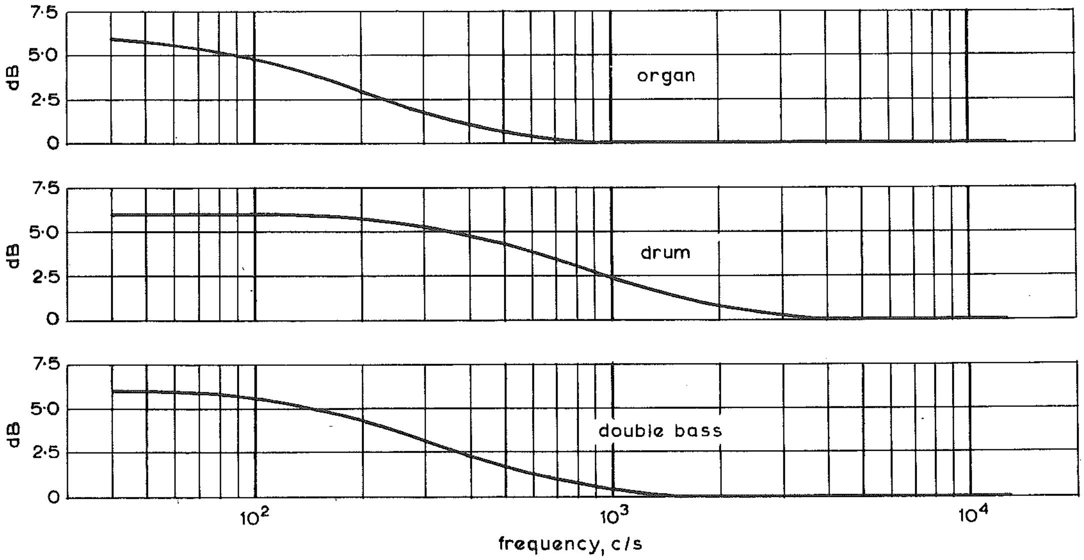


Fig. 18 - Difference between amplitude/frequency characteristics of left and right channels for which the edge of the image was less than 0·1 stage width from centre in 50% of observations

Frequency characteristics of left and right channels diverging at low frequencies

——— f_1 variable

In drawing conclusions from this data, the following points should be specially noted:

(a) The experiments were confined to the case in which the amplitude/frequency characteristics of the left- and right-hand channels depart from uniformity by equal and opposite amounts. In applying the results to the more general case, it is tacitly assumed that dispersion of the stereophonic image is unaffected by changes in amplitude/frequency characteristic applying to both channels equally.

(b) The curves in Figs. 14 to 18 represent a circuit condition for which the effects described were observed on programme material covering a range of frequencies; they do not represent the effect of differences in the gain or loss of the left- and right-hand channels at any one frequency considered separately.

(c) Interchannel amplitude differences may be of opposite sign at the two ends of the audio-frequency band. A nominally central image having components at both extremes of the band could then be dispersed both to left and to right, the overall width being determined by the sum of the two effects.

As a basis for discussion, it seems reasonable to consider two degrees of tolerance, the first based on the most critical case and the second representing a practical compromise when the more stringent requirements cannot be met. The former limit could be derived from the data for imperceptible impairment in 50% of cases; the latter could appropriately be arrived at by assuming the edge of a nominally central image to be, in 50% of cases, off-centre by less than 0·1 of a stage width. In Fig. 19 an attempt has been made to draw up a set of tolerances on these lines. It is assumed that the gain or loss of the left- and right-hand channels is made equal at 800 c/s; an arbitrary tolerance of 0·5 dB has been allowed in the mid-band region. Curve (a) represents the limit of perceptibility, below which it is unnecessary to go, curve (b) the higher limit, representing a detectable but small degree of impairment. The dotted line (c) shows for comparison the possible differences in amplitude/frequency characteristic between two lines conforming to the C.C.I.T.T. limits (1960) for normal Type A programme circuits.

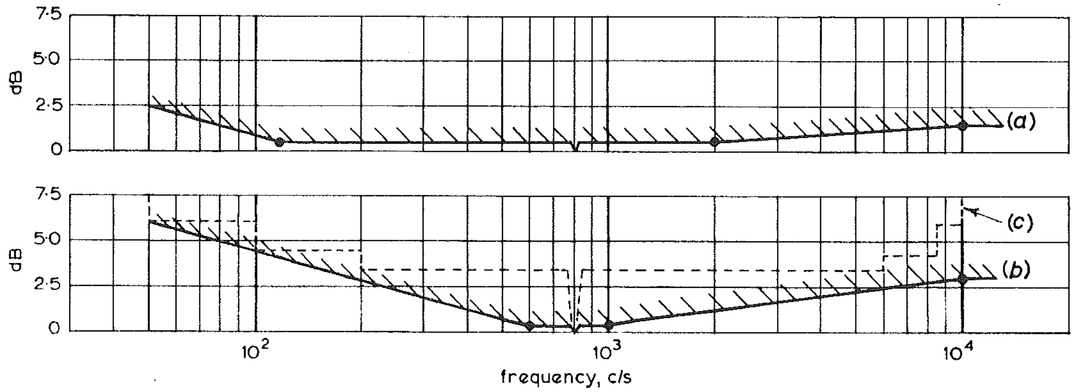


Fig. 19

(a), (b) Suggested tolerances for difference between frequency characteristics of left and right channels taking gain or loss of 800 c/s as zero

(a) Limit of perceptibility (b) Acceptable limit if necessary

(c) Overall limit of variation in frequency characteristic permitted by C.C.I.T.T. tolerances of normal Type A programme circuits

The experiments described in this report were carried out as a contribution to the work of the E.B.U. Working Party S.

6. ACKNOWLEDGEMENTS

Acknowledgements are due to Messrs. R.L. Deane, A.A. Harris, K.H. Hewitt and M.E. Massey, who constructed the experimental equipment and carried out most of the subjective testing.

7. REFERENCES

1. 'Stereophony: The Effect of Differences between the Phase-Frequency Characteristics of Left and Right Channels', Research Department Report No. L-049/3, Serial No. 1964/8.

2. 'Proposals for improving the Loss/Frequency Characteristics of Long Chains', Designs Department Report No. 2.13 (51).

3. 'Stereophony: The Effect of Crosstalk Between Left and Right Channels', Research Department Report No. L-049/2, Serial No. 1964/1.

