How Loud is Silence?

Research has determined that the lower limit of our hearing threshold is close to the noise level generated by the movement of the air molecules. The possibility of reaching this sensitivity appears remote, however, because of the noises continually present within the ear itself.

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IN AUDIOLOGY, as in all scientific studies, a knowledge of measurable limits is always desirable and, if unknown, extensive efforts are made to establish their values. Considerable work has been done and numerous reports written concerning the maximum limit of sound tolerated by the human ear. The other limit, that of the threshold of hearing, also has received a great deal of attention and the trend in the past twenty years has been to push back this limit to lower and lower values. Consequently, there arises a healthy interest in what constitutes the theoretical minimum sound field which might be distinguished by the ear.

Calculation of Brownian Motion

The minimum sound field which could be distinguished by the ear is that intensity which just exceeds the Brownian movement of the particles of air. Through the work of a number of scientists there are available considerable data relating to the presence and detection of the absolute minimum field. In the forefront appear the references to the theoretical limit of aural acuity as discussed by Sivian and White[1] in 1933.

Employed in their dissertation was a relationship between the energy generated by thermal agitation, or the Johnson effect, and the energy capable of being propagated, or detected, by a piston source within an infinite baffle, which is used as an analogy for the ear.

Thermal Energy $= 4KTR \times df$

Received or Propogated Energy $= (S \times P_f)^2 \times df$

where K is Boltzman's constant,

T is absolute temperature Centigrade,

R is the resistance component of the impedance across which is developed thermal agitation,

P_f is the thermal-acoustic pressure,

S is the area over which P_f is developed.

From these relationships is expressed an equation:

$$(S \times P_f)^2 \frac{df}{R} = 4KT \times df \qquad (1)$$

where R is denoted as the acoustic radiation resistance at the frequency df. If S is considered to be a disc, equation (1) becomes

$$(\pi a^2 P_f)^2 \frac{df}{R} = 4KT \times df \qquad (2)$$

By reference to Rayleigh[2], the reaction of air to the displacement of a disc in an infinite baffle is represented in part by a frictional force which is proportional to the radius of the disc and the displacement of the disc surface and inversely proportional to wavelength.

From the equation for this frictional force, the radiation resistance may be determined, and when substituted into equation (2), the thermal acoustic pressure becomes

$$Pf = \left| \frac{4KT\rho c}{a^2 \mu \pi} \left(1 - \frac{J_1(2Ka)}{Ka} \right) \right|^{\frac{1}{2}} \qquad (3)$$

where $J_1(2Ka)$ is a Bessel function. As a approaches zero, the original energy equation becomes

$$P_f^2 \times df = 8\pi KT \frac{\rho}{c} f^2 \times df \qquad (4)$$

and the r.m.s. pressure p in any frequency interval $(f_2 - f_1)$ is determined to be

$$\overline{P} = \left| \frac{8}{3} \pi KT \frac{\rho}{c} (f_2^3 - f_1^3) \right|^{\frac{1}{2}} \qquad (5)$$

Herein was presented for the first time an approach to the calculation of absolute hearing threshold. Using equation (5) Sivian and White determined the pressure P to be equal to approximately 5×10^{-5} microbar for a frequency range 1000–6000 cps. This level, which is 86 db below one microbar, was felt by them to be quite close to the minimum threshold measured in the laboratory, which is an average of 76 db below one microbar in the same frequency range.

In 1948, deVries[3] approached the subject from the physioneural viewpoint. The referenced article dealt with the minimum perceptible stimulus for vision, touched on nerve excitation and then briefly touched upon hearing stimulus. In the article, deVries stated that the minimum perceptible stimulus corresponded to the absorption of a single light quantum by a molecule of visual purple in each of several retinal rods. For simplification, he assumed that only one rod need be excited. This gave an equation for the number of spontaneous thermal excitations:

