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ON THE CONSTRUCTION

OF

HEARING AND SPEAKING INSTRUMENTS.

BY

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It does not appear that any attention has of late been paid to the acoustic laws which should regulate the construction of Hearing-trumpets, and the result is, as might naturally be expected, that many empirical methods have been employed, and many extravagant notions of their value entertained, the fallacy of which, however, a slight investigation would be sufficient to demonstrate.

It must have struck the most superficial inquirer into these subjects, that the instruments now in use answer the purpose of the patient very well as long as the person with whom he is in conversation keeps his mouth within a very small distance of the external aperture of the instrument; but that, whenever the speaker removes a few feet from the aperture, his voice becomes totally inaudible by the deaf person whom he addresses.

To find a remedy for these defects, so as to enable a deaf person to hear at any other distance sounds which are audible by him with an ear-trumpet of a given aperture at a given distance from the speaker, is the problem we propose to investigate. We know by the theory of acoustics, that a sound diminishes in intensity in proportion to the square of the distance of the organs of hearing from the origin of the sound; and we also know from geometry, that the areas of similar figures are as the squares of their corresponding lines. From these acoustic and geometric laws we can easily determine the area of an ear instrument, when the distance between the speaker and the hearer is altered. Let A be the diameter of the aperture of the instrument through which the patient can hear a person speaking at the distance D from the external aperture, then, at any other distance mD, the intensity of the sound at the aperture will, by the first of the above-mentioned laws, be to its intensity at the original distance D, as $D^2 : m^2D^2$, or as $1 : m^2$. From this calculation, as well as from experience, it is clear that the same instrument cannot collect the same amount of sound at different distances; and, since the quantity of sound collected depends upon the area of the aperture, we must, in order to collect the same amount of sound, vary that area in exactly the same proportion as the intensity of the sound has been changed; and therefore by the second law, the diameter of the aperture must become mA, for the new area will then be to the original area : : $m^2A^2 : A^2$, or as $m^2 : 1$; in other words, in whatever proportion we diminish or increase the intensity of the sound by altering the distance, in just the same proportion we must increase or diminish the area of the aperture, and therefore the amount of sound collected, by altering its diameter. If, for instance, a person can by means of an instrument with an aperture, of which the diameter is 2 inches, hear distinctly one speaking at 3 inches distance from the aperture, and wishes to have a similar instrument enabling him to hear equally well the same person speaking at a distance of 3 feet, the new instrument must have a diameter of 2 feet, since the voice of the speaker, when removed 3 feet, will only have $\frac{1}{144}$th part of its effect when at 3 inches; and consequently the new instrument must be able to collect 144 times as much of this weakened sound as the former one would do at the same distance, *i. e.* the diameter of the aperture must be 24 inches, which, being 12 times as long, will give an area 144 times as large as it was before.

From these laws we can easily conclude how difficult and inconvenient it would be to construct instruments with an aperture large enough to collect sounds of sufficient intensity at distances exceeding 2 or 3 feet. This difficulty is, however, in some measure obviated by constructing an instrument in the form of an elongated and flexible cylindrical tube, such as those now made of gutta percha. The advantage of this plan consists in the facility which it affords of transferring the external aperture to different distances between the speaker and hearer. Now the intensity of sound appears not to be sensibly diminished, within moderate distances, when the air passes through a straight and rigid tube*; but gutta percha, which on account of its flexibility is most convenient for actual use, is, owing to this very quality, ill-adapted to transmit sound without loss, as is found to be the case in public offices, where the voice has to be conveyed to considerable distances. Another disadvantage attending the use of the elastic ear-tube by deaf persons, arises from the necessity of carrying a long coil of the tube, in order to converse with persons even across an ordinary table. Now, although some disadvantage attends every artificial method of improving the sense of hearing, it must be borne in mind that the same objection applies to the instruments used for assisting the sight: spectacles and telescopes require to have their focal lengths varied, when the objects to be seen are at various distances.

It was not until Lambert undertook the task of rigidly examining the principles of speaking- and hearing-trumpets, that any very precise notions of their laws had been attained †. He has gone very fully into the subject, and after a thorough mathematical investigation, principally devoted to speaking instruments, which will be more particularly noticed

* Biot, vol. i. p. 316.

