A NEW POSSIBILITY TO EXPLAIN THE DIRECTIONAL PERCEPTION BY TWO-CHANNEL STEREOPHONIC SYSTEMS

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Introduction

Man's hearing process and the directional perception with its aid are decisively binaural. When the symmetry of certain meaning of the signals presented at the two ears ceases to exist the perceived sound image is more or less laterally displaced. In the case of a single sound source the chief reason of the asymmetry is the fact that the impulse-like signals are not presented at the two ears with the same amplitudes, and simultaneously.

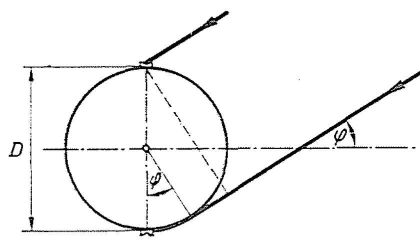

Fig. 1. An approaching determination of the interaural time differences

The time difference arises from the differences of the ways covered by the sound wave. Further on it will be denoted with δt, and will be named interaural time difference. Assuming that the head is of spherical form (Fig. 1) we can write

$$\delta t = \frac{D}{2c}(\sin\varphi + \varphi),$$

where D is the diameter of the head, and c is the velocity of sound. We can averagely write in practical calculations made for the air

$$\delta t = 0{,}24(\sin\varphi + \varphi)\ \text{msec}.$$

The non-identical signal amplitude is the result of the special situation of the external ears, and that of the screening effect of the head. Let us denote the amplitude of sound pressure in the left- and right-ear p_l and p_r, respectively. The ratio of these is $K = \frac{p_l}{p_r}$. The interaural level difference can be described in dB too by the following relationship

$$n = 20 \lg \frac{P_l}{P_r} .$$

We suppose such a process in the mechanism of the directional perception which can give an account of the origin of a single phantom source also in the case of two or more sound sources.

An attempt of this kind is not new. An electronic model has been elaborated e.g. by FRANSSEN [1] in which the directional determination is due to the state of equilibrium of a bridge connection. He uses in his model two parameters determined in such a way that his calculations, made for the stereophonic listening, should give a possibly good coincidence with the experimental results.

In listening to a natural sound source we always perceive simultaneously the time and level differences, so it is evident that our brain uses both data for determining the direction. When we produce artificially only a time difference in a tone presented at the two ears, also in that case a determined directional sensation would be brought about in our mind. The situation is similar even when only a level difference is produced. When time and level differences simultaneously exist between the two ears then the sum of the separately perceived angles will be the actually perceived dircetion and we can write

$$\varphi\ (n,\ \delta t) = \varphi\ (0,\ \delta t) + \varphi\ (n,\ 0).$$

This expresses the principle of the integral-localization which is verified in the case of small angles. Based on this principle it is possible to artificially reduce the directional angle of perception produced by level difference with a time difference of opposite sense, and even perfect direction compensation can be brought about.

It is remarkable that a real directional sensation arises using such time and intensity combinations which would never occur in natural observations. This can be seen as an essential fact to establish that the determination of direction is mostly a physiological process in which psychological elements (e.g. memory) do not play a considerable role yet. Based on this, we assume that the directional detection is produced before the signals from the ears are presented in the brain. We must imagine a mechanism making a comparison between the signals from the two ears, and based on this action a direction determining quantity is produced and transmitted to the brain.

The electrical model

The basic idea of the model proposed by us for describing the interaction is that the comparative system measures the differences between the pulses of the sound pressure coming from the two sides, namely, at a perfectly definite moment. The analogous electrical model is shown in the Fig. 2.

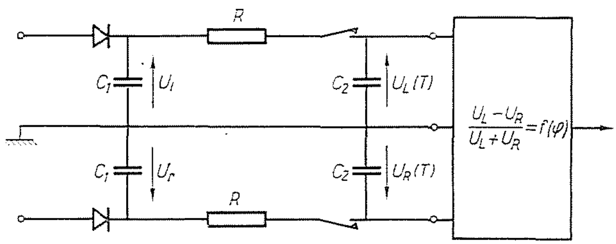

Fig. 2. Electrical analogue of a direction determining model

The first stage is an integrator, the second one is a comparative circuit. Let us assume that the voltages at the input are proportional to the sound pressures in the left- and right ear. Then U_L and U_R are the voltages proportional to the timeintegral of the amplitudes of the sound pressure. We must

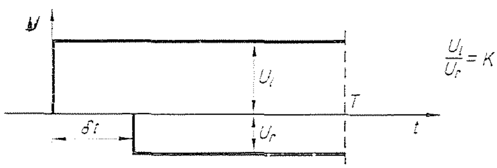

Fig. 3. The envelopes of the input voltages of the electrical model

assume that C_1 is small enough to quickly follow the voltage-peak in time, and the RC_2 time-constant is great enough that we can regard the $R-C_2$ term as an integrating circuit. This sort of condition for the denominator of the formula in the functioning of the comparative circuit is justified by the normalization and reasons of symmetry.