$$q \doteq \left[\frac{N}{\tau} \right]^{-E/KT} \qquad (6)$$

In this equation, E is the energy necessary to decompose a visual purple molecule. The exponent denotes the probability that the essential part of the molecule has a thermal energy greater than E at a given moment. In every second, there are $1/\tau$ new distributions of energy and N is the number of sensitive molecules in one cell. Equation (6) is rewritten as

$$E = 2.3KT \log \left(\frac{1}{q} \frac{N}{\tau} \right) \qquad (7)$$

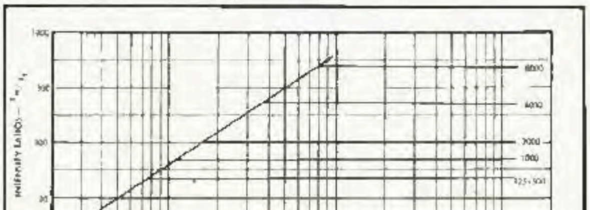

Fig. 1. Ratio of intensity of masked tone, I_m, to intensity per cycle of noise, I_c, plotted against width of noise band in cycles. (After Fletcher, Revs. Modern Phys., Vol. 12: pp. 47-65, 1940.)

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[1] Sivian and White, "Minimum audible sound fields." *J. Acous. Soc. Am.*, 4, pp. 305–307, 1933.

[2] Lord Rayleigh, *"Theory of Sound,"* Vol. 2, Sect. 302. Dover, 1945.

[3] deVries. "Minimum perceptible energy of Brownian motion in sensory process." *Nature*, Vol. 161, p. 63, Jan. 10, 1948.

From this formula it is possible to calculate the energy required to excite the molecules or, more aptly, to set a minimum boundary for excitation which will prevent the eye from incurring spontaneous excitations. This value has been calculated from experimental anatomical data giving a figure of $E = 53KT$ for excitation of less than one response per second. Carrying on this line of reasoning, deVries then pointed out that it is possible to calculate the energy necessary to excite a nerve. He derived a figure of $25\ KT$ as being the least figure for which a nerve would be stable.

In deriving a formula for calculating the pressure of the Brownian movement, Sivian and White[1] observed that it was extremely doubtful that the loudness of the various frequencies over the band considered by them would add together in a simple manner. Continuing in this vein, deVries stated[4] that it was more probable that subliminal excitations would add only if they corresponded to the same region of the basilar membrane. Using this reasoning, he selected a band width of 400 cycles at a frequency of 2000 cps and calculated the Brownian movement to be equal to 4.8×10^{-13} erg/sec or an equivalent energy of $0.4 \times 4.8 \times 10^{-13}$ erg, (1.9×10^{-13} erg). Compared with the standard minimum audible energy threshold at the eardrum of 2.4×10^{-10} erg, the figure obtained by deVries is approximately -31.0 db.

Here it should be noted that the use of a band width of 400 cycles by deVries was based upon the masking studies of Wegel and Lane as reported in the *Physics Review*, Volume 23, p. 266, 1924. Since this report, considerable experimentation has been carried out to determine the critical bands of frequency which are effective in masking pure tones. Fletcher[5] presented the results of his work on this subject in the form of a graph, *Fig.* 1. This graph is a plot of the ratio of the intensities of the tone under observation I_m and the intensity of the noise band I_f versus the width of the noise band in cycles. The parameters are the frequencies of the pure tones employed in the study.

It will be noted that for a particular test frequency, the ratio of I_m/I_f increases with increase in band width until the band width reaches a value beyond which no effective increase in the ratio of I_m/I_f is required. This value is represented on the figure by the intersection of the horizontal line pertaining to the definite frequency with the sloping line originating at 30.30.

Reference to the figure gives a band width of 80 cycles for a frequency of 1500 cps. Substitution of this value into the equation of Sivian and White results in a noise value of 2.48×10^{-8} dynes/cm² or a level of -39.3 db relative to standard threshold of 2.0×10^{-4} dyne/cm². These calculations are repeated for enough points to give the curve (F) in *Fig.* 2.

