THE INFLUENCE OF ANTIPHASE CROSSTALK ON THE LOCALIZATION CUES IN STEREO SIGNALS

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THE INFLUENCE OF ANTIPHASE CROSSTALK ON THE LOCALIZATION CUES IN STEREO SIGNALS

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ABSTRACT:

Widening of the stereo base is an attractive feature for stereo sets with closely spaced loudspeakers. This effect is brought about by the introduction of crosstalk in antiphase between the two stereo channels.

An analysis of this phenomenon must be based on the directional localization cues of human hearing. The most important cues are interaural differences of level, phase delay and group delay. We show that the localization directly in front of the loudspeakers is determined by the interaural time delay differences only; to either side of this position interaural level differences play a part too. At some positions, however, level effects and time delay effects provide conflicting localization cues, leading to a rather vague image of a virtual source.

Listening experiments were carried out to verify these results.

From this investigation it follows that the introduction of a small time delay in the crosstalk circuit shifts the regions with reinforcing localization cues in the direction of the listener, thus improving the localization of virtual sources in the widened stereo image.

1.INTRODUCTION

Stereo sound reproduction from two loudspeakers in a standard stereo set-up may create virtual sources at every position between the loudspeakers, i.e. the stereo base. Lauridsen and Schlegel [1] found a way to widen the stereo base beyond two closely spaced loudspeakers. They use an arrangement that allows for crosstalk in antiphase between the two stereo channels. Hanson and Kock [2] state that at equal distances from two loudspeakers radiating in antiphase the intensity must show a minimum. By means of a phasor model Bauer [3] shows that signals in antiphase from two loudspeakers produce a phase difference between both ears of a listener positioned in the middle. Tappan [4] uses two loudspeakers for reproduction of the stereo difference signal in antiphase and a loudspeaker for the sum signal in the middle, resulting in a better stereo image at the stereo base if the ratio of difference signal to sum signal is increased. from the large number of publications on the subject we further mention Sandel et al. [5], Schodder [6], Gardner [7] and Hentschke [8]. To the best of the author´s knowledge no detailed description of the effect has been published up to now. Therefore we investigated, as a function of the listener position, the localization cues leading to the stereo base widening effect when crosstalk in antiphase is applied between two closely spaced loudspeakers. Crosstalk is assumed from the left channel output to the right loudspeaker and from the right channel output to the left loudspeaker.

Since the introduction of small stereo sets with built-in loudspeakers, the widening of the stereo base has gained renewed interest. Essentially, stereo base widening is brought about by acoustic interference at the position of the listener, due to the application of crosstalk in antiphase. An accompanying effect is the increase of the stereo difference signal with respect to the sum signal, thus emphasizing signals not equally present in both channels, such as the early reflections and the reverberation. In section 2 we analyse the localization cues of one virtual image for a listener in front of two closely spaced loudspeakers radiating a signal and its crosstalk in antiphase. Listening experiments to verify the calculations are described in section 3. The results of calculation and experiment are compared and some conclusions are given in section 4. In section 5 we discuss the consequences of our findings, such as: the improvement of the stereo image when a small delay is added to the crosstalk. Further, we deal with the dependence of the stereo base widening on the geometry of the set-up and the localization of sources recorded in both the left and the right channel.

2.THEORY

The human hearing mechanism is able to localize the direction of an acoustic source using Interaural Level Difference (ILD) and Interaural Time delay Difference (ITD). If more uncorrelated sources are present at the same time, our hearing can isolate one of them, probably using a form of cross-correlation, as was first suggested by Licklider [9],[10] (for further references see Blauert [11]). This section deals with the localization of a single source in one stereo channel and its crosstalk in antiphase in the other.

Assume a point P on a circle and two loudspeakers on either side of the centre M (fig.1), with a mutual separation much smaller than the radius. The listening position is on the circle in the region of the symmetry axis. Reflections from walls etc., which are delayed more than one millisecond with respect to the direct sound, are not important for the localization. This may be concluded from the law of the first wavefront (Cremer [12]). Therefore reflections can be neglected. The amplitude at the right loudspeaker is R and if we call the crosstalk factor , then the signal at the left loudspeaker is $-\alpha R$. When the angle ψ between the symmetry axis and the line MP equals zero, the propagation times from both loudspeakers to P are equal. If P is shifted along the circle, the increase τ in propagation time from one loudspeaker is to a very good approximation equal to the decrease in propagation time from the other loudspeaker, as shown in fig.2. Neglecting the amplitude variation at P, due to the change in distance from P to the loudspeakers, the sound pressure in P is:

$$p = R \exp[-j\omega(t-\tau)] - \alpha R \exp[-j\omega(t+\tau)] \qquad (1)$$

Neglecting the common propagation time t, the amplitude becomes:

$$p = R \exp[+j\omega\tau] - \alpha R \exp[-j\omega\tau] \qquad (2)$$

The magnitude $|p|$ is:

$$|p| = R\sqrt{(1-\alpha)^2\cos^2(\omega\tau)+(1+\alpha)^2\sin^2(\omega\tau)} \qquad (3)$$

