ON MINIMUM AUDIBLE SOUND FIELDS*

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ABSTRACT

The minimum audible field (M.A.F.) has been determined from data taken on 14 ears over the frequency range from 100 to 15,000 c.p.s. The observer is placed in a sound field which is substantially that of a plane progressive wave, facing the source and listening monaurally. The M.A.F. is expressed as the intensity of the free field, measured prior to the insertion of the observer. Similar data are presented for binaural hearing, over the range from 60 to 15,000 c.p.s., obtained with 13 observers. At 1000 c.p.s. the average M.A.F. observed is $1.9 \times 10^{-6}$ watts per cm$^2$, corresponding to a pressure 71 db below 1 bar. Included are data showing how the M.A.F. varies with the observer's azimuth relative to the wave front. Another type of threshold data refers to minimum audible pressures (M.A.P.) as measured at the observer's ear drum. The differences obviously to be expected between M.A.F. and M.A.P. values are due to wave motion in the ear canal and to diffraction caused by the head. The M.A.F. data are discussed in relation to the M.A.P. determinations from several sources. Some possible causes of difference between the two, which are due to experimental procedure and may add to the causes already mentioned, are pointed out.

THRESHOLD OF HEARING—GENERAL DISCUSSION

Ideally, an absolute measurement of the least audible sound would state the stimulus in terms independent of the particular apparatus used to produce it. With this in view, most threshold determinations roughly

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fall into two classes: the "minimum audible field" (M.A.F.) and the "minimum audible pressure" (M.A.P.). The former is in terms of the intensity of the sound field in which the observer's head is placed; the latter, in terms of the pressure amplitude at the observer's ear drum. This paper is concerned only with steady tones; i.e., with tones sustained over one second or longer. Even with this restriction, the generation and measurement of the stimulus over the audio range of frequencies entail considerable difficulty. Because of the technique required, threshold measurements usually have been made by physicists. However, essentially this is an experiment in physiology and psychology, and the data are subject to a number of nonphysical influences.

The M.A.F. values directly relate to the usual mode of hearing, i.e., with the unaided ear. They are the more applicable when extended to include the effects of binaural hearing and of the listener's orientation with respect to the sound field. The M.A.P. data are of interest in the study of the ear mechanism. At sufficiently low frequencies they can be used in conjunction with drum impedance data, to throw some light on the least audible drum displacements. Given anatomically reasonable assumptions as to the low-frequency mechanism of the ear and the cochlea, the minimum audible forces exerted by the basilar membrane may be surmised. One of the requisites for any such deductions is that the frequency be sufficiently low so that the impedance, as measured looking into the ear drum, is predominantly a stiffness reactance. This probably means frequencies below 600 c.p.s. The M.A.P. becomes indefinite at frequencies so high that the pressure on the ear drum can no longer be assumed to be approximately uniform. There is no direct evidence as to where this occurs. For air in a circular cylinder of 1 cm diameter and having rigid walls, the gravest purely transverse mode of vibration corresponds to a frequency of 20,000 c.p.s. This is the case of one nodal diameter and no nodal circles. From this and from similar indirect considerations, it is thought that up to 10,000 c.p.s. at any rate, the pressure is uniform over the area of the drum, well within the limits of threshold work accuracy.

The methods used for threshold determinations, and more detailed definitions of the stimulus, are given in the following three sections. The threshold data discussed are those in which the stimulus either is a pure sinusoidal wave, or a very narrow frequency band within which the ear sensitivity is substantially constant. The graphs representing the M.A.F. or M.A.P. stimulus as a function of frequency are briefly referred to as M.A.F. or M.A.P. curves, respectively. The M.A.F. curves
are supplemented by some data showing the effect of the observer's orientation with respect to the sound field, as given in "azimuth" curves.

**THE PRESENT MINIMUM AUDIBLE FIELD (M.A.F.) DETERMINATION**

**The quantity measured**

This is the intensity of a progressive wave which produces a minimum audible field for an observer placed in it. The intensity measured is that of the undistorted free field, prior to placing of the observer into it. Ideally, the field would be that of a progressive plane wave. In that case the pressure $p$, which is the quantity best suited to direct measurement, and the intensity $W$ are simply related: $W = \frac{p^2}{\rho c}$, where $\rho c =$ air density $\times$ sound velocity = 41.2 C.G.S. units at 76 cm barometric pressure and 23°C

$$\rho = \text{r.m.s. pressure in bars}$$

$$W = \text{intensity in ergs per second through 1 cm}^2 \text{ of wave front.}$$

The same equation applies to a progressive spherical wave. It was impractical accurately to realize either of these sound fields over the range of frequencies to be covered: $f = 60$ cycles to $f = 15,000$ cycles, corresponding to wave-lengths of $\lambda = 574$ cm and $\lambda = 2.3$ cm, respectively. "Impractical" is used with reference to extensive threshold measurements in which it was desired to use a number of observers and to avoid the interruptions attendant upon work outdoors.

**The sound field**

Actually, the data were obtained in the field established at one meter in front of a loud speaking receiver in a highly absorbing acoustic structure (referred to later as the "sound stage"). This structure is of the type developed by Wente and Bedell.* It consists of 12 layers of flannel and muslin, separated by air layers, making a total thickness of 12 inches. The receiver radiates from an area of 3.8 cm diameter, in the center of a cylindrical case 16 cm in diameter. The sound stage, the sound source and an observer are shown in Fig. 1. This arrangement establishes in a limited volume a field approximately like that of a progressive spherical wave. If this zone, especially its horizontal dimensions at the level of the observer's ears, is several times larger than the observer's head, the effect on the latter will be nearly the same as that due to a progressive spherical wave.

The center of the observer’s ear-line (i.e., of a straight line about 18 cm long joining the two ears), is at one meter from the source, on the receiver axis. The ear-line nowhere departs from a circular arc by more than 0.5 cm, which is small relative to all but the shortest wavelengths used. The difference between the diffraction effects of a plane

wave and of a spherical wave of one meter radius, is quite small for our purposes. This can further be inferred from the theory of diffraction at a rigid sphere,² caused by plane and spherical waves, respectively. Thus Fig. 2 shows the diffraction produced at a 20 cm diameter sphere by two 5500 cycle waves: one plane (\(kR = \infty, k = 2\pi/\lambda\)), the other spherical of 1 m radius (\(kR = 100, k = 2\pi/\lambda\)). The two are seen to be quite similar; the maximum difference of 2.5 db may in part be due to the limits of

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Fig. 1. The sound stage and sound source, with an observer in position.
accuracy with which the zonal harmonics were evaluated. In what follows, no distinction will be made between a plane wave and a spherical wave of 1 m radius, as far as threshold of hearing is concerned.

The sound field was measured by means of a condenser transmitter, whose "field" calibration was obtained with a Rayleigh disk. The sound stage was placed in a corner of a large, carefully sound-proofed room. At no time during the threshold measurements, was either the observer or the operator conscious of sufficient noise to affect the threshold.

The threshold measurement procedure

The observer was provided with a push button which lighted a small lamp before the operator and which was held down whenever and as long as the tone was audible. The operator allowed the observer to listen to the tone at a level well above threshold, say 30 or 40 db, for a few seconds, and then gradually reduced the intensity by turning up the receiver current attenuator until the observer signalled that he could no longer hear the tone. This level served as a convenient one at which to start interrupting the tone as usually the observer could hear an intermittent tone 10 to 20 db lower.

