ON BINAURAL SPACE.

BY

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The fundamental fact of binaural space is that when two component sounds heard by the two ears are perceived as a single sound the resultant sound is "localized in space." This "localization in space" is a direct experience of every person with binaural audition.

Aside from such problems as the influence of visual and muscular space on this localization, the fundamental problem is that of the localization of the resultant sound as dependent on the two components. The simplest sounds, tones, vary in pitch, intensity and duration. The only property which comes essentially into question in the case of the two components is that of intensity. The following paragraphs will present a hypothesis in respect to the law of localization as dependent on the intensity of the components.

The fundamental observation is as follows: When two component tones, e. g., from the telephones opposite the two ears, are heard as one tone, this tone is located in a certain direction in respect to the observer. When the intensities of the two components are equal, the resultant appears to be in the median plane, e. g., directly in front. As one of the components is weakened, the resultant appears to pass toward the side of the stronger one, finally reaching a line nearly opposite the ear—the auditory axis—and proceeding outward along it. The localization thus depends on the difference between the intensities of the components. Various observations lead me to believe that the following equations express this dependence.

Let I_R and I_L be the intensities of the right and left components, and let $d = I_R - I_L$ be the difference between the two intensities.

Let the plane in which the resultant lies contain a system of rectangular coördinates, with the origin in the median plane, the axis X identical with the acoustic axis, and the axis Y perpendicular to X; thus Y may lie anywhere in the median plane. Since the position of the sound with respect to these axes depends on the difference of intensity, we have $x = f(d)$ and, since there is a definite relation between y and x, $y = f(x)$.

In the experiments it is observed that when the two sounds are equal, i. e., $d = 0$, the resultant is located in the median plane, i. e., on the axis Y at a certain distance m from the center. Thus for $d = 0$ we have $x = 0$, $y = m$. As the sound on the right is made louder we have $I_R > I_L$ and d positive; when the sound on the left is made louder d becomes negative. As one component becomes louder than the other, the resultant moves toward the side of the louder component; indicating the right side by $+$ and the left by $-$ we have $+x = f(+d)$ and $-x = f(-a)$. The resultant lies always on the positive side of the Y axis, which we can express by considering y as a function of the square of x, or $y = F(x^2)$.

The path described by the resultant sound appears to me to be a curve of the form given by the equation

$$y = me^{-\frac{x^2}{am}}$$

where m is the value for $x = 0$ and a is a constant of proportionality.

On the basis of these observations and considerations I venture to make the following two hypotheses: 1. that the distance right or left of the median plane is proportional to the difference between the intensities of the two components, i. e., $x = c\,d$, when c is the factor of proportionality; 2. that the relation between the distance from the median plane and the distance from the auditory axis is expressed by

$$y = me^{-\frac{x^2}{am}}$$

where m is the distance of the sound when $x = 0$ (i. e., $d = 0$), and a is a proportionality factor.

The values m and a depend on certain properties of the sounds used, but mainly on the absolute intensity. Sometimes the sound appears to remain always in the auditory axis,

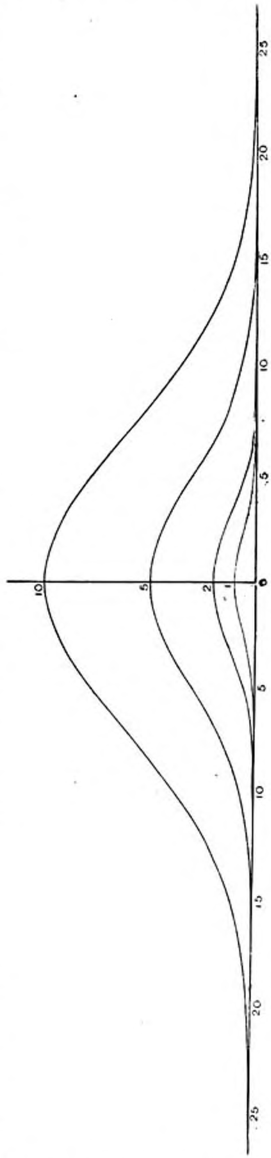

FIG. 22.

in which case $m = 0$. A series of curves for different values of m is shown in Fig. 22. The values from which the curves were plotted are given in the table.

TABLE OF $y = me^{-\frac{x^2}{am}}$ FOR $a = 10$.