For the phase we write:

$$\varphi = \arctan\frac{(1+\alpha)\sin\omega\tau}{(1-\alpha)\cos\omega\tau} \qquad (4)$$

In fig.3 a,b the magnitude and the phase are drawn as a function of $\omega\tau$ for α=0.98, 0.7 and 0. The value of α=0.7 is chosen because this value results in an appropriate stereo base widening. The values of α=0.98 and 0 illustrate two limiting cases. α is not taken equal to 1.0, because various characteristics (see e.g. fig.3b) would coincide with the axis. In the region of ψ=0 the magnitude of the sound pressure has a minimum value of $R(1-\alpha)$ for all frequencies. For high values of α this region shows a phase jump from $-\pi/2$ to $+\pi/2$ at all frequencies for which $\omega\tau \ll \pi$. If the value of α is decreased, the minimum of the magnitude of the sound pressure and phase jump become less pronounced. For α=0 both characteristics are straight lines. First, the amplitude variation due to the changing distance from P to the right loudspeaker is neglected and thus the amplitude does not depend on $\omega\tau$. Second, for a fixed position (or τ) the phase shows a linear dependence on ω, the slope being equal to the decrease τ in propagation time to the right loudspeaker. From fig.2 we see that an almost linear relationship exists between τ and ψ. Therefore in the next pictures, which we plot for a fixed frequency, we may replace the $\omega\tau$ scale on the abcissa by a ψ scale. Fig.4a,b,c, and d shows for α=0.98 and 0.7 the magnitude and the phase of the sound pressure for narrow frequency bands around 1, 2 and 4 kHz as obtained from eqs. (3) and (4). From the above results ILD and ITD will be derived in the following sections.

2.1. INTERAURAL LEVEL DIFFERENCE

When a signal consists of one single frequency, the acoustic intensity is proportional to p^2. In the case of a signal containing a wide range of frequencies, the acoustic intensity is found by integrating p^2 over all frequencies. The maximum frequency ω_M is determined by the frequency range of the signal. The intensity is proportional to:

$$I = \int_0^{\omega_M} p^2 \, d\omega \qquad (5)$$

After substituting eq. (3) we find:

$$I = \frac{R}{\tau} \int_0^{\omega_M} [(1-\alpha)^2 \cos^2(\omega\tau)+(1+\alpha)^2 \sin^2(\omega\tau)] d\omega\tau \qquad (6)$$

$$= \omega_M R^2 \left\{ 1+\alpha^2 - 2\alpha \frac{\sin(2\omega_M\tau)}{2\omega_M\tau} \right\} \qquad (7)$$

In fig.5a,b,e and f the intensity for narrow and wide frequency bands are plotted for α=0.98 and 0.7. From these results the ILD is obtained for two points 0.17 m apart at a listening distance of 2 m and a loudspeaker separation of 0.4 m. Fig.6a,b and fig.8a,b show the ILD for narrow and wide-band signals for α =0.98 and 0.7. A positive value of the ILD means that the intensity is higher at the right ear and thus that the source is localized at the right-hand side.

For all values of α, the ILD equals zero on the symmetry-axis. This means that if the ILD were the only cue at this position, the source would be localized between the loudspeakers. Because the intensity is an even function of ψ, we conclude that the same localization cues would have been found if the calculations had been carried out for a signal at the left loudspeaker and the antiphase crosstalk towards the right one.

2.2. INTERAURAL TIME DELAY DIFFERENCE

As Fig.3b shows, the phase does not vary linearly with ω, so we have to evaluate both the Interaural Phase Delay (IPD) and the Interaural Group Delay (IGD). Both these quantities are known to influence the localization. First we calculate the variation of phase delay and group delay with ψ. By definition the phase delay for $\omega = \omega_M$ is:

$$\tau_{PH} = -\varphi / \omega_M \tag{8}$$

$$= -\frac{1}{\omega_M} \quad \arctan \frac{(1+\alpha)\ \sin \omega_M \tau}{(1-\alpha)\ \cos \omega_M \tau} \tag{9}$$

The group delay in a narrow frequency band around ω_M is:

$$\tau_{GK} = -\, d\varphi / d\omega \tag{10}$$

$$= -\frac{(1-\alpha)\ (1+\alpha)\ \tau}{(1-\alpha)^2 \cos^2 \omega\tau \ + (1-\alpha)^2 \sin^2 \omega\tau} \tag{11}$$

