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26. 5. 05.
vom Verfasser

KONINKLIJKE AKADEMIE VAN WETENSCHAPPEN
TE AMSTERDAM.

"On the relative sensitiveness of the human ear for tones of different pitch, measured by means of organ pipes."

By Prof. H. ZWAARDEMAKER Cz.

Reprinted from:

Proceedings of the Meeting of Saturday February 25, 1905.

(March 22, 1905).

Physiology. — *"On the relative sensitiveness of the human ear for tones of different pitch, measured by means of organ pipes."* By Prof. H. ZWAARDEMAKER Cz.

(Communicated in the meeting of January 28, 1905.)

Almost simultaneously, but by different methods, the relative sensitiveness of the human ear as depending on pitch, was investigated by MAX WIEN [1]) and by F. H. QUIX and myself [2]). The result of

[1]) MAX WIEN. Physik. Ztschr. IV p. 69. Pflüger's Archiv Bd. 97. p. 1. 1903.

[2]) ZWAARDEMAKER and QUIX. Ned. Tijdschr. v. Geneesk. 1901 II p. 1374: 1902 II p. 417. and Engelmann's Archiv. 1902 suppl. p. 367.

these parallel investigations were concordant in some respects, different in others. They agree in this that:

1st. there is only one maximum of sensitiveness;

2nd. that this maximum lies at g^4;

3rd. that the zone of fair sensitiveness extends from c^1 to g^5.

4th. that outside this region toward the limits of the scale the sensitiveness diminishes very strongly.

They differ in this that:

1st. with MAX WIEN the sensitiveness still diverges very much within the zone of fair sensitiveness, whereas with us it is of the same order.

2nd. that the perceptible minimum for the most sensitive point is with him 100.000.000 times smaller than with us.

In this state of affairs it seemed desirable once more to determine the perceptible minima throughout the whole scale by an entirely different method. Telephone as well as tuning-forks ought thereby to be avoided. So we had recourse to wide roofed organ pipes of which a wooden set of uniform pattern, extending from C to g^4 was at our disposal which partly coincided with the well-known EDELMANN whistles and could be continued by the Galton whistle.

Some series of such experiments were made, partly on the heath at Milligen, partly in the gallery of the university library at Utrecht, partly in the sound-tight room of the physiological-laboratory. Since the results, generally speaking, agree fairly well and a full account of them will be published later, for the present only two series taken under the simplest conditions, will be dealt with. These are: *a*, the concluding series on the heath, *b*, in the gallery. The arrangement, which was the same for both, will first be described.

The organ pipe which serves as the source of sound, is mounted vertically on a stand, near the floor, with as little contact as possible. It is connected with a HUTCHINSON spirometer. Close under the air-room of the organ pipe and connected with this latter by a wide opening, is a ligroine manometer. The manometer being bent into an obtuse angle as little as $^1/_4$ mm. of waterpressure can be read. The spirometer is now loaded with a little box containing sand, so that it forces out the air very regularly and causes the organ pipe to emit a soft sound without an audible frictional noise and without partial tones. The air used is read off on the scale of the spirometer and calculated per second by at the same time starting a timing watch. The product of the volume of air, pressure and acceleration of gravity (all in cm.) then give the energy supplied per second in ergs.

What part of this energy is converted into sound is unknown. WEBSTER [1]) values the "efficiency" at 0,0013 to 0,0038; RAYLEIGH [2]) on the other hand supposed in 1877 as a preliminary estimate, that all was converted into sound ("supposing the whole energy of the escaping air converted into sound and no dissipation on the way"). The truth will probably lie between these two, since we have always paid attention to clear and easy sounding. For such a case MAX WIEN remarked in 1888: A loss of energy certainly takes place, first on account of the fact that part of the air-current is not converted into sound-waves at all, but is lost by the formation of vortices, partly inside, partly outside the pipe. We shall see later that this part is small only for a definite position of the lip of the pipe and for a definite pressure. A second loss of energy takes place by friction on the walls of the pipe and by tremors imparted to them; a third on the way between source and observer by friction on the floor, motion of the air (wind) and viscosity of the air. This latter part especially is relatively large with RAYLEIGH, since by viscosity a loss of energy of ± 22°/₀ took place [3]).