Inspired by Fletcher's work in developing the subject of critical bands, Schafer, Gale, Shewmaker and Thompson continued the study[6] at three test frequencies—200, 800, and 3200 cps. Their experiments showed critical band widths of 65, 65, and 240 cycles at the three test frequencies respectively. Employing these band widths for computation of the Brownian movement and extrapolating results in a curve (S) which very closely approximates curve (F).

Threshold of Audibility

At this point, consideration should be given to the value obtained for the intensity of sound at threshold as derived by a number of experimenters. Greatest sensitivity obtained by Sivian and White[1] for free field conditions was 1.9×10^{-10} erg/cm²/sec at a frequency of 3800 cps. At 1500 cps, the sensitivity obtained was 7.6×10^{-10} erg/cm²/sec. Using a figure of 0.43 cm² for the area of the ear drum, the figures obtained may be converted to energies which are equal to 8.2×10^{-11} erg/sec at 3800 cps and 3.3×10^{-10} erg/sec at 1500 cps.

One other factor affecting the sensitivity of the ear drum needs to be considered—namely, that factor representing the percentage of energy transmitted to the inner ear. It is considered that approximately 20 per cent of the acoustic energy presented to the ear drum is reflected at a frequency of 1500 cps.[7] As a consequence, Sivian and White's data would give a threshold energy flow of 2.6×10^{-10} erg/sec.

In a series of experiments, deVries found[7] that duration of the signal determined the minimum audible intensity of sound. For short signals (0.2 second or less) the intensity was inversely proportional to the length of signal, indicating that the energy for audibility was a constant. By comparing with longer duration signals, he obtained a factor of 0.4 which he used to convert data obtained by Sivian and White to minimum audible energy. Use of this factor gives the minimum audible energy at 1500 cps as 7.2×10^{-11} erg for an average good observer.

Through this same procedure, deVries converted data[7] obtained from Geffcken[8] giving a threshold energy of 0.8×10^{-11} erg at a frequency of 1500 cps for a good observer. It must be borne in mind that Geffcken's data were obtained by the minimum audible pressure method which he claimed, in this case, to give results which agree with those of the minimum

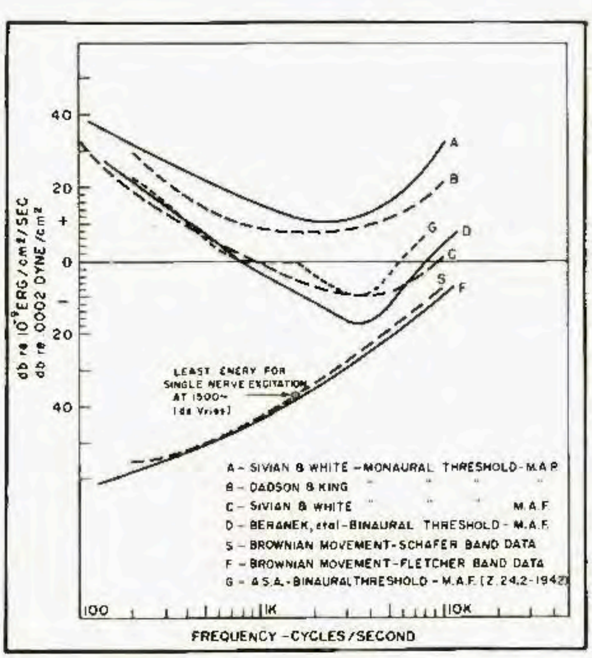

Fig. 2. Relationship between auditory thresholds and calculated Brownian movement of air at 27° C.

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[4] deVries, "Brownian movement and hearing," *Physica*, Vol. 14, No. 1, pp. 48–60, 1948.

[5] Fletcher, *Speech and Hearing*, pp. 171–2. Van Nostrand, 1953.

[6] Schafer, et al. "Frequency selectivity of the ear as determined by masking experiments." *J. Acous. Soc. Am.*, Vol. 22, No. 4, pp. 492–3, 1950.

[7] deVries, "The minimum audible energy." *Acta Oto-Laryngology*, Vol. 36, pp. 230–235, 1948.

