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The subjective effects of interchannel phase-shifts on the stereophonic image localisation of narrowband audio signals

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THE SUBJECTIVE EFFECTS OF INTERCHANNEL PHASE-SHIFTS ON THE STEREOPHONIC IMAGE LOCALISATION OF NARROWBAND AUDIO SIGNALS

J.S. Bower, B.Sc. (Hons.)

Summary

A previous report[1] studied the effects of interchannel phase-differences on stereophonic-image localisation. The present report continues this work by quantifying some of the frequency-dependent localisation effects which occur when phase-shifts are present. This information, together with that in the previous report, is relevant when considering stereophonic signal processing which introduces phase-differences between the left and right signals.

The narrowband results broadly confirm those relating to wideband signals and additionally show the importance of the inter-aural time and intensity difference. When the louder loudspeaker leads in phase, consistent trends are found as frequency is increased but in the contrary situation where the weaker loudspeaker leads in phase the ear appears to be confused and consistent changes with frequency are not found.

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Research Department, Engineering Division,
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1. Introduction

Various forms of signal processing can introduce phase errors into audio signals, the audibility of such errors being dependent on their magnitude, their variation with frequency, and on the signal bandwidth. In particular, two-channel (4-2-4) matrix quadraphonic systems can introduce large controlled phase-differences between stereo-like signals. It is the aim of this present report, together with another already published,[1] to examine the audible effects of inter-channel phase-differences on the stereophonic reproduction of sound.

The earlier report dealt in detail with the effects of phase differences on the stereophonic presentation of wide-bandwidth audio signals; this report examines the variation of these effects with frequency.

2. Test signal specification and test procedure

In order to investigate the effects of phase shifts at different frequencies, band-limited or narrow-bandwidth signals have been used.

An initial check quickly indicated the type of signal needed for this evaluation. First, it was found that the stereophonic image created by very-narrow bandwidth signals (less than or equal to one-third of an octave) was far more difficult to localise than the image created by wider bandwidth signals (one octave). Second, the type of signal used could also affect the results. It was found that speech filtered into bands each an octave wide produced very much sharper images than octave-bandwidth noise. Presumably the familiarity of speech, together with the presence of characteristic transients, aided image localis-

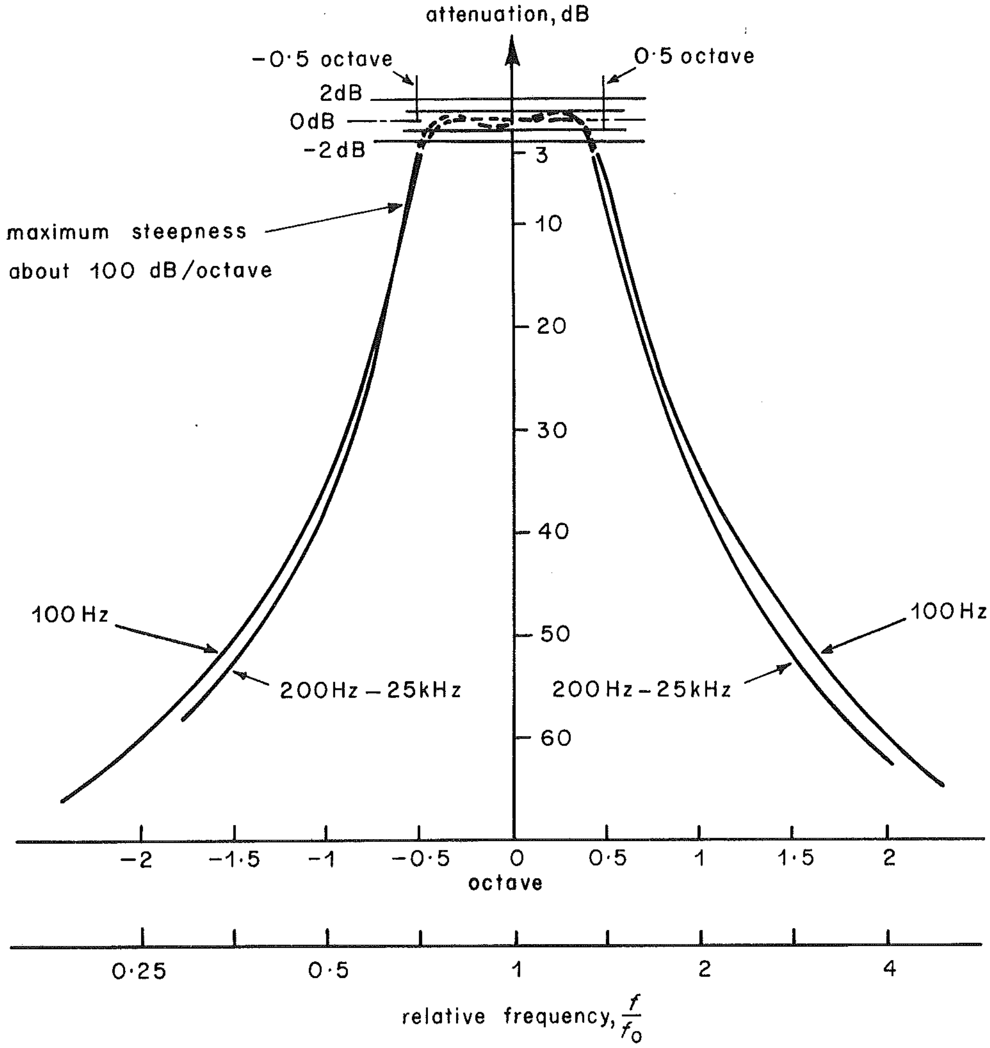

Fig. 1 - Frequency response of octave filter

ation. It was therefore decided to use octave-band filtered speech for this series of tests. In fact, the same recording of a male voice, as used in the wideband tests,[1] was used as source material in the present series of tests.

The octave bandwidth filtering was obtained by using an audio-frequency spectrometer with the characteristics shown in Fig. 1. The signals, after overall gain adjustments, had characteristics lying within the following tolerances:

interchannel phase differences = $\theta\pm1^{\circ}$ within the octave band

interchannel level differences = $D\pm0{\cdot}7$ dB within the octave band

where θ is the intended phase-difference and D is the intended level-difference.

The tests used the following variables:

(a) interchannel phase-difference = 0°, ±45°, ±90°, 180°

(b) interchannel level-difference = 0 dB, 4 dB, 8 dB, 14 dB

(c) octave bands centred on 125 kHz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz.

