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The subjective performance of various quadraphonic matrix systems

Based on work by T.W.J. Crompton

Research Department, Engineering Division
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THE SUBJECTIVE PERFORMANCE OF VARIOUS QUADRAPHONIC MATRIX SYSTEMS

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Summary

This report describes experiments made to evaluate subjectively the sound reproduction which results in two-channel (stereo) and four-channel (quadraphonic) presentations when the four original channels of a quadraphonic programme are 'matrixed' or combined into two channels for transmission or recording. At the present stage, mono compatibility is discussed mainly from a theoretical standpoint.

It was found that the results obtained differed significantly between the various systems proposed, particularly with regard to stereo (and mono) compatibility.

A system suitable for broadcasting must cope with a very wide variety of programme material and the investigations show that the 4-2-4 systems currently used for discs have not, as yet, proved to be satisfactory. Some other 4-2-4 systems gave promising results and merit further study. However, as a result of experience some of these systems have been, and may continue to be, modified by their proponents to improve their performance. Throughout this investigation, which occupied more than a year, efforts were made to use current equipment representative of these systems.

It should be remembered that the final judgement of any quadraphonic system is a subjective matter and, particularly in the context of broadcasting, depends on a number of additional factors not considered in this Report.

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1. Introduction

Quadraphonic presentation of sound is capable of producing subjective effects that are impossible to create with a stereophonic system. This is particularly true where the programme material exploits the full potential of a quadraphonic system and generates, for the listener, a sense of participation. There are, however, a number of unquantified problems connected with the broadcasting of four-channel signals (e.g. problems of bandwidth and compatibility with present broadcasts) and any reduction in channel capacity requirements could be well worthwhile.

One approach, known as a '4-2-4' matrix system, combines the four original audio signals into two channels for transmission in such a way that they resemble conventional stereo; they can be decoded if desired, by additional circuits at the receiver, into four channels again, albeit with crosstalk. When fed to four loudspeakers, these reconstituted signals hopefully give a satisfactory approximation to the original sound. A number of such matrix systems have been adopted commercially and indeed discs have already been issued by some recording companies using one or other of these systems.

In order to evaluate how satisfactory '4-2-4' systems are likely to be in practice, a series of subjective tests has been carried out with listeners skilled in assessing high-quality sound-reproduction.

2. Experimental details

2.1. Test material

In order to provide test material representative of broadcasting microphone techniques the subjective tests used, in the main, two tapes, (a) a 'cardioid' test tape, and (b) a 'pan-pot' test tape.

The cardioid test tape was recorded using four 'coincident' microphones, each having a cardioid response, which were arranged so that they faced out along the diagonals of a square (Fig. 1). This array was placed in a studio, together with a high quality loudspeaker which acted as a sound source. The loudspeaker was located about two metres (six feet) from the microphone array, and the latter was rotated through the appropriate horizontal angle to simulate the arrival of sound from different directions. Sixteen angular positions were used, each spaced by 22·5°. The four microphone signals were amplified and recorded on a four-track tape recorder.

The 'pan-pot' test tape was generated electrically by recording a signal on selected pairs of the four tracks, corresponding, on replay, to pairs of adjacent loudspeakers. The signal was divided between the pairs of tracks according to the usual sine-cosine law used for pan-pot stereo.

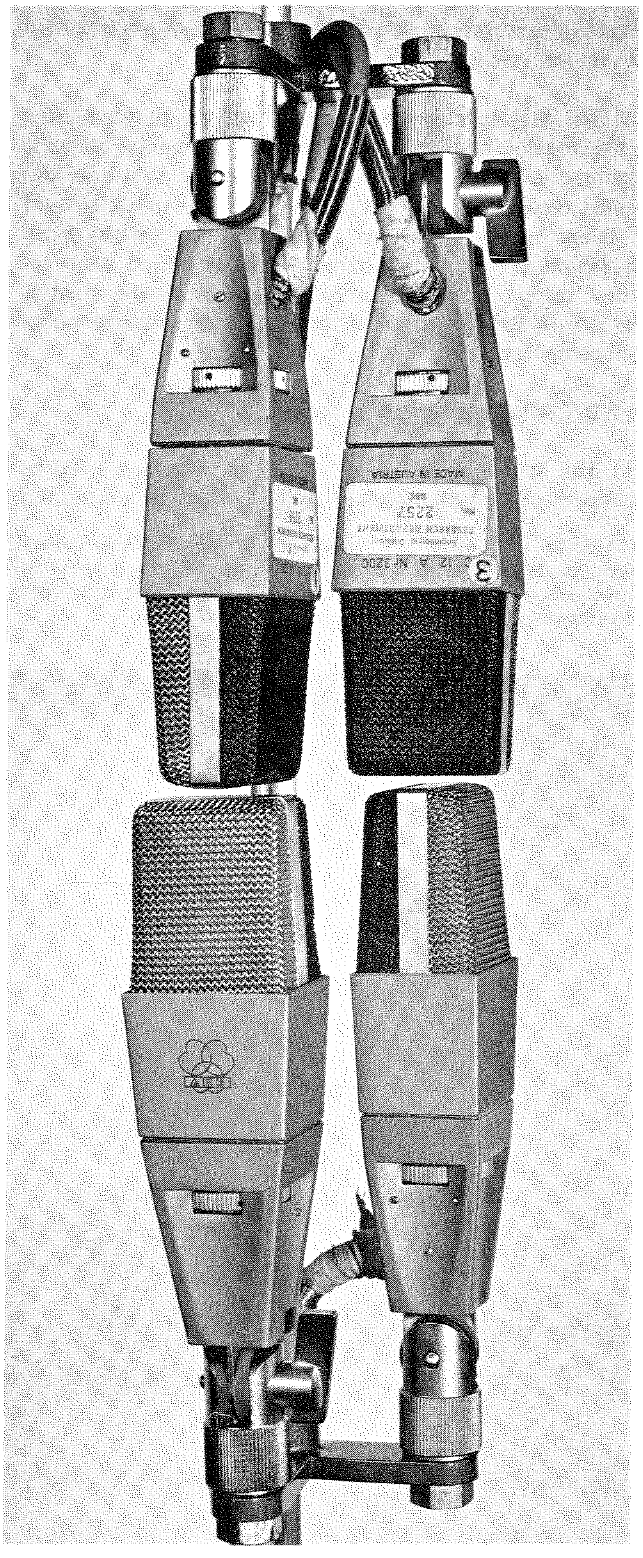

Fig. 1 - Coincident cardioid microphone array

Both the cardioid and pan-pot test tapes used the same programme extracts. These consisted of 30-second passages of four items; percussive music, female singing with an orchestra, male speech and pink noise. The various extracts and directions of presentation were selected in random order when recording both tapes. For reasons to be discussed in Section 5.1, the pan-pot source material used for the stereo compatibility tests was an extract of a news bulletin (male speech only).

The test tapes were used to assess the performances of the matrix systems using isolated stationary sources. Further qualitative tests were carried out to find how the systems responded to multiple sources; the material used for these further tests was a selection of excerpts from quadraphonic programme-items, some of which were recorded using a cardioid array, and others were quadraphonic 'mix-downs' produced from multi-microphone multi-track recordings.

2.2. Coding and decoding apparatus

The four signals from the tape recorder were fed to the inputs of a multi-standard coder,* which generated the two coded outputs, 'Left' and 'Right'. These were then either fed directly to loudspeakers for the stereophonic tests or, alternatively, were passed through a decoder* which reconstituted the four signals required for the matrix quadraphony listening tests.

* The coder and decoder, designed by P. Shelswell of this Department, could be set up to provide any required four-channel to two-channel, and two-channel to four-channel phase-and-amplitude (complex-coefficient) matrices.

Tests involving logic-controlled decoders used coding and decoding apparatus supplied by the particular system proponent concerned.

2.3. Listening conditions

The listening room was approximately 5·4 m x 4·2 m (17 ft x 13 ft) by 2·8 m (8½ ft) high, had a carpeted floor, and had acoustic treatment on the walls and ceiling, giving a reverberation time of about 0·35 second.

For the quadraphonic tests, four identical high-quality loudspeakers were placed on plinths at the corners of a square of side 3·1 m (10 ft) and were arranged to face the centre of the square, where the observers sat, one at a time, in an accurately placed chair. The observer faced the centre of one side of the square and was allowed to turn his head slightly. The apparent direction of the sound was assigned a numerical value by reference to a chart (Fig. 2) fixed directly in front of the subject.