† Mémoires de l'Académie Royale des Sciences. Berlin, 1763.

hereafter, he came to the conclusion that the paraboloid is the best form for a hearing-trumpet; but, since his conclusion is based upon the fact of the origin of the sound being so distant that all the "phonic rays," as he terms them, enter the trumpet nearly parallel to the axis, and are therefore collected in its focus, where, or near to which, the ear is to be placed, it is evident that his reasoning does not apply to instruments intended to assist ordinary conversation with deaf persons. Lambert, however, shows that hearing-trumpets may be conoids, which is the form he demonstrates to be the best adapted for speaking-trumpets; proving that the same laws regulate both, and that owing to the size of the mouth-piece in the latter being much greater than the orifice for the ear in the former, the speaking- must be proportionally larger than the hearing-trumpet.

Assuming the conoid to be the most practicable form of the hearing-trumpet, we will now, without giving the details of the philosophical reasoning, state the results for the instruction of instrument-makers.

Suppose ACB to be a section of the conoid through the axis, $Ce = \frac{1}{2} AB = AE$ to be the distance of the orifice of the ear from the apex of the cone, *ed* perpendicular to the axis is the diameter of the orifice, which may be taken as $\frac{1}{3}$rd of an inch.

Then if ϕ = half the angle of the cone, CA : C*e* : : 1 : sin ϕ, and since $Ce \sin \phi = \frac{1}{6}$, $Ce = \frac{1}{6 \sin \phi}$ and

$CA = \frac{1}{6 \sin^2 \phi}$, then A*e*, the length of the tube, $= CA - Ce$. By this formula we determine either the length of the tube of a given angular aperture, or the proper angle to be given to a tube of any required length.

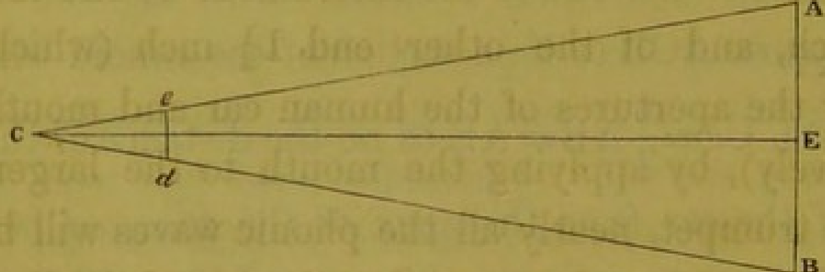
Let it be proposed, for instance, to make an instrument to enable a person to hear at 10 times the distance at which he can hear without it. We know from what has preceded that the area of the aperture of the instrument must be 100 times as large as the orifice of the ear, and consequently that the semi-diameter of the instrument must be 10 times that of the ear, *i. e.* $Ce = \frac{10}{6} = 1\frac{2}{3}$ inch $= \frac{1}{6 \sin \phi}$, whence

$$\sin \phi = \frac{1}{10}, \text{ and } \phi = 5^\circ\, 44'\, 21'',$$

and the angle of the cone $= 2\phi = 11^\circ\, 28'\, 42''$,

$$CA = \frac{1}{6 \sin^2 \phi} = \frac{100}{6} = 16\tfrac{2}{3} \text{ inches},$$

and A*e*, the length of the tube, $= CA - Ce = 15$ inches.



To take another instance, let the distance at which a very deaf person can hear a sound of a given intensity be only 1 inch, and let it be required to make an ear-trumpet to enable him to hear at 36 inches, then will