If 22°/₀ is considered relatively much, we may assume that MAX WIEN at that time supposed for the losses by other causes a similar or smaller amount. But whatever the "efficiency" of the supplied energy may have been, there is no reason for assuming that it has been appreciably different for the different pipes. The wooden pipes at any rate belonged to the same set of uniform pattern. So the method suffices for comparative measurements.

While one observer read the scales of spirometer and manometer, the other moved to the greatest distance at which the tone was just heard and recognised ("Erkennungsschwelle"). This distance was then later taken as the radius of a hemisphere through which the energy of the sound spread.

A. *Experiments on the heath at Milligen.*

Perfectly level ground, trees only at 600 metres. Quiet, fine evening, October 19, 1904. Acoustical observer F. H. QUIX, optical observer H. F. MINKEMA (See Table I).

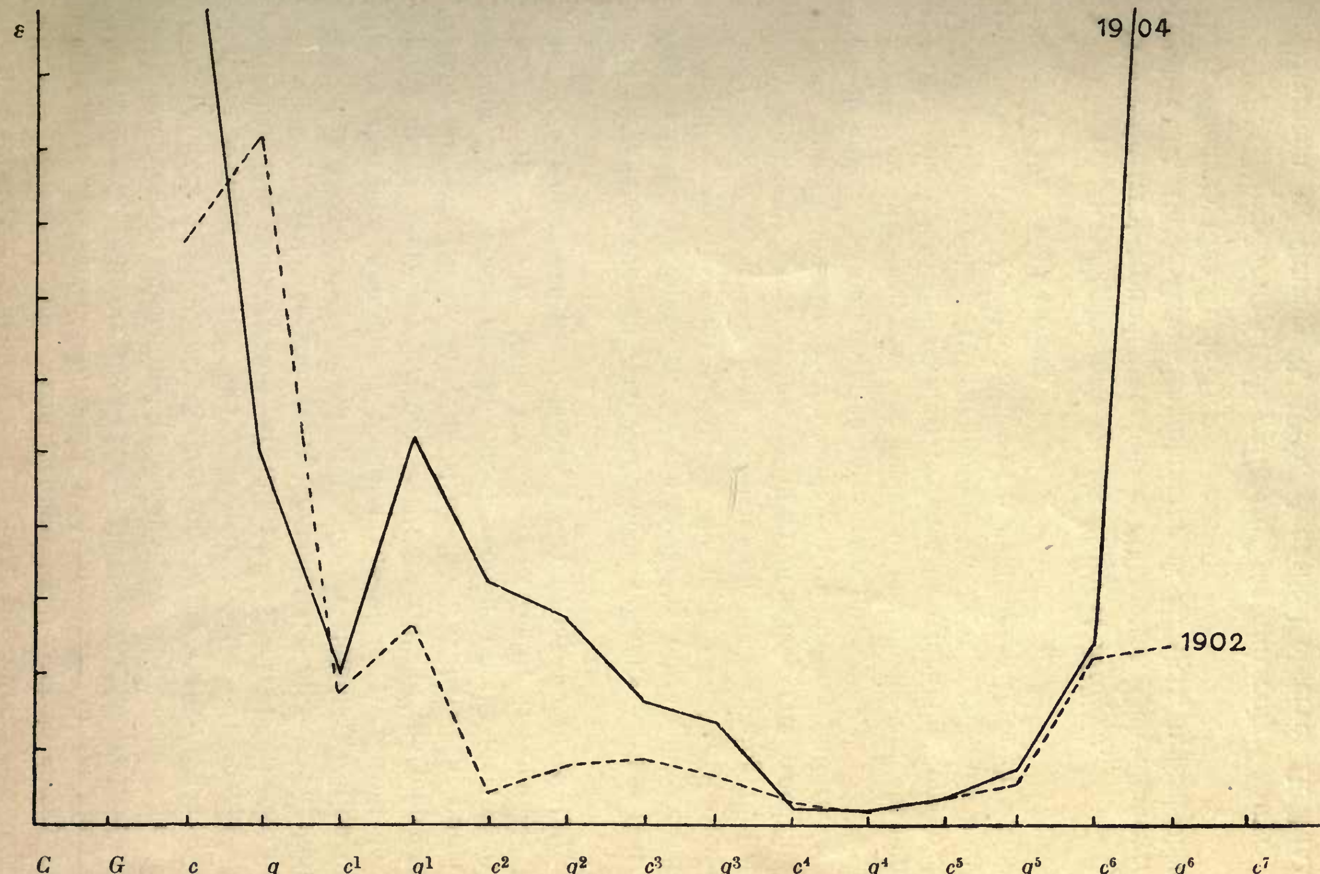
B. *Experiments in the gallery of the university library.*