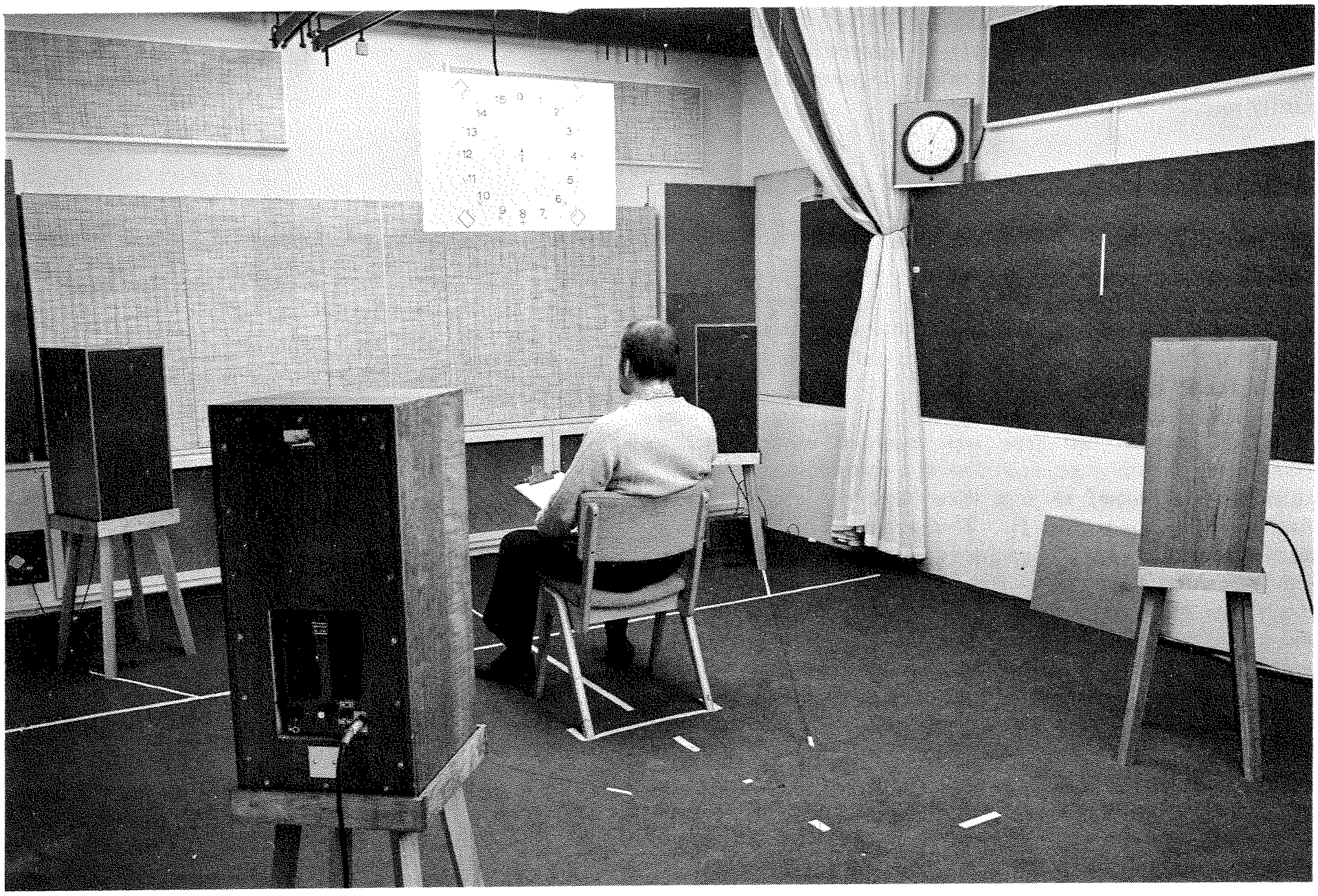

Fig. 2 - Quadraphonic listening conditions

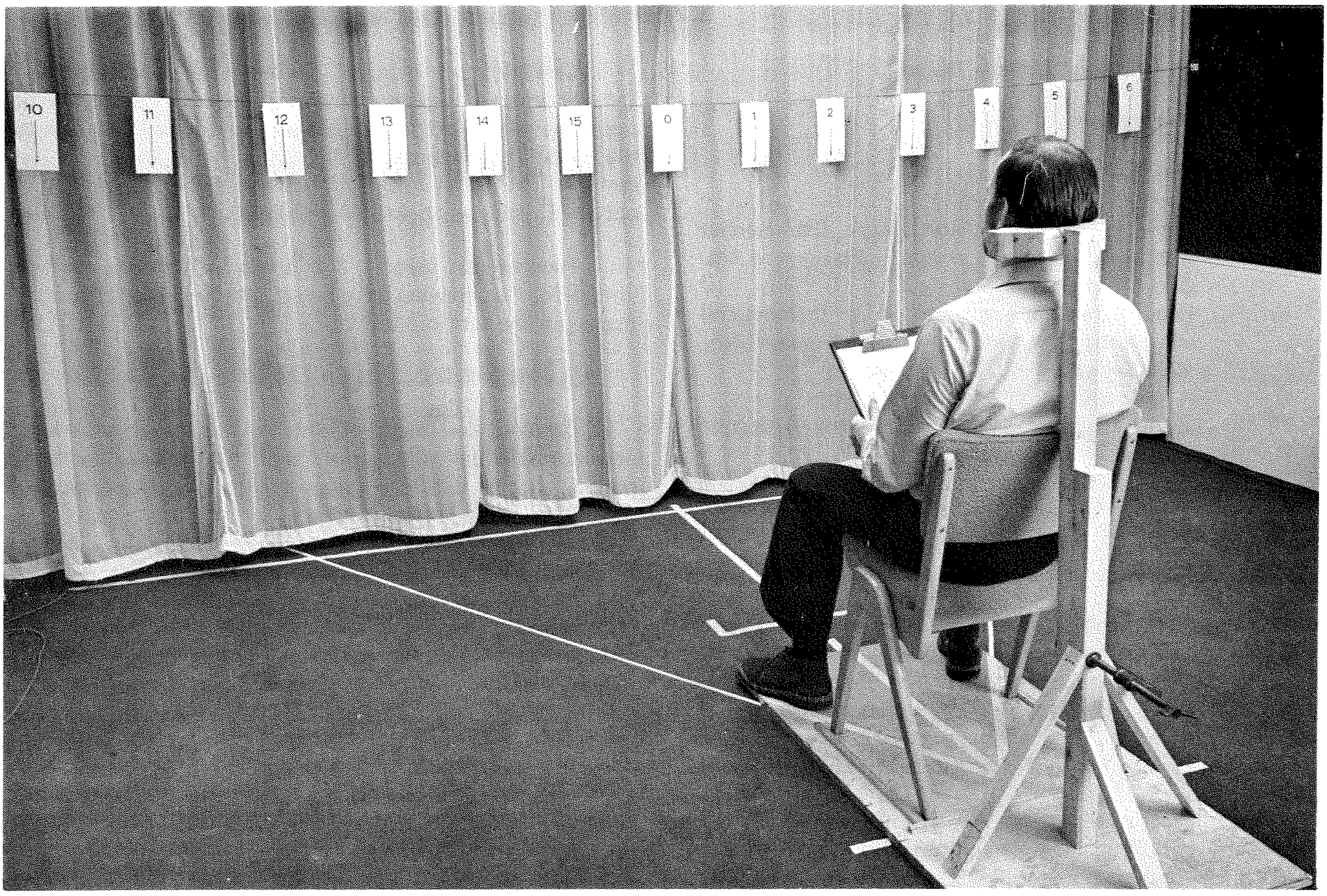

Fig. 3 - Stereophonic listening conditions

For the stereo tests the observer's chair was moved to a position further towards the back of the room, so that the two front loudspeakers subtended 60° at the observer, as is normally recommended for stereo listening and the two loudspeakers were re-oriented slightly so as to face the observer. Acoustically transparent curtains were then drawn in front of the loudspeakers and thirteen equally-spaced numbered markers were suspended on the curtains so as to enable numerical judgements of image position to be made; these markers were 0·3 m (1 ft) apart, and there was a total of eight spaces covering the 60° sound stage. Two additional markers were included at each end of the sound stage beyond the loudspeakers to cater for the possibility of some of the reproduced images falling outside the ±30° angular range (Fig. 3).

It was found that the exact lateral position of the observer's head was very critical indeed when judging the position of a central image and so, for the stereo tests, an additional support for the back of the head was used. This support constrained lateral movement of the head to about ±25 mm (±1 inch) but still allowed an amount of head rotation sufficient to enable the listener to face the apparent source if desired.

A short experiment was carried out to evaluate the use of such a headrest during quadraphonic tests in the listening-room environment, but it was found that more accurate and consistent results were obtained when the head was allowed more freedom of movement. The headrest was therefore only used during the stereo tests.

3. Matrixed quadraphony tests

3.1. Systems tested

Table 1 lists the matrices that were tested. Full details of the matrices, their derivation and relevant formulae, are given in the Appendix.

Matrices C and D are the commercial 'QS'[1] and 'SQ'[2] systems respectively, using 'logic-controlled' decoders.* A and B have the same matrix equations as C and D respectively, but use simple decoders without logic enhancement.

Matrix E is one example of a family of high-separation tetrahedral matrices suggested by Scheiber.[3]

Matrix F is a 'symmetrical' matrix virtually identical to the 'BMX' matrix suggested by Cooper and Shiga.[4]

Matrices G and H are two of the matrices that have been derived in an attempt to improve the stereophonic

* See Appendix.

TABLE 1

*Matrix Systems Tested**

Matrix	Description
A	The 'QS' matrix (Japan)
B	The 'SQ' matrix (USA)
C	Logic controlled version of A (commercial equipment: quad. only). Equipment No. QSE-4 and QSD-4.
D	Logic controlled version of B (commercial equipment: quad. only). Equipment No. 4200 Series.
E	A 'high-separation tetrahedral' matrix
F	'Symmetrical matrix': a simplified version of the BMX matrix
G	A stereo-mono compatible matrix
H	'Hearing-properties matrix': parameters optimised to exploit certain restrictions in hearing acuity.

(and monophonic) performances of 4-2-4 matrices; these also are aimed at reducing the objectionable effects of phase shifts, and can be used with both cardioid-derived and pan-pot material. G is a fairly symmetrical matrix and H exploits further the limitations of hearing acuity with quadraphonic presentation[8] for a forward-facing listener.

A further arrangement was assessed as a 'control' during the investigation of stereo compatibility. This was the 'front-back blend' system which was derived simply by adding (without phase-shifts) the left-front and left-back inputs to form the 'left' stereo signal, and the right-front and right-back inputs to form the 'right' stereo signal. It provided an indication of image sharpness that could be expected in the stereophonic listening tests.

3.2. Test procedure

The coder and decoder were adjusted in accordance with the equations appropriate to the matrix system under investigation. The signals from the tape recorder were connected to the inputs of the coder, and the two coder outputs were fed directly to the decoder. The decoder outputs were connected to the appropriate loudspeakers in the listening room and each test tape was played to five experienced observers (one at a time). The observers were asked to judge the apparent positions and 'spreads' (total angular widths) of the sound images, and to note any comments relevant to the reproduced sound, such as elevated image' or 'double image', etc.

4. Results of the matrixed quadraphony tests (4-2-4)

The average results of the quadraphonic listening tests are summarised in Table 2, and are discussed in more detail in the subsequent sub-sections. These tests were carried out during the period January to May 1973.

* It is understood that all these systems are the subject of patent applications.

4.1. Matrix A (QS: without logic)

Cardioid test tape: 'In-the-head' sensations and 'double' images were reported very frequently and some of the observers failed to allocate any particular direction to the sound images produced by some of the 30-second test items. The mean image spread was some 2½ times that obtained with the original (4-4-4) tape.