From this level on down, the operator reduced the sound in steps until threshold was determined, interrupting the tone several times at each attenuator setting. The tone was left on for approximately two seconds, then cut off for about the same length of time, then the tone
again, etc. The transition from tone to silence and *vice versa* was made with no audible clicks whatever, by a gradual change in the amplifier filament current. The operator judged from the ability of the observer to follow the interruptions with his key whether or not he heard the tone at each intensity. The sizes of the steps were determined by the operator to give most rapidly an accurate figure for the threshold level and were usually about 5 db at first, becoming smaller down to the 1 db steps of the attenuator as threshold was approached.

The element of fatigue was carefully guarded against. As soon as an observer became conscious of any appreciable fatigue, or if the operator suspected it, that observer was relieved for a while and another observer used.

In measuring monaural threshold, it is essential to have the other ear sealed off. The seal should be definitely better than the difference between the acuities of the two ears. This was effected by inserting absorbent cotton into the ear canal; the first layer plain, the second impregnated with petrolatum which completely sealed the entrance to the ear canal. The usual attenuation obtained in this way was 30 to 34 db, and at no frequency in our range was it less than 20 db. The adequacy of the seal was proved by making threshold settings with and without the seal, and comparing the difference with the acuity difference as measured on an audiometer.

The tones used were 100, 200, 300, 400, 500, 800, 1100, 1600, 2240, 2700, 3200, 3700, 4200, 5000, 6400, 7600, 9000, 10,000, 12,000, 12,800 and 15,000 c.p.s. The electrical circuit and the sound source were so designed and operated that the tone reaching the observer's ear at levels near threshold was completely free from extraneous frequencies. The first six tones were pure sinusoidal waves. The others were "warble" tones centering about the nominal frequencies given. The "warble" range progressively increased from ±50 cycles at 1100 c.p.s. to ±146 cycles at 15,000 c.p.s. For all frequencies the warble was at the rate of 10 times per second. The advantage of using the warble is psychological, in that it reduces fatigue and uncertainty on the part of the observer; and physical, because of smoothing out of the residual standing wave patterns produced by reflections. A few check measurements made by the same individual with and without the warble indicated no other systematic differences between the threshold values in the two cases.

Data were obtained on 14 ears: 10 men's, left and right of 5 observers; 4 women's, right of 4 observers. The men's ages ranged from 18 to 26, except one of 40; the women's, from 20 to 23; the average age, about 23.
All observers had good hearing: "normal" or above normal, throughout the greater part of the frequency range, as judged by their audiometer audiograms. This group will hereafter be referred to as group A.

The observed M.A.F. values

Fig. 3 gives the M.A.F. values found, logarithmically averaged for the 14 ears in group A. At each frequency the mean deviation from the average is indicated in the figure. The corresponding standard deviations are given together with those for binaural thresholds in Table I.

It should be borne in mind that this M.A.F. curve is for a group of young people with generally excellent hearing, favored by freedom from fatigue and noise and by the contrast of the intermittent test tone.

Binaural M.A.F.

The binaural M.A.F. data are based on two groups of observers. Group B consisted of the 5 men included in the above group A. Group C consisted of 8 men and 2 women, average age about 24. The two women and three of the men were included in group A above.

The threshold measurements for group C were made under the direction of Mr. W. A. Munson, to whom we gratefully acknowledge our indebtedness for the data.

For group B all measurement conditions were identical with those described in the section on threshold measurement procedure. For two

* The one exception is at 15,000 c.p.s. where one observer's left ear showed abnormally low acuity; at all other frequencies that ear was easily as good as the average of the group.
members of the group data were available binaurally, as well as on each ear separately. These data showed no significant difference between the binaural M.A.F. and the best ear M.A.F. Accordingly for the three others in the group, the best ear M.A.F. was taken to be the binaural M.A.F.

**TABLE I. Standard deviations from average M.A.F.'s.**

<table>
<thead>
<tr>
<th>Frequency (c.p.s.)</th>
<th>Group A (db)</th>
<th>Group B (db)</th>
<th>Group C (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5.1</td>
<td>5.26</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td>3.55</td>
</tr>
<tr>
<td>200</td>
<td>6.65</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>240</td>
<td></td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td>300</td>
<td>6.76</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>9.83</td>
<td>11.72</td>
<td></td>
</tr>
<tr>
<td>480</td>
<td></td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>560</td>
<td>7.94</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>680</td>
<td>9.08</td>
<td>9.11</td>
<td></td>
</tr>
<tr>
<td>960</td>
<td></td>
<td></td>
<td>3.35</td>
</tr>
<tr>
<td>1100</td>
<td>8.28</td>
<td>8.69</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>9.31</td>
<td>10.28</td>
<td></td>
</tr>
<tr>
<td>1920</td>
<td></td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>2240</td>
<td>7.25</td>
<td>6.74</td>
<td></td>
</tr>
<tr>
<td>2700</td>
<td>6.55</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>3200</td>
<td>6.11</td>
<td>7.05</td>
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</tr>
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<td>3700</td>
<td>5.87</td>
<td>5.85</td>
<td></td>
</tr>
<tr>
<td>3850</td>
<td></td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td>4200</td>
<td>7.62</td>
<td>7.25</td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td>6.34</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>5400</td>
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<td>5.8</td>
</tr>
<tr>
<td>6400</td>
<td>7.06</td>
<td>6.61</td>
<td></td>
</tr>
<tr>
<td>7600</td>
<td>7.44</td>
<td>6.76</td>
<td></td>
</tr>
<tr>
<td>7800</td>
<td></td>
<td></td>
<td>5.1</td>
</tr>
<tr>
<td>9000</td>
<td>5.45</td>
<td>6.76</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>11.52</td>
<td>8.97</td>
<td></td>
</tr>
<tr>
<td>10500</td>
<td></td>
<td></td>
<td>5.9</td>
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<td>12000</td>
<td>6.49</td>
<td>6.75</td>
<td></td>
</tr>
<tr>
<td>12800</td>
<td>9.31</td>
<td>8.77</td>
<td></td>
</tr>
<tr>
<td>15000</td>
<td>18.2</td>
<td>10.32</td>
<td>12.85</td>
</tr>
</tbody>
</table>

For group C at all frequencies above 240 c.p.s. the measurement conditions were the same as in the section on threshold measurement procedure, except that single frequency tones rather than "warble" tones were employed throughout. At 60, 120 and 240 c.p.s. the sound source arrangement was somewhat different. The source was a moving coil loud
speaker, radiating from an 18 inch diaphragm. At these low frequencies the angle of incidence of the sound wave is unimportant, and it was only necessary to insure by direct measurement that the observer's head was placed in a region of substantially uniform pressure.

The results are shown in Fig. 4, for the two groups separately. The mean deviations from the average M.A.F. at each frequency are also shown in this figure, while the standard deviations are given in Table I.

The remark at the end of the section on the observed M.A.F. values, concerning the observers and the test conditions applies to groups B and C as well.

![Graph](image)

**Fig. 4. Binaural M.A.F., groups B and C.**

**M.A.F. vs. azimuth**

So far we have been concerned with the M.A.F. values for a progressive wave whose vertical wave front is parallel to the listener's ear-line ($0^\circ$ incidence). They will be different for other angles of incidence; the more so, in general, the higher the frequency. The M.A.F. values for any angle of incidence other than those corresponding to vertical wave fronts, are experimentally difficult to obtain. The variation of the monaural M.A.F. with the azimuth of a vertical wave are the M.A.F.—azimuth curves given in Fig. 5. The notation used, is: $0^\circ$ observer facing sound source; $+90^\circ$ — open ear toward source. The ordinate $F_\theta$ at any angle $\theta$, gives the ratio (in db) of the M.A.F. for $0^\circ$ incidence to that for $\theta^\circ$.