With equation (3):

$$\tau_{GR} = -(1-\alpha)\ (1+\alpha)\, \tau \ R^2 / \ p^2 \tag{12}$$

The phase delay for frequencies of 1,2 and 4 kHz is shown in fig.5c and g for α =0.98 and 0.7 respectively. The group delay as a function of ψ for narrow-band signals of 1,2 and 4 kHz is shown in fig.5d and h for α=0.98 and 0.7 respectively. For the same listening situation as described in 2.1. we find the IPD and the IGD by subtracting the values of the phase delay and the group delay at two points 0.17 m apart. Fig.6c,d and fig.8c,d show for α=0.98 and 0.70 respectively the IPD for 1 kHz and the IGD for 1,2 and 4 kHz. Human hearing is not sensitive to IPD for frequencies higher than 1.6 kHz (Blauert [11]), so this region is neglected here. Not too far from the symmetry axis the IPD is positive, so that the virtual image of the right-hand source is shifted in the correct direction. In contrast to the intensity, the time delays are odd functions of ψ. Therefore a calculation carried out for a left stereo signal and cross-over towards the right loudspeaker would show the inverted time delay functions and therefore a localization shifted towards the left. For α =1 the phase on either side of the symmetry axis differs by an amount π. This means that the ign of the IPD at positions where $\psi \sim 0$ is ambiguous.

3.EXPERIMENTS

To verify the results of the calculations we carried out listening experiments in an anechoic room. Two mid-range loudspeakers with a frequency range from 0.4 to 6 kHz were placed 0.40 m apart. The loudspeakers were selected because of their directivity pattern. At 4 kHz the intensity was only 3 dB down for $\psi = \pm 30$ degrees. Differences in the outputs of the two loudspeakers will influence the interference of the signal and its inverted crosstalk. Therefore we measured at the position $\psi = 0$ and for $\alpha = 1$ the decrease in intensity. Depending on frequency the decrease varied between 15 and 30 dB and for white noise the level of the signal decreased 20 dB. From this we conclude that the symmetry of the acoustic level around the position for which $\psi = 0$ is sufficient.
From three subjects, whose results will be presented here, audiograms were measured up to 6 kHz. From the results we conclude that no deviations from normal localization are to be expected. The subjects were seated in front of and facing the loudspeakers at a distance of 2 m. A mirror was fixed to the loudspeakers and marked at some places to help the subjects maintain their correct positions. Eight reference loudspeakers, of the same type as described before, were placed at either side of the measuring loudspeakers. The subjects could, by means of a remote control, send a stimulus to the two measuring loudspeakers, or they could choose one of the reference loudspeakers to check the direction in which the virtual source was localized.
We will start with a description of the measurements for the condition $\alpha = 1$. Continuous narrow-band noise of 1, 2 and 4 kHz was first used as a stimulus. Bandwidths were 0.1, 0.3 and 0.3 kHz respectively. It turned out that the localization of the 1 kHz signal was difficult because the virtual image was blurred too much. The frequency was therefore lowered to 0.7 kHz. Localization could then be done, although the image was still rather vague in the region of $\psi = 0$. In these cases the subjects were asked for the most likely position of the source. In fig.7a,b and c the angle θ (see fig.1) is shown as a function of the position of the listener. Because of the symmetry of both the measuring set-up and the stimulus, reversing the loudspeaker signals is not meaningful for $\alpha = 1$. For $\alpha = 1$ we also measured the localization for a wide-band noise stimulus (see fig.7d). The noise was limited by the loudspeaker from 0.4 to 6 kHz. No difference in the localization was found when the experiment was repeated using white-noise pulses of 0.2 s at 1 s intervals.
Since the stimulus for $\alpha = 0.7$ is not a symmetric one, two experiments were carried out. First with the higher amplitude at the right loudspeaker and the crosstalk at the left one and then the reversed situation. For continuous narrow-band noise the localization as a function of position of the listener is drawn in fig.9a,b and c. When a stimulus of continuous wide-band noise was used two images could be localized at the same time. One image with a low frequency timbre was localized according to the results of the 0.7 kHz narrow-band noise measurement (fig.9a). The other image, which was of a high frequency character, was localized very much the same as the 2 and 4 kHz narrow-band noise signals (fig.9b and c). Because our main interest was in virtual images, where all parts of the signal

were fused by our hearing, pulsed wide-band noise was used instead (see fig.10). The pulses had a duration of 0.2 s at 1 s intervals. None of the subjects detected two images in this experiment.

4.CONCLUSIONS

The agreement between calculations and experiments is demonstrated by the results for frequencies of 2 and 4 kHz and for $\alpha=1$ (fig.6a and 7b,c). No ITD is involved here because the IGD is negligibly small (fig.6d) and the IPD is imperceptible. The small differences in the maximum localization shift can be attributed to the imperfect cancellation of the signal, as described in section 3.