The test procedure was very similar to that used in the wideband tests.[1] The listeners were asked to estimate subjectively the position, width, and degree of phasiness of

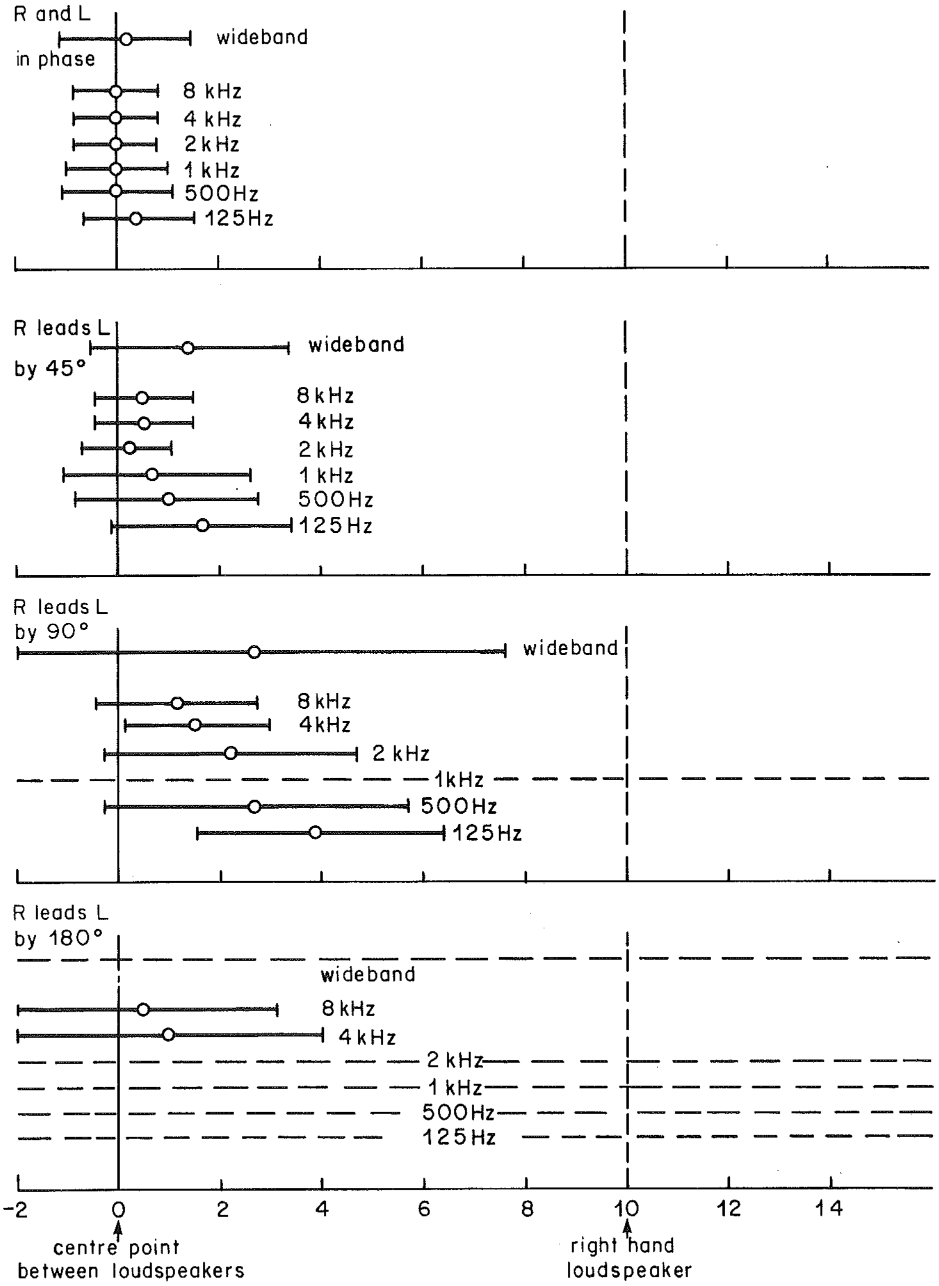

Fig. 2 - Image localisation for narrow bandwidth phase-shifted signals, $|R| - |L| = 0$ dB

each of the stereophonic images when presented in A/B comparisons. In each of these comparisons, one of the conditions was characterised by a particular combination of level difference and frequency with the left and right signals in phase, whilst the other condition used the same combinations of level difference and frequency with a known phase difference between the left and right signals. The image position and width were judged against a twenty-point scale (see Fig. 3 of Ref. 1) with the left and right loudspeakers placed at −10 and +10 respectively. The tests were all carried out in a listening room, 5·4 m (17 ft) x 4·2 m (13 ft) x 2·8 m (8·5 ft) high, having a mean reverberation-time of 0·35 seconds: the loudspeakers were positioned at two corners of a 1·8 m (6 ft) sided equilateral triangle, with the listener at the third corner.

3. Interpretation of results

The numerical results are given in Tables 1–4 in the Appendix, and are displayed graphically in Figs. 2–8. As in the previous report, the results have been normalised to show right-dominant signals. (The results for left-dominant signals show mirror symmetry about the centre position.)

Each image can be numerically characterised by three subjectively assessed parameters.

a) its position with respect to the loudspeakers
b) its width, expressed as an angle*

* An image width of, say, 20° is equivalent to one third of the stereophonic stage width.

