THE FUNCTION OF INTENSITY AND PHASE IN THE BINAURAL LOCATION OF PURE TONES. I.

By G. W. Stewart.

PART I. INTENSITY.

Synopsis.

Logarithmic Law.—The only published quantitative experiments giving the effect of intensity alone are those of Hovda and the author who found a "logarithmic law," viz., that the effect of intensity only was an apparent angular displacement from the median plane proportional to the logarithm of the ratio of intensities at the ears.

Logarithmic Law Extended; the Value of the "Constant."—The law just cited is found to be correct for the three frequencies 256, 512, and 1,024 d.v., and for a displacement range from 0° to almost 90°. But some individuals (two out of four) do not have a fused tone or phantom source at the frequency last named and indeed, at other frequencies also. The constant, in the logarithmic law, *i.e.*, the value of the displacement when the logarithm of the ratio of intensities is unity, is ascertained for several individuals at the above frequencies. For each individual the constant *decreased* with *increasing* frequency.

The experimental method is the one previously used. The logarithmic law is shown not to be an extension of Weber's law, well known to psychologists, but a new law.

Computed Values of Intensity Ratios for Given Positions of Source.—The actual intensities obtaining at the ears when a source of sound is placed at different positions relative to the ears are considered and the theoretical results are plotted and compared with the experimental results.

Intensity Not an Important Factor.—The wide divergence between experimental and theoretical values shows that an explanation in terms of intensity of the ability to locate a pure tone, 256 to 1024 d.v., is not possible. Intensity cannot be an important factor in localization of pure tones in this range of frequencies.

I. Introduction.

A SURVEY of the many reports of experiments in the localization of sound that discuss the function of intensity would not prove of sufficient interest here for, in every instance except those noted, the experimenters have not studied intensity effects with the assistance of quantitative measurements. Indeed, for the most part, writers have been content to discuss what appeared to them must be the effect of intensity differences at the ears. Rayleigh[1] was the first to point out that for frequencies of 128 and 256 d. v. the difference in intensity at the ears could not account for the ability to locate the source of sound.

[1] Rayleigh, Phil. Mag., 1907, 13, p. 217.

The first quantitative measurements of the intensity effect with a pure tone were made by the writer, and Hovda[1] who discovered that if relative intensities at the ears of a pure tone, 256 d.v., were varied, but with the phase difference maintained at zero, there resulted a displacement of the apparent source of the fused sound from the median plane, this displacement, θ, to the right, and the intensities at the ears, I_R and I_L, having the following relation,

$$\theta = K \log_e \frac{I_R}{I_L},$$

wherein K was a constant for an individual. This source of fused sound appeared to have a position external to the head in a plane approximately horizontal, usually in front rather than in the rear, and the displacement occurred in a circle of constant radius.

The purpose of the present paper is to present the effect of intensity only in producing a displacement of the apparent source, or the image,[2] from the median plane, to discuss these results in comparison with intensity relations existing when a similar source is displaced in a circular path about the head, to make note of the limitations of the logarithmic law just cited and to derive conclusions as to the importance of intensity as a factor in the location of pure tones of the range of frequency here considered.

II. Apparatus.

The apparatus and method used throughout these as well as the previous experiments of Stewart and Hovda are similar in all essential respects and have received sufficient description in the article[3] already published. For the sake of clearness it should be briefly stated that the source of the sound was a tuning fork, that the observer used stethoscope binaurals and sat at the center of a circular scale in order to ascertain the angular displacement of the image, and that the intensities were varied by altering the position of one of the receiving tubes at the fork without producing a phase difference, and that the relative intensities at the ears I_R and I_L were ascertained by means of a Rayleigh disc.

III. Results.

Values of K.—The procedure was to take at one sitting a number of observations of θ, the angular displacement, with known relative values of I_R and I_L, the intensities at the ears, and then subsequently to draw the straight line representing the mean of the observations and calculate

[1] Stewart and Hovda, Psych. Rev., XXV., No. 3, May, 1918, p. 242.

[2] The term "image" is here used as commonly in physics, *i.e.*, to refer to an apparent source of sound.

[3] Stewart and Hovda (loc. cit.).

the value of K. At least 24 to 50 observations were made for each curve, these being scattered so as to be "at random." In Table I. are shown the results thus far obtained, which, though not many, doubtless are sufficient to enable definite conclusions to be drawn.

Table I.

Frequency.	Observer.	Number of Curves.	Value of K.
256	S	3	16°
	B	5	30°
512	B	4	21°
	F	4	14°
	M	4	21°
1,024	B	8	10°
	F	8	7.8°
	M	8	18°

In Fig. 2 the straight lines represent the observations of B, the only experimenter who used all three frequencies. The observations of S are taken from the cited work of Stewart and Hovda, the 256 d.v. observations of B were taken by Mr. E. M. Berry in experiments conducted by himself and Mr. C. C. Bunch, the observations of B for the 512 and 1,024 d.v. were made by Mr. Berry in experiments conducted by Miss Caroline McGuire and the observations of F and M were also made with McGuire apparatus. In every case the linear logarithmic law seemed to hold Berry and Bunch showing that it held up to θ but slightly less than 90°. Two conclusions are to be drieved from the table, viz., that the constant K varies with individuals and that for an individual it decreases with increasing frequency.