Also, the localization of pulsed or continuous white noise signals for $\alpha=1$ closely follows the calculated characteristic of the wide-band noise (fig.6b and 7d). According to Blauert [11] (and the references therein) the ILD and the IGD dominate the localization when frequencies higher than 1.6 kHz are present. Therefore the IPD is not expected to have any influence on the results for wide-band noice (fig.7d). A signal containing only frequencies around 0.7 kHz is localized as indicated in fig.7a. Around the symmetry axis the IPD is equal to π and thus is amiguous (fig.6c). Therefore to either side of the position for which $\phi=0$ the ILD (fig.6a) determines whether the signal at the left or the right ear should be considered as leading in phase and consequently fixes the sign of the angle of localization θ.

Decreasing the crosstalk to $\alpha=0.7$ leads to various changes in the calculated characteristics. The values of the ILD are decreased. The values of the IGD are increased, being higher for the low frequencies. The increased value of the IGD may be the cause of the small shift of the localized direction of the 2 and 4 kHz noise away from the loudspeaker radiating the crosstalk signal (fig.9b and c). Fig.9a shows almost even characteristics, which therefore must be caused by the ITD. The phase difference is decreased to less than π, so the IPD is no longer ambiguous. The virtual source must now be localized at the side of the leading phase. There may also be some influence of the ILD. Although rather small at these frequencies, it may be the cause of the slight asymmetry in fig.9a.

From the experiments with pulsed noise shown in fig.10 the stereo widening effect of antiphase crosstalk can be recognized. At the position $\phi=0$ and for $\alpha=0.7$ the stereo base extends, on the average, from $-20<\theta<+20$ degrees. From the calculations we see that the ILD cannot cause the widening at this position (fig.8b). From this we conclude that time delays are responsible. High frequency signals have a very small IGD (fig.8d) and an IPD undetectable by our hearing (as we mentioned earlier). Thus low frequency parts with a relatively high ITD must be the cause of this shift in localization. If the listening position is shifted to that side of the symmetry axis where the loudspeaker with the higher amplitude is situated, the localization shifts even further in this direction. In this region the ILD and the ITD cooperate (i.e. shift the localization in the same directior) leading to a large shift of the virtual image and a relative sharply defined image.

At positions closer to the loudspeaker with the crosstalk signal (the smaller amplitude), the ILD and the ITD provide conflicting localization cues. Probably because of this, a rather vague virtual image is formed, often localized in the wrong direction. At these positions two images were simultaneously detected in the continuous wide-band noise experiment. The results presented in fig.10 indicate that, depending on the subject, the two cues may partly cancel, or that one cue may dominate the other. In this respect it is interesting to note the finding of McFadden et al. [13] that some subjects may be more sensitive to the ILD, while others rather use the ITD.

5.DISCUSSION

In short we have found that: 1) In the mid-position the localization shift is not brought about by intensity effects, but only by time delays. 2) At positions closer to the loudspeaker with the higher amplitude, intensity effects and time delay effects reinforce each other to form a virtual image, which is shifted further in the correct direction. 3) At positions where the loudspeaker with the smaller amplitude is closer, intensity effects conflict with time delay effects. Here the image is less clearly defined and often localized in the wrong direction.
The best listening positions, i.e. where a considerable shift of the localization in the correct direction still results in a well defined image, do not coincide for both stereo channels (fig.10). The stereo image can be improved when the best listening positions of both channels are shifted towards a listener in the mid-position. This can be achieved by delaying the crosstalk from the right channel towards the left loudspeaker, which has the same effect as a backward shift of the left loudspeaker. Consequently, the interference pattern, and thus the best listening position, will be rotated towards the symmetry axis. The same can be done for the left signal. For a loudspeaker separation of 0.4 m, as in the set-up discussed in sections 2 and 3, a delay of about 50 microseconds is sufficient. A delay as small as this can easily be realized using two analog lowpass filters, one in each of the crosstalk circuits.

A process related to the one described in this paper is TRADIS: True Reproduction of All Directional Information by Stereophony (see Damaske [14]). Here delayed and inverted crosstalk is used to reproduce artificial head recordings by means of loudspeakers positioned far apart in a standard stereo set-up. In this case the listener's left ear should only receive the signal of the left recording channel. The undesired signal reaching the right ear can be cancelled by delayed and inverted crosstalk from the right loudspeaker. During reproduction, when the loudspeakers are placed far apart, a considerable difference exists in the transfer function from one loudspeaker to the left and to the right ear. The crosstalk must therefore be filtered to account for the difference. We assumed in section 2 that the loudspeaker separation is much smaller than the loudspeaker-to-listener distance, so the difference between the two transfer functions can be neglected.