4. Leakey, D.M., 'Further Thoughts on Stereophonic Sound Systems', Wireless World, Vol. 66, No. 4, April 1960.

CHS

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey

CLSG

RESEARCH DEPARTMENT

An investigation of the law of displacement and of width of a stereophonic image for male speech

RESEARCH REPORT No. PH-7

UDC 534.76 1967/24

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

AN INVESTIGATION OF THE LAW OF DISPLACEMENT AND OF WIDTH OF A STEREOPHONIC IMAGE FOR MALE SPEECH

Research Report No. PH-7
UDC 534.76 1967/24

H.D. Harwood, B.Sc.

D. Maurice
for Head of Research Department

This Report is the property of the British Broadcasting Corporation and may not be reproduced in any form without the written permission of the Corporation.

This Report uses SI units in accordance with B.S. document PD 5686.

Research Report No. PH-7

AN INVESTIGATION OF THE LAW OF DISPLACEMENT AND OF WIDTH OF A STEREOPHONIC IMAGE FOR MALE SPEECH

May 1967

Research Report No. PH-7
UDC 534.76 1967/24

AN INVESTIGATION OF THE LAW OF DISPLACEMENT AND OF WIDTH OF A STEREOPHONIC IMAGE FOR MALE SPEECH

SUMMARY

An account is given of the present position, both in theory and practice, regarding the relation between the displacement of a stereophonic image and the corresponding interchannel difference in level. The disagreement amongst published results is indicated.

Experiments are described which show that for male speech this relation is largely independent of the acoustic surroundings. The variation in the width of the image of a nominally point source is found to vary both with image position and with listening conditions, being least in fairly live surroundings.

A circuit, which is claimed in the literature to reduce image width, was tested and found, in contrast, to increase this width.

1. INTRODUCTION

Two important aspects of dual channel stereophonic reproduction are firstly the relationship connecting image position and difference in level between the two loudspeakers and secondly the sharpness of the resulting image. In any attempts to improve the stereophonic effect by changes in circuits, loudspeakers or acoustics of the listening room, both of the aspects mentioned must be measured in order to determine the effect of the changes. For example, the introduction of a circuit which had the effect of improving image sharpness might distort the image position to an extent which was unacceptable.

There are several references[1,3,4,5,6,7] in the literature to the relationship between image position and interchannel level difference but, as is shown in the next section, the conclusions vary considerably; very little quantitative information has been published on image width, and none on the way in which it varies for differing positions across the stage or with the acoustics of the listening room.

This report deals with images of a point source which ideally should have no width at all, but which in practice do have a finite size. A description is given of experiments employing male speech and designed to measure the relation between image position and interchannel level difference, to determine the variation of image width for differing image positions across the stage and to investigate the efficacy of a circuit, described in one of the references given, in reducing image width. The tests were with one exception carried out both in a listening room, simulating the average domestic acoustic environment, and in a free-field room, which has the advantage of providing not only one extreme acoustic condition but an environment that could be duplicated accurately in laboratories elsewhere. The experiments on the image-width reducing circuit were carried out only in the free-field room.

2. PREVIOUS WORK

2.1. Image Position

The first reference in the literature to a measurement of the relation between image position and interchannel level difference is an article by de Boer[1]. No details are given of the acoustics of the listening room, the number of observers, nor of the programme employed, other than that it was from a gramophone record. His results are reproduced in curve (*a*) of Fig. 1. To account for the relationship shown by the curve he considered that diffraction around the head, resulting in difference in sound level at the two ears, was the main factor in providing directional information and that the difference in the time of arrival of the sound at the two ears played only a minor part. The interaural level difference due to diffraction varies considerably with frequency[2] and he weighted it according to the corresponding variation in energy density for speech, to arrive at the relationship between level difference and angle of incidence. It is, however, difficult to see how a single relation connecting image position with interchannel level difference can hold for all types of programme material if the hearing mechanism has to make a similar weighting for differing types of sound.

The next publication was by Brittain and Leakey[3] who employed excerpts, a few seconds long, of recorded speech with a frequency range up to 5 kHz; the measurements were made in the open air on a site free of reflecting obstacles. The number of observers is not stated; their results are given in Fig. 1 curve (*b*).

In an article describing the "Stereosonic" system Clark et al[4] develop a theoretical expression determining the image position for low frequency sounds as a function of the interchannel level difference. For the experimental layout shown in Fig. 2, in which the subject faces stage centre, the theoretical relation is given as $\sin\alpha = \{(L-R)/(L+R)\}\sin\theta$ and from data obtained with 4 observers this is claimed to be accurate up to about two thirds of the stage width. They state that the results of experiments carried out with a variety of programme materials are in agreement with this relation for frequencies up to 700 Hz, but that above this frequency the experimental displacements are greater than the predicted value and it is necessary for the value of $\sin\alpha$ obtained from the above expression to be increased in the ratio of 1·4 to 1; to correct this they employ what they call a shuffle circuit. The paper by de Boer[1] is quoted in support of this requirement, but this support is not at all clear from an examination of the article in question. The theoretical relationships for both low and high frequencies are plotted as curves (*c*) and (*d*) in Fig. 1; it should be noted that the shuffle circuit is claimed to reduce the image width, presumably by an amount corresponding approximately to the difference between these two curves. In a subsequent article[5] one of the authors gives data to show that the acoustic environment has only a small effect on image position for a given interchannel level difference.

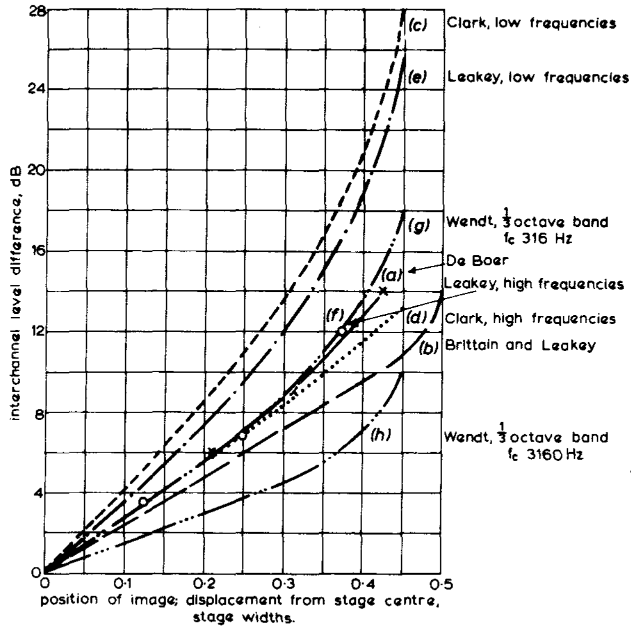


Fig. 1 - Relation between Image Position and Interchannel Amplitude Difference, by Various Authors