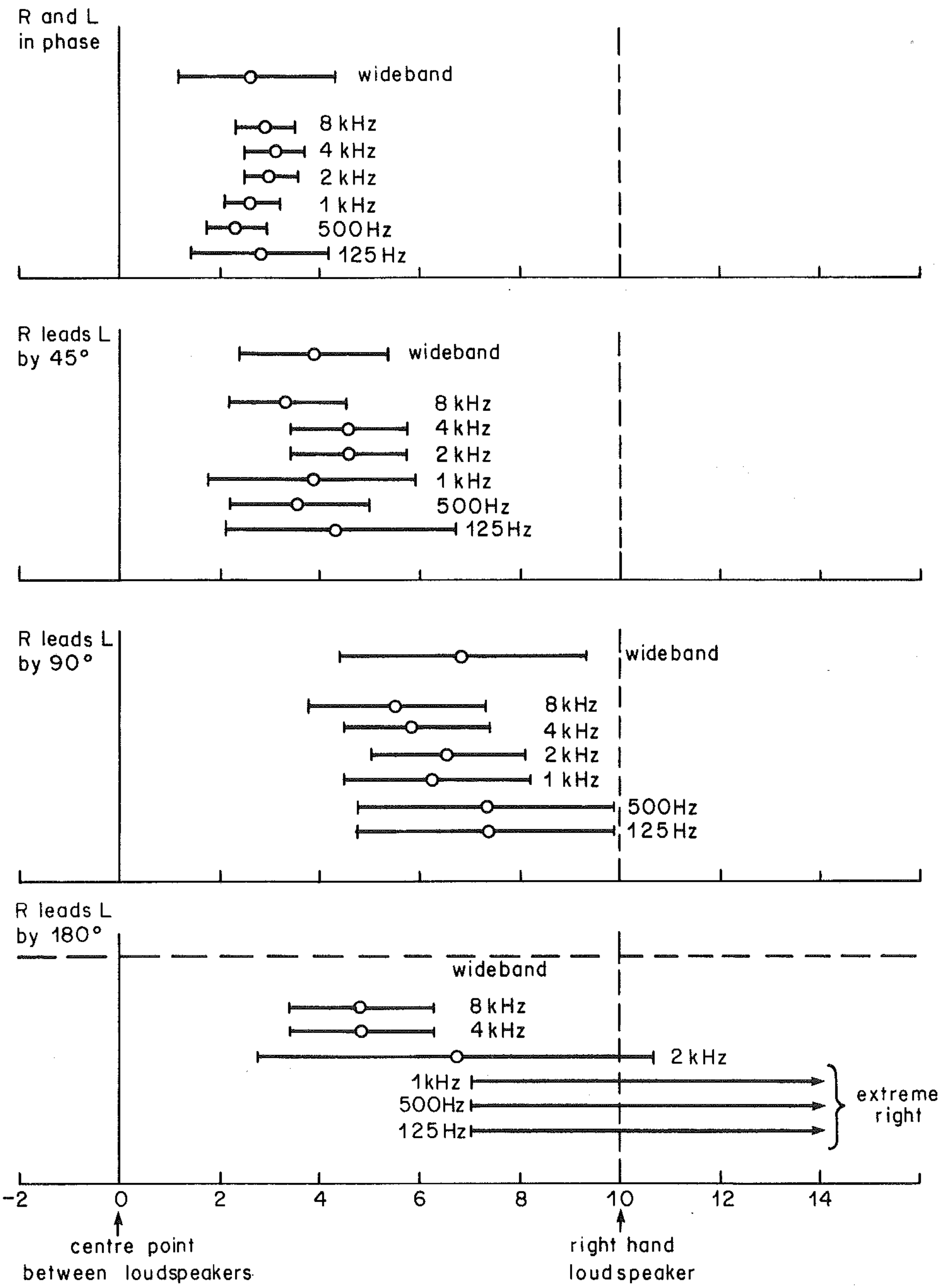

Fig. 3 - Image localisation for narrow bandwidth phase-shifted signals, |R| − |L| = 4 dB; R phase leading L

c) its subjective degree of phasiness, expressed on the scale

0 = 'not phasey'
1 = 'just noticeably phasey'
2 = 'distinctly phasey'
3 = 'objectionably phasey'

Thus, referring to Table 1, for an octave band centred on 500 Hz, the image formed by signals with an inter-channel level difference of 0 dB and an interchannel phase difference of 90°, is found to be situated at ±2·7 with an image width of 27° and a just noticeably phasey quality.

Images so diffuse as to be unlocateable are marked 'U'. The 'wideband' results obtained in the previous tests[1] have been added to the tables for comparison.

4. Discussion of results

Before discussing the results, it is worthwhile to consider existing ideas on the mechanism of image localisation. Much useful work has already been done in this field,[2,3,4] and it is now believed that image localisation predominantly involves two factors: (i) inter-aural time delay (this gives rise to the Haas effect mentioned in the previous report), and (ii) inter-aural intensity difference.

Consider a plane wave arriving at the head from a direction with angle θ to the normal, as shown in Fig. 9. The sound is diffracted round the head, reaching one ear at a time $T = {}^{b}/_{c} = {}^{a}/_{c}\ (\theta + \sin\theta)$ after the other. (c = sound velocity, $2a$ = head width, b = path difference.) As well as this inter-aural time delay (about $2{\cdot}5 \times 10^{-4}$ secs