$$Ce = \frac{36}{6} = 6 \text{ inches} = \frac{1}{6 \sin \phi},$$

$$\text{whence } \sin \phi = \frac{1}{36},$$

$$\phi = 1^\circ\, 35'\, 33''. \quad 2\phi = 3^\circ\, 11'\, 6'',$$

$$CA = \frac{\overline{36}|^2}{6} = 6^3 = 216 \text{ in.} = 18 \text{ ft.};$$

$$\therefore Ae = 17\tfrac{1}{2} \text{ feet.}$$

We see then that, according to Lambert's formula, the instrument alone ought to be nearly six times as long as the distance to which it is desired to extend the hearing. In this case the speaker is supposed to stand at the distance of 36 inches from the external aperture of the trumpet. We see, by means of these formulæ, that in very deaf persons the trumpet must be made of inconvenient length in order to render the voice audible at the distance of 3 feet; but since the object of the trumpet is to convey as much sound to the ear by means of the instrument as the ear itself can collect at the lesser distance, it is obvious that if the orifice of one end of the instrument be one-third of an inch, and of the other end $1\frac{1}{2}$ inch (which are nearly the apertures of the human ear and mouth respectively), by applying the mouth to the larger end of the trumpet, nearly all the phonic waves will be reflected inwards and conveyed to the ear of the listener.

We can now easily account for the fact, that hearing-trumpets of very dissimilar characters answer tolerably, although if the principles on which some are constructed be correct, those of others which seem to act equally well must necessarily be faulty; the reason is, that by putting the mouth close to or within the larger end of the trumpet, most of the voice is confined within its parietes and conveyed to the ear.

Having shown how, and on what principles, ear-trumpets should be constructed, I shall now very briefly enter upon the theory of speaking-trumpets. On this subject we are also indebted to the researches of Lambert for perhaps the only profound examination of the subject. His treatise is indeed chiefly devoted to speaking-trumpets, and he seems to have solved the problem of the proper form of such instruments, which had baffled Morland, Conyers, Hasse and others, who were his predecessors in the same inquiry. The object to be obtained by means of a speaking-trumpet evidently is to keep together and direct towards a distant hearer as many of the "phonic undulations," or, in other words, as much of the speaker's voice, as possible. This appears from the history of the instrument; since it was originally designed for the purpose of reinforcing the human voice, in order that the crews of ships passing each other at considerable distances might be enabled to communicate.

It is sometimes used by persons in the open air for attracting the attention of a multitude, and its use has also been suggested for military purposes; but the trumpet or bugle-horn is generally employed to make known to the soldiers the orders of commanding officers.

Sir Samuel Morland, who appears to have been one of the first to construct a speaking-trumpet, states that with an instrument which he made he was enabled to convey the voice to great distances; the dimensions were, length 5 feet 6 inches, diameter at the mouth 2 inches, and at the external orifice 21 inches.

In the construction of the speaking-trumpet there are several circumstances worthy of remark;—in the first place, the power of these instruments to produce a reinforcement of articulate sounds.

Now, that the intensity of the voice is capable of being greatly augmented by means of the speaking-trumpet is an incontrovertible fact; and, although the phenomenon appears at first sight to present (as Lambert observes) an acoustic paradox, for it seems as if the effect were greater than the cause, still, with the aid of the investigations of Lambert, Hassenfratz and others, it seems possible to give a philosophical solution of the problem.

We know by acoustics that the sound issuing from the mouth spreads in all directions and forms a sphere of undulations to a certain distance, depending on its initial intensity; it follows, that if the mouth be applied to the aperture of a conoidal speaking-trumpet, the sound, instead of expanding into a sphere, will be transmitted through the instrument; and we may therefore reduce the subject, as Lambert has remarked, to the considerations of certain geometrical relations of the sphere and cone.

When sound spreads unimpeded, it diminishes as the square of the distance from its origin; so that, for example, two persons in conversation at 3 feet from each other will hear only one-ninth the quantity of sound that would affect their ears, were they at a distance of 1 foot; but the case is very different if the sound is made to traverse a cylindrical, or conoidal pipe. In the cylinder, when the internal surface is smooth and rigid, Biot has shown that very little sound is lost, except at very considerable distances, that is, provided the ear is placed at one end of the cylinder. But Lambert has proved that the cylinder is not well adapted for a speaking-trumpet, because the sound, after it has passed through the tube, is dispersed much more rapidly than after it has passed through a conoid.