The loudspeaker separation strongly influences the side shift of the localization. To a good approximation we may write:

$$\tau = \psi D/(2v) \qquad (13)$$

Here ψ (see fig.1) is in radians and v is the sound velocity. D is the distance between the loudspeakers. So the increase of τ with increasing ψ (fig.2) will become smaller when the loudspeaker separation is decreased. In eqs.(3) and (4), from which our results are derived, $\omega\tau$ and α are the only variables. Therefore all results for a fixed α, but plotted as a function of ψ, will maintain their shapes, but are expanded over a larger range of ψ. As the interaural differences are based on a fixed ear-to-ear distance, these results cannot be scaled. The expanded functions will lead to smaller interaural differences. So a decrease of the loudspeaker separation will result in a smaller interaural difference, these values being less dependent on position. In other words the localization shifts are smaller, but extend to positions of the listener further away from the middle.
From eq.(13) we see that phase and amplitude, which depend on the value of τ, do not change along a line of constant ψ. This means that the interference pattern spreads with increasing distance from the loudspeakers and so the interaural differences will be diminished. But again, as in the case of decreasing loudspeaker separation, the localization shift will extend to positions of the listener further away from the middle.

Next, we briefly consider the effect of a rotation of the listener's head. As in the case of natural sources, a rotation introduces an additional ILD by the shadowing effect of the head and an additional ITD, such that the perceived position of the source remains unchanged. However, the ear-to-ear distance projected on the circle MP (see fig.1) is reduced. Therefore, a decrease of the ILD and the ITD is expected depending on the angle of rotation. However, it was verified that the inevitable small rotations of the head during the experiments did not influence the direction in which the virtual source was localized.

We now consider the case in which one source is recorded simultaneously by two coincident microphones, as in the M-S technique, described among others by Dooley and Streicher [15]. We have to distinguish between the sound of a source arriving from a position directly in front of the microphones and the sound arriving from aside. The direct sound of a source directly in front of the microphones will be recorded in both channels with the same amplitude. Other sources, positioned more to one side, will be recorded in both channels with different amplitudes. The ratio of these amplitudes we will call the recording crosstalk factor β, with $0<\beta<1$. The effect of the antiphase crosstalk will be diminished or even cancelled by the in-phase crosstalk For a source directly in front of the microphones, $\beta=1$. As long as the recording crosstalk β exceeds the antiphase crosstalk α, the loudspeaker signals will be in phase and the virtual source will remain between the loudspeakers. Sources further aside will be recorded with a smaller value of β. If, during the recording, the source is so far aside that $\alpha > \beta$, then the loudspeaker signals are in antiphase. As a result, the virtual source will be localized beyond the conventional stereo base. The extreme case $\beta=0$, for which the calculation and the experiments were carried out, describes a source far aside during recording, leading to a maximum localization shift. Indirect sound - in particular reverberation - will only be partially coherent in both channels. Low frequency reverberation, which is the most coherent part in the two channels, will be present with equal amplitudes and thus localized in the middle. The high frequency part of the reverberation, which appears less coherent in the left and right channels, will be localized at larger angles the lower the degree of coherence. Therefore, the reverberation seems to reach the listener from all directions.

A second effect of the inverted crosstalk, which also depends on the coherence of the left and right channel signals, is the attenuation. Signals recorded coherently and with equal amplitudes in both channels, such as the direct sound of a source directly in front of the microphones and all low frequency signals, are electrically attenuated in the crosstalk circuit. The amplitudes decrease to $1-\alpha$ times their previous value. For $\alpha=0.7$ this amounts to 10.5 dB. Acoustic summation of these in-phase signals reduces this number to 4.5 dB. Signals without a coherent counterpart in the other channel are attenuated by acoustic interference only. This attenuation is limited to the region around the symmetry axis, as was calculated before.

From the above, we conclude that the localization shift and the attenuation of a virtual source both depend on the degree to which the recordings of this source in both channels differ from each other. Thus, for a fixed value of α, sources localized in the middle are inevitably attenuated with respect to sources localized at larger angles.
This implies that the increase of the difference signal with respect to the sum signal is essential to the phenomenon of the stereo base widening. In the circuit proposed by Cohen [16],[17], the difference signal is delayed, attenuated, added to one channel and subtracted from the other. According to Cohen, this circuit does not show the attenuation of the sum signal. This sum signal contains practically all low frequency components. However, for closely spaced loudspeakers, where the delay must be kept small, this processing is equivalent to the application of antiphase crosstalk in the way assumed in section 1. Although the sum signal is indeed not attenuated, a straightforward calculation of the output signals shows that the ratio of the sum signal to the difference signal remains the same.
When the loudspeakers are further apart, so that the delay in the crosstalk circuit must have a larger value, Cohen's circuit does not result in the desired delayed crosstalk in antiphase. The reason is that a delayed fraction of itself is added to the signal, resulting in a distorted interference pattern at the position of the listener. A better way to compensate for the inevitable attenuation of the sum signal, and thus the low frequencies, is to emphasize this frequency region by amplification before the antiphase crosstalk is applied.

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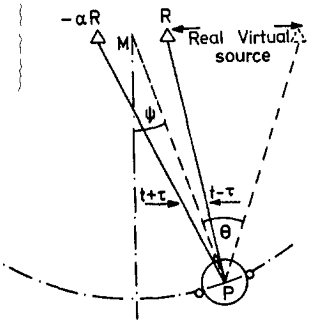

FIG.1
The arrangement of loudspeakers with signal amplitude R and crosstalk amplitude $-\alpha R$. The position of the listener at point P is determined by ψ. The direction in which the virtual source is localized is given by θ.