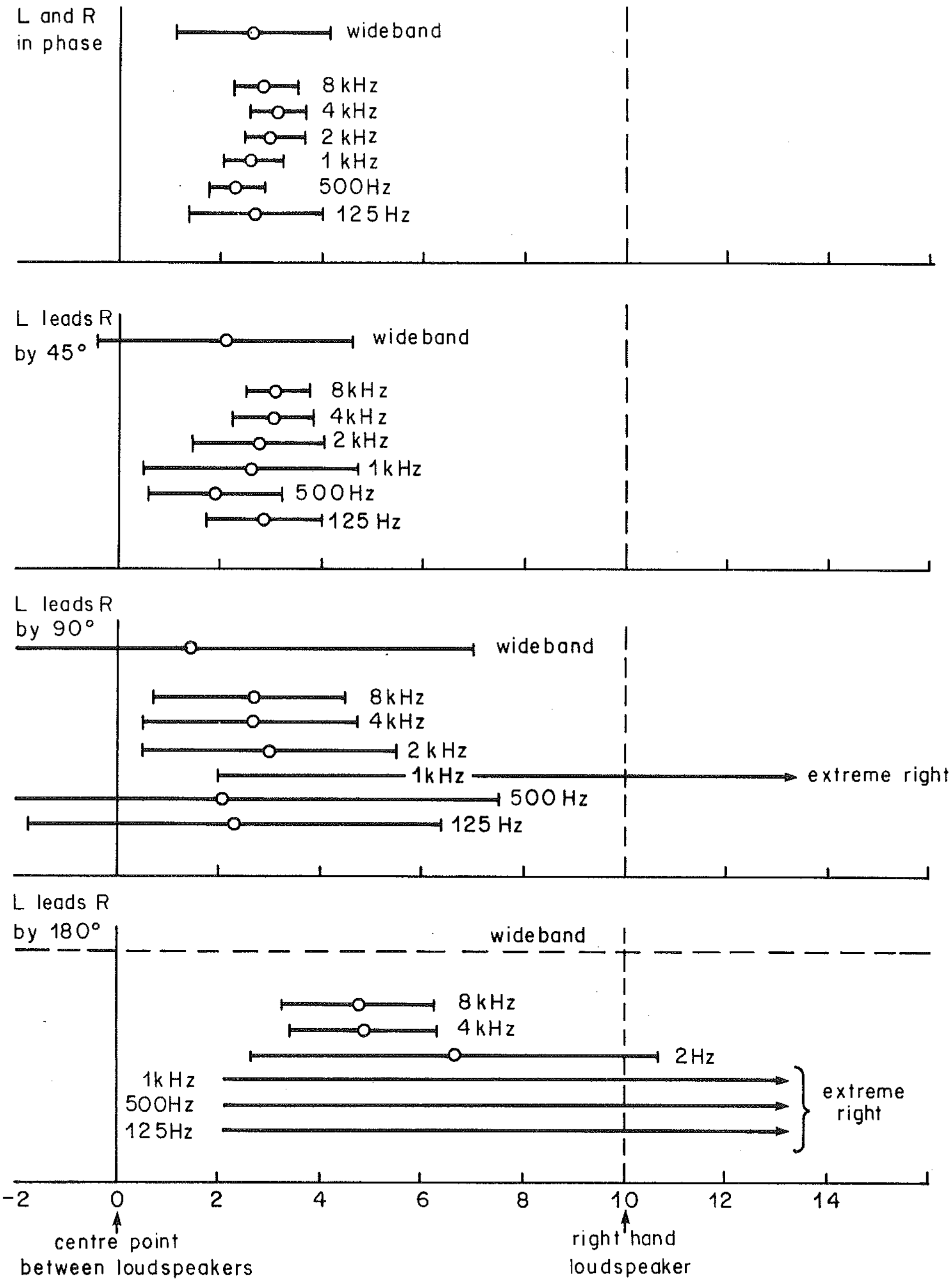

Fig. 4 - Image localisation for narrow bandwidth phase-shifted signals, |R| – |L| = 4 dB; L phase leading R

for $\theta = 30^{\circ}$), there is an inter-aural intensity difference, as the sound diffracted round the head is somewhat attenuated and the degree of attenuation is dependent on the frequency of the sound. Frequencies below about 500 Hz are diffracted round the head with negligible loss: the resulting inter-aural intensity difference is small, and not markedly dependent on θ. For mid-frequencies however, from about 500 Hz to 2 kHz where the wavelengths are of the order of the head dimensions, the attenuation is significant and dependent on θ. It is therefore to be expected that diffraction effects play an important part in image localisation in this frequency range. For high frequencies, diffraction does not occur to a significant extent, and the inter-aural intensity difference is large and substantially independent of θ.

Referring now to the results shown in Figs. 2–8, comparisons between the wideband results obtained previously and the narrowband results are of interest. It should be recalled that the wideband signals had little information above 3 kHz (see Fig. 2, Ref. 1) and, taking this into account, it can be seen that the correlation between wideband and narrowband results is good. The only case where wideband and narrowband results differ significantly is for antiphase signals; more will be said about this later.

Fig. 2 shows the results obtained for zero level-difference between loudspeakers. In general, it can be seen that phase shifts affect low frequencies rather more than high frequencies. This is not surprising since a given phase shift represents a larger interchannel time delay at

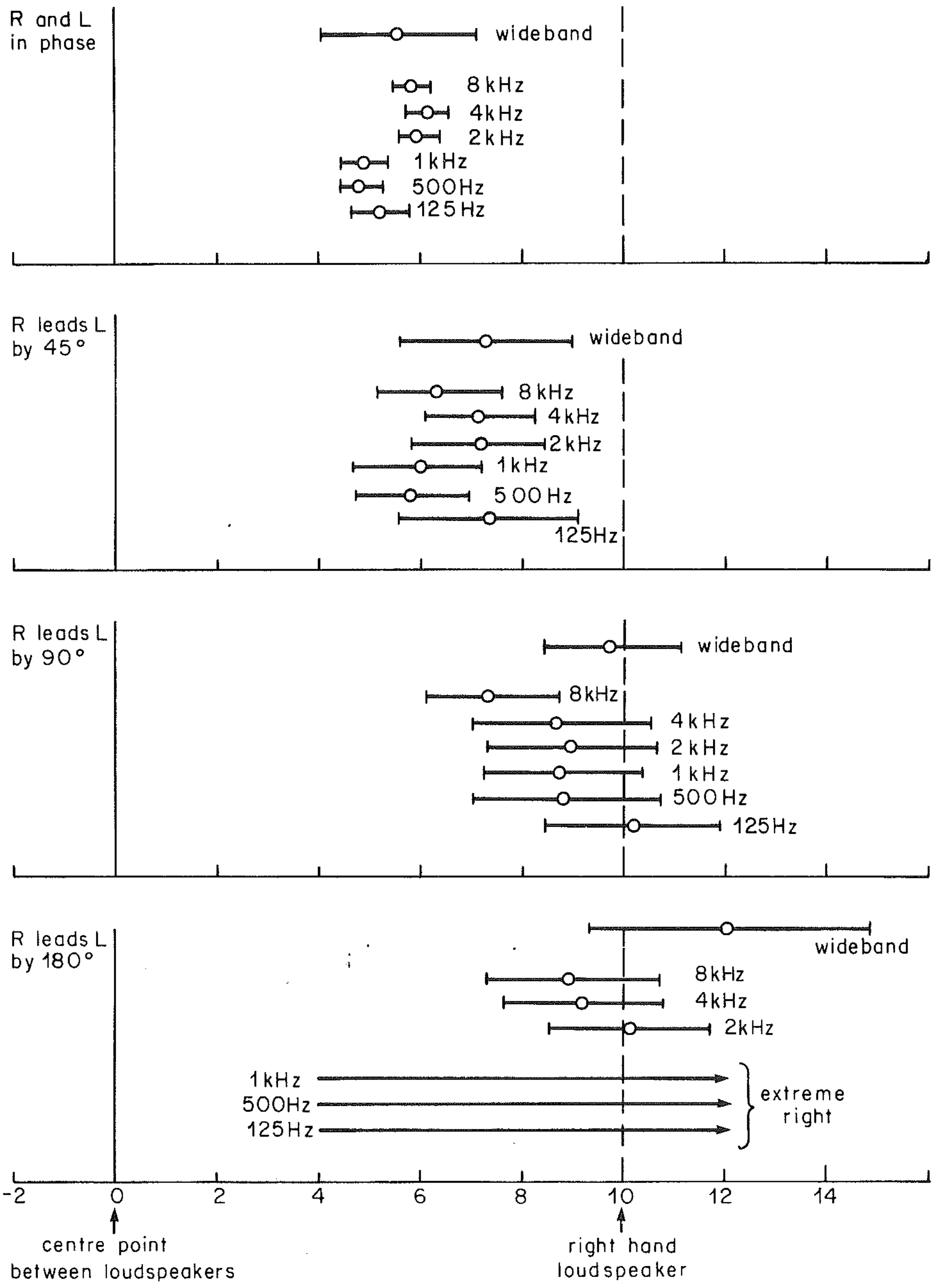

Fig. 5 - Image localisation for narrow bandwidth phase-shifted signals, $|R| - |L| = 8$ dB; R phase leading L