Afternoon of January 3, 1905. Acoustical observer H. ZWAARDEMAKER, optical observer H. F. MINKEMA. (See Table II).

1) A. G. WEBSTER Boltzmann's Festschrift 1904 p. 870

2) RAYLEIGH Proc. Roy. Soc. vol 26 p. 248 1877.

3) M. WIEN, Die Messung der Tonstärke, Inauguraldissertation. Berlin 1888 p. 45.



Minima perceptibilia in the course of the scale; the minimum for $g^4 = 1$
(absolute value of the chosen minimum: in 1902 $0.79.10^{-8}$ Erg, in 1904 $0.32.10^{-8}$ Erg).

I. *Experiments on the heath at Milligen,* Oct. 19, 1904. 3rd series; acoustical observer F. H. Quix, optical observer H. F. Minkema.

Source of sound.	Pitch.	Frequency.	Air-supply per sec. in cc.	Water-pressure under the pipe in cm.	Energy supplied p. second vol. × press. × 981 (in ergs.)	Distance of the observer in M.	Surface of a hemi-sphere in cm^2., the distance being the radius.	Energy of the sound at the limit of audibility per sec. and per cm^2 in ergs.	Energy of the sound on the tympanum per number of necessary periods in ergs.	Number of necessary periods.	Remarks.
Roofed wooden organ-pipes	C	64	238	0.68	$15.9\ 10^{4}$	80	$4.0\ 10^{8}$	$39\ 10^{-5}$	$411.5\ 10^{-8}$	2	
	G	96	208	1.60	32.7 »	100	6.3 »	52.0 »	361.0 »	2	
»	c	128	69 4	0.40	2.7 »	60	2.3 »	12 0 »	62.7 »	2	
»	g	192	75	0.46	3.4 »	150	14.1 »	2.4 »	8.3 »	2	
»	c^1	256	44.6	0.40	1.8 »	150	14.1 »	1.2 »	3.2 »	2	
»	g^1	384	43.1	0.74	3 1 »	100	6.3 »	5 0 »	8.7 »	2	
»	c^2	512	28.9	0.91	2 6 »	100	6.3 »	4.1 »	5.4 »	2	
Large Edelmann whistle	g^2	768	58.1	1 25	7.1 »	145	13.2 »	5.4 »	4.7 »	2	
	c^3	1024	69.4	1 65	11.2 »	205	26.4 »	4.3 »	2.8 »	2	
»	g^3	1536	113.6	2.51	28.0 »	280	49.2 »	5.7 »	2.5 »	2	
Small Edelmann whistle.	c^4	2048	64.1	2.74	17.2 »	505	160.2 »	1.1 »	0.4 »	2	
	g^4	3072	63.3	2.79	17 3 »	430	116.1 »	1.5 »	0.3 »	2	
Galton	c^5	4096	46.4	3.02	13.7 »	275	47.5 »	2.9 »	0.6 „	2.5	
whistle.	g^5	6144	43	3.02	12.7 »	250	39.3 »	3.2 »	1.0 »	5.5	
»	c^6	8192	46.7	3.14	14.4 »	220	28.1 »	5.1 »	4.2 »	20	
„	g^6	12288	43.8	3.25	14.0 »	70	3.1 »	45.5 »	24.8 »	20	
»	c^7	16384	45.8	3.25	14.6 »	20	0.3 »	581.3 »			

Now, if for the present we only take into account the energy supplied and neglect the necessary loss of energy in the organ pipe and in the air; if we further assume the validity of the theoretical law of distances (extension over a hemisphere), we obtain the following results:

1. that the sensitiveness of our ear has only one maximum, lying in the four times marked octave.

2. that there is a zone of fair sensitiveness, extending from g^1 to g^5.