The data were obtained in the sound field described on page 400,
with the exception of the 300 c.p.s. and 500 c.p.s. values which had been obtained earlier in another connection. At the other frequencies shown, three observers were employed, two men and one woman. Readings were taken every thirty degrees, as well as at the positions

![Graphs showing directivity of monaural hearing](image)

**Fig. 5. Directivity of monaural hearing.** 0°—observer facing source; +90°—open ear toward source.
of maxima and minima located by each observer in a preliminary exploration of the field. The curves shown were obtained not by averaging the three individuals’ values for each angle, but by estimating a single curve to present the characteristic features of the individual curves.

The azimuth data, particularly those at high frequencies, indicate shadows so deep that one cannot be certain of their accuracy because of residual reflections modifying the sound field used. However, at a few frequencies similar data were available, which had been obtained outdoors in the field of a nearly perfectly progressive wave. They are so similar to the indoor data that the latter are inferred to present a fairly correct picture.

It may be of interest to compare these M.A.F.-azimuth curves with some of the pressure-azimuth curves which have been computed for a plane wave incident upon a rigid sphere. Two such curves are given in Fig. 6.* The notation used is: $c =$ radius of the sphere; $k = \frac{2\pi}{\lambda}$; $\lambda =$ sound wave-length. The curves are for $kc=10$ and $kc=20$, respectively.*

* Detailed variation shown only for: $\theta > 150^\circ$ ($kc=10$) and $\theta > 140^\circ$ ($kc=20$). The deepest shadow ($M$) for $kc=10$ is based on Rayleigh’s data.
Taking $c = 9$ cm (roughly the size of the human head), the curves will represent 6000 and 12,000 c.p.s., respectively. Of course, the head is not a rigid sphere and at high frequencies the contour of the external ear may be important. No quantitative agreement between the observed and computed curves need be expected.

From the monaural M.A.F.-azimuth curves of Fig. 5, binaural azimuth curves can be derived provided the monaural M.A.F. curves are given for each ear; also, it is assumed that at each angle the binaural M.A.F. is equal to the smaller of the M.A.F.’s for each ear alone at their respective azimuths. We shall consider the simplest case: the two ears taken equal. If we now assign to each angle $\theta$ an ordinate $F$ equal to the larger of the two ordinates $F_\theta$ and $F_{-\theta}$ of the monaural azimuth curve, the binaural azimuth is obtained. As an illustration the binaural curve for 4200 c.p.s. is shown in Fig. 5, its right half coinciding with the monaural curve.

Suppose now that the observer is exposed to random horizontal incidence; i.e., to a diffuse sound field in which all wave fronts are vertical, all azimuths equally probable, all amplitudes equal, and all time-phase angles distributed at random. For such a field the resultant binaural M.A.F. is equal to the binaural M.A.F. observed for $\theta = 0^\circ$ multiplied by the factor

$$R = \left( \int_0^{2\pi} F_\theta^2 \cdot d\theta \right)^{1/2} / 2\pi F_\theta^2.$$

Purely geometric randomness is assumed, ignoring the more complex question of ear response vs. stimulus wave form.

**Other Data Similar to the M.A.F. Type**

Some threshold determinations have been made elsewhere, which resemble our M.A.F. work in that the listening ear is exposed to the open sound field, rather than to a source fitted on or in the ear. Otherwise most of them differ from the M.A.F. procedure in that the field is not that of a nearly progressive spherical wave; the normal diffraction by the head and outer ear is altered; the observer does not face the source, etc. Unless otherwise stated, the data reviewed all are for monaural hearing. The list given does not pretend to be complete.

Two chronologically arranged lists of references to threshold determinations are given by H. Fletcher in *Speech and Hearing* (1929, D. Van Nostrand Co., New York), and by H. C. Huizing (Diss. Univ. Groningen, 1932). They include both M.A.F. and M.A.P. types, and
to a large extent overlap with the references discussed in this section and in the section on minimum audible pressures beginning on page 307.

In 1870 Toepier and Boltzmann measured the sound output of an organ pipe by a light interference method. From this and from the distance between the observer and the source, the M.A.F. was obtained. At 181 c.p.s., threshold was found at −57 db (relative to 1 bar).

Rayleigh in 1877 and 1894 reported threshold data obtained with an organ pipe and with tuning forks, respectively. In the former the sound output is computed on the basis that the work used up in pumping air through the pipe, is all converted into sound. This at 2730 c.p.s., gave a threshold field of approximately −28 db. The later work employed tuning forks whose initial amplitudes of vibration and rates of decay were known. The thresholds found were:

<table>
<thead>
<tr>
<th>Freq.:</th>
<th>256</th>
<th>384</th>
<th>512</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press. (db):</td>
<td>−44</td>
<td>−47</td>
<td>−47</td>
</tr>
</tbody>
</table>

Wead, in 1883, using a method much like Rayleigh’s 1894 work, obtained:

<table>
<thead>
<tr>
<th>Freq.:</th>
<th>128</th>
<th>256</th>
<th>384</th>
<th>512</th>
<th>786</th>
<th>1024</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press. (db):</td>
<td>−25</td>
<td>−38</td>
<td>−39</td>
<td>−44</td>
<td>−33</td>
<td>−36</td>
</tr>
</tbody>
</table>

Webster in 1904, used an electrically driven diaphragm whose sound output could be computed. At 256 c.p.s., he gives a threshold at −42 db.

In all the foregoing it is difficult to obtain an accurate picture of the acoustic conditions, particularly as to possible disturbances caused by reflections; also the numbers of ears tested and frequencies used, were rather small.

Of the earlier work, that of M. Wien is best known, and still frequently cited. Usually it is pointed out that his results give thresholds much lower, and hence ear sensitivities much higher, than those found by later workers. A recent paper by Langenbeck is devoted to a detailed discussion of various reasons that might account for the discrepancy. It concludes with the remark, “It follows that upon making allowances for the room acoustics and sound field distortion, a large part of the observed discrepancy still must be assigned to an unknown effect.”

Wien’s final data cover the range from 200 to 12,800 c.p.s., insofar as obtained with the open ear; his values below 200 c.p.s. were obtained with a receiver on the ear. The open ear values are shown in Fig. 7.
They were obtained mostly on Wien's own ear; some are based on two
ears and a few, on three. The observer's head is situated behind a sheet
iron screen, his ear protruding through a hole in the screen. The sound
source, a telephone receiver, is 30 cm distant from the screen opening.
The pressure values used are those which would obtain at 30 cm from
the receiver when situated in an infinite baffle and radiating into free
space on one side of the baffle. On these assumptions the pressure is
computed from the optically measured diaphragm displacements, by
means of Rayleigh's formula. The effect of the head as a whole is
eliminated; to a considerable extent the effect of the pinna probably is
also different from that in our M.A.F. determination. If now—while

![Graph](image)

**Fig. 7. M.A.F.**

bearing in mind the important differences between the two procedures
in point of acoustic conditions, number of observers and number of fre-
quencies—Wien's data be compared with those here reported, the
difference is not nearly so startling as that obtained by comparing them
with the average of a large number of other determinations obtained
mostly with sound sources tightly fitting on the ear (substantially
M.A.P. data). In fact, if we select M.A.F. values for one of our ob-
servers (R.L.V.) at those frequencies which lie closest to Wien's par-
ticular frequencies, and select the +90° azimuth as being most nearly
comparable with Wien's situation, we obtain Table II.

The two sets agree quite well, considering the inherently large varia-
tions met with in any threshold work. It is perhaps unnecessary to
consider Wien's sensitivities as anything more than might be obtained
for a young individual with exceptionally good hearing, listening with
an open ear under most favorable azimuth conditions.