Pan-pot test tape: 'Non-locatable', ambiguous and 'in-the-head' comments were noted, although less frequently than with the cardioid test tape.

4.2. Matrix B (SQ: without logic)

Cardioid test tape: Some of the assessments were non-locatable or ambiguous, and 'in-the-head' effects, double images, and 'anti-phase' effects were reported frequently. The overall results were less satisfactory than those for matrix A.

Pan-pot test tape: Although the pan-pot results represented a small improvement over the cardioid-array results, the opinion given by some observers was that this matrix produced rather unpleasant 'in-the-head' effects.

4.3. Matrix C (QS: with logic)

Cardioid test tape: The results for this logic-controlled decoding matrix indicate a slight improvement on matrix A (which was a 'fixed' decoder), but the mean positional error and mean image spread results are still rather unsatisfactory.

Pan-pot test tape: The pan-pot results obtained with this matrix were generally the best of those obtained in the tests, and a noticeable improvement on those for matrix A. This was considered to be a satisfactory set of results and so further tests were conducted using typical programme material.

Qualitative test tape: The logic decoder did not cope satisfactorily with what was considered to be typical programme material. One recorded item of dance music, for example, contained a piano originally located at front-right. The beginning of each piano note was initially reproduced at centre-front and the image then moved rapidly across to the front-right loudspeaker and back again in time with the music. Whilst this form of logic decoding worked well with isolated single stationary sources (as recorded on the pan-pot test tape), the results with typical programme material were rather disturbing, especially for extended periods of listening.

4.4. Matrix D (SQ: with logic)

Cardioid test tape: Many of the assessments of image position were seriously mislocated,* and ambiguous**

* In error by 135° or more.

** Appearing to come from either one of two positions, 135° or more apart, (perhaps) according to the listener's mental concentration on one or the other.

TABLE 2

Results of the Matrix Quadraphony Tests

Matrix	CARDIOID TEST TAPE			PAN-POT TEST TAPE		
	Mean Positional Error (mean error w.r.t. original position)	Mean Image Spread (total angular width of reproduced image)	Anomalous Assessments* (mislocated ambiguous 'in-the-head' or unlocatable results)	Mean Positional Error	Mean Image Spread	Anomalous Assessments
A	20°	102°	26%	22°	75°	9%
B	32°	113°	25%	27°	104°	18%
C	25°	81°	16%	7°	34°	6%
D	29°	151°	34%	19°	135°	28%
E	16°**	95°	19%	11°**	87°	21%
F	See Section 4.6 and Appendix			14°	66°	5%
G	12°	72°	17%***	15°	63°	3%
H	12°	50°	10%***	9°	47°	9%***
Discrete (4-4-4) for comparison	8°	39°	1%	5°	20°	0%

* Where the position of the reproduced image was judged to be ⩾135° from the position of the original source, or where the parts of a 'double-image were ⩾135° apart, or where the total subjective spread of the image exceeded 135°, the assessment was judged to be 'anomalous'. These anomalous assessments are included in the calculation of mean image spread but are not included in the mean positional error.

** Rear-quadrant totally ambiguous and reproduced in front; therefore excluded in the 'Mean Positional Error' (see Section 4.5).

*** For the general nature of these anomalies see discussion of results, particularly Section 4.7.

results were noted. The mean image-spread was also increased compared with that produced using matrix B (no 'logic').

Pan-pot test tape: The arrangement was again found to be very unsatisfactory with regard to image-spread although, for this test, the mean positional error was reduced significantly. Most of the observers' assessments included comments on severe image wandering even for originally static single sources, and 'in-the-head' sensations were also reported; in addition some assessments of location were ambiguous. Objective measurements on the unit supplied (see Appendix A1.1) indicated that it might be expected to behave in an unsatisfactory manner, and the manufacturere have, very recently, proposed decoders which employ more sophisticated forms of logic control. These will be tested when they become available.

Qualitative test tape: When compared directly with the discrete quadraphonic programme material, particularly that derived from cardioid microphones, the reproduced image mislocations were often very obvious. 'In-the-head' sensations and audible logic action on some items were found by most observers to be objectionable.

4.5. Matrix E ('high-separation' tetrahedral matrix)

Cardioid test tape: Although there were few unfavourable remarks in the 'comments' column of the test forms, subsequent analysis of the subjective positions of the sound images revealed that there was a significant proportion of bad mislocations.* In general these occurred when the original direction of the source was from behind the listener, although occasional ambiguities occurred when the original location was elsewhere.

Pan-pot test tape: Some assessments were accompanied by comments on unpleasant 'anti-phase' or 'in-the-head' effects, and again mislocations and ambiguities were experienced when the original source position was in the rear quadrant.

* In error by 135° or more.

4.6. Matrix F (symmetrical matrix)

This matrix encodes correctly only for 'pan-pot' signals: different encoding equations are required for the cardioid type of signal (see Appendix). Thus only the pan-pot test tape was used for the locational-accuracy and image-sharpness assessments.

Pan-pot test tape: The overall result was satisfactory, being slightly worse for mean positional error than matrix E* (excluding centre-back) but better with regard to image spread and anomalous assessments. Only one of the five subjects reported any 'in-the-head' and non-locatable items.

Qualitative test tape: Listening tests involved various items of recorded music and drama were also fairly satisfactory. There was, however, a tendency for many of the images to be somewhat elevated, giving to the listener an impression of his being 'seated in a hole'. This was more noticeable on items which originated from cardioid microphones. However, the horizontal component of positional accuracy was very good.

4.7. Matrix G (stereo-mono compatible matrix)

Cardioid test tape: Despite the overall comparatively good result, the matrix was not entirely free from unfavourable comments; some 'double' images were reported and some 'asymmetrical-spread' effects were noted.

Non-locatable and 'in-the-head' effects accounted for only 4½% of the assessments, but subjectively less disturbing subsidiary-location ambiguities** (associated usually with the 'double' images) made up the further 12½%. These effects may have been caused by the asymmetric crosstalk generated by this matrix (see Appendix A1.4). The mean positional error was 1·5 times that obtained with the reference tape. These results compare favourably with those obtained with other matrices.

Pan-pot test tape: Once again encouraging results were obtained with this matrix.

Qualitative test tape: Listening tests with items of recorded music and drama were satisfactory. Images in the side quadrants were more sharply defined than with the other systems,*** but this advantage only seemed to hold when the observer sat in the front-facing chair. This point needs further investigation.

The relatively high crosstalk components generated by this matrix (and indeed by all the non-logic controlled decoding matrices) did not cause any gross mislocations of images but listeners commented on a 'closing in' effect when switching from 4-4-4 to this 4-2-4 system.

* Note that mean positional error results for matrix E excludes its ambiguous centre-back position.

** An effect whereby the main image is at full amplitude in the 'correct' location, but it has a 'subsidiary' (but somewhat audible) image at low amplitude elsewhere.

*** Including 4-4-4 (discrete) quadraphony, which itself does not give as sharp side-quadrant images as elsewhere.[8]

4.8. Matrix H ('hearing-properties' matrix)

The results for matrix G led to an investigation of the effects of minor variations to it,* with particular regard to factors which were likely to be advantageous to a listener seated in a front-facing chair.[8] This led to the development of matrix H.

Cardioid test tape: It was found that the mean positional error for this matrix was the same as with matrix G, but the mean subjective image spread was reduced significantly. The proportion of 'anomalous' assessments was also reduced significantly, although such anomalies as did occur were of similar psycho-acoustic nature to those reported by some observers in the matrix G tests (see Section 4.7, footnote**). This matrix gave the best result of all the 4-2-4 matrices tested when using the cardioid-array test tape as source material.

Pan-pot test tape: The mean positional error and mean subjective image-spread results were significantly better than those obtained from all other non-logic controlled matrices. The anomalies obtained were of the same nature as those which occurred with the cardioid test tape.

Overall, the results indicate that this matrix gives satisfactory and similar results whether cardioid or pan-pot material is used.

Qualitative test tape: Using a selection of various programme material, the 4-2-4 presentation was judged to be a better approximation to the 4-4-4 reproduction than was obtained with the other non-logic matrices, although for most items the observers preferred discrete quadraphony, when permitted to make a direct comparison. This preference was again due to a 'closing in' effect as observed using matrix G.

5. Stereo compatibility tests (4-2-2)

5.1. Test procedure: resumé

The conditions for these listening tests and the equipment arrangements are outlined in Section 2. The tests continued until July 1974.

Each of five observers was asked to judge the apparent positions of the sound images and their total widths (angular subtenses), making use of the head rest to restrict lateral head movements. The intervals between the numbered markers on the curtains (see Fig. 3) subtended angles of 7·5° at the listening position. As with the quadraphonic tests, the observers were requested to report any unusual or unpleasant effects. The cardioid-array test tape with randomly positioned items was used as source material for the stereo tests; also further tests were carried out using

* Using a computer program derived by D.J. Meares.

a 16-position pan-pot test tape, containing a high-quality extract from a news bulletin (i.e. male speech only). This was less tiring to the observers. As explained in Section 6.1, high-quality male speech was found to be a more reliable and representative item for location and image-spread tests of this type.

5.2. Interpretation of matrix-stereo results: positional compatibility

Good positioning of stereo images, when they are derived from quadraphonic source material, is to some extent an artistic matter, and the most subjectively satisfying solution to this problem may vary according to programme material. It is hence not possible to assign a generally agreed numerical parameter to this concept, although it is possible to make useful general comments on the positional results obtained by the various systems.

Most listeners would agree that a front-centre sound source in quadraphony should give rise to a central image in stereophonic presentation; likewise back-centre, by symmetry. The problem arises as to whether there is a 'preferred' distribution of images which should result from sound sources located originally around the circle (Fig. 4). It might be expected that a subjectively satisfying result would be one in which the sound images are distributed fairly evenly across the stereophonic stage, with little evidence of 'bunching'. By way of example, if certain images were permitted to be placed slightly outside* the normal stage width, an 'equi-spaced' distribution for images from L_B through front-centre to R_B (as in Fig. 4) could be envisaged. However, this distribution of images 'compresses' sources originating in the front quadrant (14 to 2) into only half of the normal stereophonic stage width. This is considered by many to be undesirable for some types of programme (e.g. classical music concerts).