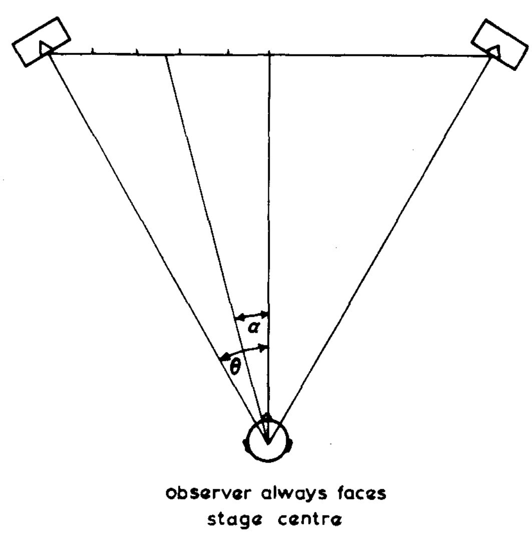


Fig. 2 - Relative Position of Loudspeakers and Observers

Leakey[6a,6c] describes the limitations, even at low frequencies, of the sine law given above and derives another relation $\tan\alpha = \{(L-R)/(L+R)\}\tan\theta$ which takes account of the variation of interaural time differences with small involuntary head movements; measurements he made in the open air with a number of observers varying from 4 to 12 and using a band of noise covering the frequency range 250 to 500 Hz are in reasonable agreement with this law but he states that "to obtain a somewhat closer agreement with the practical results it is necessary to allow for the effect of signal attenuation around the head". Although he does not claim it, his formula implies that image position as a fraction of stage width is independent of the distance of the observer from the loudspeakers, and it can be seen from his results that this holds fairly well except at close range; on the other hand this cannot hold, except at small angles, for the formula given by Clark et al although they claim that it does. At high frequencies Leakey makes allowance for the shadowing effect of the head and assumes that it is the envelope function of the waveform reaching the ears which contains the directional information. The final expression is somewhat complex but agrees well with his own experimental results for a band of noise extending from 2 to 4 KHz. Data calculated from these theoretical expressions for low and high frequency sounds are presented in Fig. 1 as curves (*e*) and (*f*). To the extent that these curves differ from each other, Leakey also implies the need for some form of shuffle circuit although not to the degree indicated by Clark et al. In contrast to this, however, he also gives a curve[6b] showing the image displacement for "wide range speech", apparently 250 Hz to 4000 Hz bandwidth. This curve follows closely his curve for displacement of low frequency sounds only and does not show the deviation which might be expected if the high frequency components followed a different law.

Wendt[7] also carried out experiments in a room, whose characteristics were not stated, by a team of ten observers. He used various 1/3 octave bands of noise separated by half a decade, and found that for a given interchannel level difference the image displacement varied with the frequency of the test band; the results for the bands centred at 316 and 3160 Hz respectively, i.e. similar to those of Leakey, are reproduced in Fig. 1 curves (*g*) and (*h*). From the slopes of these curves and the corresponding ones for other frequency bands, he obtained a weighting factor for middle and high frequencies somewhat resembling that obtained by Clark et al.

It will thus be seen that there is a considerable divergence not only in the results predicted by the theories mentioned but also in the experimental results.

2.2. Previous Work on Image Width

The only data on image width appears to be that given by Clark et al[3] who state that image widths within about $\pm 2°$ were obtained for recorded music investigated in two separate bands: from the bass up to 700 Hz and 600 Hz upwards. This comment appears to cover differing image positions but the acoustic conditions are not stated.

3. EXPERIMENTAL DETAILS

In the present series of tests the observer faced stage centre in accordance with normal practice and with the requirements of the remarks given in the previous section. The arrangement of loudspeakers, scale divisions and position of subject, see Fig. 2, was the same as that described in Research Department Report L-049/3. Fig. 3 shows a plan of the listening room; the volume is approximately 85 m^3

