BINAURAL BEATS.

BY G. W. STEWART.

THE first recorded experiments with binaural beats seem to have been made by Dove[1] in 1839. He found that beats were obtained with two forks in unison by separating the forks with one near each ear as well as by presenting both of them to one ear. Obviously these and indeed all binaural experiments have a considerable interest to the physicist, the physiologist, the anatomist, and the psychologist. This breadth of interest has resulted in a scattering of the literature and in serious omissions of recognition of earlier work. Paul Rostosky[2] has prepared an apparently thorough review of the experiments concerning the results obtained by and conditioned upon bilateral excitation of the organs of hearing. The review includes all results obtained up to and including the year 1896. The excellence of Rostosky's résumé enables the writer to abbreviate greatly references to the work therein described. The policy has been adopted in this paper of accepting results that are amply confirmed by relatively recent workers, without attempting to explain the earlier disagreements which were probably due to individual differences and to the limitations imposed by the particular forms of apparatus.

The chief phenomena observed when two tones differing in frequency are led one to each ear are as follows:[3]

(*a*) Beats occur whether the tones are presented to one ear or one to each ear. This was discovered by Dove,[4] observed subsequently by various experimenters and discovered independently by S. P. Thompson.[5] This phenomenon is observed by all, even by the partially deaf.

(*b*) With bilateral presentation of the tones, the minimum intensity observed in each beat does not (even with carefully adjusted equal intensities of the two sources) approximate zero. This is mentioned by S. P. Thompson[6] but doubtless was observed very much earlier by others.

[1] H. W. Dove, Repertorium d. Physik, Bd. 3, p. 404, 1839.

[2] Paul Rostosky, Beiträge zur Psychologie und Philosophie, I, 1905, pp. 173–273.

[3] Unless otherwise stated, the difference of frequencies is assumed to be small.

[4] *Loc. cit.*

[5] S. P. Thompson, Phil. Mag., 5, IV., 1877, p. 274.

[6] *Loc. cit.*

(*c*) When the tones at the ears are alike in intensity and phase, there is a localization in the median plane, the position in this plane varying with the observer and presumably with the apparatus arrangement. Purkyně[1] was the first to record this localization, which has been shown through numerous experiments of other observers, to be a usual accompaniment of binaural perception.

(*d*) With opposition in phase and equality in intensity, the sound is localized according to S. P. Thompson[2] at the back of the head. To several observers, with apparatus of a form different than that of Thompson's the localization is in the median plane. Doubtless the position in the median plane is influenced by the method of observation.

(*e*) The sound is localized on the side of the fork leading in phase when the phase difference is approximately 90°. Thus with phase differences the sound wanders from the median plane at 0° to one side at 90°, to the median plane at 180°, to the other side at 270° and again to the median plane at 360°. Perhaps S. P. Thompson[3] first observed the wandering from ear to ear but the periodic displacement of the localization was first most clearly described by Paul Rostosky.[4] Later workers, who were not aware of Rostosky's results, observed this lateral displacement. Lord Rayleigh[5] experimenting with forks, recognized the lateral effect and its relation to phase difference, and later[6] confirmed these observations with experiments conducted by the use of telephones. L. T. More and H. S. Fry[7] made preliminary experiments which were followed by those of L. T. More.[8] His results showed unmistakably the lateral displacement. More used an apparatus similar to that earlier adopted by C. S. Myers and H. A. Wilson.[9] A single source, branched pipes to the ears and an arrangement whereby the lengths of the pipes could be altered in opposite senses, were used. The experiments of Myers and Wilson also gave full confirmation of the lateral effects. Bowlker's[10] experiments do not seem to furnish reliable evidence. All the workers just mentioned were not aware of the splendid experiments of Rostosky published in 1902.[11]

(*f*) There is a limit to the frequency of the tone with which the

[1] Purkyně, Prager Vierteljahrsschrift, Bd. 67, p. 91, 1860.
[2] S. P. Thompson, Phil. Mag., 5, IV., 1877, p. 274, and Phil. Mag., 5, VI., 1878, p. 383.
[3] S. P. Thompson, Phil. Mag., 5, XII., 1881, p. 351.
[4] P. Rostosky, Philosophische Studien, 19, 1902, p. 557.
[5] Lord Rayleigh, Phil. Mag., XIII., 1907, p. 214.
[6] Lord Rayleigh, Phil. Mag., XIII., 1907, pp. 316–319.
[7] L. T. More and H. S. Fry, Phil. Mag., XIII., 1907, p. 452.
[8] L. T. More, Phil. Mag., XVIII., 1909, p. 308.
[9] C. S. Myers and H. A. Wilson, Proc. Roy. Soc., LXXX., 1908, p. 260.
[10] T. J. Bowlker, Phil. Mag., (6) XV., 1908, p. 318.
[11] *Loc. cit.*

effect just described (*e*) can be obtained. L. T. More[1] states that a fork of 512 d.v. is near to his limit of accuracy in the judgment by phase differences, that with 1,024 d.v. his judgment became untrustworthy and that with 3,000 d.v. he had no sense whatever of direction. Lord Rayleigh[2] gives the limiting frequency of his right and left sensations as 768 d.v. C. S. Myers and H. A. Wilson[3] state in general terms that with very high frequencies the lateral effects cannot be obtained.