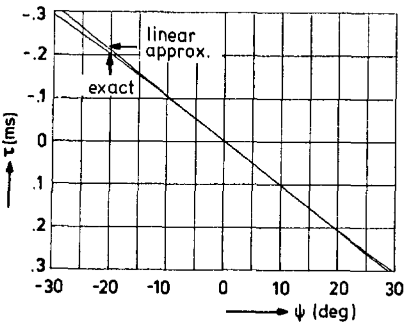

FIG.2
The variation of the delay from the right loudspeaker to P vs. ψ and the linear approximation used in the calculation. The distance from the loudspeakers to the listener is 2 m and the loudspeaker separation is 0.4 m.

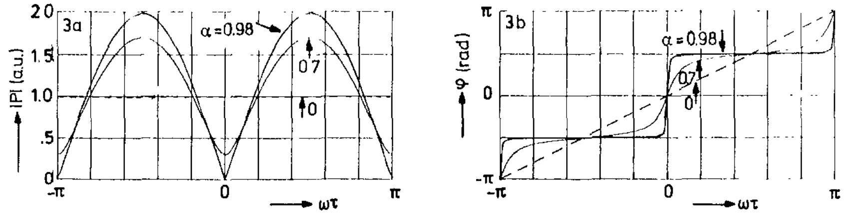

FIG.3
Modulus |p| (3a) and phase φ (3b) of the sound pressure vs. $\omega\tau$, calculated for crosstalk of α=0.98, 0.70 and 0 at the left loudspeaker.

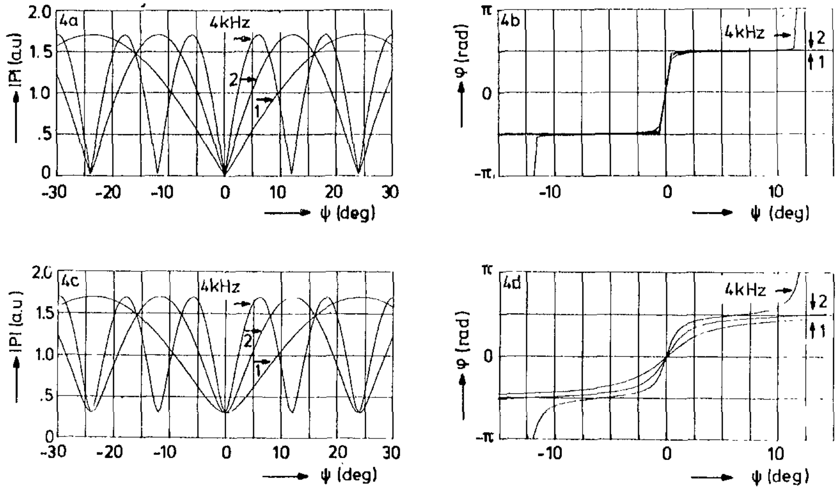

FIG.4
Calculated values of modulus |p| and phase φ of the sound pressure for narrow-band signals vs. position ψ of point P:
4a,b: α =0.98
4c,d: α =0.70 (crosstalk at the left loudspeaker)