On the other hand, an alternative distribution giving the full stereo stage width to the front quadrant gives rise to a different but still somewhat undesirable situation with regard to stereo positional compatibility. Most of the current 4-4-4 (and some 4-3-4) proposals for discs and broadcasting generate 'front-back blend' stereo which can result in the whole 90° of each side quadrant becoming completely superimposed at the left or right loudspeakers.

As already mentioned in Section 3.1, a 'front-back blend' was included in the 4-2-2 tests as an indication of image sharpnesses and reproduced image positions which might be expected of a two-channel stereo system derived

* This may be achieved in practice by the use of suitable phase relationships.[7]

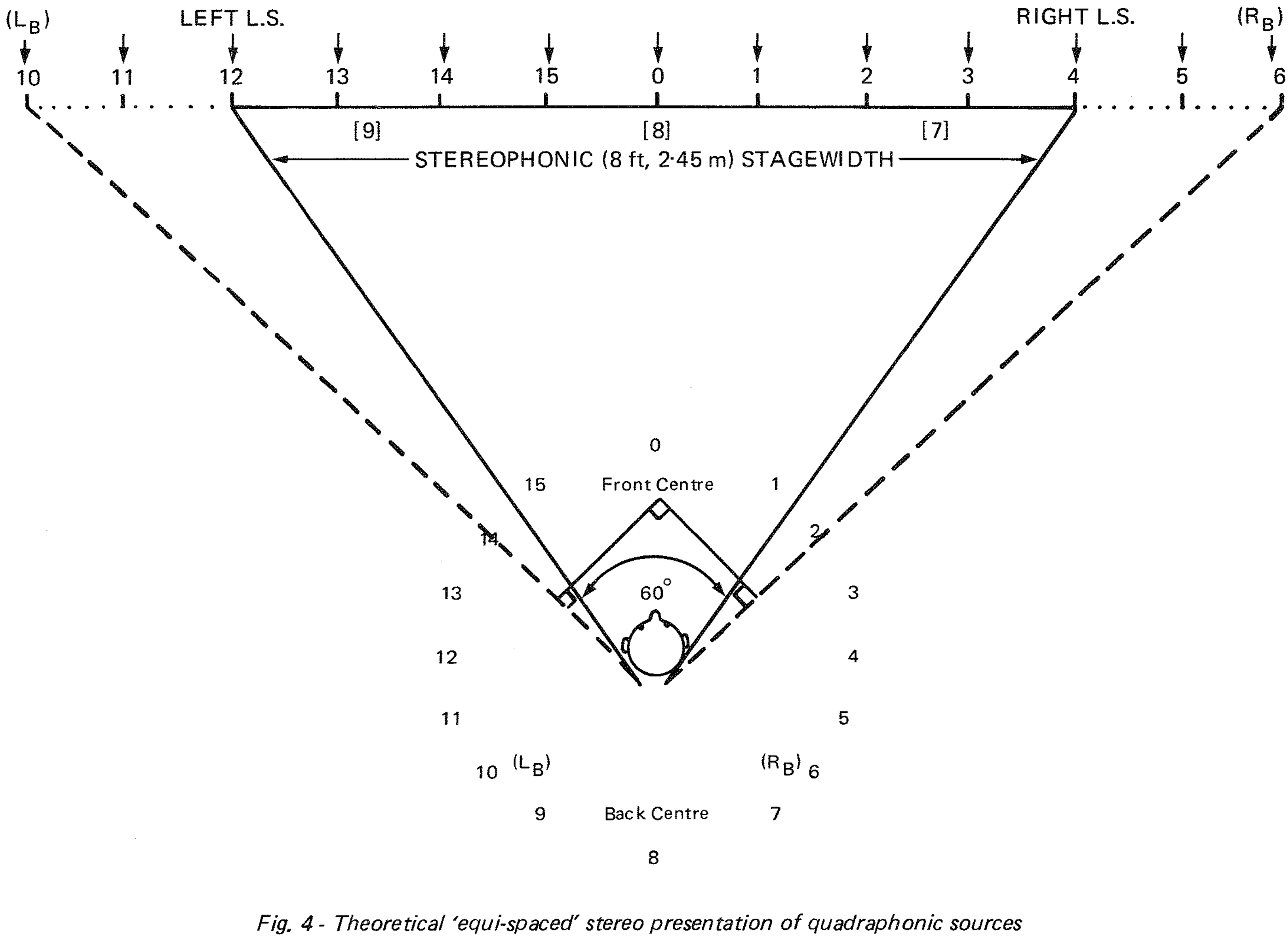

Fig. 4 - Theoretical 'equi-spaced' stereo presentation of quadraphonic sources

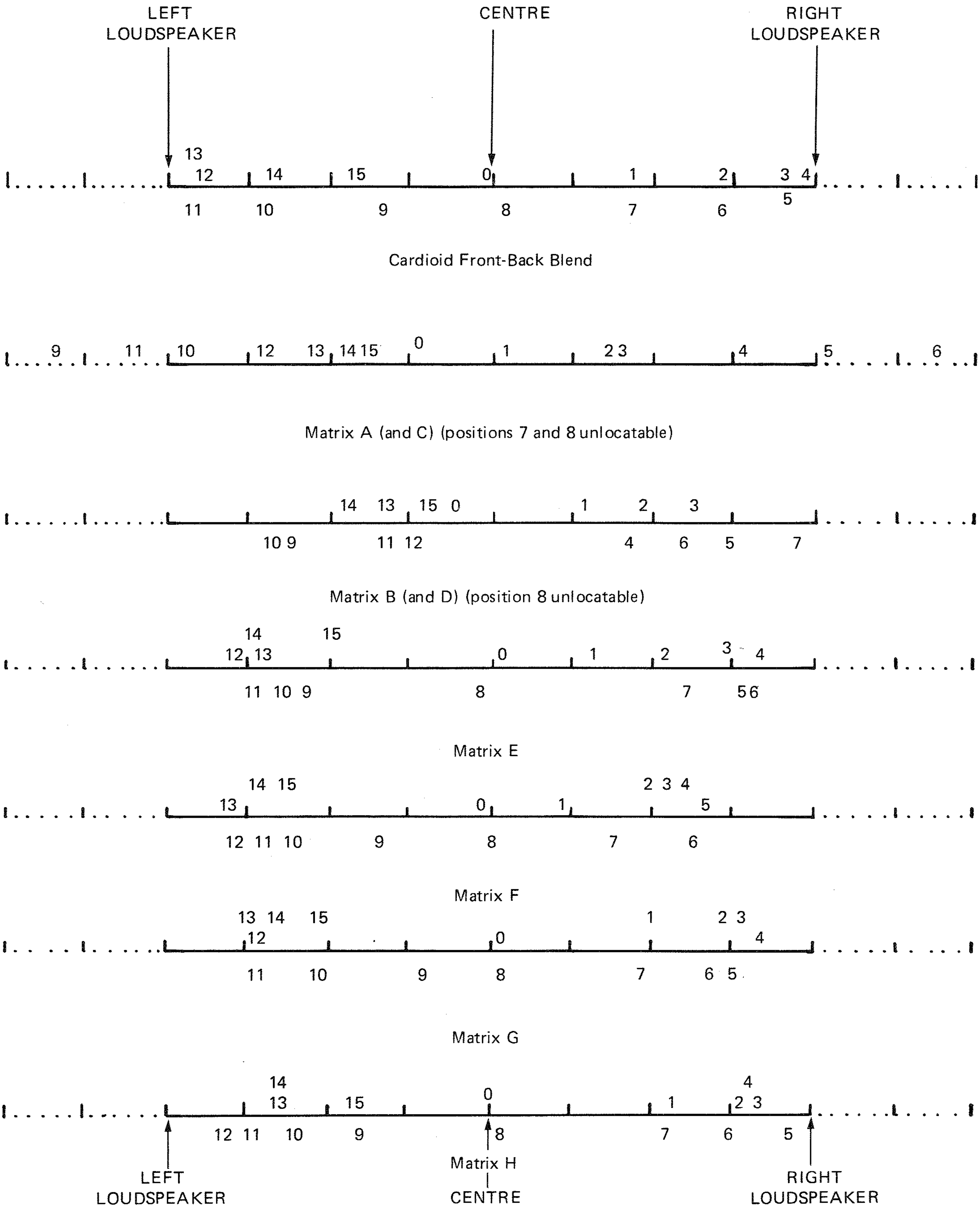

Fig. 5 - Subjective image positions — matrix stereo (cardioid-array material)

from four-channel material. Although this gives satisfactory image-position results for signals derived from four cardioid microphones (see Fig. 5), it is a very unsatisfactory method for deriving stereo from multi-microphone or pan-pot quadraphonic signals, as it gives rise to the complete superimposition of side source locations together with the complete separation left-to-right, i.e. 'ping-pong' stereo (see Fig. 6).