x	$p_{10} = \frac{x^2}{100}$	$m = 10$		y_{10}	$p_5 = \frac{x^2}{50}$	$m = 5$		y_5	$p_2 = \frac{x^2}{20}$	$m = 2$		y_2	$p_1 = \frac{x^2}{10}$	$m = 1$		y_1
		$r_{10} = p_{10} \times 0.4343$	$1.0000 - r_{10} = \log y_{10}$			$r_5 = p_5 \times 0.4343$	$0.6990 - r_5 = \log y_5$			$r_2 = p_2 \times 0.4343$	$0.3010 - r_2 = \log y_2$			$r_1 = p_1 \times 0.4343$	$0.0000 - r_1 = \log y_1$	
0	0.00	0.0000	1.0000	10.000	0.00	0.0000	0.6990	5.000	0.00	0.0000	0.3010	2.000	0.0	0.0000	0.0000	1.000
1	0.01	0.0043	0.9957	9.902	0.02	0.0087	0.6903	4.901	0.05	0.0217	0.2793	1.904	0.1	0.0434	0.9566—1	0.905
2	0.04	0.0174	0.9826	9.607	0.08	0.0347	0.6643	4.616	0.20	0.0869	0.2141	1.637	0.4	0.1737	0.8263—1	0.670
3	0.09	0.0393	0.9607	9.135	0.18	0.0785	0.6205	4.174	0.45	0.1964	0.1046	1.273	0.9	0.3927	0.6073—1	0.405
4	0.16	0.0695	0.9305	8.521	0.32	0.1389	0.5660	3.681	0.80	0.3480	0.9530—1	0.897	1.6	0.6949	0.3050—1	0.202
5	0.25	0.1086	0.8914	7.787	0.50	0.2172	0.4718	2.956	1.25	0.5430	0.7580—1	0.573	2.5	1.0857	0.9141—2	0.082
6	0.36	0.1564	0.8435	6.974	0.72	0.3127	0.3763	2.379	1.80	0.7817	0.5193—1	0.331	3.6	1.5635	0.4365—2	0.037
7	0.49	0.2128	0.7872	6.126	0.98	0.4256	0.2734	1.878	2.45	1.0640	0.2370—1	0.173	4.9	2.1280	0.8720—3	0.007
8	0.64	0.2779	0.7221	5.273	1.48	0.5559	0.1431	1.391	3.20	1.3897	0.9113—2	0.082				
9	0.81	0.351	0.6482	4.447	1.62	0.7036	0.9954—1	0.989	4.05	1.7589	0.5421—2	0.035				
10	1.00	0.4343	0.5657	3.679	2.00	0.8686	0.8305—1	0.677	5.00	2.1715	0.1295—2	0.013				
11	1.21	0.5255	0.4744	2.981	2.42	1.0509	0.6481—1	0.445	6.05	2.6275	0.6735—3	0.005				
12	1.44	0.6254	0.3746	2.369	2.88	1.2508	0.4492—1	0.281								
13	1.69	0.7340	0.2660	1.845	3.78	1.4679	0.2310—1	0.170								
14	1.96	0.8512	0.1488	1.409	3.92	1.7026	0.9964—2	0.099								
15	2.25	0.9771	0.0229	1.069	4.50	1.9543	0.7447—2	0.056								
16	2.56	1.1112	0.8888—1	0.774	5.12	2.2236	0.4754—2	0.030								
17	2.89	1.2550	0.7440—1	0.554	5.78	2.5100	0.1890—2	0.015								
18	3.24	1.4071	0.5919—1	0.391	6.48	2.8142	0.8848—3	0.009								
19	3.61	1.5778	0.4222—1	0.264												
20	4.00	1.7372	0.2628—1	0.183												
21	4.41	1.9153	0.0847—1	0.122												
22	4.84	2.1020	0.8980—2	0.079												
23	5.29	2.2974	0.7026—2	0.050												
24	5.76	2.5016	0.4984—2	0.032												
25	6.25	2.7144	0.2856—2	0.019												
26	6.76	2.9359	0.0641—2	0.012												
27	7.29	3.1650	0.8350—3	0.007												

There still remains the fact that the plane of XY (which we have considered) may be in any position around the auditory axis; thus the sound may pass in front of, above, behind or below the head, or in any intermediate position. Four such positions are shown in Fig. 23. To fully

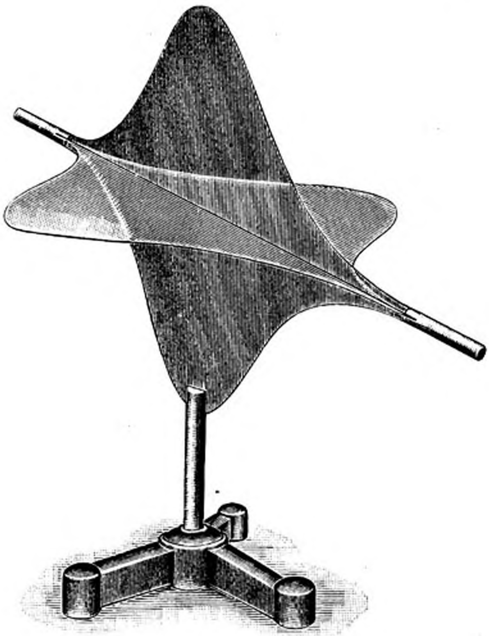

FIG. 23.

define the apparent position of the sound, we must introduce a system of coördinates in which X is the auditory axial line through the head, Z is a line perpendicular to this at the central point in the head and extending in the direction which the subject considers to be directly in front, and Y is perpendicular to both X and Z. We thus have $x = cd$ as before. Then in a case where the sound lies in the XZ plane to the front we have $y = 0$ and

$$z = me^{-\frac{x_2}{am}}.$$

When the sound is upward in the XY plane we have $x = 0$ and

$$y\ me = ^{-\frac{x2}{am}}.$$

The complete relation is expressed by

$$x = cd,$$

$$y = me^{-\frac{x^2}{am}} \cdot \sin a,$$

$$z = me^{-\frac{x^2}{am}} \cdot \cos a,$$

where a is the angle of elevation above the plane XZ.

This series of hypotheses agrees with the facts reported by MR. MATSUMOTO in the preceding pages, but cannot be proven until the experiments are repeated with tones of carefully measured intensities. I cannot say that I expect them to be confirmed just as they stand; I propose them simply as an attempt to give definite form to our notions of one of the laws of binaural localization.