Limits of the Application of the Logarithmic Law.—The first intimation that the law was not applicable to all ordinary frequencies with all individuals was found when the writer was unable at 1,024 d.v. to observe the rotation of the fused sound about the head with altered intensity ratios. This fact led to a brief series of experiments intended to ascertain at least some of the limitations of the applicability of the law. The apparatus, which is to be described in Part II. of this article, consisted essentially of a toothed wheel rotating in front of two bipolar telephone receivers. The currents produced actuated two head receivers and these, in turn, were attached in a suitable manner to stethoscope binaurals. With the apparatus adjusted for equal phase and intensity at the two ears, one of the rubber stethoscope tubes, right or left, was pinched, thus lessening the intensity on that side. Attention was confined to answering the following questions, using a range of frequencies possible with the apparatus. Is there complete fusion and a rotation about the head of the image, apparently in accord with the logarithmic law? If partial fusion, where are the other images? Obviously, one could not test the law with such an apparatus quantitatively, but he could ascertain roughly at least some of the limitations of the applicability of the law. The purpose in these initial experiments was to find some of the limitations of the law and to point the way for future work. For the present purpose, then, it will be assumed that whenever a fused image moves from the median plane around to 90° right or left of that plane, the logarithmic law is followed. Clearly, when the image does move it is necessarily "fused" and hence in what follows the terms "fused image" or "complete fusion" or "incomplete fusion" imply an image moving as described. Only those frequencies were chosen which could be checked up by convenient tuning forks. Thus the frequencies 512, 640, 768, 896, 1,024, 1,280, 1,536, and 1,792 d.v. are the only ones referred to in this brief record.

With four observers H, F, S and B the following results were obtained. For H, with frequencies from 512 to 1,792 d.v. there was never complete fusion; from 640 d.v. to 1,536 there was no fusion; but below and above the two frequencies last named there was incomplete fusion. For F, up to 768 d.v. the fusion was complete, from 768 to and including 1,792 d.v. the fusion was incomplete. For S there is complete fusion up to 896 d.v., for 896 d.v. there was incomplete fusion, for 1,024 d.v. and 1,280 d.v. there was no fusion, and for 1,536 d.v. and 1,792 d.v. the fusion was practically complete. For B there were no frequencies possessing complete fusion, but there was a fused tone over the entire range and almost complete fusion at 1,792 d.v. These results are presented in Fig. 1, the two tones being represented by the single lines and fusion by the completeness of the connection between them.

When there was only partial fusion, one image did not rotate but remained directly in front, or, by trial, in the position determined by the difference of phase. It could, therefore, be ascribed to the phase difference effect. Thus the terms "partial" or "incomplete" fusion really mean fusion in more than one image. In the case where there was no fusion, and the tube at the left ear was being pinched the single image remained in front until the ratio of intensities was very large, *i.e.*, of the order of 200 with observer S, and then there appeared directly at the right, or approximately so, a second image which increased in clearness with further pinching, the image in front simultaneously disappearing, giving in the limit, as would be anticipated, but the one image to the right.

These experiments indicate that probably with most individuals (here four out of four) there is not complete fusion throughout all ordinary frequencies, but yet usually enough fusion to furnish a displaced image, that with some individuals (here two out of four) there are frequency gaps where the logarithmic law or any other law does not apply because of the absence of any fused image at all, and these gaps occur in the region having a frequency of the order of 1,000.

Another exception to the applicability of the law is the occasional serious deviation[1] from a straight line in attempting to represent a single individual's observations. Instead of a single straight line, required by the linear relation, the observations can, in these unusual cases, best be represented by two or three connecting straight lines of decidedly different slopes. The causes of such changes in the constant K at certain relative intensities are unknown.

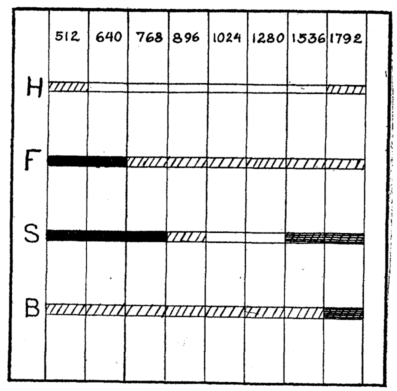

Fig. 1.

Intensity Combined with Phase Difference.—In actual localization there is a variation of both phase and intensity difference for a variation of position of the source, and it might be supposed that there might be found in the combination of the two factors an influence if the intensity factor were the only one. Yet such does not prove to be the fact. This was tested repeatedly, but not for all frequencies. Further reference will be made to these experiments in Part II.