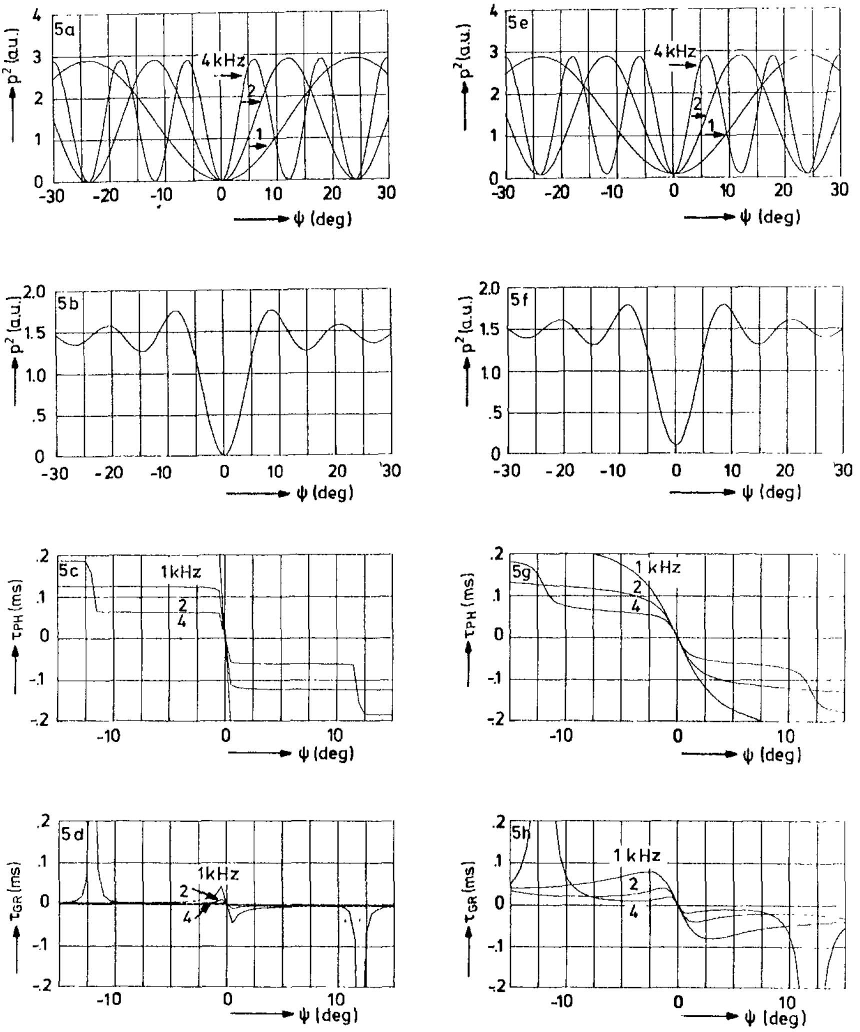

FIG.5

Calculation of various quantities vs. position ψ of P for $\alpha = 0.98$ (5a to d) and $\alpha = 0.7$ (5e to h). Crosstalk at the left loudspeaker.

5a,e: square of the sound pressure for narrow-band signals
5b,f: sound intensity for a wide-band signal up to 4 kHz.
5c,g: phase delay
5d,h: group delay

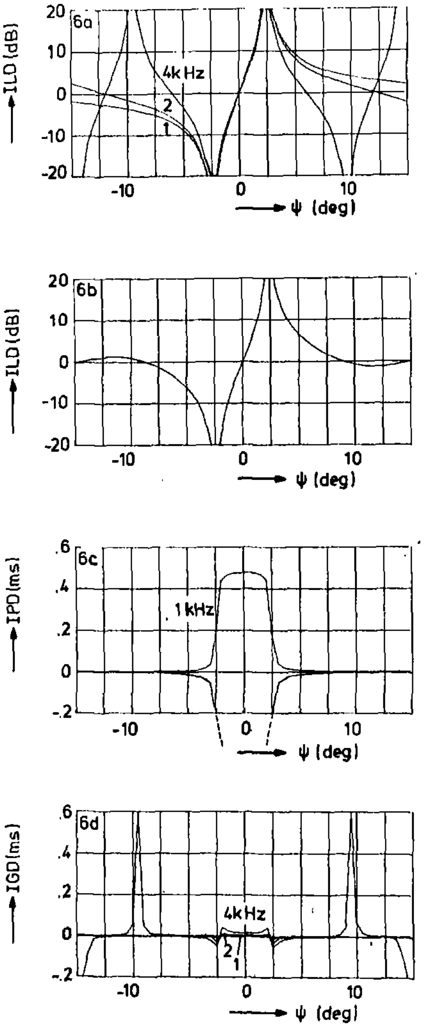

FIG.6
Calculation of the interaural differences vs. position ψ of the listener for $\alpha=0.98$.

6a: interaural level differences for narrow-band signals
6b: interaural level differences for wide-band signals up to 4 kHz
6c: interaural phase delay
6d: interaural group delay

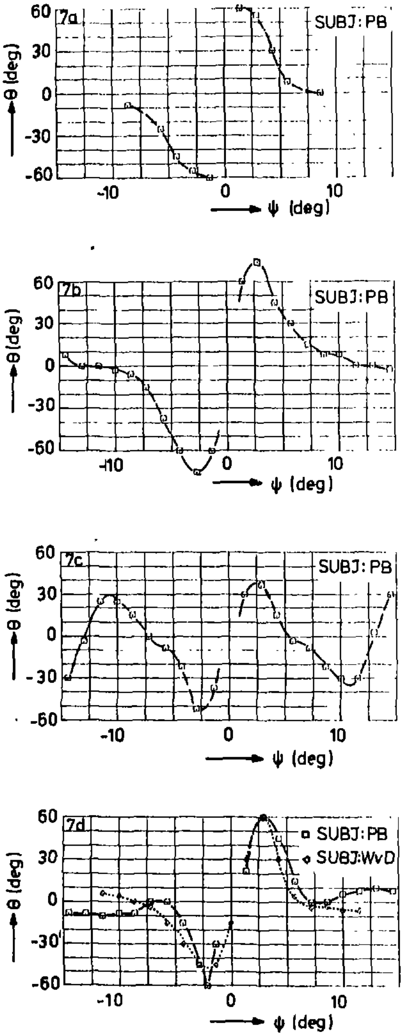

FIG.7
Listening experiments showing the localization angle θ of a virtual source vs. the position ψ of the listener for $\alpha=1$. The stimulus is continuous noise.