Let us assume that U_l and U_r as the functions of time are as it is shown in Fig. 3.

If the breakers switch off at T-moment by an exterior control, and $\delta t < T$ then we can write

$$f(\varphi) = \frac{(K-1)\,T + \delta t}{(K+1)\,T - \delta t}\,.$$

When $\delta t \geq T$ then of course $f(\varphi) = 1$, and the phantom source will be displaced by 90 degrees to the left. $f(0) = 0$ equation corresponds to the $\varphi = 0°$ middle impression, since in this case, perceiving a real sound source $K = 1$, and $\delta t = 0$.

It can directly be seen that an artificial establishment of the perception of the middle impression is possible by a registration by which the time difference is compensated by introducing an additional level ratio of opposite sense. This is true if

$$(K-1)\,T + \delta t = 0.$$

In the case of the compensation of small time differences $K = 1-0.115n$ so from our previous equation it follows that

$$T = 8.7\,\frac{\delta t}{n}.$$

The empirical determination of T is possible since the experiments confirm the result that by compensating small time differences δt is proportional to n. Considering the survey data reported by numerous authors we can obtain $T = 2.7$ msec as a mean value.

The related values of K and δt connected with the different φ directions have been determined by DE BOER [2] in the case of speech sound on the basis of Sivian's and White's measurements. On the basis of this the $f(\varphi)$ function can be determined (see table in the appendix).

For small angles (approximately up to 40 degrees) $f(\varphi)$ is linear, therefore

$$\frac{(K-1)\,T + \delta t}{(K+1)\,T - \delta t} = 0.0575n + 0.185\,\delta t = c_1\,\varphi\,.$$

This equation corresponds to the principle of the integrallocalization.

The adaptation of the model to directional determination

Further on the model is used for reproductions by two-channel stereophonic systems. To realise this we choose the arrangement experimentally used by DE BOER, for which calculations have been made by FRANSSEN too. There are two different ways in which the observer may determine the direction of the phantom source:

a) The observer may keep his head still straight forward, and will indicate the direction of the phantom source e.g. with his arm.

b) The observer will turn his head and look in that direction from which he hears the sound.

These two ways are shown in Figs 4a and 4b.

In a given case it is not necessary that the results obtained from the two different observations should coincidence. Denoting the ratio of the intensities in the two ears with D, and the time delay of the right-hand loudspeaker to the left-hand one with δT then the calculations were made for two different cases:

I) $D = 0 dB$ (time stereophony)
II) $\delta T = 0$ (intensity stereophony)

Let us assume that very steep sound pulses are given out by the two loudspeakers. In this case U_l and U_r achieve their final values in two steps. The voltages have always been normalized by choosing the voltage brought about by the smallest component of the signals arriving at the ears as a unit.

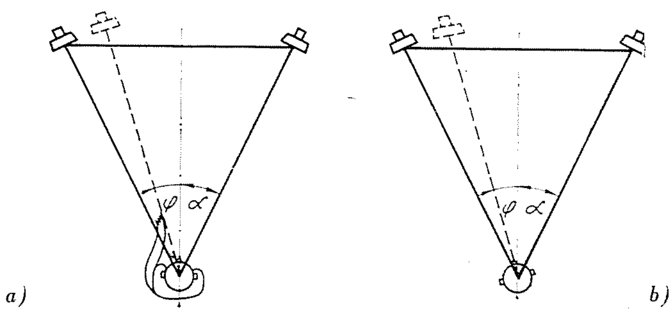

Fig. 4a. Indication of the direction of the phantom source when head is kept straight forward
Fig. 4b. Indication of the direction when the head is turned in the direction of the phantom source

The proceeding voltage of a signal coming from the two loudspeakers to the ears is determined on the basis of the principle that the voltages will be integrated, i.e. there is no interference. In this case the resulting voltage is just the square root extracted from the square sum of the two partial voltages.

I/a Let us consider the change of φ of the direction of a phantom source as a function of δT when $D = 1$, in the case of listening shown in Fig. 4a. The sound pressure achieves its maximal value in both ears in two steps but in the right-side representation the order of succession could be of two different kinds according to the cases where δT is more or less than δt.