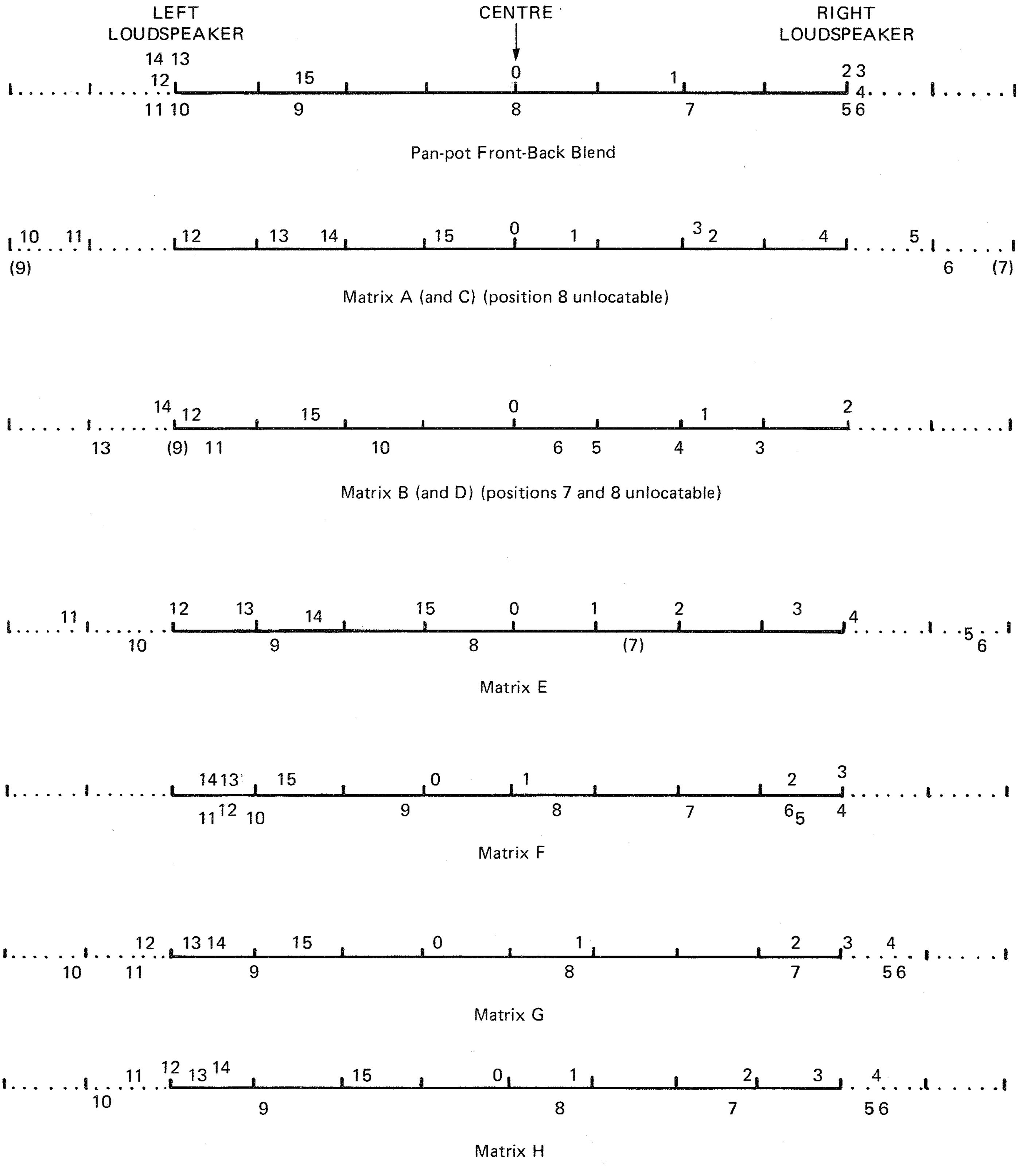

Fig. 6 - Subjective image positions — matrix stereo (pan-pot material)
Bracketed figures indicate positions found difficult to locate

Thus, taking into account the requirement that any distribution of quadraphonic images in the original programme material should be capable of giving a reasonable distribution of stereo images, some compromise must be made between front-quadrant separation and side-quadrant bunching.

It is suggested that a suitable compromise would be for the front quadrant to occupy, say, three-quarters of the stage width, with left-centre and right-centre sources being reproduced at or slightly beyond the loudspeakers, the rear quadrant being approximately 'mirrored' onto the front, perhaps either slightly wider or slightly narrower than the front quadrant.

6. Results of stereo compatibilty tests

The average positional distributions obtained by using the various matrices, including the front-back blend arrangement, to derive two-channel mix-downs from quadraphonic cardioid material, are shown in Fig. 5. The corresponding results for 'pan-pot' material are given in Fig. 6.

The average image-spreads (angular subtenses) produced by each system are shown in Table 3, together with the proportions of unlocatable images or anomalous assessments (image-spreads ⩾¾ of the stage width).

The stereo results obtained for matrix A also apply to matrix C as they both use the same coder; it is only the decoders that behave differently. Similarly, the stereo results for matrix B also apply to matrix D.

6.1. Front-back blend

Cardioid material: The average image-spread was assessed at about 10° (about one-sixth of the stage width). This was slightly higher than expected, but it should be remembered that the source material was recorded using four cardioid microphones in a real studio with reverberation present from all directions. The subjective positional distribution of images (Fig. 5) compares well with the distribution that would be expected from a consideration of interchannel level differences.

Some of the image sharpnesses were fairly poor, particularly 'pink noise' items, which in some tests exhibited 'double-image' or frequency-selective effects which were probably due to the characteristics of the added reverberation. This effect may well be one of the unavoidable consequences of deriving signals from microphones giving total 360° angular coverage in an acoustically 'live' environment. Male speech items gave results closest to the average, and so this item alone was used for the pan-pot tests.

Pan-pot material: The image sharpnesses produced by the front-back blend were consistently good from all original source directions, the average subtense value of 8° being typical.

60% of the observers noticed that the centre-side locations were reproduced in stereo at a higher sound-level relative to other source positions, and as has already been mentioned in Section 5.2 the positional compatibility was somewhat poor in that it would give rise to 'ping-pong' stereo for quadraphonic programmes where the side quadrants contained important sound sources (see also Fig. 6).

TABLE 3

Stereo Compatibility: Image Spreads and Percentage of Unsatisfactory Results

System	Percentage of anomalous assessments (i.e. image spreads ⩾¾ stage width)		Mean image spread relative to 60° stage width	
	Pan-pot	Cardioid	Pan-pot	Cardioid
Front-back blend arrangement	0%	0·5%	8°	10°
Matrix A (and C)	10%	25%	18°*	28°*
Matrix B (and D)	14%	15·5%	19°*	19°*
Matrix E	2·5%	1·5%	11°	9°
Matrix F	1·2%	0·5%	11°	14°
Matrix G	1·2%	0·5%	11°	12°
Matrix H	0%	0%	10°	10°

* Rear-quadrant sounds are reproduced out-of-phase on the two loudspeakers and give rise to an image width of 60° or more.

6.2. Matrix A (and C) (QS)

Cardioid material: As would be expected from the coding equations for this commercial system, many of the rear-quadrant original-source locations produced non-locatable images when reproduced in stereo due to the 180° phase difference between the 'left' and 'right' signals. All five subjects found such cases very objectionable. For original source locations between centre-left and left-back (also centre-right to right-back) the reproduced image positions in stereo were judged to fall outside the normal sound stage enclosed by the two loudspeakers. However, these images were very diffuse; the subjective spreads ranged from about one-third to three-quarters of the normal stage-width. Many of these observations were also accompanied by 'anti-phase' or 'in-the-head' comments.

The positional compatibility was judged to be only fair; the reproduced positions corresponding to original sound locations in the front quadrant were confined to less than half the normal stage width. This result arises from the blending effect of the coding matrix which, with cardioid-signal inputs, produced coded 'left' and 'right' stereo signals exhibiting an amplitude separation of only 3 dB for left-front and right-front sources.

Pan-pot material: The front quadrant occupied marginally more than half the stage width, and again rear quadrant images were either very diffuse or unlocatable, giving rise to 'in-the-head' sensations which all observers found most unpleasant. However, other than for the rear quadrant, the overall result was a slight improvement compared with its performance with cardioid material.

6.3. Matrix B (and D) (SQ)

Cardioid material: This commercial matrix claims the advantage that the front-quadrant sound is not 'blended' in the coder and so gives complete left-to-right front-quadrant separation in stereo reproduction. Whilst this is true for pan-pot material (see below), it does not apply if cardioid material is used; the front quadrant was reproduced occupying half the normal stage width. Due to the phase shifts used for the rear-channel coding, the maximum subjective separation between left and right signals was obtained when the original source direction corresponded approximately to positions 7 and 10, and there was more crowding of reproduced positions on the left than on the right. Front-centre was reproduced slightly to the left of centre.

The centre-back position produces a phase difference of 180° between left and right signals, and gave rise to 'non-locatable', 'in-the-head' and 'anti-phase' comments.

Other than for rear-quadrant locations, this matrix shows a slight improvement in general compatibility over matrix A, but positional compatibility is very dependent on source material. The peculiar meanderings (see Fig. 5) of the stereo image as the original source rotates from position 0 through to 15 (Fig. 4) is one consequence of using cardioid-array source material with a matrix designed only for pan-pot material.

Pan-pot material: As claimed, the front quadrant was reproduced occupying the whole of the normal stage width, with the rear-corner sounds being reproduced somewhat diffusely, close to the central position. There was a slight departure from left-right symmetry. All observers found that source positions 7 and 8 were unlocatable, whilst 80% of observers also found position 9 objectionably out-of-phase.

Whilst the positional compatibility showed an improvement over the cardioid performance, other than in the front quadrant the images were rather diffuse and hence the overall pan-pot result was not significantly improved in respect of image spreads and anomalous assessments.

6.4. Matrix E ('high-separation' tetrahedral matrix)

Cardioid material: This matrix gave rise to hardly any adverse comments in stereo, and all the reproduced images were readily locatable and quite sharp. The most frequent effect commented upon was image-wandering, due to unavoidable tape-weave in the recorder causing differential phase shifts* between the four recorded audio signals fed to the coder. It can be shown that this coding matrix is particularly sensitive to this parameter.

Positional compatibility was also fairly good, the maximum left-to-right separation being achieved between centre-left and centre-right sources.

There was some 'crowding' of the reproduced positions near to the loudspeakers in comparison with the results for the front-back blend system. This might give rise to a tendency for 'ping-pong' effects in stereo on some types of quadraphonic programme material, although it would give good stereo separation between the left and right channels for programmes where all the important sources were located in the front quadrant only.

The subjective mean image-spread was slightly better than that which the front-back blend method produced. perhaps due to the slightly narrower stage width.

Pan-pot material: The positional compatibility of this matrix followed a rather different pattern to its cardioid performance, the pan-pot case generating a good approximation to the 'equi-spaced' presentation discussed in Section 5.2 (see also Fig. 4). However, the image corresponding to source location 7 was very diffuse, and one of the five observers was not able to locate it. Three of the five observers also noticed that location 9 was reproduced somewhat quietly with respect to most of the other tests. This was not unexpected, as partial cancellation of rear quadrant signals takes place in the coder for this system.