(*g*) In addition to the maximum at 0° phase difference, there are also two additional maxima occurring one before and the other after opposition in phase, but distinctly perceptible only when the beats are less frequent than one in two to five seconds. These additional maxima were first studied by Paul Rostosky[4] in 1902, but in the succeeding literature no reference is made to his important contribution. Thus the subsequent discovery of these secondary maxima by the writer was an independent one. The results of the investigation of the latter are presented in this report.

(*h*) There are several other phenomena of importance, such as the effects obtained by placing forks on the skull, by using forks of large frequency differences, the result of practice of one ear upon the acuteness of the other, and the binaural audibility of two tones each one of which alone may be subliminal. For the present, we will be contented merely with this mention of them.

APPARATUS.

Mirrors were attached on the prongs of tuning forks so that the plane of each mirror was perpendicular to the vibration of its prong. The forks were then mounted so that their vibrations were in perpendicular planes. The light from an arc lamp, by the use of lenses and an aperture, was reflected from two of the mirrors, one on each fork, and formed a small spot of light or an image of the aperture, upon a screen. With vibration of the forks, Lissajou's figures were traced upon the screen, and by these the phase relation of the forks could be ascertained. Glass tubes were mounted, one close to a prong of each fork and were connected by means of two pieces of rubber tubing each a meter in length, to ear tubes such as are used with stethoscopes. In certain experiments the manner of introducing the sound to the ear was changed, but of this mention will later be made. The forks were operated electrically by using a short helical spring contact, 0.3 cm. in radius, of platinum

[1] *Loc. cit.*

[2] Lord Rayleigh, Phil. Mag., XIII., 1907, p. 214.

[3] *Loc. cit.*

[4] *Loc. cit.*

wire, No. 29 B. & S. gage. The contacts were very quiet and gave a remarkable constancy of amplitude. Indeed the writer has observed the amplitude of a fork so actuated to remain constant, within one per cent., for an hour. No difficulty was experienced because of the presence of both forks in the same room. After many months' work with the apparatus, experimenting upon numerous individuals and confirming completely the experiments of Rostosky and others wherein even greater precautions were taken, the writer can confidently state that the results are in no wise dependent upon any "stray" sounds. Indeed, all the important results were confirmed by leading the tubes into an adjacent room where the forks were not at all audible to the unstopped ears. In practically all the experiments in the same room with the forks, the latter were scarcely, if at all, audible save when the tubes were placed in the ears.

THE RESULTS.

The following results were obtained with the assistance of Mr. F. C. Bruene.

1. The beats with the tones of two forks, one applied to each ear, were heard distinctly. Indeed, of twenty-three inexperienced observers listening for three periods of five minutes each, seventeen noticed the beats distinctly enough to report them. All experienced observers can hear them and record them with very satisfactory accuracy.

2. There existed a distinct wandering of the localization; in front at 0° difference of phase, on the side of the fork with the higher frequency leading in phase from 0° to 180°, and on the side of the slower fork with the higher frequency leading in phase from 180° to 360°, the changes of position being continuous, from front to rear (or within the head) and from rear to front. This wandering when first recognized might be described as occurring in a circular path. A more accurate description occurs in what follows.

3. This rotation of the localization just described was quickly and distinctly observed by some hearers; on the other hand all observers did not recognize it, even with an hour or more of practice. Eleven of the twenty-three uninstructed and inexperienced observers reported their observation of this "rotation" after fifteen minutes' trial (three trials of five minutes each). Six of these eleven noticed the effect within the first five minutes, and three in the second.

4. All of the eleven just mentioned, with the possible exception of one or two, noticed that the localization was much more distinct in the half cycle in which the lead of the faster fork varies from $-90°$ to $+90°$. With experienced observers, the effect is very noticeable.

5. Extended experiments with four experienced observers showed that the most accurate judgment as to phase difference, made by the localization, occurred when that difference is 0°.

6. With the experienced observers the change in the localization at 0° phase difference by the production of a very marked inequality in intensities, is slight. The rotation of the localization was modified by a slight circular shift in the direction of the side of the greater excitation. The effect upon the localization at the sides became very marked, that on the side of the greater intensity becoming more prominent and that on the other almost vanishing.