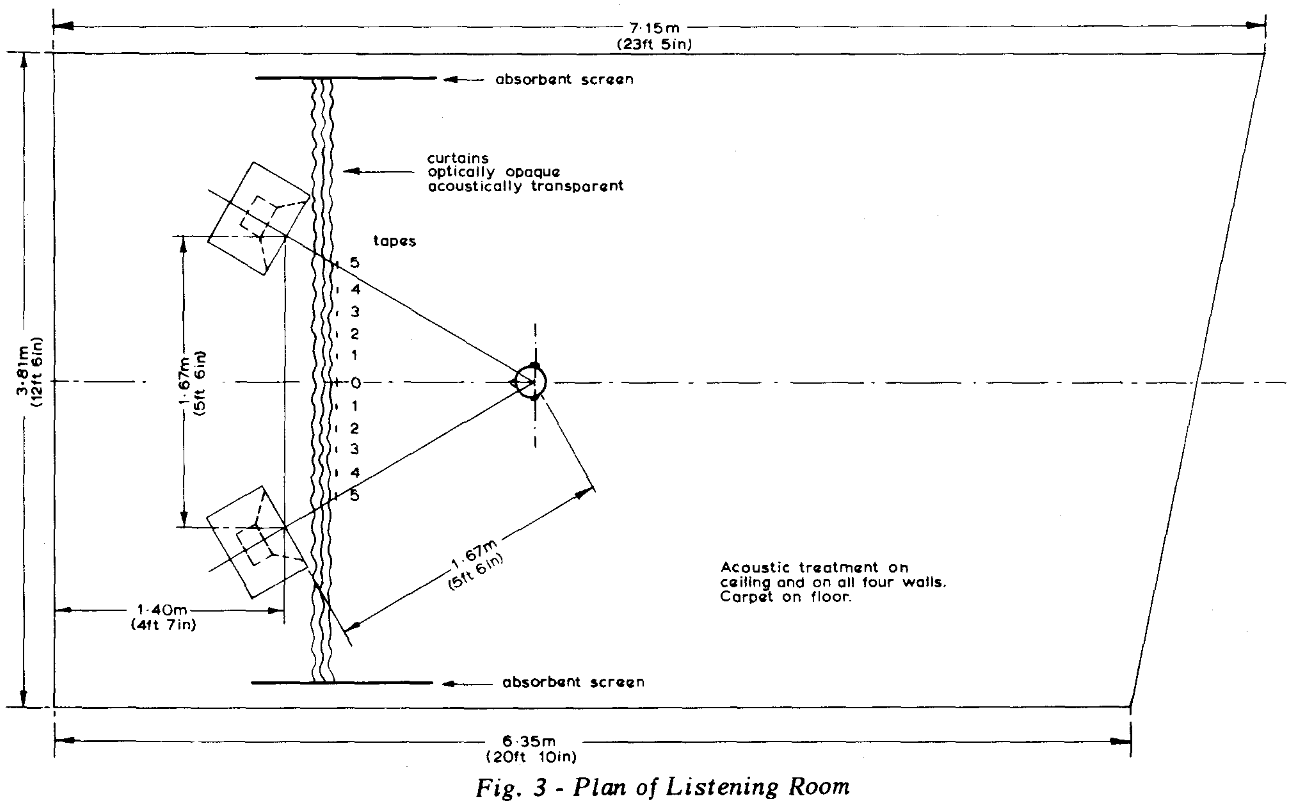


Fig. 3 - Plan of Listening Room

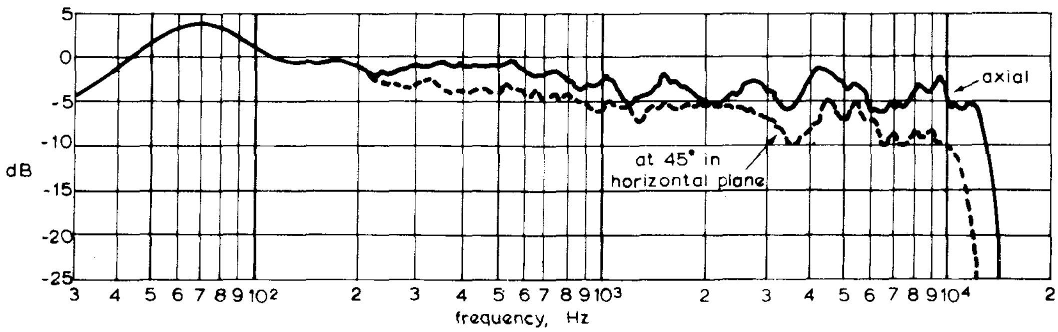


Fig. 4 - Frequency Characteristics of Loudspeaker; on Axis and at 45° in Horizontal Plane

and the average reverberation time is 0·3 seconds. The same arrangement was used in the free-field room, but in this case the reflexion coefficient of the surfaces was less than 10% for frequencies down to about 80 Hz. Twelve observers took part; they were all experienced in making subjective judgements.

Fig. 4 shows the frequency characteristics of one of the loudspeakers at 0° and at 45° to the axis in the horizontal plane. The characteristics of the second loudspeaker were within ± 1 dB of the first except around the crossover region from 800 Hz to 1600 Hz where the differences reached 2 dB in narrow frequency bands.

To take account of any asymmetrical effects in the listening conditions, the loudspeaker system or the observer's reactions, tests were carried out with the image displaced both to the left and to the right of the central position. There is some evidence[8a] that the position of components at either of the extreme ends of the audio-frequency range is masked by that of components further within the band. To avoid this effect in the present series of measurements the test material employed was male speech, which is known to contain very little energy at either very low or very high frequencies; other advantages were the relatively constant level and continuous spectrum compared with other programmes. In the tests, recorded speech was played continuously to the observer, until he had made his decision, at a maximum sound level reading of 74 dB on an unweighted sound level meter; this level has been shown[8b] to be that preferred both by the team and by the general public. The observer was provided with a double attenuator with which he could change the relative levels of signal in the right- and left-hand channels, thus displacing the image position without changing the loudness.

The first set of experiments was designed to measure three things: the law connecting image position with interchannel level difference, the width of the image at various positions across the stage, and the minimum perceptible image shift. The observer was therefore asked to adjust the attenuator for the following conditions:

(a) Centre of image coinciding with each of the tapes 0 to 5 (Fig. 3)

(b) Left-hand edge of image coinciding with each of the tapes 0 to 5

(c) Right-hand edge of image coinciding with each of the tapes 0 to 5

(d) Minimum perceptible shifts of image from centre to left-hand side and to right-hand side.

The order in which tests were made was random.

The second set of measurements was designed to check the claim made by Clark, Dutton and Vanderlyn[4,5] which was mentioned in Section 3, that the sharpness of the image can be improved by electrical means. According to those authors the part of the spectrum above 700 Hz requires a smaller interchannel level difference for a given image displacement than the portion below this frequency. They designed the circuit shown in Fig. 5(*a*) having the amplitude frequency characteristic shown in Fig. 6, to be inserted in the difference channel of

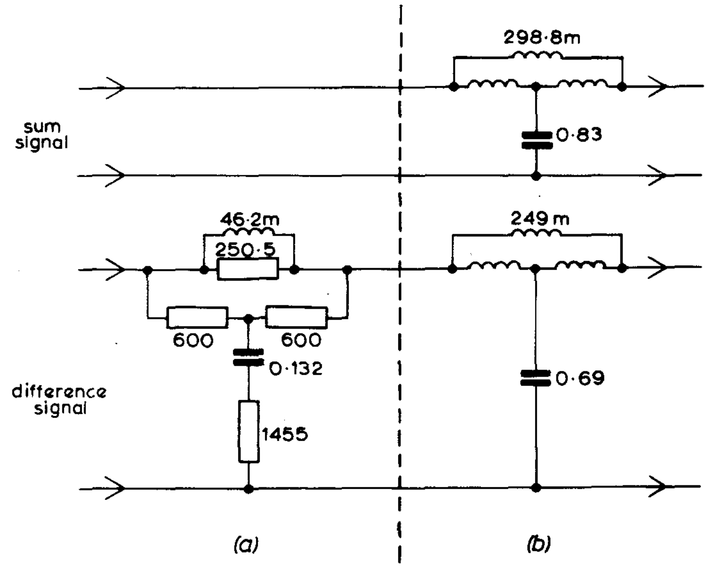


Fig. 5 - Shuffle Circuit
(*a*) Frequency Dependent Network
(*b*) Phase Correction Networks