6.5. Matrix F (symmetrical matrix)

Cardioid material: Subjectively, these results showed a small amount of asymmetry which, although it was not

* This varied between ±3° at 1 kHz and ±25° at 10 kHz, measuring a first generation recording between the two outer tracks on a 1 inch tape.

initially expected, is certainly due to the phase shifts* between the left and right coded signals.[7]

The overall reproduced stage width (representing left-centre to right-centre) was reduced** by this matrix, as expected, to about three-quarters of the total 60° stage-width. Taking into account this narrowing and neglecting the 'phase shift' effect, the reproduced positions were in fair agreement with those claimed,[5] which correspond approximately to the projections of the original positions around the circle onto its diameter. The average subjective spread of images was satisfactory at 1·3 times the value for 'stereo', the worst cases, as expected, being some of the centre-front and centre-back positions.

Pan-pot material: There was rather more evidence of side-quadrant bunching than with cardioid material, but the overall stereo stage was reduced less, to about 0·9 of the 60° total. Front and rear quadrants occupied most of this. The front-centre and back-centre images were noticeably displaced from the central position, in the direction of the leading-phase loudspeaker.[7] These central images were assessed as 'slightly phasey' by four out of five observers, their average width being between one-quarter and one-third of the stage width. Elsewhere, the images were quite sharp. Only one of the total of 80 assessments was accompanied by a comment indicating that an anomaly had been perceived.

6.6. Matrix G (stereo-mono compatible matrix)

Cardioid material: As one of the five subjects commented, this matrix in stereo was 'noticeably free from anti-phase or 'in-the-head' effects', and only one out of the total of 180 assessments by the five subjects was of dubious location. Positional compatibility was very good; good subjective separation was produced in the front quadrant (almost three-quarters of the total stage width) and the maximum separation between left and right signals was produced by left-centre and right-centre sources. Left-right separation for the rear quadrant was judged subjectively*** to be slightly different to that at the front (just over two-thirds of the total stage width). These factors taken together should reduce the probability of 'ping-pong' effects with certain types of quadraphonic programme material, without paying the price of poor separation for the front quadrant. Good separation is needed in the front quadrant when the programme source material is situated mainly in the front, as with classical music concerts, if the stereo listener is to receive an impression virtually indistinguishable from normal stereo. The mean subjective image spread was satisfactory.

Pan-pot material: The results for image-spreads (and anomalous assessments) and comments on central images were almost identical to the pan-pot results for matrix F, but the positional compatibility showed a significant improvement. The sound stage extended slightly beyond the speakers, thus considerably reducing the side-quadrant bunching. Unlike the matrix G cardioid results, the rear quadrant was reproduced wider than the front quadrant, which itself occupied almost 0·9 of the normal 60° stage. Other than for the slightly diffuse and displaced central images, this was considered to be a good result, and so it was decided to listen to quadraphonic programme items in stereo derived by this matrix.

Quatitative test tape: Listening tests using recorded music and other items confirmed that this matrix produces stereophonic results subjectively very similar to those obtained with the front-back blend system, with which it was directly compared.

6.7. Matrix H ('hearing-properties' matrix)

Cardioid material: The total reproduced stereo stage width (left-centre to right-centre) produced by this matrix when fed with cardioid-source quadraphonic material was judged subjectively to be just under 0·9 of the 60° maximum.

The front quadrant occupied three-quarters of the total, and the rear quadrant marginally less. Thus the front quadrant subjectively occupied a marginally greater proportion of the stereo stage than the corresponding result for the front-back blend system. The mean image spread for this matrix was assessed to be almost identical to the value for the front-back blend system.

This matrix gave the best overall result for stereo compatibility of cardioid material.

Pan-pot material: The front quadrant occupied 0·8 of the stage width, with the central image only marginally displaced to the left. The rear-quadrant positional compatibility results were very similar to those for matrix G, with some images slightly beyond the speakers. The image sharpnesses were also similar to those of matrix G for the rear; but much improved in the front, giving the best overall result of all the matrices tested. There was also less divergence between the pan-pot and cardioid results using this system, which is in good agreement with the computed prediction.

7. Orders of preference of the matrices

With a multiplicity of factors to be taken into account, difficulties arise in producing a fully comprehensive and compact presentation of all the results, particularly if a rank order of preference is required. However, based on the discussions of all the results, Table 4 is an attempt to meet this requirement.

* For original source locations in the front half of the sound field, the left channel leads the right in phase (53° max. for cardioid, 71° for pan-pot), and lags in the rear half. The effect of this would be worse with the 'rigorously encoded' 90° phase-shifts produced by the specified BMX[4] system.

** This overall narrowing of the stage-width with cardioid material would not take place with the specified BMX[4] system, which requires slightly different coding equations for cardioid material and pan-pot material.

*** A mathematical analysis based on amplitude-ratios does not predict this difference between front and rear for cardioid material.

TABLE 4

Order of Preference and Summary of Results

Order	CARDIOID QUAD			PAN-POT QUAD			STEREO				MONO
							Cardioid Material		Pan-Pot Material		In order[g] of 'omni-directionality'
							Positional Compatibility: Fig. 5		Positional Compatibility: Fig. 6		
	Accuracy of mean position Mx. no.	Mean image spread Mx. no.	Anomalous assessments Mx. no.	Accuracy of mean position Mx. no.	Mean image spread Mx. no.	Anomalous assessments Mx. no.	Mean image spread Mx. no.	Anomalous assessments Mx. no.	Mean image spread Mx. no.	Anomalous assessments Mx. no.	Mx. no.
1st	H 12°	H 50°	H 10%	C 7°	C 34°	G 3%	E[b] 9°	H 0%	H 10°	H 0%	F[c]
2nd	G 12°	G 72°	C 16%	H 9°	H 47°	F 5%	H 10°	G 0·5%	G 11°	G 1·2%	G
3rd	E[a] 16°	C 81°	G 17%	E[a] 11°	G 63°	C 6%	G 12°	F 0·5%	F 11°	F 1·2%	H[f]
4th	A 20°	E 95°	E 19%	F 14°	F 66°	H 9%	F 14°	E 1·5%	E[b] 11°	E 2·5%	E
5th	C 25°	A 102°	B 25%	G 15°	A 75°	A 9%	B (& D)[d] 19°	B (& D)[b] 15·5%	A (& C)[d] 18°	A (& C) 10%	B (& D)[e]
6th	D 29°	B 113°	A 26%	D 19°	E 87°	B 18%	A (& C)[d] 28°	A (& C) 25%	B (& D)[d] 19°	B (& D)[b] 14%	A (& C)[e]
7th	B 32°	D 151°	D 34%	A 22°	B 104°	E 21%	— —	— —	— —	— —	—
8th	— —	— —	— —	B 27°	D 135°	D 28%	— —	— —	— —	— —	—

(a) Centre-back location ambiguous and reproduced in front; not included in figure for positional accuracy

(b) Positional compatibility is very programme-source dependent

(c) Perfectly omnidirectional for cardioid-array source material

(d) Centre-back gives total stage-width image spread

(e) Centre-back not reproduced in mono for pan-pot material (reproduced at −15·3 dB for cardioid material)

(f) Virtually identical with matrix G for cardioid material, but marginally worse in the rear-quadrant for pan-pot material

(g) Order of preference assesses a mixture of pan-pot and cardioid material

The mono compatibility of matrix-quadraphony is probably best dealt with theoretically at the present stage, and polar diagrams have been computed for each matrix. The extent to which rear-quadrant sound sources should be attenuated in mono reproduction is largely an artistic function of the programme material. Table 4 assumes that the goal is a truly omnidirectional characteristic for the mono signal, but only matrix F used with cardioid material achieves this. The rank order for mono is not affected to any great degree by the use of pan-pot rather than cardioid material; though for all the matrices tested a slightly better approximation to an omnidirectional response is obtained with cardioid material.

A rank order is not given for stereo positional compatibility because the relevant factors are discussed in some detail in Sections 5 and 6. The particular programme material will inevitably have some effect on this aspect of the results for all matrices. Figs. 5 and 6 show these results in detail.

From this analysis it can be seen that, for non-logic-enhanced systems, matrices F, G and H are consistently near the top of the list whilst matrices A and B are consistently near the bottom. For the logic-enhanced systems, C is shown to be very much better than D in its quadraphonic performance but its stereophonic performance remains rather poor. It should be remembered, however, that both of the logic-enhanced systems gave relatively poor results with 'real' quadraphonic programme material (see Sections 4.3 and 4.4).

8. Conclusions and recommendations

8.1. Commercial systems

Neither of the two main commercial matrices is mono compatible in that rear-central sounds are not reproduced in mono. Matrix B (SQ), however, is preferable in this respect since at least the rear corner signals are reproduced at the same level as the front corner signals. Stereo compatibility is also poor; matrix A (QS) produced poor separation for front-quadrant sources as well as very unpleasantly-phased components elsewhere. Matrix B might be considered as giving just acceptable results in stereo (and mono) if rear-quadrant positions were avoided (and pan-pot only material were used), but unfortunately the overall quadraphonic performance of SQ is more unsatisfactory than that of QS. Quadraphonic positional accuracy is very poor if used with cardioid source material. The performance of either commercial system using logic-controlled decoders, whilst giving improvement of some parameters over the basic decoders for single-source tests, is not satisfactory at present, primarily because of the very unpleasant effects* produced on some types of programme material, particularly where two or more principal sources (solo instruments) are in use simultaneously. The greater cost of these decoders should also be considered a disadvantage. The rear-centre location is encoded as a 180° phase-shift between the left and right signals in these two commercial systems, therefore the comparatively 'noisy' difference (L-R) signals as received over FM radio if subsequently decoded by an SQ or QS system decoder may give rise to a locatable* hissing from the rear loudspeakers. It is not expected that this effect could occur to the same degree with any of the other systems investigated; these should distribute the difference-signal noise more evenly around the listener.

* Principally 'image wandering' and 'image flutter' effects.

8.2. Matrix E

Scheiber's 'high-separation' tetrahedral matrix (E) exhibited good stereo compatibility but, for quadraphonic reproduction, a high proportion of wrongly positioned images were reported. These mislocations and ambiguities could be avoided by introducing a different phase-shift in the rear channels on coding, but this would affect both stereo and mono compatibility and the image-spreads in quadraphonic reproduction. This may be investigated further.