1. $\delta T \leq \delta t$. In this case both ears receive the first signal from the loudspeaker on its own side. The integrand voltages are represented on Fig. 5. By reason of this

$$f(\varphi) = \frac{\delta T\left(2K - \sqrt{K^2 + 1}\right)}{2K\,\delta t + (5.4 - \delta T - 2\delta t)\sqrt{K^2 + 1}} .$$

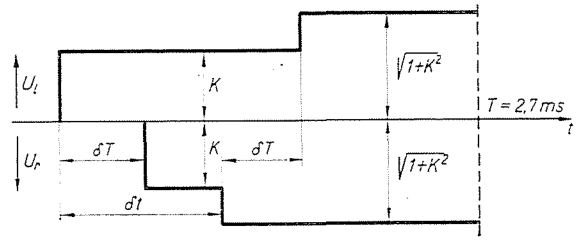

Fig. 5. Envelopes of the left-ear (L) and right-ear (R) signal at the electrical model where the direction of the sound is indicated when the head is kept straight forward and $\delta T \leq \delta t$

2. $\delta T \geq \delta t$. In this case both ears receive the first signal from the left-hand loudspeaker, and on the basis of the Fig. 6.

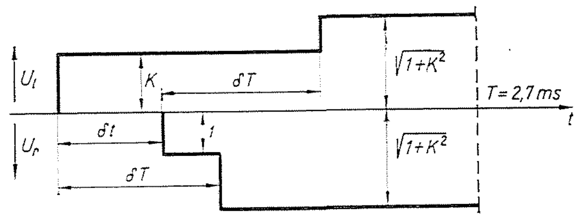

Fig. 6. Envelopes of the left-ear (L) and right-ear (R) signal at the electrical model where the direction of the sound is indicated when the head is kept straight forward and $\delta T > \delta t$

$$f(\varphi) = \frac{K(\delta T + \delta t) - (\delta T - \delta t) - \delta t\sqrt{K^2+1}}{K(\delta T + \delta t) + \delta T - \delta t + (5.4 - \delta t - 2\delta T)\sqrt{K^2+1}} \,.$$

$K = 1.56$, and $\delta t = 0.24$ msec when the basic angle is of 27 degrees. The results of the calculation are given in Table I.

Table I

Time differences in msec between the signals in the two channels, while keeping the head straight forward

$\delta T_{[ms]}$	0.1	0.2	0.3	0.5	1	1.5	2	2.5
$f_{(\varphi)}$	0.013	0.026	0.036	0.050	0.086	0.127	0.175	0.229
$\varphi_{[°]}$	1.3	2.5	3.5	4.8	8.2	12.5	18.0	23.7

I/b. According to the Fig. 4b the observer is turning his head in the direction of the phantom source, so for him $f = 0$ owing to the perfect compensation. Now that condition is considered for different δT in the case where $D = 1$.

Now in certain sense the calculation is more complicated because the screening factor of the right-hand loudspeaker K, and the interaural time difference δt must be taken at $27^\circ + \varphi$, while the screening factor of the left-hand loudspeaker K' and $\delta t'$, respectively, must be taken at $27^\circ - \varphi$. The amplitudes of the signals arriving at the right ear from the left-hand loudspeaker and arriving at the left ear from the right-hand loudspeaker will not be equal. Their ratio is the function of φ as it can be seen from the following relationship

$$a = \text{numlog}\,\frac{n_r(27^\circ - \varphi) - n_r(27^\circ + \varphi)}{20}.$$

$n_r(\alpha)$ is that attenuation which occurs in the right ear when the loudspeaker is displaced by α angle to the left from the central position along a circular line.

From the measurements of SIVIAN and WHITE [3]

$$n_r = \frac{2}{3}\,n.$$

In the calculation there are two cases to discriminate.

1. $\delta T - 0.427 \sin\varphi \leqslant \delta t'$. In this case the voltages become as it is shown in Fig. 7.