low frequencies. It is also interesting to note the large effects of phase shifts in the mid-frequency range, where diffraction effects are most marked. The result obtained for a phase difference of 90° with a band centred on 1 kHz is especially significant; a 90° phase shift at this frequency corresponds to a time delay of $2{\cdot}5 \times 10^{-4}$ secs., which is identical to the value quoted earlier for the inter-aural time delay for a source displaced by 30° from the centre-front direction. It is therefore hardly surprising that the ear is especially sensitive to directional effects in this case: indeed, anomalous results are obtained with 1 kHz/90° signals for other interchannel level-difference figures.

For antiphase signals, image localisation is impossible at low and middle frequencies. The images are unlocateable, and somewhat reduced in intensity; high frequency images can be located, but are rather subjectively disturbing (although not in the conventional sense of being 'phasey').

Fig. 3 shows the results for an interchannel level-difference of 4 dB, with the louder loudspeaker leading in phase. The results for in-phase signals are interesting: it appears that in-phase signals of 2 kHz and above are displaced with respect to low frequencies, this phenomenon, which appears throughout the tests, has not been satisfactorily explained.* Comparing the 45° and 90° images to

* At first sight this might be thought to have been caused by the loudspeaker crossover points. However, this is unlikely, both because of the experimental procedure which set the channel gain independently for each frequency, and because the loudspeakers which were used, has a crossover frequency (bass unit to tweeter) at approximately 3 kHz.

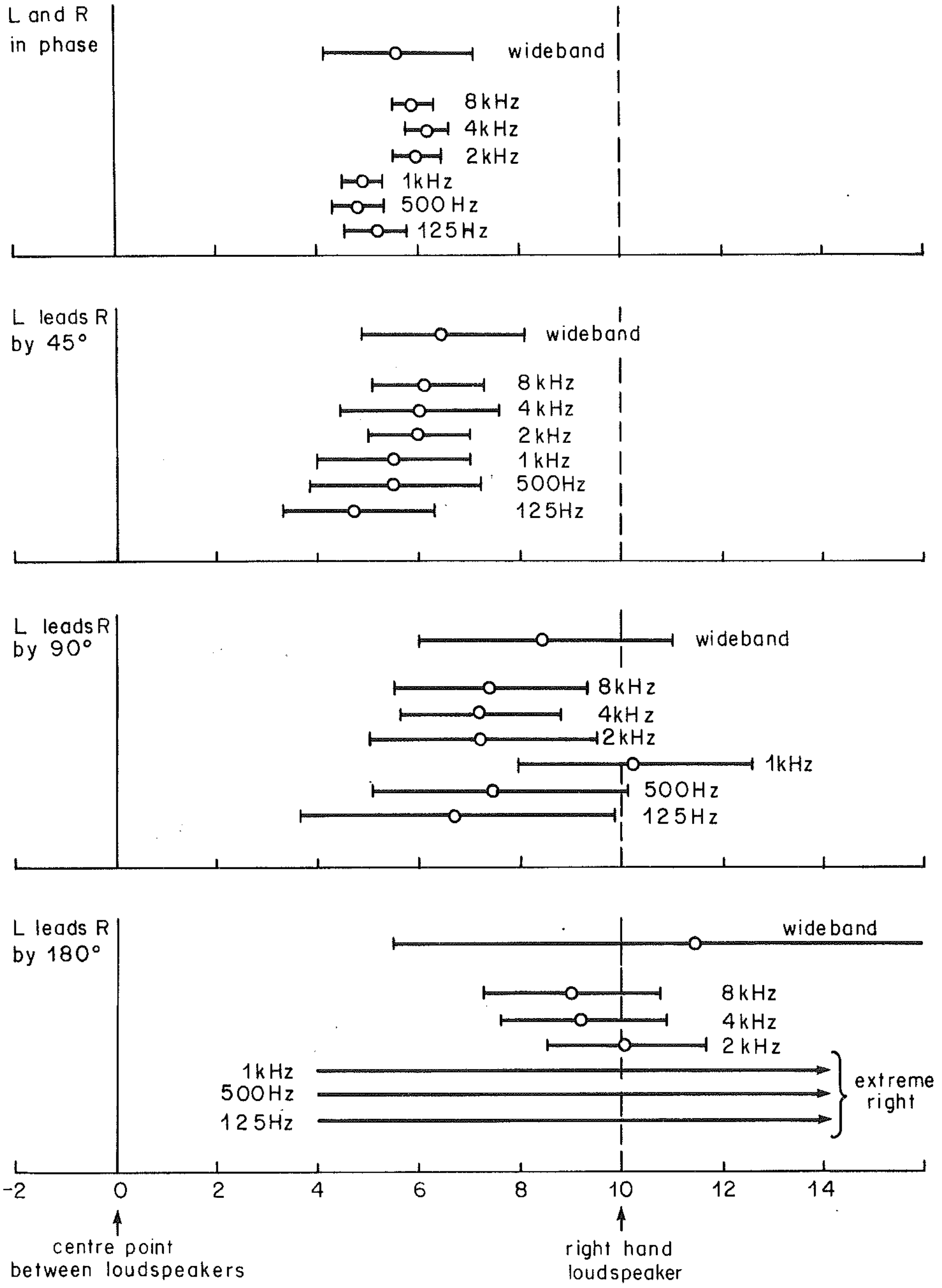

Fig. 6 - Image localisation for narrow bandwidth phase-shifted signals, |R| – |L| = 8 dB; L phase leading R

the reference in-phase images, it can be seen that the results follow trends observed previously, with the image displacement and broadening due to phase differences being more marked at low frequencies. Considering antiphase signals, it can be seen that low and middle frequencies are shifted to the extreme right, appearing to come from a direction in line with the right ear. As before, appreciable cancellation of signals takes place, and the resulting images are somewhat reduced in intensity. Since wideband antiphase signals become unlocateable, the shift to extreme right is rather surprising. It is suspected that this anomoly could possibly be due to the listening room acoustic, which was slightly different from that used in the wideband tests. This slight difference, normally unnoticeable, could affect localisation when other information presented to the ears was contradictory.