IV. Theoretical Results.

The logarithmic law as shown above, is in harmony with experimental facts, at least as high as 1,042 d.v. with some individuals. We should, in order to be able to determine the importance of intensity in the binaural location of a pure tone, determine the relation between intensity and angular displacement existing in actual experience. With the present stage of development in sound measuring devices, we must resort to theory for the results. Assume the head to be rigid sphere 60 cm. in circumference and the ears diametrically opposite one another. The computations for the intensities at the two ears with the source at certain different distances and having certain different frequencies have already

[1] Referred to in Stewart and Hovda article, loc. cit.

been published.[1] We select from available data the distance 477 cm. as a common one, though at distances of this magnitude or greater there is but little difference in relative intensities. The computations apply to wave-lengths of 120 cm., 60 cm. and 30 cm. and these are frequencies of 287, 574, and 1,148 d.v. at room temperature.

If the comparison is to be made with experiment, the values must be plotted in the same manner. Inasmuch as the experimental values will

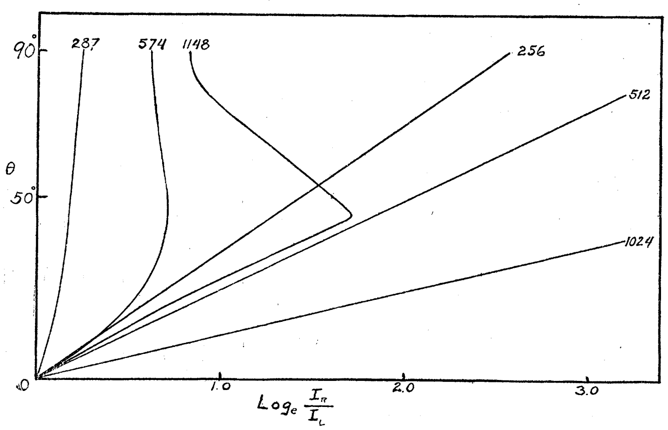

Fig. 2.

give straight lines only if θ and $\log_e I_R/I_L$ are used as coördinates, these are adopted in Fig. 2, the curved lines representing the computed values.

Discussion.

Comparison of Theory and Experiment.—In Fig. 2, the experimental curves are not extended to angles of 90° though the logarithmic law holds approximately to that displacement, but are shortened in order to show the theoretical curves clearly without using too large a figure. Thus, in making a comparison, the reader should extend these straight line curves to $\theta = 90°$. Clearly there exists neither quantitative nor qualitative agreement between the two curves for similar frequencies. In fact, the theory shows the existence of two values of θ for one value of relative intensity, whereas experiment shows only single values. The disagreement, quantitative and qualitative, is so very great that intensity cannot be an important factor in the location of a pure tone. Moreover, inasmuch as the intensity when combined with phase difference does not seem to have an importance not possessed by intensity when the phase difference is zero, we must conclude that for frequencies of 256 to 1,024 intensity can be only a minor factor.

It may occur to the reader to question the soundness of the conclusion

[1] Stewart, PHYS. REV., XXXIII., No. 6, 1911, p. 467.

because of the fact that the two ears may differ in sensitivity to sounds. But a consideration of the nature of the experiments and of the logarithmic law shows at once that minor deafness in one ear would not change the slope of the curves, or the value of K, but would merely displace the curve along the logarithmic axis.

Errors.—It is not advantageous to discuss sources of error in the apparatus itself when, as shown in the cited article by Stewart and Hovda, the individual errors are relatively large. But these errors in no way weaken the conclusion given above, for the divergence between theoretical and experimental values are too enormous. An objection may be made to the use of the stethoscope binaurals which were inserted in the ears thus closing the external meatus, a condition which does not obtain in actual binaural location. This objection is removed by the experiments in the article last mentioned wherein it is shown that binaurals inserted give the same effects as open binaurals which do not close the external meatus.

Intensity Effect with Complex Tones.—The conclusions of our paper refer to pure tones only. When complex tones are used there enters a difference in the quality at the ears occasioned by the variation of the ratio of intensity at the ears with frequency. The effect of this difference in quality in assisting in localization is unknown and should be ascertained by experimental investigation. Moreover, there is also an effect upon quality determined by the position of the source, *i.e.*, around a corner, behind a building, in another room, etc. That this effect upon quality assists in determining location is a matter of common experience. Hence intensity does become, indirectly, an important factor in the location of complex tones.

Weber's Law.—In the former paper already cited, the logarithmic law was presented as an extension of Weber's law. But it is difficult for the writer now to accept this position. Weber's Law seems to be a law of the nervous system, and, in its integrated form, states that the response is proportional to the logarithm of the stimulus. Now the nerve response in each ear is to a first approximation, independent of what transpires in the other. The apparent displacement, θ, is not the effect of either nerve response alone, but, in fact, is the form taken by the recognition of the differences between the nature of these two nerve responses and hence is not at all a law concerning nerve response and stimulus as is Weber's Law.

The author wishes to acknowledge the invaluable assistance of Mr. A. E. T. Fant throughout these experiments.

Physical Laboratory,
State University of Iowa.