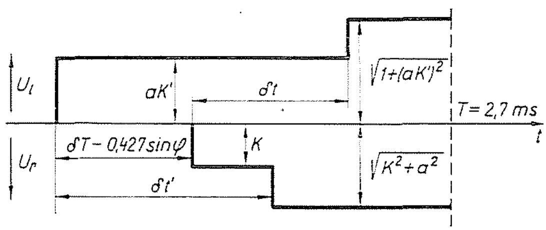

Fig. 7. Envelopes of the left-ear (L) and right-ear (R) signal at the selector where the direction of the sound is indicated when the head is turned to the direction of the phantom source, and $\delta T - 0.427 \sin\varphi \leq \delta t'$

The condition of the equilibrium is $f = 0$. Using this relation after the reduction we can obtain

$$\delta T = \frac{(2.7 - \delta t + 0.427 \sin\varphi)\sqrt{1 + (aK')^2} + aK'(\delta t - 0.427 \sin\varphi) - K(\delta t' + 0.427 \sin\varphi) - (2{,}7 - \delta t')\sqrt{a^2 + K^2}}{\sqrt{1 + (aK')^2} - aK' - K}$$

2. $\delta T - 0.427 \sin\varphi > \delta t'$. In this case the order of arrival of the two signals will be interchanged at the right ear as shown in Fig. 8.

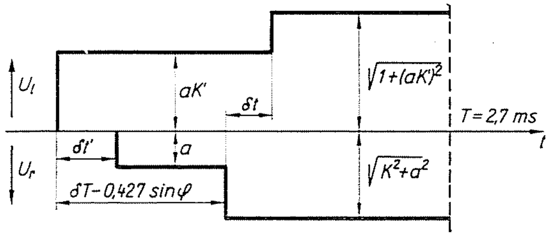

Fig. 8. Envelopes of the left-ear (L) and right-ear (R) signal at the selector where the direction of the sound is indicated when the head is turned to the direction of the phantom source, and $\delta T - 0.427 \sin \varphi > \delta t'$

In a similar way as in the preceding case after reduction we can get

$$\delta T = \frac{(2.7 - \delta t + 0.427 \sin \varphi)\sqrt{1 + (aK')^2} + aK'(\delta t - 0.427 \sin \varphi) - (2.7 + 0.427 \sin \varphi)\sqrt{K^2 + a^2} - a(\delta t' + 0.427 \sin \varphi)}{\sqrt{1 + (aK')^2} - \sqrt{a^2 + K^2} - a(K' - 1)}$$

The calculated values of the $\delta T(\varphi)$ function are given in Table II.

Table II

Time differences in msec between the signals in the two channels as a function of the head turned to the left

$\varphi_{[°]}$	1	2	4	8	12	16	20	25
$\delta T_{[ms]}$	0.06	0.14	0.32	0.84	1.32	1.74	2.13	2.78

II/a Be $\delta T = 0$, and let D change. The envelopes of the sound pressures in both ears in the observation according to Fig. 4a are shown in Fig. 9. Based on this

$$f(\varphi) = \frac{(D - 1)K\delta t + \left(\sqrt{1 + (DK)^2} - \sqrt{K^2 + D^2}\right)(2.7 - \delta t)}{(D + 1)K\delta t + \left(\sqrt{1 + (DK)^2} + \sqrt{K^2 + D^2}\right)(2.7 - \delta t)}.$$

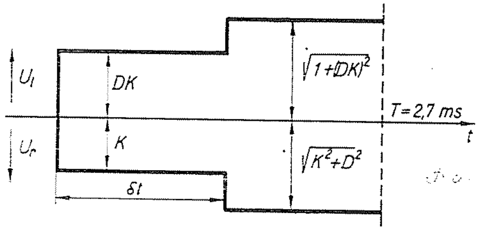

Fig. 9. Envelopes of the left-ear (L) and right-ear (R) signal at the selector where the direction of the sound is indicated when the head is turned to the direction of the phantom source

$K = 1.56$, and $\delta t = 0.24$msec in the given arrangement, and the results of the calculation can be seen in Table III.

Table III

Level differences in dB between the signals in the two channels as a function of the deviation of the sound image, while keeping the head straight forward

$D_{[dB]}$	1	2	3	4	6	8	10	12
D	1.12	1.26	1.41	1.58	2	2.52	3.17	3.99
$f_{(\varphi)}$	0.026	0.052	0.076	0.100	0.142	0.175	0.203	0.217
$\varphi_{[°]}$	2.5	5	7.2	9.5	14	18	21	22

II/b Let us assume that $\delta T = 0$, and D is changing. The envelopes of the sound pressures at both ears in the observation according to Fig. 4a are shown in Fig. 10. The designation are in coincidence with those used on I/b.