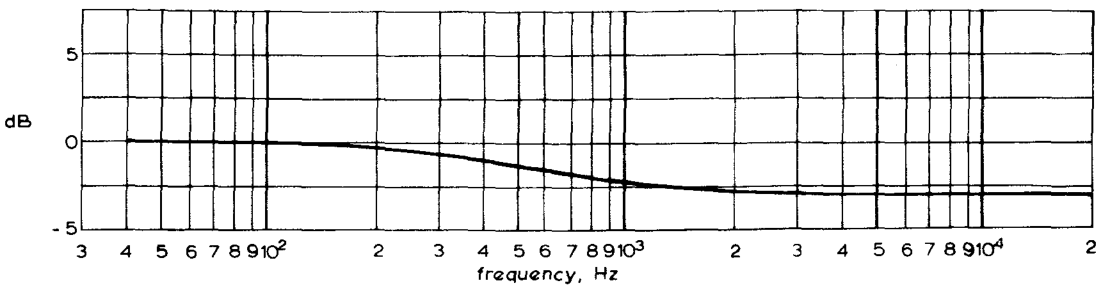


Fig. 6 - Amplitude/Frequency Characteristic of Shuffle Circuit

a sum-and-difference network. The circuits marked (*b*) in Fig. 5 are to compensate for the unwanted phase delay introduced by circuit (*a*); losses in the two circuits are equalised by means of attenuators not shown.

The efficacy of this device in reducing image width was tested in the free-field room by repeating observations (b) and (c) with the new device in circuit. For a central image there is no difference signal and therefore the added circuit has no effect; it is equally clear that when the image is at one extreme of the stage the sound is radiated effectively by one loudspeaker only and again the added circuit cannot change the image width or position although it does change the sound quality. Observations were therefore confined to the case of an image at tape 3, where calculations indicated that the effect on image width should be most noticeable.

4. RESULTS

4.1. Image Position

The results of the first set of experiments are given in Fig. 7. The curves (*a*) and (*b*) show the image position as a function of the interchannel level difference for the tests in the listening room and free-field room respectively. The points plotted are the median values for the team and the standard error for each value is also shown. It will be seen that the results in the two rooms are very similar and that the relationship is substantially a linear one except near tape number 5. This position will be seen from Fig. 3 to represent the extreme edge of the stage and in order that the image should be displaced to this extent, substantially all the sound must come from one loudspeaker. A linear relation therefore cannot be expected; in fact, owing to the finite image width smaller displacements must also be affected. Another factor involved is that most observers are found to have a bias in their observations so that the number of decibels required to shift the image to a tape on the left is different from that required for the corresponding tape on the right.

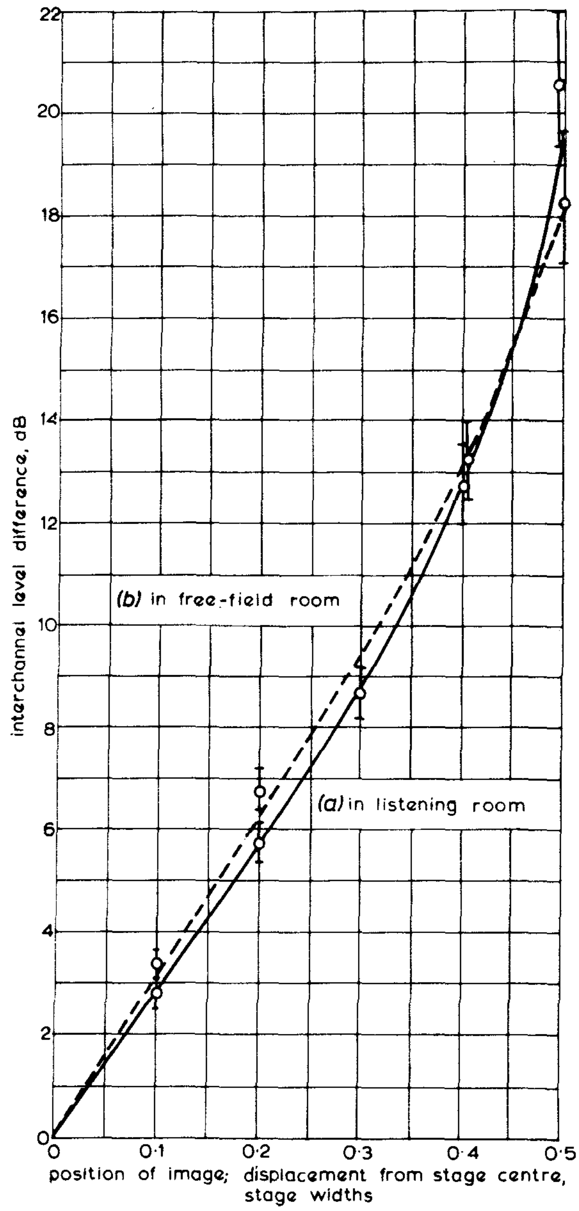


Fig. 7 - Relation between Image Position and Interchannel Level Difference

Magnitude of One Standard Error about the Mean

Fig. 8 shows this bias averaged for the team (curves (*a*) and (*c*)) and, the average of the absolute values (irrespective of sign) for the individual observers as a function of the image position both in the listening room and in the free-field room. Some persons found it impossible to displace the image centre to tape 5 on one side of the stage although on the other side they could displace it even beyond this position. The values shown in Fig. 7 for tape 5 are thus affected by the fact that subjects on one side of the mean have not been able to give a reading for the test, this applied particularly in the listening room, and the size of the standard error is also increased. On the other hand, the extreme value shown is in very good agreement with our figure of 19 dB given elsewhere[8a] for the inter-channel difference required to give a minimum perceptible displacement of the image from tape No. 5.