7. With observers of experience, but who had not yet recognized the secondary maxima,[1] the maxima intensity seemed to occur at 0° phase difference when the beat-period was less than perhaps two seconds. With a greater and gradually increasing period there arose an uncertainty until with a period of perhaps five seconds, the judgment of maximum intensity shifted to a phase difference noticeably less than 180°, or approximately to the first occurring secondary maximum.

8. The rotation of localization with experienced observers occurred as follows: At 0° phase difference the sound was localized as in front and distant, *i. e.*, external to the head. The localization then described in a horizontal plane a path which appeared to be somewhat circular, but in which the apparent distance contracted until the path entered the ear leading in phase. Then at about 180° phase difference the localization passed quickly through the head, into the other ear and from thence around to the front along a path symmetrical to the one just described.

9. When an experienced observer gave his attention to apparent intensity rather than to localization, there appeared three fairly distinct maxima. One occurred at 0° difference of phase, one at $180° - \delta$ and one at $180° + \delta$, δ being less than 45°. The earlier of the additional maxima at $180° - \delta$ phase difference, coincided with the localization in the ear near the higher frequency, and the later one with the localization in the other ear. With a 128 d.v. fork the secondary maxima seemed clearly discernible only if the beat-period exceeded a value of approximately two seconds. The value given is only approximate as the variation in the perception of the secondary maxima is continuous with the changing of the beat-frequency. The significant fact is that the 0° maximum was always present, whereas the secondary ones required a beat-period exceeding at least a second in order to become clearly evident.

10. The localization in the ears as described seemed to depend upon

[1] See (*g*) and (9).

the perception of the secondary maxima. If they were absent, as at high beat-frequency, the localization seemed confined to the region near the front. In other words the localization in approximately one half the cycle seemed to be due to the secondary maxima or the causes producing them.

Discussion of Results.

All of the results are not new. (1) was first discovered by Dove as already stated. (2) was in part reported by S. P. Thompson,[1] Lord Rayleigh,[2] C. S. Myers and H. A. Wilson,[3] and L. T. More.[4] Paul Rostosky was the first to record (2) and (8) and (9) completely. As previously stated in this article, Rostosky's work was unknown to Lord Rayleigh, C. S. Myers and H. A. Wilson, and L. T. More. Thus it chanced that the writer's discovery of the secondary maxima and the rotary character of the localization was an independent one.

None of the phenomena described owed its origin to sounds or noises other than the tones of the forks. Neither did any sound enter the left ear by aerial conduction from the tube entering the right ear. The former statement was tested by conducting the tubes to an adjoining room and by the many alterations in apparatus necessitated by the changing of the forks in experiments described in a succeeding article. The latter statement was verified by the use of tones of very faint audibility and by changing the character of the introduction of sound to the ear (*i. e.*, by the use of binaurals that are not inserted in the ears), without changing the phenomena observed in either case. Reference to Rostosky's experiments will show that he took much more elaborate precautions. Yet our results are in agreement with his at every point. The evidence thus favors the judgment that our precautions were sufficient.

There is an objection to the use of binaurals inserted in the ears, for by partially closing the external meatus they emphasize sounds that are conveyed from the skull to the volume of enclosed air. From the physical point of view, this partial closing of the external meatus would not be likely to change the characteristics of the phenomena and experiment shows this to be the case. Indeed, Rostosky used binaurals that were not inserted into but merely presented in front of the opening of the ear. The writer was also able to detect all the phenomena without the use of inserted binaurals. But there is an additional objection to the inserted binaurals, for there is the chance of conduction from the terminal of the binaural to skull. Experiments in stopping the openings

[1] *Loc. cit.*
[2] *Loc. cit.*
[3] *Loc. cit.*
[4] *Loc. cit.*

of the binaurals showed that there remained only an exceedingly faint trace of sound which could be fully explained by the failure of the stoppage. The conclusion of the writer is that the results with inserted and with non-inserted binaurals are not qualitatively different.

The results given point definitely to distinct differences between the causes of the localization in front and in the rear, or in the ears. The two halves of the cycle differ in distinctness of localization, in independence of beat frequency, in effects produced by inequalities of intensities, and in the apparent distance from the head, the localization in one half being external and in the other half internal. These differences must be accounted for in any adequate theory.

The fact that some observers by the single source method of C. S. Myers and H. A. Wilson[1] do not obtain such a clearly defined "rotation" but rather a wandering back and forth from the median plane to the sides, is apparently due to the difference in the method of observing. In our experiments, with the continually changing phase difference, the rotation is observed in every case where localization is obtained.

This article gives the chief phenomena characteristic of binaural beats. In succeeding articles will be presented a study of the secondary maxima and a physical theory of all the phenomena involved. It will appear that the experiments do furnish excellent evidence as to the perception of phase by the ear and as to a two-fold nature of the hearing organ.

I wish to acknowledge my indebtedness to Mr. F. C. Bruene for his assistance in the experimental work.

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[1] *Loc. cit.*