For an intensity difference of 4 dB, with the quieter loudspeaker leading in phase, the intensity-difference and time-difference information presented to the ears is contradictory. In these circumstances, Fig. 4 shows that the effects tend to cancel, and consistent image shifts are not obtained. However, the shifts for the 1 kHz/90° case are again very marked, and the low and mid-frequency antiphase images again appear to come from the extreme right.

For interchannel level-differences of 8 and 14 dB, the results, shown in Figs. 5–8 continue the trends described above, with frequency-dependent image shifts occurring when the louder loudspeaker leads in phase, and inconsistent shifts being obtained when it lags. Another difference between these cases is shown by considering the 1 kHz/90° images; these show exaggerated shifts only when the louder

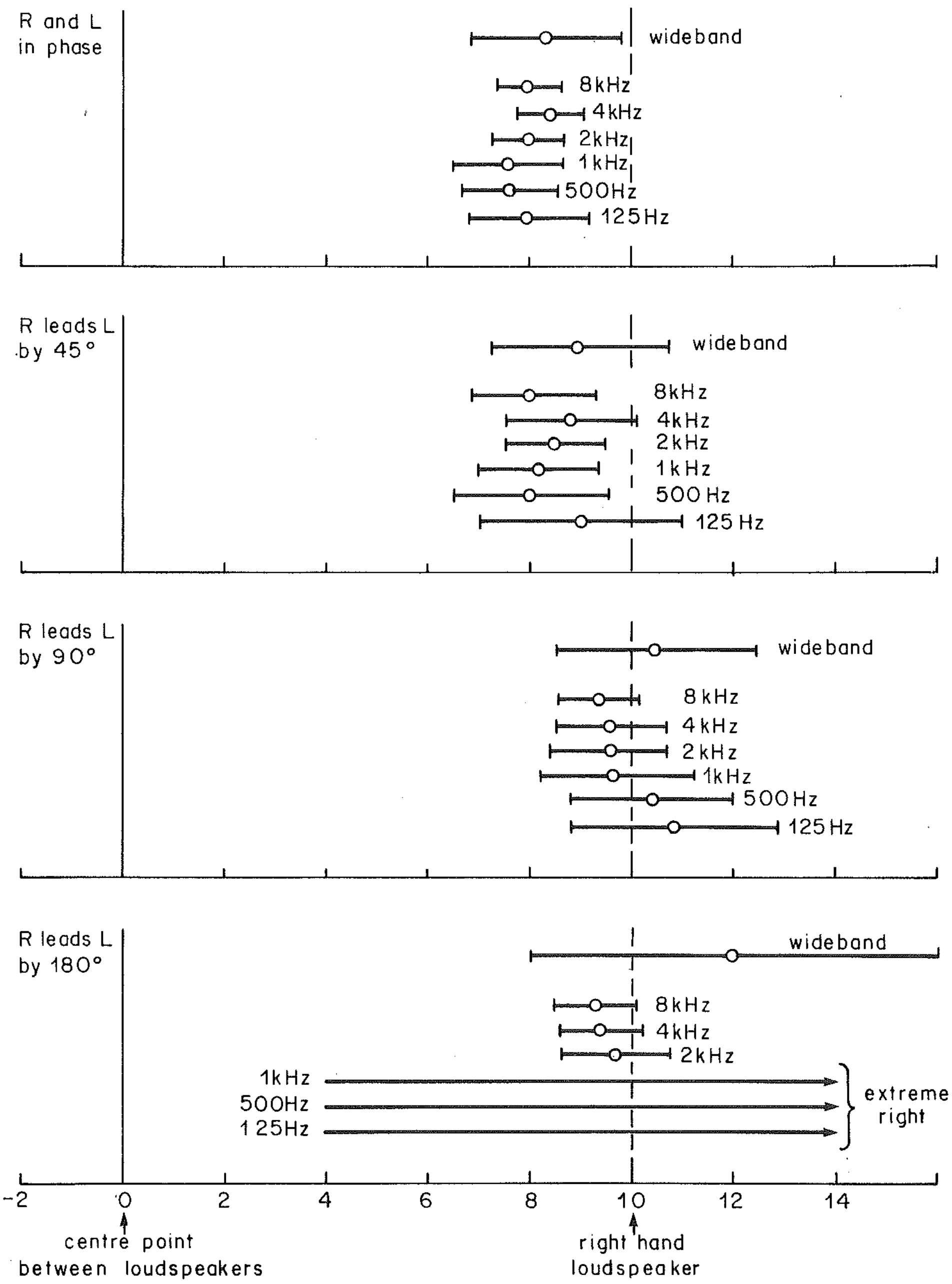

Fig. 7 - Image localisation for narrow bandwidth phase-shifted signals, |R| – |L| = 14 dB; R phase leading L

loudspeaker is lagging. It therefore appears that the 'head phenomena' mentioned earlier only manifest themselves when the primary sources of information, the inter-aural time delay and intensity difference, are contradictory.

5. Conclusions

The effects of phase shifts on narrow bandwidth, stereophonically presented audio signals have been investigated. As well as substantially confirming the previous work which used wide bandwidth signals, the following results have been obtained.

1. It is confirmed that inter-aural time delay and inter-aural intensity difference, induced by diffraction of sound round the head, seem to be the primary factors affecting image localisation.

2. When these two factors reinforce in the stereophonic listening mode, as in the case of the louder loudspeaker leading in phase, the effects of phase shift on narrow bandwidth signals show consistent trends. Image shifts are frequency-dependent, with low frequency bands being affected more by a given phase shift than high frequencies (because they involve larger time differences).