8.3. Matrix F

The BMX matrix offers excellent mono compatibility, fairly good stereo compatibility** and fairly good quadraphonic reproduction; a further claim[4] is that the addition of a third (or fourth) 'acutance' channel of narrow bandwidth (about 4 kHz) can improve the performance to the point where it is virtually indistinguishable from the original four-channel programme. This aspect should be investigated as it is very relevant to FM broadcasting. For optimum results using this system, however, different coding matrices are required for cardioid and pan-pot material. BMX discs have been made, but are not available in the UK as far as is known.

8.4. Matrix G

This matrix appears to give good mono compatibility, satisfactory stereo compatibility, and a reasonably good overall performance in quadraphonic reproduction, regardless of source material. Side-quadrant images are sharper using this system, though the sharp side-image advantage is only maintained*** whilst facing the front. This system (like the BMX) is suitable for augmentation by a third (or fourth) narrow-band channel, and as it placed all the quadrature phase-shifted components (carrying the front-back information) in the difference signal,**** it could be relevant when considering FM broadcasting.

8.5. Matrix H

Other minor variations in the general form of coding used for matrix G have also been investigated, distributing

* Tests have shown that a given level of 'noise', in quadraphonic playback, is subjectively more disturbing if it comes from behind the listener than if the same level of 'noise' came from the front.

** See Appendix A1.3, particularly first footnote.

*** This advantage holds even when compared to discrete quadraphony.[8]

**** The difference signal thus contains all the directional information (both left-right and front-back), thus distributing 'random noise' evenly.

amplitude and phase asymmetries in slightly different ways. The results show that it is possible to optimise some parameters, for example, locational accuracy at the expense of image-spread or vice-versa. Other forms of asymmetry designed to be advantageous to a front-facing listener can give significant theoretical 'improvements', but if this process is taken too far it produces subjective effects which result in the need for severe restrictions on listeners' head movements. There is also more evidence of disagreement between individual observers and between individual programme items.

Matrix H appears to be the most subjectively acceptable set of compromises, and mathematically represents a very good compromise for the requirements of a 4-2-4 matrix designed for both cardioid and pan-pot sources, this is reflected in the remarkably close results using these two types of input. The stereo compatibility is also highly satisfactory, particularly so in the important front-quadrant.

8.6. Recommendations

The results of the tests show that a suitably designed 4-2-4 matrix system can give quadraphonic images with a mean subjective locational error and image spreads of the order of only 1·5 to 1·8 times those of a discrete four-channel system, whilst maintaining stereo and mono compatibility.

It is recommended, therefore, that further work be carried out using systems based on matrices F, G and H. The results using these show that a 4-2-4 matrix system can be made capable of a reasonable degree of mono and stereo compatibility, consistent with a 4-2-4 quadraphonic performance which, although not as good as a discrete (4-4-4) system, is a significant improvement over conventional stereo in that front-back information is portrayed in addition to left-right.

The main difference between the performances of matrices F, G and H and the discrete 4-4-4 system appears to be the subjective impression of a 'closing in' of sound images which is a direct consequence of the low separation between adjacent channels (about 3 dB). This property may eventually prove to be a fundamental limitation for any non-logic enhanced 4-2-4 system.

The effects of a possible future addition of 'optional' third or fourth channels of information should therefore be investigated. Such transmissions could preserve compatible reception in mono (4-2-1), stereo (4-2-2), and quadraphonic (4-2-4, 4-3-4 or 4-4-4) modes.

The assessment of the results of an investigation into properties of hearing[7,8] may reveal whether the 'symmetrical' approach of matrix F is the most satisfactory 4-2-4 system or whether some controlled asymmetry, as in systems G or H would be subjectively preferable for the 4-2-4 listener. The results leave little doubt that the 4-2-2 listener (stereo) benefits from these departures from complete symmetry, but future work on quadraphony should also include tests on rotated and off-centre listening positions as this may show up possible limitations of the asymmetrical approach of matrix H.

There is a possibility that improvements to logic-enhanced decoders may eliminate the unwanted audible effects noted in these tests.

It should be remembered that the final judgement of any quadraphonic system is a subjective matter and particularly in the context of broadcasting, depends on a number of additional factors not considered in this Report.

In addition it should be noted that this Report assumes that the ideal quadraphonic system makes possible the accurate location of sound images in a controlled environment. It ignores the efforts of production staff who will attempt to conceal a system's deficiencies and exploit its virtues in order to provide an entertaining product. This Report assesses the situation from an engineering point of view. More engineering and production experience will be necessary before any final opinion can be formed.

9. References

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Appendix

A1 Matrix Systems Tested

A1.1. Commercial matrices

Two matrix systems are widely used for coding quadraphonic discs and give, using a basic decoder, 3 dB separation between the decoded channel carrying the wanted signal and two of the other channels, with infinite separation to the remaining channel. The crosstalks are, however, differently disposed in the two cases.

One example, the QS matrix system, uses the following coding equations:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} \cdot 924, & \cdot 383, & j\cdot 924, & j\cdot 383 \\ \cdot 383, & \cdot 924, & -j\cdot 383, & -j\cdot 924 \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

This was known as matrix A for the tests.

The other, the SQ matrix, was matrix B, and uses the following as its encoding equations:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} 1\cdot 000, & 0, & -j\cdot 707, & \cdot 707 \\ 0, & 1\cdot 000, & -\cdot 707, & j\cdot 707 \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

The manufacturers of commercially available versions of these two matrix systems include, in their range of equipment, decoders containing logic circuits designed to reduce the effects of the decoded crosstalks which are generated by the basic decoding matrix.

In the QS logic system circuit elements detect the channel carrying the loudest signal and alter the decoding matrix so as to give this channel maximum electrical separation from the other three channels. Unfortunately this means that these 'other three channels' have almost zero electrical separation from each other, and of course as the loudest signal moves from channel to channel the separation moves correspondingly.

The logic system incorporated in the SQ system is designed to detect the crosstalk signals generated by the matrix and alter the gains of variable-gain amplifiers in an attempt to remove the unwanted signals. If, however, a particular channel carried both a large crosstalk signal and a small wanted signal the system is incapable of correct operation and in fact both signals are reduced in level.

These two logic systems therefore can only be at their most effective when a single sound source is dominant (as is precisely the case for the test material on the pan-pot test tape). When multiple sources are present simultaneously, as in normal programme material, and dispersed at various locations around 360°, the effects produced are very programme-dependent. Logic systems were tested for both of the commercial matrices described (using coding and decoding apparatus supplied by the manufacturers). These were known as matrices C and D respectively for the QS logic system and the SQ logic system.

A1.2. 'High-separation' matrices

Scheiber[3] suggests a form of coding such that each individual decoded channel has a separation with respect to each of the other three of 4·77 dB. This is known as 'regular tetrahedral' encoding. The equations of two such matrices are given in his paper but only one of them 'Hi-Sep 1', the matrix E, is reported herein, although both were in fact tested and gave very similar results. It should be noted that the phase shifts used in their rear channels are optimised for stereo compatibility rather than for optimum quadraphonic performance.

The encoding equations for matrix E are:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} (\cdot 820 + j\cdot 339), & (\cdot 425 - j\cdot 176), & (\cdot 820 + j\cdot 339), & (-\cdot 425 + j\cdot 176) \\ (\cdot 425 - j\cdot 176), & (\cdot 820 + j\cdot 339), & (-\cdot 425 + j\cdot 176), & (\cdot 820 + j\cdot 339) \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

A1.3. Symmetrical matrix ('simplified' BMX): Matrix F

Matrix F achieves complete phase and amplitude symmetry in the decoded signals, together with infinite* diagonal separation, but at the slight expense of stereo compatibility.** Its relationship with the family of 'compatible' matrices (to be discussed in Section A1.4) is mainly a change of the coded phase relationships of the rear channels with respect to the front.

The BMX coded signals can be considered conveniently in their sum-and-difference forms as explained below. The sum of coded 'Left' and 'Right' signals (the 'mono' signal) consists of a quasi-omnidirectional*** in-phase-only

* Infinite diagonal separation only for pan-pot inputs; 9·5 dB with cardioid material.

** c.f. Section 6.5. For a centre-front (or centre-back) source, the 'left' and 'right' encoded signals exhibit a phase difference of 70·6° for conventional pan-pot input signals, thus causing an audible spread of the stereo image. If this 'simplified' matrix F is used with cardioid inputs, the phase shift between L' and R' for a centre-front source is reduced to 53°.

*** Exactly equal amplitude for any source direction is achieved only with cardioid inputs.

signal, and the stereo-difference signal is nominally also 'omnidirectional', but its phase differs from that of the 'sum' signal by an amount directly related to the direction of the sound source. Compatibility with conventional stereo occurs when the phase of the difference signal ($L' - R'$) is arranged to be identical with that of the 'mono' or sum signal when the source is located at centre-left. This difference signal is therefore in quadrature for a centre-front or centre-back source (although ideal stereo compatibility would demand zero amplitude), and 180° out of phase for a centre-right source. Thus adding 'mono' and '$L' - R'$' (difference) signals, as is normally done for stereo reception, gives predominantly 'left' information and subtracting gives predominantly 'right' information. To decode quadraphonically, the phase of the difference signal is first changed relative to the 'sum' signal by an amount directly related to the azimuth (direction) being decoded, and then the sum and phase-shifted difference signals are added together. Thus if a sound source coded by this system were originally located at an azimuth diametrically opposite to that of the 'decoding' azimuth, the difference signal, instead of increasing the amplitude of the resultant when added to the sum signal, would be in anti-phase and so would cancel, thus giving infinite diagonal separation. Matrix F is the symmetrical member of this family; its coding equations are:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} (\cdot 854 + j\cdot 353), & (\cdot 146 + j\cdot 353), & (\cdot 854 - j\cdot 353), & (\cdot 146 - j\cdot 353) \\ (\cdot 146 - j\cdot 353), & (\cdot 854 - j\cdot 353), & (\cdot 146 + j\cdot 353), & (\cdot 854 + j\cdot 353) \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

The mono or sum signal ($L' + R'$) is therefore:

$$M = L_F + R_F + L_B + R_B$$

and the difference signal ($L' - R'$) is:

$$S = (\cdot 707 + j\cdot 707)L_F + (-\cdot 707 + j\cdot 707)R_F +$$

$$+ (\cdot 707 - j\cdot 707)L_B + (-\cdot 707 - j\cdot 707)R_B$$

This coding matrix is identical for discrete corner-sources to the BMX member of the UMX faimly proposed by Cooper and Shiga.[4] BMX gives completely symmetrical decoded signals with infinite separation across diagonals and adjacent channel crosstalk of −3 dB. The crosstalk phases between adjacent decoded channels are at the symmetrical minimum of ±45° respectively.