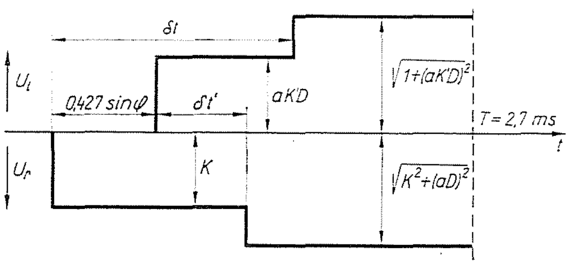

Fig. 10. Envelopes of the left-ear (L) and right-ear (R) signal at the selector where the direction of the sound is indicated when the head is turned to the direction of the phantom source

The condition of the equilibrium

$$aK'D(\delta t - 0.427 \sin \varphi) + (2.7 - \delta t)\sqrt{1 + (aK'D)^2} =$$
$$= K(\delta t' + 0.427 \sin \varphi) + (2.7 - \delta t' - 0.427 \sin \varphi)\sqrt{K^2 + (aD)^2}$$

Now the $\varphi(D)$ function can be obtained by the solution of the equation for D. The particular results are given in Table IV.

Table IV

Level differences in dB between the signals in the two channels as a function of the head turned to the left

$\varphi_{[°]}$	1	2	4	8	12	16	20	25
$D_{[dB]}$	0.26	0.71	1.4	2.9	4.5	6.2	8.5	14.8

For a better perspicuity the cases I/a; I/b, and II/a; II/b are given in the appendix in a diagram. In that diagram there is also given the experimental curve of De Boer.

In agreement with the experiment the results show that the observations "a" and "b" give the same directional detection. This means that the turning of the head practically does not make any change in the situation of the phantom source.

Calculations made for quite general situations are possible in consequence of the very great simplicity of the model. It is very important in the technical practice.

Appendix

φ [o]	δt [ms]	$K_{(lin)}$	n [dB]	n_r [dB]	$f(\varphi)$
1	0.01	1.018	0.15	0.1	0.0108
2	0.02	1.035	0.30	0.2	0.0209
3	0.03	1.053	0.45	0.3	0.0314
4	0.04	1.072	0.60	0.4	0.0422
5	0.05	1.090	0.75	0.5	0.0524
6	0.06	1.11	0.90	0.6	0.0633
7	0.07	1.13	1.05	0.7	0.0741
8	0.08	1.15	1.20	0.8	0.0847
9	0.09	1.17	1.35	0.9	0.0952
10	0.10	1.19	1.50	1.0	0.105
12	0.12	1.22	1.76	1.175	0.122
14	0.135	1.26	2.02	1.35	0.140
16	0.15	1.30	2.28	1.52	0.158
18	0.165	1.34	2.54	1.695	0.176
20	0.18	1.38	2.80	1.87	0.193
25	0.22	1.50	3.55	2.37	0.240
30	0.26	1.64	4.30	2.87	0.289
35	0.30	1.79	5.05	3.37	0.336
40	0.34	1.95	5.8	3.87	0.381
45	0.37	2.07	6.3	4.20	0.412
50	0.40	2.19	6.8	4.54	0.440
55	0.43	2.24	7.0	4.67	0.454
60	0.46	2.27	7.1	4.76	0.465

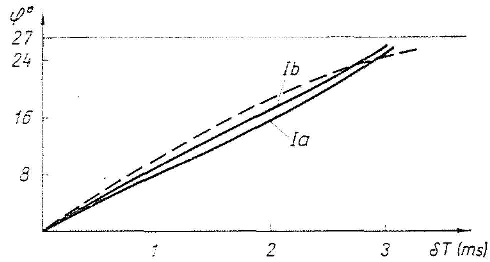

Diagram 1. The influence of time differences on the stereofonic perception.
- - - measurements made by DE BOER; I/a calculated for head kept straight forward; I/b calculated for head turned to the direction of the phantom source

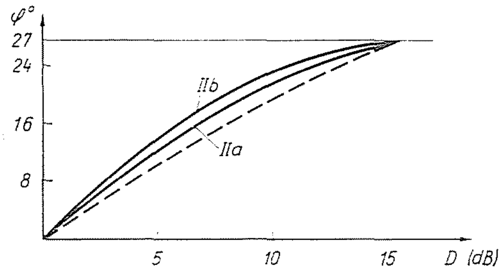

Diagram 2. The influence of level differences on the stereophonic perception.
- - - - measurements made by DE BOER; II/a calculated for head kept straight forward; II/b calculated for head turned to the direction of the phantom source

Summary

This paper reports on a possible model for the directional perception which is able to explain the stereophonic effect. The model includes the fundamental assumption that every partial measurement of directional determination indicates a pulse difference for a definite *T*-period.

The curves of the intensity- and time-stereophony measured by DE BOER are very well reproduced by the calculations based on our model where we used for *T* the value of 2.7 msec, in agreement with experience. The calculations show that the perceived situation of the sound image is practically invariant against the turning of the head.

References

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