[8] Geffcken, "Untersuchungen über akustische Schwellerwerte." *Ann d. Physik* 19, pp. 829–848, 1934.

audible method. This agreement of data is at slight variance with results determined by Munson.[9] Of more importance is the fact that Wever and Lawrence[10] indicate that deVries is in error in these calculations by assuming an area of 0.3 cm² for the ear drum and a duration time factor of 0.4. It is their contention that more correct data would be an area of 0.43 cm² and a time factor of 0.2. For the purpose of continuity in this article, however, data employed by deVries will be used to complete the discussion.

Previously, a value of $25KT$ was presented as the least figure of energy for which a nerve would be stable. This corresponds to an energy of 4.14×10^{-14} erg at a temperature of 27° C. Use is made at this point of the standard threshold intensity of 10^{-9} erg/cm²/sec which, converted to energy absorbed by the ear drum per second becomes 2.4×10^{-10} erg. By comparison to the standard reference level, the least required energy to excite a nerve is -37.6 db.

The average threshold of hearing obtained by Sivian and White, using the minimum audible field method, at a frequency of 1500 cps. was -3.8 db relative to standard threshold. The threshold obtained by Geffcken was -14.8 db relative to standard threshold. It is readily apparent that a wide gap exists between these thresholds and the threshold of spontaneous excitation of nerves.

Figure 2 presents part of the threshold data discussed previously in this paper and illustrates the proximity of the calculated Brownian movement to the thresholds as determined by various experimenters. In order to evaluate the auditory threshold data more accurately, the figure not only illustrates the results of experiments by Sivian and White[1] but includes as well, data collated by Beranek[11] and experimental data from Dadson and King.[12] Note particularly, that closest approach of auditory threshold to detection of Brownian movement is in the frequency range 3000–5000 cps and in this range, detection of Brownian movement is separated from the extrapolated curve derived from Schafer's data by merely 6 db when compared with Curve (D). Before assumption is made that we are poised (audibly) on the verge of a vast new sound field, it is well to recognize that Curve (D) is not the direct result of measured data nor is this made clear in the caption beneath the curve as presented in Beranek's book. A personal communication from Dr. Beranek states in part "It is very possible that curve No. 3 in my paper is not a curve that can be actually measured because it was obtained by the following process. I took the threshold of hearing as published by the American Standards Association and subtracted from it the difference between the binaural curve for a sound source in front of the listener and the binaural curve for a number of sources located randomly in a horizontal plane about the listener's head. Therefore Curve No. 3 was a derived curve and not a measured curve."

Under the circumstances, we are restricted to use of the curves (C) and (G), both of which are substantiated by laboratory data from subjective measurements. Deviation of these curves from the calculated Brownian movement is approximately 14.5 db at the closest proximity, indicating inability to detect the Brownian motion of the air.

A consideration of greater importance, as concerns Brownian motion in general, is the Brownian movement of the ear itself. Generally speaking, the movement of the air will cause only a part of the total phenomena ascribed to Brownian motion as detected by ear. It is pointed out by deVries[4] that the ear drum and the inner ear may be compared to two electrical circuits coupled by a transformer. Under conditions of good coupling, there will be correlation between the Brownian currents in the two circuits. If there is a decrease in the coupling, the correlation between currents will be smaller but the energies will remain the same. Through this analogy then, deVries believes that, if Brownian movement could be heard, it would be that of the ear itself, not the movement of the air at the drum. He estimates the former movement to be 100 times larger in the frequency range 1000–1500 cps. From this, we may expect that the ultimate audible threshold will be determined by the ear's Brownian motion and not that of the air at the ear drum.

Detectability of Brownian Motion

Data have been presented previously concerning the estimated requirement for least energy to excite single nerves. This value ($25KT$) has been indicated in *Fig.* 2. A question arises immediately concerning the lack of detection of the Brownian movement signals by the ear. This has been examined by deVries[13] and the discussion which follows is based upon his reasoning.