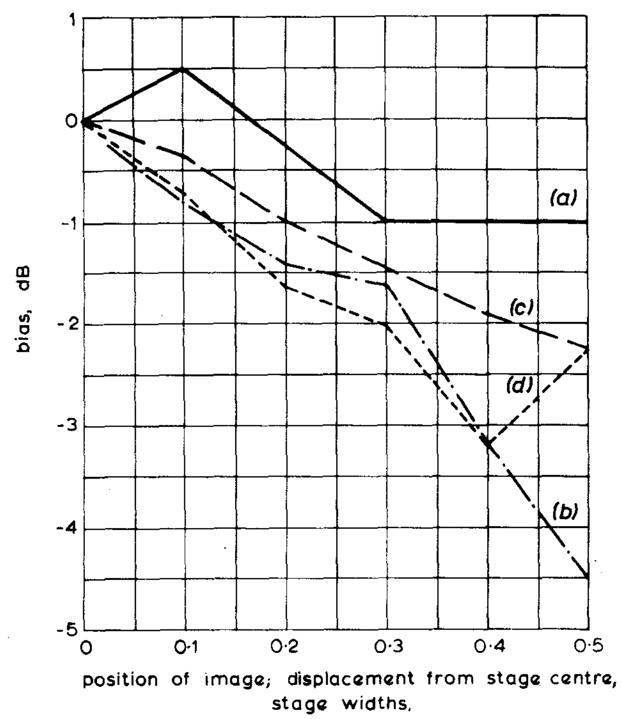


Fig. 8 - Variation of Bias with Image Position

(*a*) In Free-Field Room; Centre of Image, Average of Team
(*b*) In Free-Field Room; Centre of Image, Average for Individuals irrespective of Sign.
(*c*) In Listening Room, Centre of Image, Average of Team
(*d*) In Listening Room, Centre of Image, Average for Individuals irrespective of Sign.

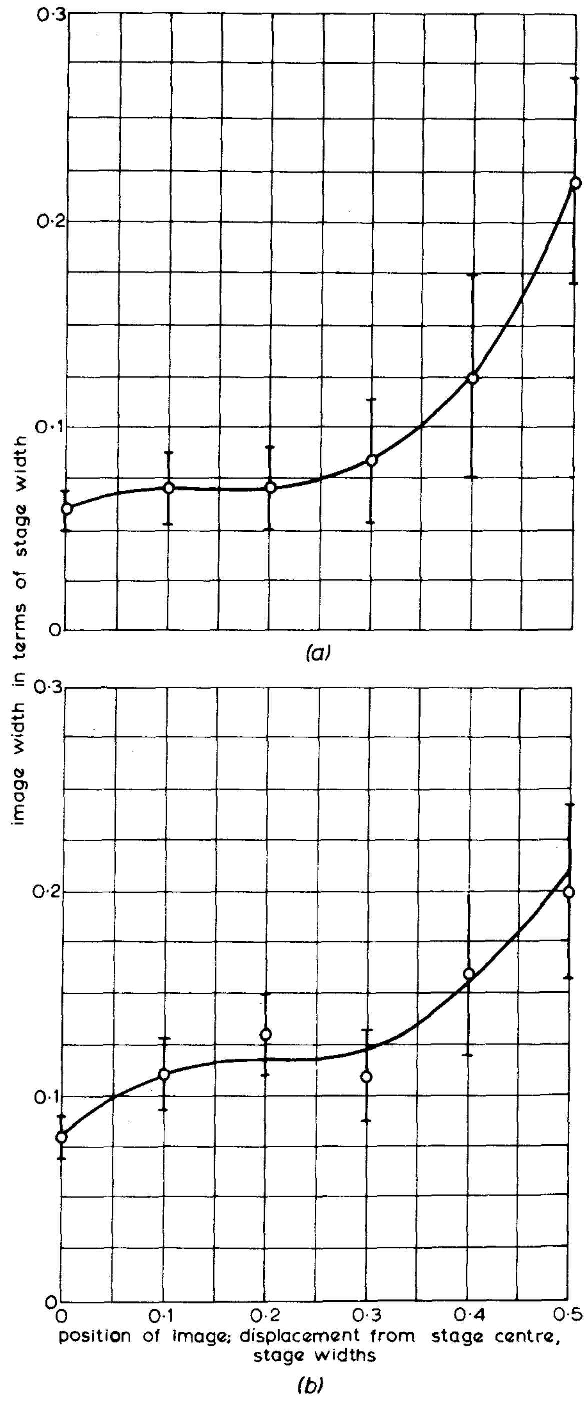


Fig. 9 - Variation of Image Width with Image Position

(*a*) In Listening Room (*b*) In Free-Field Room
Magnitude of One Standard Error about the Mean

4.2. Image Width

Figs. 9(*a*) and 9(*b*) show the relationship between width of image and image position for tests in the listening room and free-field room respectively. For tapes 0 to 4 these results were obtained from the team averages for the positions of the inner and outer edges of the image. For tape 5 it was not generally possible to displace the inner edge of the image to the tape, as this involved displacing the centre to a position beyond the corresponding loudspeaker axis; the image width could not therefore be obtained directly. However, an examination of the results for the other positions showed that the position assigned by the team to the centre of the image was in fact very closely half-way between the two edges and it was assumed that this would probably hold at tape 5 also; to obtain the point plotted for tape 5 the difference between centre and outer edge of the image was therefore doubled.

It will be seen that up to 0·4 of a stage width the image is always narrower in the listening room than in the free-field room with a fairly constant ratio of 1 to 1·4; moreover the standard errors are similar in the two rooms for the same image positions so this difference cannot be accounted for by the test being more difficult in one room than in the other.

At tape 5 the values of image width, having been estimated, are somewhat less certain, but the value is the same in both rooms and, as a matter of interest, amounts to about two thirds of the loudspeaker width. For this image position the sound is radiated almost entirely from one loudspeaker and so it might be expected that as faults due to imperfect matching of the two loudspeakers are at a minimum the image would be sharpest. What is surprising therefore is that the image width at stage centre is only about one third of that at tape 5; it is possible that if observers had always faced the image rather than the stage centre, this result would have been different for the off-centre image positions.

The median value of the minimum perceptible shift for a central image in the listening room is 0·03 of a stage width, with a standard error of 0·007; the corresponding figures for the free-field room are 0·02 and 0·003 of a stage width. It will be seen therefore that the limit determined by the powers of discrimination of the ear has not been reached and it would seem that given suitable conditions the image width even for a central image could still be appreciably reduced.

The results were further analysed to see if there was any correlation between the width of image determined by a particular subject and the interchannel level difference necessary to displace the image position by a given amount. It is clear that for image positions near the stage centre such a connection must exist; for example, it is almost certain that a person who hears an image extending almost to tape 1 will require less interchannel level difference to displace the image to that tape than will someone for whom the image is narrower. The analysis showed this expected correlation for tape 2; for tapes 3 and 4, however, the correlation coefficients were too low to be significant. These low values are in part due to the smallness of the team, 12 persons, but it seems probable that even if a larger sample were taken the correlation would not be very marked.