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Wien (db)</th>
<th>R.I.V. (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>−60</td>
<td>−68.5</td>
</tr>
<tr>
<td>400</td>
<td>−78</td>
<td>−82</td>
</tr>
<tr>
<td>800</td>
<td>−93</td>
<td>−89</td>
</tr>
<tr>
<td>1600</td>
<td>−97</td>
<td>−95</td>
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<tr>
<td>3200</td>
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</tr>
<tr>
<td>12800</td>
<td>−82.5</td>
<td>−79.5</td>
</tr>
</tbody>
</table>

Guernsey's\textsuperscript{10} work was done at much later date, in a psychological
laboratory. The procedure employed was very similar to Wien's. The
frequency range is from 120 to 13,650 c.p.s. At most of the frequencies,
three observers were used. The data plotted in Fig. 7 represent loga-
Rithmic averages of the values given for individual observers.

Lane's\textsuperscript{11} observations cover the high-frequency range, from 2000 to
18,500 c.p.s. They were obtained outdoors with the source and ob-
servers 5 meters above the ground, separated by 1.5 meters. The ob-
server's ear was turned toward the source, which is +90° azimuth. The
source was an eddy-current loud speaker of the Hewlett type, with a
diaphragm 10 cm in diameter. The total sound output was computed
using Hewlett's theory. It was assumed that: (1) the diaphragm moves
as a rigid piston; (2) it has a radiation resistance of $\rho C (=41.5$ c.g.s.)
per cm$^2$. In addition, an empirical correction was necessary to allow
for the spatial distribution of the total sound power. The results, re-
duced to our db pressure scale, are shown in Fig. 7. They are averages
for 8 ears of 7 individuals from 19 to 35 years of age. Lane's work and
the present M.A.F. work are quite similar as to acoustic conditions,
excepting the 90° azimuth displacement. The large difference between
the results in the direction of larger M.A.F.'s for Lane's observers, may
be due to: (1) differences in the observer's acuities; (2) possible dis-
crepancies between the actual field intensity and that computed as
above; (3) possible increase in M.A.F. caused by insect noise, outdoors
at night.

Swan,\textsuperscript{12} in 1923, reports observations made by two observers at 121,
246, 493 and 1021 c.p.s. The total power emission of the sound source
was computed, by Rayleigh's formula, from its piston dimensions, and
from the amplitude measured microscopically. The time of decay in the
room was determined by measuring the times required for the sound to
drop to threshold from two initial levels differing by a known amount.
Then by Sabine's formula, the mean energy density in the room was
computed, and its value at threshold could be deduced. The incidence
is largely random, and the hearing presumably is binaural. The results,
reduced to our pressure scale, are:

<table>
<thead>
<tr>
<th>Freq.:</th>
<th>121</th>
<th>246</th>
<th>493</th>
<th>1021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press. (db):</td>
<td>-27</td>
<td>-60</td>
<td>-68</td>
<td>-74</td>
</tr>
</tbody>
</table>

Only the observer's head was exposed to the sound, his body being en-
closed in a box.

E. Meyer's paper gives a single curve obtained by averaging thresh-
holds for hearing in an open sound field and with a telephone receiver,
respectively. At each frequency, over the range from 100 to 12,800
c.p.s., six observers were used. It is stated that the open field and the
telephone receiver results showed no important systematic differences.
For that reason they are quoted both here, and in the section on mini-
mum audible pressures. The open field data were taken in a large, well
damped room, with an electrodynamic loud speaker mounted in a rigid
baffle, one meter square. The field intensity was measured with a con-
denser transmitter whose "field" calibration was known. The observer's
head was at 50 cm from the center of the baffle, the ear under test
presumably turned toward the source.

A. Buhl gives a "normal threshold" curve, shown in Fig. 7. The
open sound field was measured with a Rayleigh disk, at 10 cm in front
of the loud speaker. Presumably, though this is not stated in the paper,
the observer's ear is placed at that point, turned toward the source.

A recent M.A.F. determination is reported by H. C. Huizing. A
telephone receiver is used as a loud speaker. Its sound output is com-
puted from the central diaphragm amplitude, which is measured opti-
cally. One observer 20 years old, was employed. His ear was 20 cm
from the source. At that distance the field was found to be nearly that
of a progressive spherical wave. The azimuth, though not stated, pre-
sumably was +90°. The M.A.F.'s observed, are shown in Fig. 7.

Some measurements made with the ear exposed to the sound field
through a coupling tube, rather than directly, are described by Waetz-
mann and Heisig. The scheme is shown in Fig. 8. From the motional
impedance (electrically determined) of the receiver \( R \), the total sound
energy which it radiates, is computed. The hemispherical surface \( F \) is
assumed to be perfectly absorbing, the circular surface $B$, perfectly rigid. On this basis, the field intensity $U$ at the entrance to the coupling tube $T$, is computed. Threshold values, obtained for one ear at three frequencies, are expressed in a form equivalent to: $E = \frac{1}{3} S \cdot 1/U$ where $S =$ cross-sectional area of $T$ (not stated numerically); $\frac{1}{3} \text{ cm}^2 =$ area assumed for ear drum. The results given are:

<table>
<thead>
<tr>
<th>Freq.</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>890</td>
<td>$4.5 \times 10^8$</td>
</tr>
<tr>
<td>2160</td>
<td>$7.1 \times 10^8$</td>
</tr>
<tr>
<td>3020</td>
<td>$3.2 \times 10^8$</td>
</tr>
</tbody>
</table>

Thus $U$ stands for the threshold intensity of a sound field coupled to the ear through a tube of a certain length and cross section, rather than directly incident upon it.

**General comments on M.A.F. data**

This list of threshold determinations is not complete. Yet it suffices to provide an enormous range of values, the spread increasing with the frequency, as shown in Fig. 7. All these M.A.F. values have the point in common that the ear is exposed to the open sound field. In general they do not conform to the specific M.A.F. definition used in the section on the present M.A.F. work. Some of the important differences between the various sets of data are: (1) differences between individuals; (2) ages of observers; (3) number of ears tested; (4) the sound field; (5) the observer's orientation with respect to the field; (6) the number of test frequencies.
Bearing in mind the potential variations which reside in any one of these factors, the total spread shown is not quite so impressive as it at first appears. But it must be emphasized that the curves in Figs. 3 and 4 represent a group of young people with generally excellent hearing. In connection with the subsequent use made of these curves, it will be well to consider some data which show how the acuity of hearing varies with the observer's age. C. C. Bunch has examined the hearing of several hundred hospital patients, 353 in the first and 468 in the second group. The tests were made with a Western Electric No. 1-A Audiometer, the sound source being a telephone receiver held on the ear. The test frequencies ranged from 32 to 16,384 c.p.s., and the results are classified for the age decades 20-29, 30-39, 40-49, 50-59 and the "over 60" group. The outstanding result is the marked falling off in acuity with increasing age, particularly for frequencies above say 1000 c.p.s. Thus at 8192 c.p.s. the 50-59 group averages 26 db lower than the 20-29 group, and at 2048 c.p.s., 12.5 db.

Tests on 200 people, ranging in age from 20 to 60 years, "selected in such a way that the proportion having defective hearing is about what might be found in any normal group of people" are reported by H. C. Montgomery. These too indicate a decreasing acuity with rising age, though not so markedly as in Bunch's work. Thus at 2048 c.p.s. the difference between the 20-29 and 50-59 groups is about 7 db at 2048 c.p.s. and at 8192 c.p.s. about 23 db. It is possible that the hospital groups include a larger percentage of people whose ailments accentuate the normal effects of advancing age.