The trumpet constructed for musical purposes derives its powerful tones from the vibratory movements of the column of air within its parietes, together with the reinforcement which is derived from the sides of the instrument entering into a state of oscillation synchronously with the vibration of the column of air.

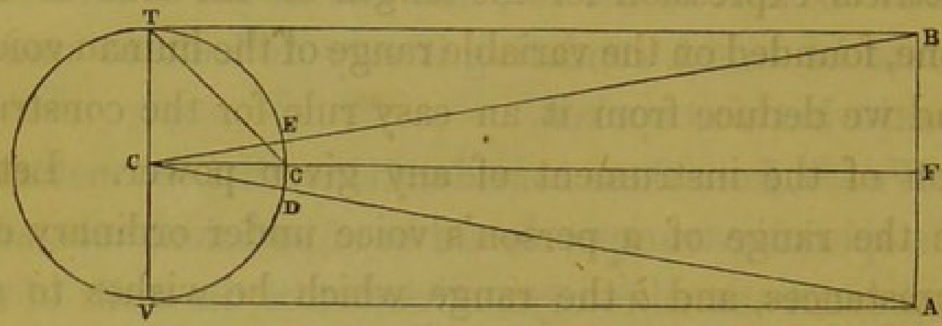
The musical trumpet is of a conoidal figure, having its larger end expanded into a bell-shaped form, which has an influence on the quality of its tone, and assists in the distribution of the sounds. But those very qualities, which confer on this instrument its specific character and value, are circumstances which would be highly detrimental in a speaking-trumpet; since if the walls in the latter were thin and of elastic materials, the vibrations of the tube would materially interfere with the distinctness of the articulation; for it is absolutely necessary when using the tube to speak very slowly; and, since the consonants are of short duration compared with the vowels, the former would be lost to the ear, and the vowel sounds only would be heard, rendering it very difficult to understand what was spoken.

We see, from these considerations, that the materials of a speaking-trumpet should be of sufficient substance to prevent the vibratory movement of the walls of the instrument from interfering with distinctness of articulation. Care should also be taken that the pitch of the voice be different from that of the trumpet; for when the voice and trumpet are of the same pitch, a resonance is produced, which also materially injures the distinctness of the articulate sounds.

But to return to the consideration of the cause of the reinforcement of the voice by the use of the speaking-trumpet.

If the walls of the instrument be sufficiently thick, so as not to interfere with the distinctness of articulation, the whole of the reinforcement of the voice may be attributed to the confinement of the air within the parietes of the tube, and to the reflexions of its undulations from the internal surface. Lambert has shown that precisely the same form of instrument is best adapted to the speaking- as well as to the hearing-trumpet, the only difference being in the size; for he takes the diameter of the opening of the mouth as $1\frac{1}{2}$ inch, whilst that of the ear is but $\frac{1}{3}$rd of an inch;

and since the former is four and a half times the latter, of course all the linear dimensions of the speaking- will be four and a half times larger than those of the hearing-trumpet.



The following is the result of the solution of the problem of speaking-trumpets by Lambert:—

Let BEDA be a tube in the form of a frustum of a cone, of which C is the apex, AB the base, and CF the axis; ED, the embouchure, being a constant quantity, viz. $1\frac{1}{2}$ inch in diameter. With centre C and radius CE=BF describe the circle TGV, of which TCV is a diameter at right angles to the axis of the cone; join TG, EG, TB, AV, the two latter will be tangents to the circle.

If now we conceive the quadrant TEG to revolve round the axis of the cone, it will generate a hemisphere, and the reinforcement of the voice by the trumpet will be to the voice without it as the surface of the hemisphere to the spherical segment generated by EG, that is, as $GT^2 : GE^2$.

From this it is obvious that the power of the instrument depends principally upon the angle of the cone, the power increasing as the angle diminishes; but as the length of the tube increases likewise, there is practically a limit to the power of the instrument for all useful purposes.