4.3. Effect of Shuffle Circuit on Image Width

In the second set of experiments the median value for the image width at tape 3 in the free field room when the shuffle circuit was used was 0·16 stage width, with a standard error of 0·025; the value obtained without this circuit and shown in Fig. 9(*b*) was 0·11 stage width, the standard error again being 0·025. It is seen that the effect of the circuit, far from reducing the image width, has been to cause an increase in width which is just significant. At this particular tape position L/R = 9 dB and the 3 dB step (Fig. 6) in the ratio of sum signal to difference signal ((L + R)/(L - R)) by the circuit at high frequencies changes the ratio of the signals in the left and right channels by 3 dB also; from Fig 7(*b*) it can be seen that an interchannel difference of this amount will displace the image by 0·09 stage width. As, however, the image width has been increased by only 0·05 (from 0·11 to 0·16) stage width it appears that the frequency components causing the increased width could previously have been well inside the image area.

5. COMPARISON WITH PREVIOUS WORK

The results given in curve (*a*) of Fig. 7 for the measurements in the listening room of the relation between image position and interchannel level difference have been replotted in Fig. 10, together with some of those from Fig. 1. It will be seen that they agree extremely well with those of de Boer and with those obtained at high frequencies by Leakey. On the other hand, the values obtained by both Clark et al and Leakey at low frequencies are well removed from our results.

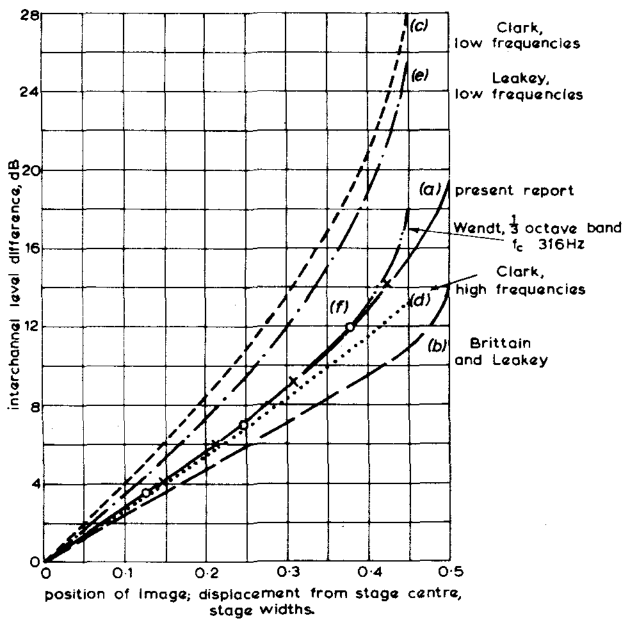


Fig. 10 - Relation between Image Position and Interchannel Amplitude Difference. Comparison with Previous Work

o Leakey, High Frequencies
× De Boer

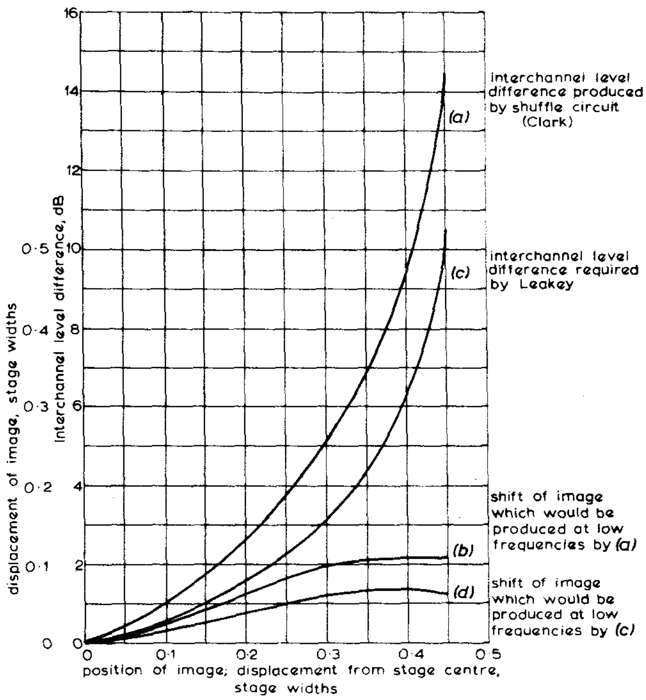


Fig. 11 - Variation in Image Parameters with Image Position

The difference between their high frequency and low frequency curves implies that in the absence of a shuffle circuit the width of image should vary in a corresponding manner and it is of interest to calculate this variation. The difference between the curves is plotted for both authors in Fig. 11(*a*) and (*c*) and the corresponding displacements of the edge of the image obtained with the aid of Fig. 10 is shown in Fig. 11(*b*) and (*d*). If it is assumed that the image area originally contained all frequencies uniformly distributed, then the width should be increased by an amount corresponding to these displacements. Fig. 12 shows the result obtained when the width for a central image, which the shuffle circuit cannot affect, is superimposed on Figs. 11(*b*) and 11(*d*). It will be seen that the resulting curves do not bear a very close resemblance to that of the actual image width obtained and shown in Fig. 9(*a*) and in Fig. 12 and thus throw further doubt on the validity of a shuffle circuit with these constants. The theories of Clark et al and Leakey both assume that the observer always faces stage centre, but it is not explicitly stated whether this condition did apply in their supporting experiments. They show that a change of head angle does affect the image position to some extent but no information is given as to the effect on image width.

It was shown in the previous section that the image width was less in the listening room than in the free-field room for a spectrum containing little energy below 100 Hz. This is in contrast to the results of other tests[10] in which most of the energy was below 100 Hz. In the latter case the programme consisted of plucked double bass, drum and organ and the image at stage centre was wider in the listening room, although least so for the organ which in turn had more sound energy above 100 Hz than did the other two programmes. It appears therefore as though at the bass end of the spectrum the effect of the acoustics of the listening conditions on the image width at stage centre varies somewhat with frequency.