The theoretical limit of aural acuity

Returning now to the data of Figs. 3 and 4, it may be inquired whether the ear sensitivity is limited by its physiological construction, or whether the limit is imposed by the air as a transmitting medium. Superposed on the average atmospheric pressure there are fluctuations caused by the distribution of thermal velocities of air molecules. What is the spectrum of the resultant thermal-acoustic noise? Is its magnitude compatible with the observed M.A.F.s?

It is interesting to note that in a recent paper by Barnes and Czerny,* a somewhat similar question is raised in regard to differential visual acuity. They conclude that there is some experimental evidence to support the view that the human eye, in that region of the visible spectrum to which it is most sensitive, has a differential sensitivity of

the same order of magnitude as the fluctuations inherent in a "steady" light due to the shot effect in photon emission.

For purposes of calculation, let us replace the ear with a rigid massless piston, of area $S$, free to vibrate in an infinite rigid wall and exposed to the atmosphere on one side. Let $R_f$ be its acoustic radiation resistance at the frequency $f$. Let $P_f^2 \cdot df$ be the square of the thermal-acoustic pressure in the interval $df$, averaged over $S$. Then by analogy with the theory* of the J. B. Johnson effect

$$[(S \cdot P_f)^2 \cdot df / R_f] = 4\kappa T \cdot df$$

(1)

where $\kappa$ = Boltzmann's constant, $T$ = absolute temperature, $\kappa T = 4 \times 10^{-14}$ ergs/sec. at $T = 300^\circ$.

Suppose now that $S$ is a circle: $S = \pi a^2$. Then (Rayleigh, *Sound*, Vol. II, §302)

$$R_f = \pi a^2 \cdot \rho c \cdot \left[ 1 - \frac{J_1(4\pi fa/c)}{2\pi fa/c} \right]$$

(2)

where $\rho c$ = air density $x$ sound velocity, and $J_1$ is the first order Bessel function.

On substituting from (2) into (1) we find that in general $P_f$ depends on the value of $a$, the radius of the circle chosen. In the limit, for $a \gg \lambda (\lambda$ = sound wave-length), $R_f = \rho c \cdot \pi a^2$ and $P_f = (4\kappa T \cdot \rho c / \pi a^2)^{1/2}$. The case of the ear drum, however, corresponds more nearly to $a \ll \lambda$, up to say 6000 c.p.s. In that case

$$1 - \frac{J_1(4\pi fa/c)}{2\pi fa/c} \approx \frac{2\pi f^2 a^2}{c^2}$$

whence

$$P_f^2 \cdot df = (8\pi \rho k T / c) \cdot f^2 \cdot df.$$

(3)

The r.m.s. pressure $\overline{P}$ in the interval between $f_1$ and $f_2$, is

$$\overline{P} = \left[ \int_{f_1}^{f_2} P_f^2 \cdot df \right]^{1/2} = \left[ \frac{8\pi \rho k T}{3c} (f_2^3 - f_1^3) \right]^{1/2}.$$

For example, if $f_1 = 1000$ and $f_2 = 6000$ c.p.s., $\overline{P} = 5 \times 10^{-5}$ bars, or 86 db below 1 bar. In that frequency range, our M.A.F. curve averages about 76 db. In individual cases of particularly excellent hearing, it may average about 85 db. But even then, the above $\overline{P}$ is not likely to be

audible, if one be permitted to apply the Fletcher-Munson tables* for the loudness of a complex spectrum to levels so near threshold, or even below it. Of course, our computation at best is but a crude approximation. It appears that in the region of maximum ear sensitivity, i.e., 1000 to 6000 c.p.s., the M.A.F. pressures for the average good ear are of the same order, perhaps about three times larger than the r.m.s. thermal-acoustic pressure. For exceptionally good ears, a further increase in physiological sensitivity would be useless in the presence of thermal noise. From this point of view, it is not unlikely that the aural acuity of animals whose outer ear dimensions (drum included) are comparable with those of the human ear, is comparable with human acuity, say in the 1000 to 6000 c.p.s. range.

MINIMUM AUDIBLE PRESSURES (M.A.P.)

Data of the M.A.P. type

The purpose of an M.A.P. determination is to give that pressure at the drum which is minimum audible pressure. Several methods have been used, all based on the idea of establishing a known pressure at some measurable level (necessarily, well above threshold). The sound is reduced to threshold by reducing the sound source output by a known amount, usually determined from the required reduction of the electrical input feeding the source. No method has been devised, sufficiently sensitive to admit of direct measurement of the pressure on the ear drum at threshold. In principle, the M.A.P. determination assumes that the pressure is uniform over the area of the drum. This point was touched upon in the first section.

The first step is to produce a known pressure at the drum, which can later be attenuated by measurable amount down to the observer's threshold. Three procedures have been used.

(a) The sound source is held as nearly sound-tightly as possible on the ear, to form an enclosure of known volume. The source—a thermo-phone or a telephone receiver or an electrodynamically driven piston—produces a known volume velocity. That velocity is either directly measured optically or electrically or computed from the output of a calibrated microphone actuated by the source in a suitable calibrating chamber. The pressure on the drum is computed from this volume velocity and the known volume enclosed between the sound source and the drum when measuring threshold. It is assumed that the pressure

* To be published in J. Acous. Soc. Am.
throughout the ear enclosure is uniform. Further, most workers have assumed that the pressure is that which would be produced in an equal volume with rigid enclosing walls. In one instance—that of Bekesy's work—all allowance was made for the yielding of the drum.

(b) The pressure is measured by means of a calibrated search transmitter whose search tube is small enough to be inserted fairly near to the ear drum. By "near" is meant an acoustically near point, at which the pressure roughly may be assumed to be the same as at the drum.

In one procedure, a telephone receiver held on the ear, is the source. The opening of the search tube is just under the receiver cap, probably between 4 and 5 cm from the drum. Experimenters using this method regard the pressures measured as representative of the drum pressures up to about 2500 c.p.s.

A second procedure is to insert a small search tube into the canal, within about 1–1.5 cm of the drum. This probably gives significant pressure measurements up to about 4000–4500 c.p.s.

(c) This method really measures energy delivered by the source, rather than pressure on the drum. It is based on computing the acoustic load which the ear imposes on a telephone receiver as determined from its electrical impedance at resonance. The energy so measured represents the total delivered to drum, ear canal and pinna. No separation of the three energy sinks is made. No drum pressure computation is possible, without the addition of other measurements. Even if all the energy, as determined from receiver motional impedance, were assumed to be absorbed by the drum, a knowledge of the drum impedance would be required to evaluate the drum pressure.

M.A.P. data obtained by method (a)

Of the early investigations, those of Wien and H. Abraham will be mentioned.

Wien in the paper already referred to, gives a series of "telephone sensitivity" measurements over the range from 50 to 8000 c.p.s. Four different receivers having progressively higher natural frequencies, were used to make sure that the diaphragm displacement-receiver current ratio was independent of frequency; each receiver being used well below the first natural frequency of its diaphragm. The four receivers had radically different dimensions and enclosed different ear volumes (the values of the latter are not stated). The data obtained with them were brought together into a single curve by making overlapping threshold observations at certain frequencies. Thus the shape
of the M.A.P.-frequency curve is determined, if it be further assumed that the ratio of the M.A.P. to the corresponding diaphragm displace-
ment, was constant with frequency. This presupposes that sound leak-
age between the receiver cap and the ear, and audiofrequency yielding
of the ear drum may be neglected. Wien recognized the importance of
sound-tightness and used special earpieces to reduce leakage, a trouble-
some factor at low frequencies. From the similarity of the shapes of the
M.A.P. curve and of his M.A.F. determination (see section on "Other
data similar to the M.A.F. type"), Wien concluded that their absolute
positions must coincide in their common frequency region, i.e., 200 to
8000 c.p.s. Wien's M.A.F. curve shown in Fig. 7 may therefore be taken
as his M.A.P. curve as well, though the latter in itself was not an
absolute determination.