For the dimensions of speaking-trumpets Lambert gives an algebraical formula derived from the trigonometrical expression for the length of the side of the cone, founded on the variable range of the human voice; and we deduce from it an easy rule for the construction of the instrument of any given power. Let a be the range of a person's voice under ordinary circumstances, and b the range which he wishes to acquire by aid of the instrument; then if x be the length of the side of the cone,

$$x = \frac{3b^2}{8a^2} = \mathrm{CB};$$

whence this proportion,

CB : CE : : BF (CE) : $\frac{1}{2}$ chord ED ($=\frac{3}{4}$ inch);

this gives the length CE, and therefore CB − CE, or the length of the side of the tube.

For example, suppose $a=\frac{1}{4}$ mile, $b=2$ miles,

then $$x = \frac{12}{\frac{1}{2}} = 24 \text{ inches},$$

and $$\mathrm{CE} = \sqrt{18} = 4{\cdot}24 \text{ inches};$$

$$\therefore \mathrm{BE} = 24 - 4{\cdot}24 = 19{\cdot}76, \text{ about } 19\tfrac{3}{4} \text{ inches}.$$

Hassenfratz has disputed the accuracy of Lambert's theory, and says that in the speaking-trumpet Lambert has attributed the augmentation of sound to its reflexion from the wall of the instrument, whilst in other instruments it is caused by the vibration of the air contained in the tube; and he asks, "Why these two causes while the effects are analogous?"

The general conclusion which he draws from his own experiments are, "that the different sounds produced in the two cases are owing to the vibration of the air in the tubes, and their strengths or intensities to the augmentation of the amplitude of their vibration arising from the greater impulse which the air necessarily receives when it is enclosed in a tube." It appears from this statement, that Hassenfratz has not studied Lambert's work with sufficient attention; for the latter expressly mentions the augmentation of sound as being the result both of the vibration of the wall of the tube and of the reflexion of the air within it; and he then goes on to show that the first of these two causes would interfere with the distinctness of articulate sounds, and is therefore to be avoided, first, by the selection of inelastic materials; and secondly, by taking care not to speak in the pitch of the tube, in order that the resonance of the air in the tube may be prevented.

Now it seems that there is only one principle, properly so called, to which the two different results, namely the musical sound and the articulate, are to be referred, and that principle is the vibration of the air; but, in the first case, the object being simply to produce a musical effect, the direction of the reflected phonic waves is not considered in the construction of the instrument, as they have no effect on the pitch of the sound, but on the quality alone; whilst in the second case, the articulate sounds are not to be produced of the same pitch as that of the trumpet, and the direction of the reflected rays is the only thing to be taken into the account in the instrument, which is formed entirely with a view of securing the concentration of the greatest number of waves along and around its axis. Hassenfratz* also seems to have drawn an erroneous conclusion when he attributes the intensity of sound to an increase in the amplitude of vibrations arising from some greater impulse which air enclosed in a tube necessarily receives. The passage is very vague, but it is clear that air set in motion by a given force must vibrate with the same velocity, whether it expands in open space or is confined within a tube; and the use of an instrument cannot possibly create any new force, but simply concentrates what already exists to the greatest possible advantage.

In concluding this brief outline of the theory of Hearing- and Speaking-trumpets, the author has been induced to lay it before the profession, in order that its members may have in our own language access to some rules for their guidance in the selection of these acoustic instruments †.

It has been no part of the author's plan to enter into any of the considerations relating to the diseases of the organs of hearing; he may, however, observe,

* Annales de Chemie, Prairial, An. xii.; and Nicholson's Journal, vol. xix. p. 233, A.D. 1804.

† Perhaps it may be useful to those who feel an interest in this subject, to notice that instruments according to the formulæ contained in this paper are constructed by Mr. Weedon, Surgical Instrument Maker, Hart Street, Bloomsbury.

that in those in which the membrana tympani is absent, Mr. Toynbee has proposed the use of an artificial membrane which he has invented, and of which he remarks,—

"The artificial Membrana Tympani has now been successfully used in every variety of case where partial or complete loss of the natural membrane has occurred, and I feel confident that in every case of deafness dependent upon such partial or complete loss of the natural organ, the artificial membrane will be found effectual in restoring the hearing."

This statement, coming as it does from a person of such extensive experience and reliable authority as Mr. Toynbee, needs no further remark from the author of this brief memoir.

THE END.

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