3. When inter-aural time delay and inter-aural intensity-difference cues are contradictory, as in the case of the louder loudspeaker lagging in phase, the two factors seem

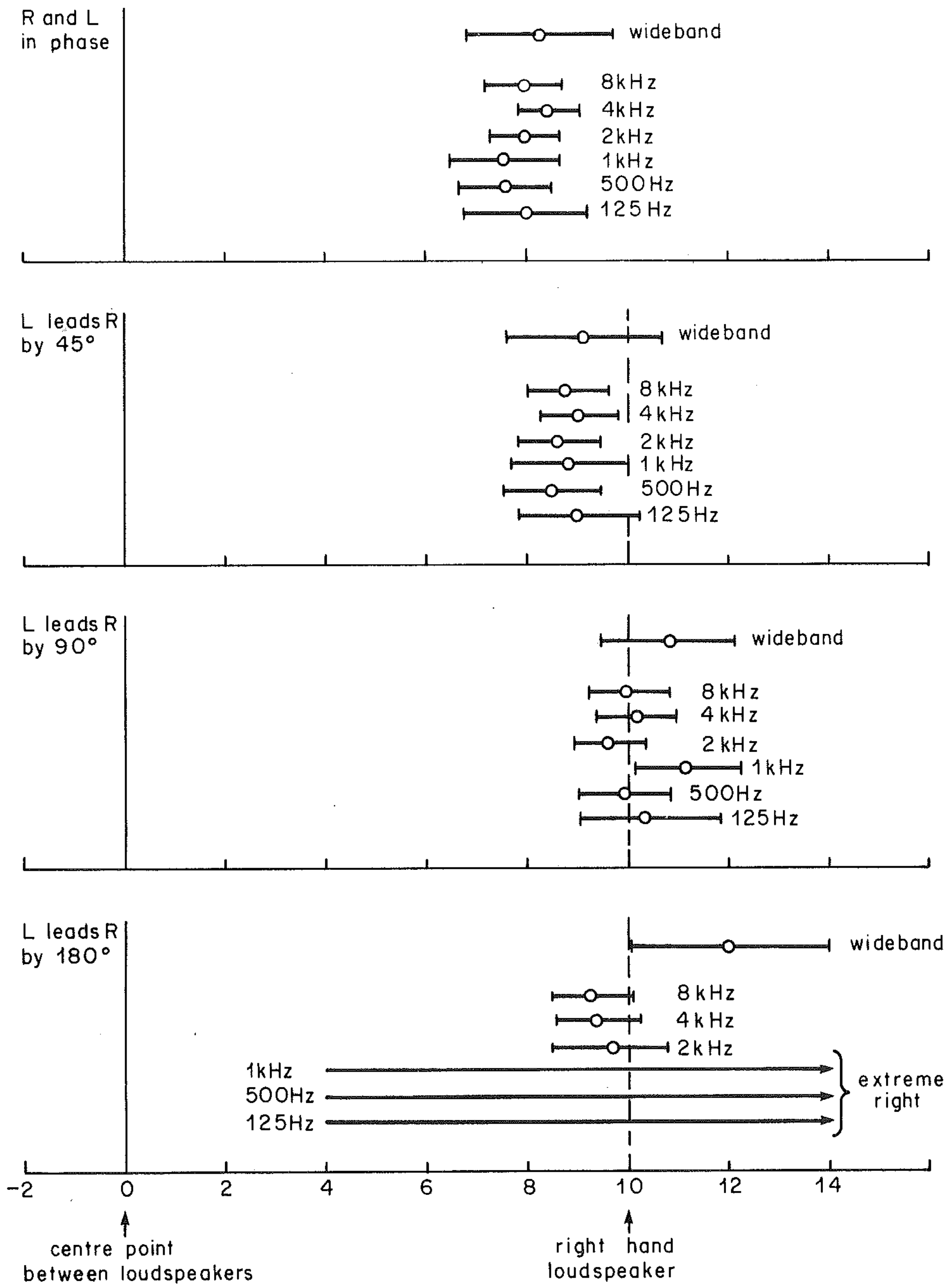

Fig. 8 - Image localisation for narrow bandwidth phase-shifted signals, $|R| - |L| = 14$ dB; L phase leading R

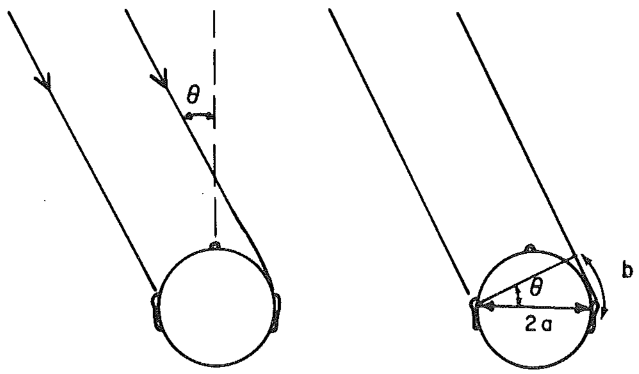

Fig. 9 - Localisation of a single sound source

to cancel to a certain extent. Inconsistent narrowband image shifts are then obtained, which do not show any reasonable frequency-dependent trends. In this situation, anomalous localisation may result when the interchannel time-difference equals the inter-aural time-difference.

A large amount of data has been accummulated on the quantitative and, to a lesser extent, the qualitative effects of phase shifts on narrow bandwidth stereophonic signals. This has been presented in a form convenient for use in, say, the design and evaluation of matrix quadraphonic systems.

6. References

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Appendix

Tabular and Graphical Presentation of Results

An image characterised by parameters x, y°, (z) is situated at position x (on the scale previously described, with the right loudspeaker situated at +10 and the left at −10). It has an overall width of y°, and a subjective degree of phasiness z:

$z = 0$: image 'not phasey'
$z = 1$: image 'just noticeably phasey'
$z = 2$: image 'distinctly phasey'
$z = 3$: image 'objectionably phasey'

TABLE 1

Results for Interchannel Level-Difference of 0 dB (R = −6 dB, L = −6 dB)

Octave frequency band	Interchannel phase difference (R leading L)			
	0°	45°	90°	180°
125 Hz	0·2, 6°, (0)	1·7, 11°, (0)	3·9, 14°, (½)	U, U, (3)
500 Hz	0 7°, (0)	1·0, 11°, (½)	2·7, 27°, (1)	U, U, (3)
1 kHz	0 6°, (0)	0·7, 11°, (½)	U, U,* (3)	U, U, (3)**
2 kHz	0 5°, (0)	0·2, 5°, (0)	2·2, 15°, (2)	U, U, (3)
4 kHz	0, 5°, (0)	0·5, 5°, (0)	1·5, 8°, (½)	1·0, 18°, (–)+
8 kHz	0, 5°, (0)	0·2, 5°, (½)	1·2, 10°, 1	0·5, 15°, (–)+
Wideband	0·1, 8°, (0)	1·5, 17°, (1)	2·7, 30°, (2)	U, U, (3)

* U – image judged to be unlocateable.
** double images and other anomalies observed.
\+ some people comment – not conventionally 'phasey' but 'nasty', and difficult to 'locate'.