H. Abraham\(^{19}\) also applied the principle of using a telephone receiver
well below its first natural frequency. An absolute calibration was ob-
tained by means of a sensitive manometer for known direct currents
through the receiver. Ear sensitivities are given for 250 and 500 c.p.s.,
both having nearly the same value: \(6.4 \times 10^{-4}\) bars or \(-64\) db.

The more recent studies are based on methods for production and
measurement of sound throughout the audio range which were made
possible largely through the use of vacuum tubes. Kranz\(^{20}\) gives several
series of measurements, in which the sound sources were both a thermo-
phone* and a telephone receiver, working into known ear volumes. The
diaphragm displacements of the receiver were measured optically. His
final data, based chiefly on four ears of two individuals, are shown in
Fig. 9.

An extensive study is reported by Fletcher and Wegel.\(^{21}\) Their pri-
mary sound source was a thermophone whose pressure output was
measured in a 1 cm\(^3\) volume closed by a condenser transmitter. A
similar air volume was enclosed by the thermophone on the ear, and the
pressure was taken to be the same as on the condenser transmitter.
Simultaneous threshold measurements were made with five ears, by
using first a telephone receiver and then the thermophone. From a com-
parison of the results, the telephone receiver was calibrated and this
calibration was assumed to hold in obtaining thresholds for 41 people
(82 ears) with the receiver. The data are shown in Fig. 9.

Minton and Wilson\(^{22}\) report a series of M.A.P. determinations, made
with a telephone receiver calibrated on a microphone with a relatively

* In this reference and in the following the absolute pressures produced by the thermo-
phone were computed from the theory given by E. C. Wente, Phys. Rev. 19, 498 (1922).
unyielding diaphragm. The total number of ears tested was 54, over the range from 100 to 5000 c.p.s. One of the average curves given in the paper for a group of observers, is reproduced in Fig. 9, converted to our pressure scale. The authors consider their data above 2000 c.p.s. as less reliable than the lower frequency values.

Recently data obtained by using a small electromagnetic receiver inserted into the ear, were reported by Wegel, Riesz and Blackman. Here again the receiver was calibrated on a condenser transmitter, enclosing the same volume as in the ear. The results are shown in Fig. 9. Tests were made on 10 ears, over the range from 35 to 1000 c.p.s.

The work of E. Meyer has been mentioned in the section on "Other data similar to the M.A.F. type." The threshold curve is given as the average of data obtained both with a telephone receiver and with the ear in an open sound field. Since Meyer finds no major systematic differences between the two, the curve is reproduced here in Fig. 9, along with other M.A.P. measurements. The telephone receiver was calibrated on a "rigid artificial ear" (not further described), and the calibration taken to apply to the human ear.

An interesting, though limited, set of data is given by Bekesy taken on his own ear at 4 frequencies. They are shown in Fig. 9. The sound source is a vibrating piston inserted into the ear canal, whose amplitude
is electrodynamically measured. This is the only investigation of which we have knowledge, which takes into account the yielding of the ear drum, as computed from Troger’s\textsuperscript{33} drum impedance data.

**M.A.P. data by method (b)**

Two unpublished series of measurements are available. The earlier, using the second method under (b) was made by Sivian\textsuperscript{26} for 8 ears over the range from 500 to 15,000 c.p.s. The results given in Fig. 9 represent the average of two determinations. In both, the ear is exposed to a fairly loud tone from a loud speaker, and the pressure in the ear canal is measured with a search tube.

From the attenuation of the loud speaker current required to produce threshold, the M.A.P. values are computed. The chief assumption is that the search tube pressures are equal to the drum pressures.

In a second procedure, a telephone receiver is made to produce in the ear a loudness sensation equal to that caused by the loud speaker. The receiver current is then attenuated to threshold. From this attenuation and from the above search tube pressure measurement, the absolute M.A.P. value is derived.

Since the attenuations measured by both methods were found to agree fairly well, it was considered justifiable to average the results.

Munson’s data\textsuperscript{27} were obtained for 22 ears, using eleven observers, over the range from 62 to 15,000 c.p.s. For frequencies below 2500 c.p.s. the telephone receiver was calibrated by the first method described in (b), page 26. For the higher frequencies a receiver calibration derived from Sivian’s work was used. This was obtained on the assumption that equality of loudness of the tones from the loud speaker and from the receiver, represent equal pressures on the drum. The results are shown in Fig. 9.

**Measurements of threshold energy delivered to the ear by a telephone receiver, by method (c), described on page 308**

Threshold measurements of this type really deal with quantities which inherently are somewhat different from those aimed at in M.A.F. and in M.A.P. work. The motional impedance (magnitude and angle) of a telephone receiver on the observer’s ear, is determined electrically. Waetzmann and Heisig,\textsuperscript{16} in the paper previously mentioned, give a minute description of such a measurement. From the motional impedances of a telephone receiver, taken on an observer’s ear and on a rigid coupler, respectively, the total energy delivered through the
opening in the receiver cap is computed. This is done for a known current, well above threshold. Its value at threshold is then obtained from the current attenuation required to produce threshold, on the assumption that the impedance looking into the ear through the receiver cap opening remains constant. Waetzmann and Heisig further assume that the entire energy is absorbed by the drum, neglecting absorption in the pinna and canal walls. If this energy be divided by \( \frac{1}{3} \) cm\(^2\) (the value assigned by them to the drum area), a certain energy flow per second per cm\(^2\) is derived, and constitutes their threshold measure. They then take this quantity to represent the threshold intensity of a progressive wave for purposes of comparison with several M.A.P. and M.A.F. determinations by others. The data were taken between 340 and 4316 c.p.s., mostly on 5 ears of 3 observers, and are plotted as individual points for each ear. These points, read off the plot and logarithmically averaged, are given in Table III. For ease of comparison with other data in this paper, equivalent pressures in db below 1 bar are given rather than the energy flows.

**Table III.**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Pressure (db)</th>
<th>Frequency</th>
<th>Pressure (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>-54.2</td>
<td>1328</td>
<td>-72.8</td>
</tr>
<tr>
<td>728</td>
<td>-68.3</td>
<td>2115</td>
<td>-69.8</td>
</tr>
<tr>
<td>852</td>
<td>-69.8</td>
<td>3130</td>
<td>-59.2</td>
</tr>
<tr>
<td>1066</td>
<td>-72.3</td>
<td>4316</td>
<td>-54.9</td>
</tr>
</tbody>
</table>

The method used is quite similar to the one originally proposed by Hahnemann and Hecht\(^{28}\) in 1919, in conjunction with their telephone receiver theory. The threshold value which they obtained at 1000 c.p.s., when expressed in the manner just outlined, was approximately -74 db.

**Discussion of M.A.F. and M.A.P. Types of Data**

From the several M.A.F. and M.A.P. determinations discussed above and the azimuth data on pages 11 and 12, the continuous threshold-frequency curves of Fig. 10 have been derived.

The M.A.F. curves are based primarily upon the data given in the section on the present minimum audible field (M.A.F.) determination. Obviously, the observed points could be fitted about equally well by a number of smooth curves, differing appreciably from one another. In adopting the particular one shown in Fig. 10 (curve 2) some account was taken of the several other M.A.F.-type determinations available.
This was done quite arbitrarily, according to the authors' judgment of the experimental procedure employed. The number of ears tested in each case also was considered. These two criteria also determined the M.A.P. choice (curve 1, Fig. 10). In this case, of course, data published by others played the larger part; particularly at low frequencies. It has been stressed before that our M.A.F. data apply to young people with good hearing. It is felt that to a lesser extent the same may be said of curve 1, although in drawing it much weight was given to data for observers whose ages were unknown to us.