3. that outside this zone the sensitiveness diminishes very rapidly.

4. that in the zone of fair sensitiveness the perceptible minima are of the same order.

5. that, for the most sensitive part of the scale the perceptible minimum is $0{,}32 \times 13^{-8}$ ergs for Mr. QUIX, $1{,}9 \times 10^{-8}$ ergs for myself.

The true perceptible minimum for the most sensitive point of the scale will of course lie lower. How much lower cannot be determined for the present, but at any rate the perceptible minimum found with organ pipes certainly remains a million times greater than that which was calculated by MAX WIEN from his telephone experiments. The minima, found on the heath and in the library, are in satisfactory agreement, however, with the minimum which we formerly calculated for tuning-forks, using the data of TÖPLER and BOLTZMANN [1].

Taking into account the "efficiency" of an organ pipe, found by WEBSTER (0,0013 and 0,0038), the perceptible minimum for the most sensitive point of the scale becomes lower, namely 0,45 to $1{,}3 . 10^{-11}$ ergs, but it does not reach the amazingly small value of MAX WIEN's telephone experiments by a long way. Even if we assume that one hears better at night in the profound silence of a laboratory, than on the heath, not to mention an afternoon hour in the library, yet this difference is by no means accounted for. But I see no reason why the results of experiments made on perfectly level ground, far from woods or buildings, which, according to MAX WIEN's former valuable investigations, fall perfectly under the theoretical law of the distribution of sound, should deserve less confidence than experiments with a telephone, which require very complicated calculations.

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[1]) TÖPLER u. BOLTZMANN. Ann. d. Physik u. Chemie Bd. 141 p. 321.

II. *Experiments in the university library* January 3, 1905; acoustical observer H. Zwaardemaker, optical observer H. F. Minkema.

Source of sound.	Pitch.	Frequency.	Air-supply per sec. in cc.	Water-pressure under the pipe in cm.	Energy supplied p. second, vol. × press. × 981 (in ergs.)	Distance of the observer in M.	Surface of a hemi-sphere in cm²., the distance being the radius.	Energy of the sound at the limit of audibility per sec. and per cm².in ergs.	Energy of the sound on the tympanum per number of necessary periods in ergs.	Number of necessary periods.	Remarks.
Roofed wooden	C	64	166.6	0.57	9.3 10^{4}	18	0 2 10^{8}	457.8 10^{-5}	4768 10^{-8}	2	
organ-pipes	G	96	138.8	1.08	14.7 »	19	0.2 »	648.7 »	4515 »	2	
»	c	128	96.1	0.91	8.6 »	27	0.5 »	187.4 »	976 »	2	
»	g	192	83.3	0.57	4.7 »	42	1.1 »	42.0 »	146 »	2	
»	c^1	256	45.4	0.51	2.3 »	42	1.1 »	20.5 »	53.4 »	2	
»	g^1	384	31.3	0.4	1.2 »	45	1.3 »	96.6 »	16.8 »	2	
»	c^2	512	25	0.63	1.5 »	58	2.1 »	7.3 »	9.5 »	2	
»	g^2	768	27.2	0.91	2.4 »	62	2.4 »	10.1 »	8.7 »	2	
»	c^3	1024	22.7	0.97	2.2 »	65	2.7 »	8.1 »	5.3 »	2	
»	g^3	1536	20	1.08	2.1 »	65	2.7 »	8.0 »	3.5 1	2	
»	c^4	2048	18.5	1.37	2.5 »	66	2.7 »	9.1 »	3.0 »	2	
»	g^4	3072	14.5	1.94	2.8 »	70	3.1 »	9.0 »	1.9 〃	2	end of the gallery.
Galton	c^5	4096	28.6	1.25	3.5 »	71	3.2 »	11.1 »	2.3 »	2.5	
whistle.	g^5	6144	29.4	1.94	5.6 »	69	3.0 »	18.7 »	5.6 »	5.5	
»	c^6	8192	27.7	1.54	4.2 »	42	1.1 »	37.8 »	30.7 »	20	
»	g^6	12288	37	1.54	5.6 »	25	0.4 »	142.4 »	77.2 »	20	
»	c^7	16384	35.7	2.28	8.0 »	20	0.3 »	317.9 »			