7a: freq.=0.7 kHz, bw.=0.1 kHz
7b: freq.= 2 kHz, bw.=0.3 kHz
7c: freq.= 4 kHz, bw.=0.3 kHz
7d: wide-band noise up to 4 kHz

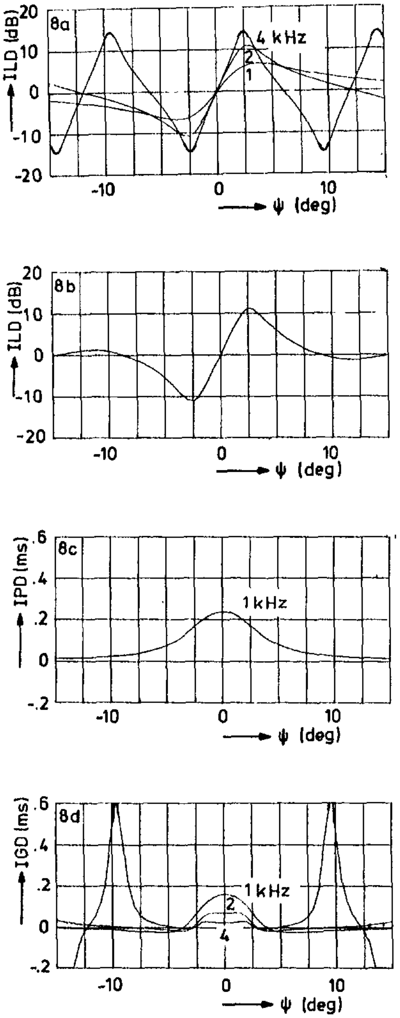

Fig.8
Calculation of the interaural differences vs. position ψ of the listener for α=0.7. Crosstalk at the left loudspeaker.

8a: interaural level differences for narrow-band signals
8b: interaural level differences for a wide-band signal up to 4 kHz
8c: interaural phase delay
8d: interaural group delay

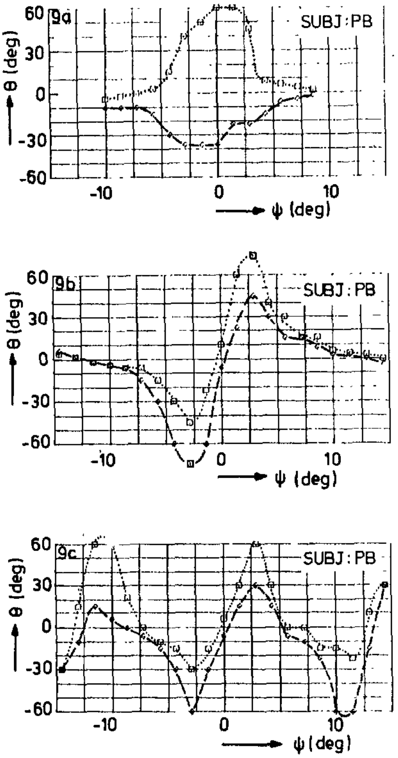

FIG.9
Listening experiments showing the localization angle θ of a virtual source vs. the position ψ of the listener for α=0.7. The stimulus is continuous noise.

9a: freq.=0.7 kHz, bw.=0.1 kHz
9b: freq.= 2 kHz, bw.=0.3 kHz
9c: freq.= 4 kHz, bw.=0.3 kHz

dashed (dotted) lines: crosstalk at the right (left) loudspeaker.

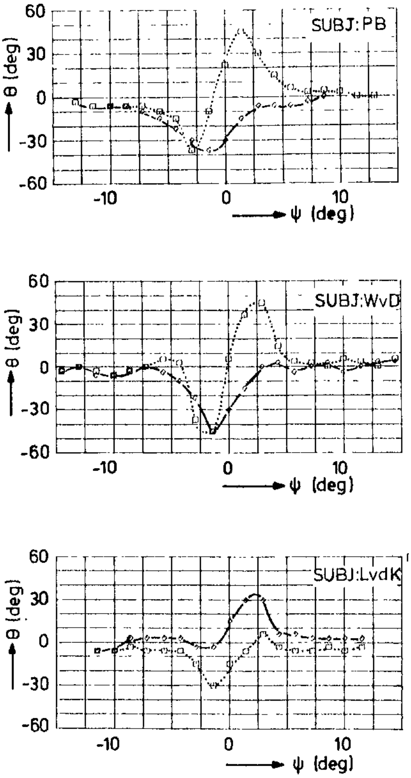

FIG.10
Listening experiments carried out by three subjects, showing the localization angle θ of a virtual source vs. the position ψ of the listener for $\alpha=0.7$. The stimulus was pulsed wide-band noise up to 4 kHz. Dashed (dotted) lines: crosstalk at the right (left) loudspeaker.