Now, it so happens that curve 2, Fig. 10, is hardly distinguishable, except at 15,000 c.p.s., from the smooth curve we would select to fit the monaural M.A.F. observations of Fig. 3, also for 0° azimuth; "hardly distinguishable"—bearing in mind the uncertainties of threshold data. Hence for convenience of comparison with the monaural M.A.P. curve, shown in the same figure, we shall in this section use curve 2 as representing either monaural or binaural M.A.F.

The M.A.F. pressures lie below the M.A.P. values throughout the frequency range. At high frequencies the two might well be expected inherently to differ, because of head and pinna diffraction, and wave motion in the auditory canal, even if the physical measurements were perfect in both cases. Thus above say 1000 c.p.s. these effects might produce differences of the order of magnitude seen in Fig. 10. Below 500 c.p.s. they are negligible. The physical pressure measurements in-

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**Fig. 10. M.A.F. and M.A.P. Note: Concerning the ordinate scale for curve I, see note under Fig. 9.**
volved in M.A.P. determinations become increasingly difficult with rising frequency. When method (a) of the section on minimum audible pressure is used, wave motion in the ear canal may vitiate the assumption that the pressure on the ear drum is the same as the sound source would produce in an equal volume but of different shape enclosed by different walls. With the first method under (b), and at higher frequencies with the second method as well, the pressures are measured at points where owing to wave motion they may be quite different from the drum pressures. Purely metric difficulties of the wave motion type probably render most of the M.A.P. data above 4000–5000 c.p.s. open to question. Below 1000 c.p.s. their effect is negligible.

These factors might account for the large differences between the M.A.F. and M.A.P. values above say 1000 c.p.s., though it is not clear why the differences are all in the same direction. But at lower frequencies the differences are much too large to be explained in this manner. Below 500 c.p.s. we must look for other causes, particularly so because it is just at the lower frequencies that any possible discrepancies due to the possibly older age of the observers used in the M.A.P. work, would disappear. It is well established that in the age range of 20 to 35 years for normal people, there is scarcely any aging effect for auditory acuity below 1000 c.p.s. There are some additional factors, partly metric, partly physiological and psychological, which may affect the M.A.P. results.

With method (a) of the section on minimum audible pressure a correction is required to allow for the yielding of the ear drum and of the canal walls.

In using either methods (a) or (b), the extrapolated threshold pressures will be affected if the ear drum behaves nonlinearly, i.e., if there be physiological accommodation of the muscles controlling the drum tension, presumably in the direction of relaxed tension on approaching threshold levels at low frequencies (below the first natural frequency of the drum).

An effect which may be termed "physiological noise" is associated with the tight fit of the sound source on the ear, as indicated in Fig. 11. Let C be the ear canal, S the sound source tightly closing it, D the drum, W walls of the canal. On account of breathing, pulse actions, etc., mechanical vibrations are transmitted through the head to W. If, as in M.A.F. work, the ear canal is open, no appreciable pressures are established in C. If, as in M.A.P. work, C is closed by S, an alternating pressure spectrum having audiofrequency components is established
in $C$. This sets $D$ in vibration, giving the sensation of a low-frequency noise which tends to raise the M.A.P. values, particularly at low frequencies.

In addition there are a few effects, much more uncertain than the above. In M.A.P. work the drum may for short intervals be subjected to static pressure in excess of atmospheric, which may make itself felt for the duration of the threshold measurement. The temperature throughout the ear canal is likely to be appreciably higher than in M.A.F. work, which may affect the drum impedance. The mechanical pressure of the sound source on (or in) the ear may cause fatigue and annoyance, tending to lower the sensitivity. The effect of bone conduc-

![Fig. 11.](image)

tion may be altered by the sound source tightly fitting on or in the ear. There is at present no way of evaluating these effects though some of them may be of consequence.

An attempt to account for the difference between the M.A.F. and M.A.P. values on the basis of the first and second of these possible sources of error and of resonance and diffraction effects, tacitly assumes that the threshold value of the pressure on the drum, as measured in the ear canal, is independent of the apparatus used to produce that pressure. If the effects mentioned in the two paragraphs immediately preceding be important, this assumption is invalid.

The reality of "physiological noise" is easily demonstrated. In terms of Fig. 11, the volume $C$ is increased by inserting an added volume $V_2$ between the auditory canal and $S$. The new configuration also is aerially sound tight, but mechanically the walls of the added volume are only loosely coupled to the head through a soft petrolatum seal. With certain two observers at 100 c.p.s., the physiological noise occasionally became irregular and was definitely disturbing with 0.7 cm³ in volume.
C; with 10 cm$^2$ they reported it quite inaudible. It is possible that this "physiological" noise causes more or less masking for all observers at low frequencies.

The importance of the yielding of the ear drum and canal walls has been recognized by a number of writers, both in connection with the development of an "artificial ear" for testing telephone receivers and for its effect on the M.A.P. values.$^{24}$

Let the volume velocity of the positively driven sound source be known, e.g., by calibration in a condenser transmitter chamber with rigid walls. Let the air volume enclosed by it while on the ear be $V_a$. If the M.A.P. be computed on the assumption that $V_a$ also is a rigid enclosure, the yielding of the drum will require the threshold pressures to be reduced by the factor

$$K = \frac{(\gamma P_a / iV_a \omega) \cdot Z_d}{(\gamma P_a / iV_a \omega) + Z_d} \pm \frac{\gamma P_a}{iV_a \omega}$$

where $Z_d$ is the acoustic impedance of the drum and $P_a$ is atmospheric pressure. If $Z_d$ be assumed preponderantly elastic, equivalent to an air volume $V_d$,

$$K \approx (V_a + V_d) / V_a.$$

We shall now consider three determinations of ear drum impedance, in each of which the human ear served as a passive object under measurement. Only the low-frequency values are quoted since the yielding of the drum above say 1000 c.p.s. has but a small effect on threshold data.

A. L. Thuras$^{29}$ gives the values in Table IV of the acoustic impedance ($Z_1$) at the opening of the ear canal, all obtained on one ear. An average figure assigned by anatomists to the air volume in the auditory canal is 1 cm$^3$. This was used here in deriving the values of $Z_d$ in the Table IV.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$Z_1$</th>
<th>$Z_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_1$</td>
<td>$X_1$</td>
</tr>
<tr>
<td>100</td>
<td>410</td>
<td>-1320</td>
</tr>
<tr>
<td>200</td>
<td>255</td>
<td>-670</td>
</tr>
<tr>
<td>400</td>
<td>173</td>
<td>-318</td>
</tr>
<tr>
<td>600</td>
<td>128</td>
<td>-255</td>
</tr>
<tr>
<td>800</td>
<td>105</td>
<td>-227</td>
</tr>
<tr>
<td>1000</td>
<td>85</td>
<td>-200</td>
</tr>
</tbody>
</table>

Table IV.
Tröger's values\(^2\) also are for one ear, and directly give the drum impedance per unit area. On dividing them by the area, 0.38 cm\(^2\) in this case, the acoustic impedances given in Table V are obtained:

**Table V.**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>(Z_d)</th>
<th>(R_d)</th>
<th>(X_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>very large</td>
<td>1.32</td>
<td>-560</td>
</tr>
<tr>
<td>250</td>
<td>1.37</td>
<td>-415</td>
<td></td>
</tr>
<tr>
<td>355</td>
<td>1.54</td>
<td>-288</td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>1.04</td>
<td>-151</td>
<td></td>
</tr>
<tr>
<td>570</td>
<td>1.02</td>
<td>-91</td>
<td></td>
</tr>
<tr>
<td>720</td>
<td>0.88</td>
<td>-76</td>
<td></td>
</tr>
<tr>
<td>758</td>
<td>0.66</td>
<td>-117</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>1.09</td>
<td>-100</td>
<td></td>
</tr>
<tr>
<td>818</td>
<td>1.33</td>
<td>-86</td>
<td></td>
</tr>
<tr>
<td>860</td>
<td>2.10</td>
<td>-135</td>
<td></td>
</tr>
</tbody>
</table>

Inglis, Gray, and Jenkins\(^1\) give the acoustic impedances at the entrance to the auditory canal, measured on 7 male human ears. (Table VI.) Here again 1 cm\(^3\) was taken as the average ear canal volume, and \(Z_d\) computed accordingly.

**Table VI.**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>(Z_1)</th>
<th>(Z_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>50 to 250</td>
<td>-1134 to -633</td>
</tr>
<tr>
<td>400</td>
<td>100</td>
<td>-530</td>
</tr>
<tr>
<td>500</td>
<td>20</td>
<td>-465</td>
</tr>
<tr>
<td>600</td>
<td>13</td>
<td>-346</td>
</tr>
<tr>
<td>800</td>
<td>35</td>
<td>-225</td>
</tr>
</tbody>
</table>

In all the foregoing computations of the drum impedance, yielding of the ear canal walls has been neglected in comparison with that of the drum. The values of \(Z_d\) in these three tables indicate large discrepancies, which is easily understood in view of the measurement difficulties and of the variations among individual ears. However, they all indicate that the drum yielding is not sufficient to account for the low-frequency difference between curves 1 and 2 in Fig. 10. Its effect is greatest when
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$V_a$ is least. Taking $V_a = 1 \text{ cm}^3$, which probably is close to the smallest volume used in any of the M.A.P. determinations, a few values of $K$ have been computed in Table VII.

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Reference</th>
<th>$K$ (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>Table V</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>Table IV</td>
<td>4.1</td>
</tr>
<tr>
<td>200</td>
<td>Table IV</td>
<td>3.8</td>
</tr>
<tr>
<td>200</td>
<td>Table VI</td>
<td>-0.1 to +4.9</td>
</tr>
<tr>
<td>250</td>
<td>Table V</td>
<td>8.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Reference</th>
<th>$K$ (db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Table IV</td>
<td>4.4</td>
</tr>
<tr>
<td>355</td>
<td>Table V</td>
<td>6.7</td>
</tr>
<tr>
<td>400</td>
<td>Table VI</td>
<td>0.4</td>
</tr>
<tr>
<td>400</td>
<td>Table IV</td>
<td>3.7</td>
</tr>
</tbody>
</table>

When the sound source is a telephone receiver calibrated in a relatively large enclosure (e.g., Meyer's calibration on a "rigid artificial ear") simulating the ear volume under a telephone receiver cap, which is of the order of 4 to 6 cm$^3$, the correction for yielding of the drum is even smaller than indicated above. In this case, however, another uncertainty may arise. At low frequencies (say below 600 c.p.s.) the sound leakage between the receiver cap and the real ear may be important, unless special means such as sponge rubber pads or plasticine seals are used.

Those M.A.P. data obtained by method (b), page 308, are not subject to any drum yielding correction since the pressure is measured directly in the ear canal.

To sum up, the effect of yielding of the ear drum and canal walls is adequate to account for only a fraction of the difference between the M.A.P. and M.A.F. values at low frequencies.

On account of the exigencies of the experiment, all the above drum impedance measurements were made at fairly high levels, perhaps 60 db or more above threshold. Possibly as threshold is approached, something in the nature of muscular accommodation takes place, in the direction of decreasing the drum stiffness as mentioned above. An attempt was made to measure the drum impedance, $Z_d$, at the threshold levels as shown schematically in Fig. 12. It assumes that at the frequencies used (100 c.p.s. and 200 c.p.s.), $Z_d$ is essentially a reactance; presumably, though not necessarily, an elastic reactance. $V_1$ is that portion of the ear canal between the drum $D$ and the plane $AB$, enclosing a fixed volume of about 0.8 cm$^3$. The volume $V_2$, between planes $AB$ and $EF$, is adjustable in magnitude; at one end it can be joined sound-tightly to the volume $V_1$ by withdrawing tube $T$ to the position
shown. The sound source is a receiver $C$, delivering sound through a long narrow tube $T$. Let the impedance of $V_1 + V_2$ be $Z_{12}$. Let $Z_0$ be the internal impedance of the source, as measured at $H$, looking toward $C$. The dimensions of $T$ were chosen so that $Z_0 \gg Z_L = \left( \frac{Z_d \times Z_{12}}{Z_d + Z_{12}} \right)$. Hence the pressure on $D$ is proportional to $Z_L$ and to the receiver current $i_c$. From any two pairs of values of $Z_{12}$ and threshold current $i_c$, $Z_d$ can be computed. The several $V_1 + V_2$ volumes used, were 0.8, 10 and 40 cm$^3$. The average results for 4 observers gave the air-volume equivalents of the ear drum, as 8.7 cm$^3$ and 2.7 cm$^3$ at 100 c.p.s. and 200 c.p.s., respectively; much larger than any $V_d$ values corresponding to drum impedances measured by others at higher pressure levels.

![Fig. 12. Schematic of apparatus for measurement of ear drum impedance at low frequencies and threshold pressures.](image)

(Tables IV, V and VI.) If a sound source is calibrated in a 1.5 cm$^3$ chamber with perfectly rigid walls, and then used to determine threshold while enclosing 1.5 cm$^3$ on the ear, the M.A.P.'s should be lowered by 16.7 and 9 db at 100 and 200 c.p.s., respectively. These values would just about account for the differences between the M.A.P. and M.A.F. curves in Fig. 10, at these two frequencies at any rate.

The low values of threshold drum impedance deduced above may appear questionable.* The above experiment is open to at least one other interpretation which would explain the low-frequency M.A.P.-M.A.F. difference on the basis of masking by physiological noise, described above. This will be clear on comparing the diagrams in Figs. 11 and 12, since the experiment was so arranged that as $V_2$ was increased,

*There is no evidence of any considerable drum accommodation in going from one high sound level to another. Thus A. L. Thuras finds no appreciable change in impedance on going from the maximum pressure amplitude which the ear could stand to an amplitude as low as 1/25 of the maximum. Of course, both these pressure levels are far above threshold, and possibly beyond the region in which drum accommodation, if any, takes place.
the coupling of $V_1 + V_2$ to the bony portion of the canal walls which transmit the noise, remained largely unchanged. Therefore, the noise level decreased as $V_2$ was increased, which would account for the results observed even though the drum impedance were very high. None of the threshold settings was made with the observer conscious of any such noise in his ear. This may be due to the normally sustained character of the noise; heard as noise only when it happens to be irregular, but causing some masking of the test tone at all times. No observer reported this noise above 100 c.p.s.; several did at 100 and at 60 c.p.s.

A definite answer to the question—why do the M.A.F. and M.A.P. curves differ at low frequencies?—cannot now be given. The evidence available indicates that: (1) the correction for drum yielding can account only for part of the discrepancy; (2) part may be due to "physiological noise," particularly from 200 c.p.s. downward; (3) that some such effects as static pressures, higher temperatures, fatigue, etc., play an important part in differentiating open field hearing from hearing with a source tightly fitting on the ear.

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