Minimum audible energy for frequencies between 1000 and 1500 cps is 8×10^{-12} erg or $200KT$.[1] From the work of von Békésy and Wegel and Lane, it has been established that 60 per cent of the energy resulting from the presentation of a pure tone at a frequency of 1000 cps causes excitation of a small length (5.0 mm) of the basilar membrane. Accordingly, presenting energy to the ear will cause excitation of approximately 5.0 mm of the basilar membrane at a frequency of 1500 cps. Such a length of the membrane will include about 3000 sense cells. Equal distribution of the original energy at threshold ($200KT$) would mean an excitation energy for each cell of $.0018KT$. More important, the damping time of the ear is about .003 second, which means that at any time an energy of only $.0018 \times .003$ or $5.4 \times 10^{-6}KT$ erg is available to the sense cell. Such a low value of energy would preclude firing of the cells unless some accumulative process was available to the ear.

Let us assume then, that the ear is capable of integrating sound over a period of 0.2 second. The original energy of $200KT$ is present for 0.2 second and distribution among 3000 cells gives an effective excitation of $0.067KT$. This is the threshold capability of the ear. Then study the effect of Brownian noise added to this excitation. Masking experiments set a band width per cell of approximately 75 cycles at a frequency of 1500 cps. The Brownian noise will correspond to $75KT$/second and in 0.2 second would be equal to $38KT$ (it cannot be more or the sense cells would be active permanently). The fluctuations will be approximately $\sqrt{38KT}$ or $6.2KT$. This signal-to-noise ratio of $.067/6.2$ would effectively prevent detection of the signal and once again an impasse is reached as regards the theory of the functioning of the ear.

These discrepancies of the hearing theories have pointed to consideration of theories not affected by the "all or nothing" nerve firing limitations and have led to the belief that the action of the basilar membrane fibers is of a nature other than that previously considered. Consideration is given by deVries[13] to a new theory which relates tension of the nerve fibers of the membrane, as affected by motion, to an electrical voltage whose polarity and magnitude are governed directly by the tension forces. Through his theory he explains that the action of the Brownian motion of a cell would be dissipated over a comparatively large area by virtue of a multipled parallel connection of cells, whereas a displacement of the tectorial membrane would cause all cells to act together, giving an in-phase voltage.

This theory, supported in part by some experiments of von Békésy, may aid in developing a better comprehension of the

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[9] Munson and Wiener, "In search of the missing 6 db," *J. Acous. Soc. Am.* 24, No. 5, pp. 498–501, 1952.

[10] Wever and Lawrence, *Physiological Acoustics*, p. 64. Princeton University Press, 1954.

[11] Beranek, *Acoustics*, p. 395. McGraw-Hill, 1953.

[12] Dadson and King, "Determination of normal threshold of hearing. *J. Laryng. and Otol.*, Vol. 46, No. 8, pp. 366–78, 1952.

[13] deVries, "Brownian motion of transmission of energy in the cochlea." *J. Acous. Soc. Am.*, Vol. 23, No. 6, pp. 527–33, 1952.

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results obtained by laboratory experimentation in the field of auditory thresholds, and the ultimate limitation by Brownian motion.

Conclusion

The most favorable circumstances encountered in acoustical research laboratories up to the present time have not been sufficient to justify an assumption that the acuity of the human ear will attain the region of Brownian movement of the air. It must be borne in mind that Curves (C) and (G) presented for thresholds in minimum audible fields are those of trained observers, sensitively alert to the faintest sounds. Conceivably, some human being possessed of phenomenal hearing may be able to approach these hearing limits. But as this approach is made, it is well to remember that biological disturbances such as the pulsing of the blood in the skin of the auditory canal, or the coursing of air through the respiratory organs will contribute to the masking of external noise. Furthermore, presence of the Brownian motion of the ear itself would, in the final analysis, mask any motion of the air. Under these circumstances, it would appear that man will never be aware of the turbulence of the air about him, if the motivating force is the Brownian motion.

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