This matrix system requires somewhat different (but related) coding equations if four cardioid (or two crossed figure-of-eight plus an omnidirectional) microphones were to be used with equal results. For cardioid source material it can be shown that this mono signal ($L_F + R_F + L_B + R_B$) produced by matrix F is 6 dB too great with respect to the difference signal. For conventional pan-pot material the mono signal is not, in fact, of equal amplitude through 360°, as might be desirable. This is because, as in conventional stereo, the 'centre' mono signals are 3 dB too great with respect to the corner signals. The difference signal is, however, correct for all azimuths regardless of whether cardioid or pan-pot material is used. Cooper and Shiga's proposal ideally requires the use of special pan-pots for rigorously correct encoding; this arrangement is sometimes referred to as 'optimal coding' or as 'position-encoding' when multi-microphone studio techniques are used.

A1.4. Stereo-mono compatible matrices

A family of matrices was devised by the author chiefly with a view to optimising stereo (and mono) compatibility, taking account of the crosstalk phases (and amplitudes) produced in decoding, and bearing in mind that the system should be able to cope with cardioid-array source material. In the matrices so far proposed commercially, mono and stereo compatibility is far from ideal; further, the phases of the crosstalk signals produced by the commercial systems are likely to give rise to unpleasant effects,[7,8] particularly with cardioid sources.

The general encoding equations for this proposed family are as follows:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} (a + jb), & (c + jd), & (a' - jb'), & (-c' - jd') \\ (c - jd), & (a - jb), & (-c' + jd), & (a' + jb') \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

where a, b, c, d, a′, b′, c′, d′ are positive.

+j = 90° phase lead

−j = 90° phase lag

It is not within the scope of this report to discuss in detail the analysis of all the effects of a′, b′, c′ and d′ differing slightly from a, b, c and d, nor of small departures from the rules given below. Assuming the 'primed' coefficients are made equal to the un-primed coefficients and if

(i) c is small compared to a

(ii) b = d

(iii) a + c = 1

(iv) $a^2 + b^2 + c^2 + d^2 = 1$

a matrix results which should have good compatibility both in stereo and mono, and which can be decoded to give an approximation to the results obtained using the original four channels, even when they are derived from an array of four cardioid microphones.

A computer analysis varying the value of 'a' for this family indicated that worthwhile quadraphonic results might be expected if a value of 'a' was chosen between 0·85 and 0·90; the value of 'a' determines the values of 'b' and 'c' according to the rules [(i), (ii), (iii), (iv)] given above.

The matrix from this family which gave the best overall results (matrix G) codes according to the following equations:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} (\cdot 890 + j\cdot 313), (\cdot 110 + j\cdot 313), (\cdot 890 - j\cdot 313), (-\cdot 110 - j\cdot 313) \\ (\cdot 110 - j\cdot 313), (\cdot 890 - j\cdot 313), (-\cdot 110 + j\cdot 313), (\cdot 890 + j\cdot 313) \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

An analysis of this matrix shows that the decoded front-to-back separation in the side quadrants is rather less than the left-to-right separation.

Matrix G is based on the value of 'a' = 0·89. Some of the deficiencies of matrix G can be improved by reducing the value of 'a'.* As the value of 'a' is reduced the crosstalk amplitude symmetry is improved but at the expense of phase symmetry (and a small loss of compatibility with stereo and mono). Also a small amount of additional diagonal crosstalk is introduced into the decoded signals. The matrix for which the value of 'a' is 0·86 gives substantially symmetrical amplitude** crosstalk values in the decoded signals, and was also tested giving broadly similar results which showed that positional accuracy can be improved at the expense of image sharpness and vice versa.

Matrix G, modified, ('a' = 0·86) uses coding equations as follows:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} (\cdot 860 + j\cdot 347), (\cdot 140 + j\cdot 347), (\cdot 860 - j\cdot 347), (-\cdot 140 - j\cdot 347) \\ (\cdot 140 - j\cdot 347), (\cdot 860 - j\cdot 347), (-\cdot 140 + j\cdot 347), (\cdot 860 + j\cdot 347) \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

A1.5. Matrix H

Minor modifications to the general form of coding used for matrix G showed that a delicate balance of compromises is necessary in order to achieve a satisfactory standard of sound reproduction for each of the mono, stereo and quadraphonic listening conditions. The parameters available can be optimised for each separate situation, but in general such optimisations can be to a large extent mutually exclusive with respect to the other listening conditions.

* This situation can also be improved by other methods which do not result in the same degree of impairment, e.g. matrix H.

** This comment, strictly speaking, refers to conventional pan-pot sources.

So far, matrix H has proved the most acceptable set of compromises, but some factors, e.g. off-centre listening, remain to the investigated and tested by a much larger number of subjects. The coding equations are:

$$\begin{bmatrix} L' \\ R' \end{bmatrix} = \begin{bmatrix} 0\cdot 926 + j0\cdot 163, 0\cdot 145 + j0\cdot 310, 0\cdot 852 - j0\cdot 397, -0\cdot 145 - j0\cdot 310 \\ 0\cdot 145 - j0\cdot 310, 0\cdot 926 - j0\cdot 163, -0\cdot 145 + j0\cdot 310, 0\cdot 852 + j0\cdot 397 \end{bmatrix} \begin{bmatrix} L_F \\ R_F \\ L_B \\ R_B \end{bmatrix}$$

The phase difference between the left and right coded signals has been kept to a minimum* for front-centre, consistent with keeping the phase shifts within acceptable limits[7] elsewhere to maintain compatibility, and as consistent as possible with the requirement to maintain an adequate degree of front-to-back separation when decoded quadraphonically.

A1.6. Decoding matrices

The decoding coefficients of a 4-2-4 matrix system need not necessarily be the reverse of the coding used for the four 'corner' sources; indeed, it is possible that in certain cases a better overall result might be produced by optimising decoding for 'centre' sources, or by modifying slightly the decoding coefficients corresponding to the four corners. This may be investigated further.

For the subjective tests carried out in this report the conventional decoding matrix (complex conjugate) coefficients appropriate to each matrix system were used, except where otherwise stated (e.g. 'logic' systems). For example, the complex conjugate decoding equations for matrix F were as follows:

$$\begin{bmatrix} L'_F \\ R'_F \\ L'_B \\ R'_B \end{bmatrix} = \begin{bmatrix} \cdot 854 - j\cdot 353 & \cdot 146 + j\cdot 353 \\ \cdot 146 - j\cdot 353 & \cdot 854 + j\cdot 353 \\ \cdot 854 + j\cdot 353 & \cdot 146 - j\cdot 353 \\ \cdot 146 + j\cdot 353 & \cdot 854 - j\cdot 353 \end{bmatrix} \begin{bmatrix} L' \\ R' \end{bmatrix}$$

* A front-centre source gives equal amplitude 'left' encoded and 'right' encoded signals but with a phase difference of 32·9° for cardioid input and 47·7° for pan-pot input; this is virtually within the present specification for long-distance high-quality analogue stereo links when two or three are used in tandem, as is necessary for links of the order of 1000 km. This implies that the compatibility of the system will be satisfactory. However, present transmission-link or 2-track tape-recording (analogue) phase tolerances may have to be somewhat rigidly maintained in operational practice for the benefit of 'distant' 4-2-4 listeners; this may prove to be the unavoidable price to be paid for a highly compatible matrix system. Digital links and recording systems are, of course, inherently superior in this respect.

Appendix

A2 Conversion Between 4-2-4 Systems

A2.1. General principals

The easiest way of comparing 4-2-4 matrices for an assessment of compatibility one with another, is by using the α, β sphere notation described by Scheiber.[3] In this notation the encoded signals, L' and R', are normalised such that

$$|L'|^2 + |R'|^2 = 1$$

It is then found that there are only two variables relating L' and R': these are the amplitude ratio and the phase difference. β can be defined directly as the phase difference between the two signals and, in order to generate the same type of parameter, α is defined as:

$$\alpha = 2 \arctan \frac{|L'|}{|R'|}$$

Thus if L' and R' vary relatively in amplitude only, α describes a circle with β constant; and if L' and R' vary only in relative phase, β describes a circle with α constant. If α and β are now envisaged as orthogonal variables with a common origin, all possible values of α and β can be represented as the surface of a sphere. Certain conventions as to sign are described by Scheiber,[3] and this is then known as 'Scheiber's sphere'.

If the α and β values produced by a particular matrix are then plotted out on the sphere, they can be seen to map out a characteristic closed locus as the sound rotates around the listener.

Using this interpretation it is found that matrices F, G and H all generate approximate 'great-circle' encoding loci with a value of β between 50° approximately and 90°. The QS matrix (A or C) approximates to great-circle encoding with $\beta = 0°$; but the locus of the SQ matrix (B or D) is a 'flattened' tetrahedron including two points of inflection. With cardioid input signals, the SQ locus is even more irregular. Systems with similar Scheiber-sphere loci will be fairly mutually compatible.[9]

A2.2. Possible conversions

Eargle[9] points out that any great-circle locus can be 'converted' (subject to certain restrictions) into any other by a linear phase-amplitude matrix. Matrices A, F, G and H however are only approximations to great-circle loci and so only approximate conversion can be achieved. For example in the case of 'converting' matrix A (QS) to matrix F (BMX) a phase shift in the R' signal of −90° would approximate this conversion. This indicates that it is possible (though not always desirable) to use, with a given system, material that was originally coded using another. There is, however, no similar simple conversion to or from the SQ matrix (matrix B) as its Schieber-sphere locus is so irregular in shape.

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