TABLE 2

Results for Interchannel Level-Difference of 4 dB (R = –4 dB, L = –8 dB)

Octave frequency band	Interchannel phase difference (R leading L)			
	0°	45°	90°	180°
125 Hz	2·7, 6°, (0)	4·3, 14°, (0)	7·3, 15°, (½)	extreme-right* (½)
500 Hz	2·3, 4°, (0)	3·7, 7°, (0)	7·3, 17°, (1)	extreme-right (1)
1 kHz	2·6, 4°, (0)	3·8, 11°, (½)	6·2, 11°, (1½)	extreme-right (2½)
2 kHz	3·0, 4°, (0)	4·5, 6°, (0)	6·5, 8°, (½)	6·7, 25°, (2½)
4 kHz	3·1, 4°, (0)	4·5, 6°, (0)	5·8, 7°, (½)	4·9, 10°, (1)
8 kHz	2·9, 4°, (0)	3·3, 6°, (0)	5·5, 11°, (0)	4·8. 10°, (2)
Wideband	2·6, 8°, (0)	4·4, 11°, (0)	6·8, 13°, (1)	U, U, (3)

Octave frequency band	Interchannel phase difference (L leading R)			
	0°	45°	90°	180°
125 Hz	2·7, 6°, (0)	2·8, 5°, (0)	2·3, 7°, (0)	extreme-right (½)
500 Hz	2·3, 4°, (0)	1·9, 7°, (0)	2·1, 30°, (2)	extreme-right (1)
1 kHz	2·6, 4°, (0)	2·6, 12°, (0)	extreme-right	extreme-right (2½)
2 kHz	3·0, 4°, (0)	2·8, 7°, (0)	3·0, 15°, (0)	6·7, 25°, (2½)
4 kHz	3·1, 4°, (0)	3·1, 4°, (0)	2·7, 14°, (0)	4·9, 10°, (1)
8 kHz	2·9, 4°, (0)	3·1, 3°, (0)	2·7, 11°, (1)	4·8, 10°, (2)
Wideband	2·6, 8°, (0)	2·1, 19°, (1)	1·4, 36°, (2)	U, U, (3)

* All 'extreme-right' images observed as coming from a direction in line with the right ear (all these images were observed to be rather less loud than their corresponding in-phase images).

TABLE 3

Results for Interchannel Level-Difference of 8 dB (R = –4 dB, L = –12 dB)

Octave frequency band	Interchannel phase difference (R leading L)			
	0°	45°	90°	180°
125 Hz	5·2, 6°, (0)	7·4, 14°, (0)	10·2, 10°, (0)	extreme-right
500 Hz	4·8, 5°, (0)	5·8, 11°, (0)	8·8, 11°, (0)	extreme-right
1 kHz	4·9, 5°, (0)	5·9, 8°, (0)	8·7, 9°, (½)	extreme-right
2 kHz	6·0, 5°, (0)	7·2, 8°, (0)	9·0, 10°, (0)	10·1, 9°, (2)
4 kHz	6·2, 5°, (0)	7·2, 7°, (0)	8·7, 11°, (0)	9·2, 9°, (2)
8 kHz	5·9, 4°, (0)	6·4, 8°, (0)	7·3, 11°, (½)	9·0, 10°, (2)
Wideband	5·6, 8°, (0)	7·3, 8°, (0)	9·8, 6°, (0)	11·7, 11°, (1)

Octave frequency band	Interchannel phase difference (L leading R)			
	0°	45°	90°	180°
125 Hz	5·2, 6°, (0)	4·7, 9°, (0)	6·7, 14°, (½)	extreme-right
500 Hz	4·8, 5°, (0)	5·5, 11°, (0)	7·5, 16°, (0)	extreme-right
1 kHz	4·9, 5°, (0)	5·5, 9°, (0)	10·1, 14°, (1)	extreme-right
2 kHz	6·0, 5°, (0)	6·0, 6°, (0)	7·2, 14°, (½)	10·1, 9°, (2)
4 kHz	6·2, 5°, (0)	6·0, 10°, (0)	7·2, 11°, (0)	9·2, 9°, (2)
8 kHz	5·9, 4°, (0)	6·1, 7°, (0)	7·4, 11°, (1)	9·0, 10°, (2)
Wideband	5·6, 8°, (0)	6·5, 11°, (0)	8·5, 13°, (1½)	11·7, 11°, (1)

TABLE 4

Results for Interchannel Level-Difference of 14 dB (R = −2 dB, L = −16 dB)

Octave frequency band	Interchannel phase difference (R leading L)			
	0°,	45°	90°	180°
125 Hz	8·0, 6°, (0)	9·0, 12°, (0)	10·8, 13°, (0)	extreme-right
500 Hz	7·6, 5°, (0)	8·0, 9°, (0)	10·4, 9°, (0)	extreme-right
1 kHz	7·6, 5°, (0)	8·0, 7°, (0)	9·6, 9°, (0)	extreme-right
2 kHz	8·0, 4°, (0)	8·5, 6°, (0)	9·6, 7°, (0)	9·7, 7°, (0)
4 kHz	8·4, 3°, (0)	8·8, 4°, (0)	9·6, 7°, (0)	9·4, 6°, (0)
8 kHz	8·0, 4°, (0)	8·0, 4°, (0)	9·4, 4°, (0)	9·3, 5°, (0)
Wideband	8·3, 9°, (0)	9·0, 8°, (0)	10·5, 7°, (0)	12·0, 8°, (½)

Octave frequency band	Interchannel phase difference (L leading R)			
	0°	45°	90°	180°
125 Hz	8·0, 6°, (0)	9·0, 7°, (0)	10·3, 8°, (0)	extreme-right
500 Hz	7·6, 5°, (0)	8·5, 6°, (0)	10·0, 5°, (0)	extreme-right
1 kHz	7·6, 5°, (0)	8·8, 7°, (0)	11·2, 6°, (0)	extreme-right
2 kHz	8·0, 4°, (0)	8·6, 4°, (0)	9·6, 4°, (0)	9·7, 7°, (0)
4 kHz	8·4, 3°, (0)	9·0, 4°, (0)	10·2, 5°, (0)	9·4, 6°, (0)
8 kHz	8·0, 4°, (0)	8·8, 5°, (0)	10·0, 5°, (0)	9·3, 5°, (0)
Wideband	8·3, 9°, (0)	9·1, 8°, (0)	10·8, 7°, (0)	12·0, 8°, (½)

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