6. FUTURE WORK

It has been shown that there is some agreement in the literature on the need for a form of shuffle circuit but the transition frequency and amount of the step appear to be based on rather scanty data. It should therefore be profitable to repeat Leakey's work with octave bands of noise over a wider frequency range in order to determine the optimum frequency characteristic and height of the step, and then to check whether in fact this relationship does appear to hold for a wide-band signal. It should be noted, in this connection, that neither of the theories proposed by Leakey and Clark and given in Section 3 takes account of the precedence effect whereby one sound reduces the apparent level of other sounds immediately following it. Leakey also admits that signals covering only a narrow frequency band give results differing from those having a wider band, and it is not clear whether signals extending over an octave will give the same results as programme.

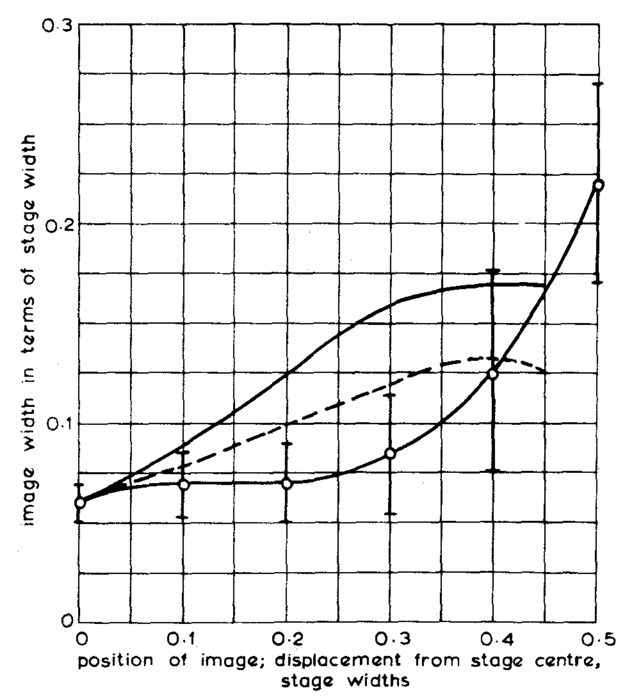


Fig. 12 - Measured and Calculated Variation of Image Width with Image Position

---- Leakey, Shift added
—— Clark et al. Shift added
Magnitude of One Standard Error about the Mean

In these tests it has always been assumed that the observer should be in a central position facing straight ahead. An examination of the data on the variation of diffraction around the head[2] and of the interaural time difference[1] with the angle of the incident sound wave indicates that the directional data supplied to the ears does not vary appreciably for angles of incidence up to ± 40° in the horizontal plane. The natural reaction, however, when attention is focussed on a particular sound is to face the direction from which it appears to come, and the possibility should be examined that if such a movement is prevented this may have an effect on the image width, and thus afford some explanation of the results given in Fig. 9. Such an effect would in some ways be similar to the corresponding optical case in which visual acuity is higher for an image in the centre of the retina than for one at the periphery. For the tests described, image width is already smaller in the listening room than in the free-field room and this fact suggests that no improvement over the range covering speech frequencies would be obtained by increasing the ratio of direct to indirect sound. The use of directional loudspeakers might help however to reduce image width for listeners in off-centre listening positions, and possibly at the lowest frequencies for those in a central position. In this connection the effect of the width of the loudspeaker cabinet on image widths should also be examined.

7. CONCLUSIONS

The relation between stereophonic image displacement and the interchannel level difference has been obtained both in a typical listening room and in a large free-field room for observers facing stage centre. The results in the two rooms are very similar and show a substantially linear relationship over most of the stage width; the bias for the team and the average bias for individuals in these experiments have also been determined for the differing image positions chosen.

The image width shows an unexpected variation with position across the stage and is much smaller at the stage centre than at the edges. The variations between individuals were similar in the listening and free-field rooms, but the absolute widths were greater in the latter; measurements of the minimum perceptible shift at the centre position show that even for this position where the image is narrowest a reduction in width would still be observable.

The circuit claimed by Clark et al to reduce image width has been tested subjectively for one image position which it was thought would show such an effect most clearly. The measurement gave the unexpected result that the effect of the circuit has been to increase the image width by an amount which is statistically just significant.

Further investigations which should be undertaken have been indicated.

8. REFERENCES

1. DE BOER, K. Stereophonic Sound Reproduction. *Philips Tech. Rev.*, 1940, **5**, 4, p.107.

2. SIVIAN, L.J. *and* WHITE, S. 1932. On minimal audible sound fields. *J. acoust. Soc. Am.*, 1933, **4**, 4, pp.288 - 321.

3. BRITTAIN, F.H. *and* LEAKEY, D.M. 1956. Two channel stereophonic sound systems. *Wireless Wld.*, 1956, **62**, 5, pp.206 - 210.

4. CLARK, H.A.M., DUTTON, G.F. *and* VANDERLYN, P.B. 1957. The stereosonic recording and reproducing system. *Proc. Instn. elect. Engrs.*, 1957, **104B**, 17, pp.417 - 432.

5. DUTTON, G.F. 1961. The assessment of two channel stereophonic reproduction. *J. Audio Engng. Soc.*, 1962, **10**, 2, pp.98 - 105.

6a. LEAKEY, D.M. 1959. Some measurements on the effects of interchannel intensity and time difference in two channel sound systems. *J. acoust. Soc. Am.*, 1959, **31**, 7, pp.977 - 986.

6b. cf. Figs. 2 and 8(*b*) loc. cit.

6c. LEAKEY, D.M. 1960. Further thoughts on stereophonic sound systems. *Wireless Wld.* 1960, **66**, 4, pp.154 - 160, 5, pp.238 - 240.

7. WENDT, K. 1960, Versuche zür Ortung von Intensitäts - Stereophonie. *Frequencz,* 1960, **14**, 1, pp.11 - 14.

8a. Stereophony: the effect of crosstalk between left and right channels. BBC Research Department Report No. L-049/2, Serial No. 1964/1.

8b. The effect of crosstalk at high frequencies between left and right channels on stereophonic reproduction. BBC Research Department Report No. L-049, Serial No. 1961/17.

9. HARWOOD, H.D. 1962. The effect on stereophonic reproduction of frequency-dependent crosstalk between left and right channels. Fourth International Congress on Acoustics, Copenhagen, 1962, Paper N35.

10. Stereophony: the effect of differences between the amplitude/frequency characteristics of left and right channels. BBC Research Department Report No. L-049/4, Serial No. 1964/67.

SMW

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey