1979 RAYLEIGH MEDAL LECTURE:

THE ELUSIVE CONNECTION

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THE ELUSIVE CONNECTION

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In his monograph Electroacoustics, F.V. HUNT (1954) described the carbon microphone as "the only 'bad connection' tolerated in the telephone system". This whimsical comment was, of course, inspired by the unique electrical properties of that remarkable transducer. A broader view, encompassing the acoustical as well as the electrical elements of the system, would surely compel us to recognize the earphone, another essential element of the telephone system, as a connection of equally questionable quality. It was indeed this doubtful connection, lying at the heart of audiometric measurements, which first prompted my colleagues and I in Ottawa to enquire about the acoustics of the external ear many years ago (SHAW and THIESSEN, 1962, SHAW and TERANISHI, 1968). It seemed then, as now, that despite the remarkable advances in electromechanical transduction since the days of Alexander Graham Bell, the coupling between earphones and ears still rested on a very flimsy acoustical foundation. We soon found that there were questions concerning the external ear which were larger than the technological artifacts that had started us on our journey and it is to these larger questions that my title refers. The "elusive connection", then, is associated with the external ear but really embraces the entire transmission path between the sound source, which may be near the ear or in the far field, and the oval window of the cochlea which is the input terminal of the inner ear. The questions which arise fall under at least five headings:

(i) Anatomy and function: How does the external ear work? What are the functions of its various components? How is it coupled to the middle ear? What parameters best define its performance?
(ii) Reception efficiency: How well does the external ear collect sound energy? How well is that energy transmitted to the inner ear?
(iii) Sound localization: To what extent are we able to localize sound sources away from the horizontal plane especially sources lying in the symmetry plane of the head? What localization tasks can we perform with a single ear? What are the relevant auditory cues?
(iv) Space perception: Under what circumstances and how well do we externalize sound when listening under artificial conditions such as those arising with earphones?
(v) Measurement techniques: How should we specify and measure acoustic stimuli?

As we shall see, some of these questions were raised more than one hundred years ago but still lack precise answers.

Though he was by no means the first to study localization, Rayleigh made significant contributions to the subject giving special attention to the lateralization of sound brought about by interaural differences of phase and intensity (RAYLEIGH, 1877, 1909). He also experimented with monaural localization (RAYLEIGH, 1877, 1882) and was aware that some subjects could in some circumstances discriminate between front and back source positions, a task requiring auditory cues not available from a pair of monopole receivers on a rigid sphere. Such discrimination, he argued, must surely be associated with an alteration in the quality of sound, especially high frequency sound, mediated by the external ears (RAYLEIGH, 1907). This view, the Klang or timbre theory of sound localization, was widely held in the last century and has had much support over the years. THOMPSON (1883) expressed the matter as follows:

> "The ear has been trained from childhood to associate certain differences in the quality of sounds (arising from differences in the relative intensities of some of the partial tones that may be present) with definite direction, and relying on these associated experiences, judgments are drawn concerning sensations of sounds whose direction is otherwise unknown..."

Mach, like Rayleigh, emphasized the importance of high frequency sounds as indicators of direction and argued that their timbre was affected by the pinna acting as a resonator. He noted, significantly, that the wavelengths of audible sounds were too great to allow reflection from surfaces as small as the folds of the pinna. (See BUTLER, 1975; MACH, 1959.) This very idea was however, adopted by PETRI (1932) and developed quite recently by BATTEAU (1967) in a long paper published in the Proceedings of the Royal Society. According to this view, sound waves reflected from various parts of the concha arrive at the eardrum with direction-dependent time delays and are sorted out later by a hypothetical inverse transformation process performed by the inner ear or nervous system.

One of the few decisive experiments of the early period is due to BLOCH (1893) who showed that the ability to localize sources in the median plane of the head was severely impaired when the upper parts of the pinnae were filled with wadding and the lobules taped to the skull. This experimental evidence came along not many years after Darwin had concluded that the various folds and prominences within the human pinna are merely rudiments which in lower mammals provide structural support for holding the pinna erect (BUTLER, 1975).

Let us now turn our attention to the ear as a physical system. As we shall see, the information which has been gathered in recent years gives us a fresh appreciation of the progress made in earlier days, sheds new light on old problems and is complementary to some of the recent work in psychoacoustics.

Figure 1 shows various parts of the external ear referred to later. Notice that the canal proper opens into a wide shallow cavity, the concha, which is partially divided into two parts, the cavum and the cymba, by the crus helias. The cymba in turn is linked to another shallow cavity, the fossa. For convenience the structures surrounding the concha are collectively described as the pinna flange or pinna extension.

Figure 2 shows the average free-field response of the human ear at the eardrum in the azimuthal plane. This self-consistent family of curves, which is based on measurements made in a dozen laboratories around the world, sets out clearly some major characteristics of the human ear. We see that the primary resonance of the external ear is at approximately 2.6 kHz not at 4 kHz as frequently stated. At this frequency, the sound pressure level at the eardrum is much greater than that of the incident field: approximately 17 dB greater than the free field level at 0° azimuth (frontal incidence) and 21 dB at 60°. Even in the shadow zone there is appreciable pressure gain. Beyond the peak, a strong resonance due to the concha sustains the response for almost one octave. Notice also the difference in response between 45° and 135° azimuth which amounts to 11 dB at 4.5 kHz. This lack of front-back symmetry, which is due to diffraction by the pinna extension, is sufficient to change substantially the timbre of sound received from a broad-band source as it moves through the lateral sector.

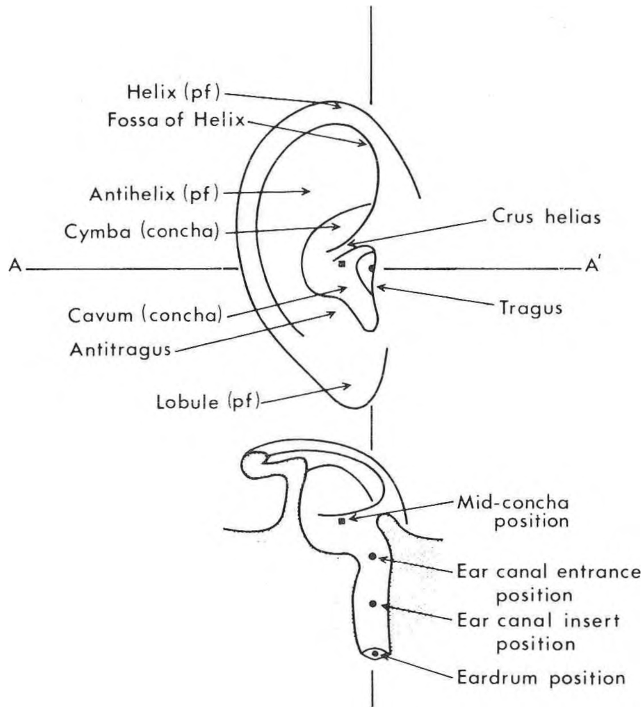

Fig. 1. Descriptive diagram of external ear and horizontal cross section at AA' showing functional components: pinna flange (helix, antihelix, lobule, etc.), fossa, concha (cymba, cavum, crus helias) and ear canal proper. After SHAW (1974b).

Several major characteristics of the human external ear can be readily demonstrated in simple physical models as shown in Fig. 3. In the first stage of development (Panel A) the concha is represented by a simple broad open cylinder whose dimensions have been chosen to bring it into resonance at approximately 4.5 kHz as in the average human ear under comparable conditions. Notice that the response is almost independent of source position up to approximately 6 kHz. In Panel B a rectangular plate has been added to represent the pinna extension. The resonance is now more strongly excited when the source is in front of the ear but hardly excited at all when the source is to the rear. In Panel C a long narrow cylinder has been added to represent the

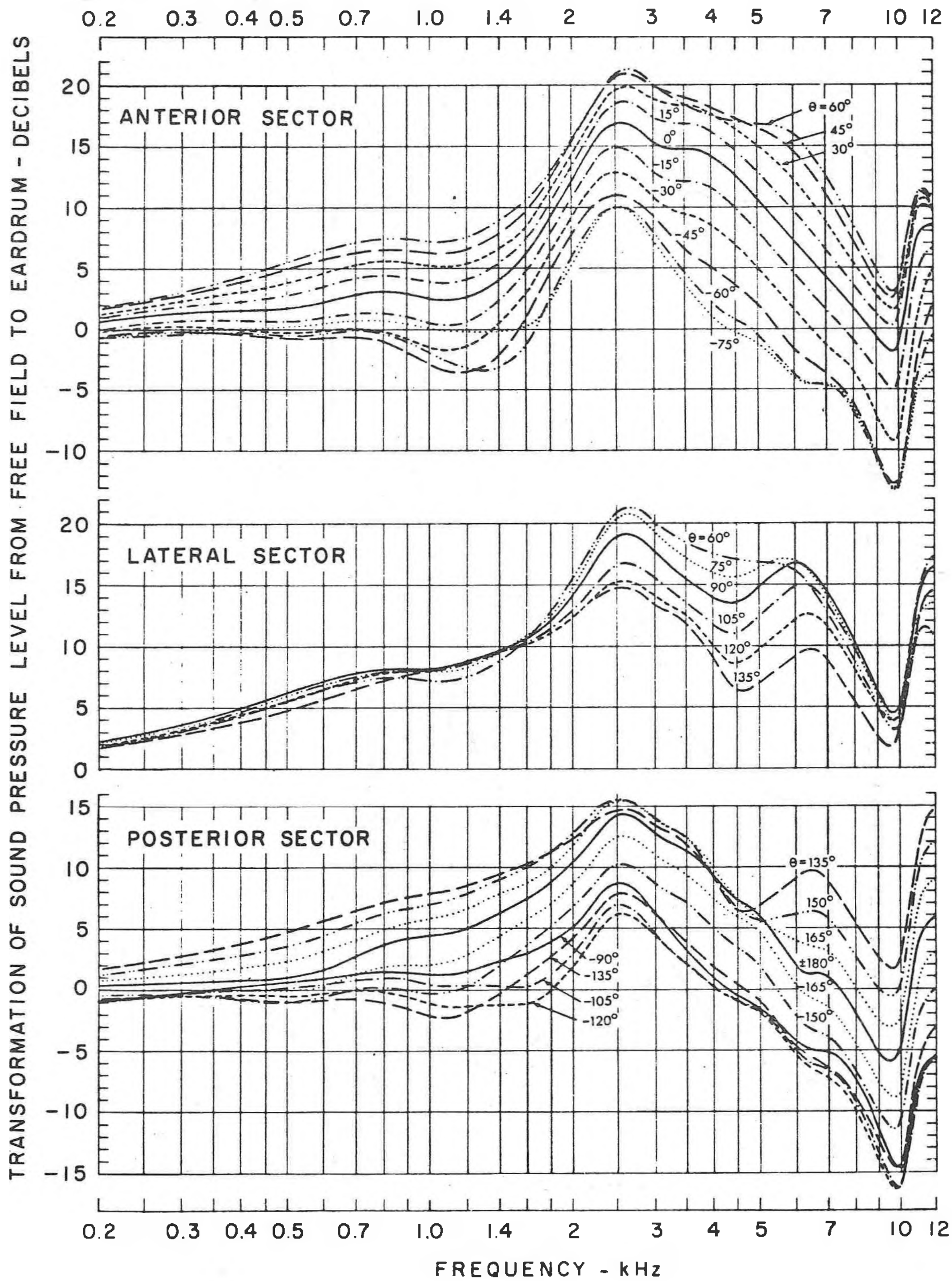

Fig. 2. Average transformation of sound pressure level from free field to human eardrum as a function of frequency at 24 angles of incidence in the horizontal plane. This family of curves was fitted to a pool of data covering a total of 100 subjects measured in 12 separate studies over a 40 year period. After SHAW (1974c).

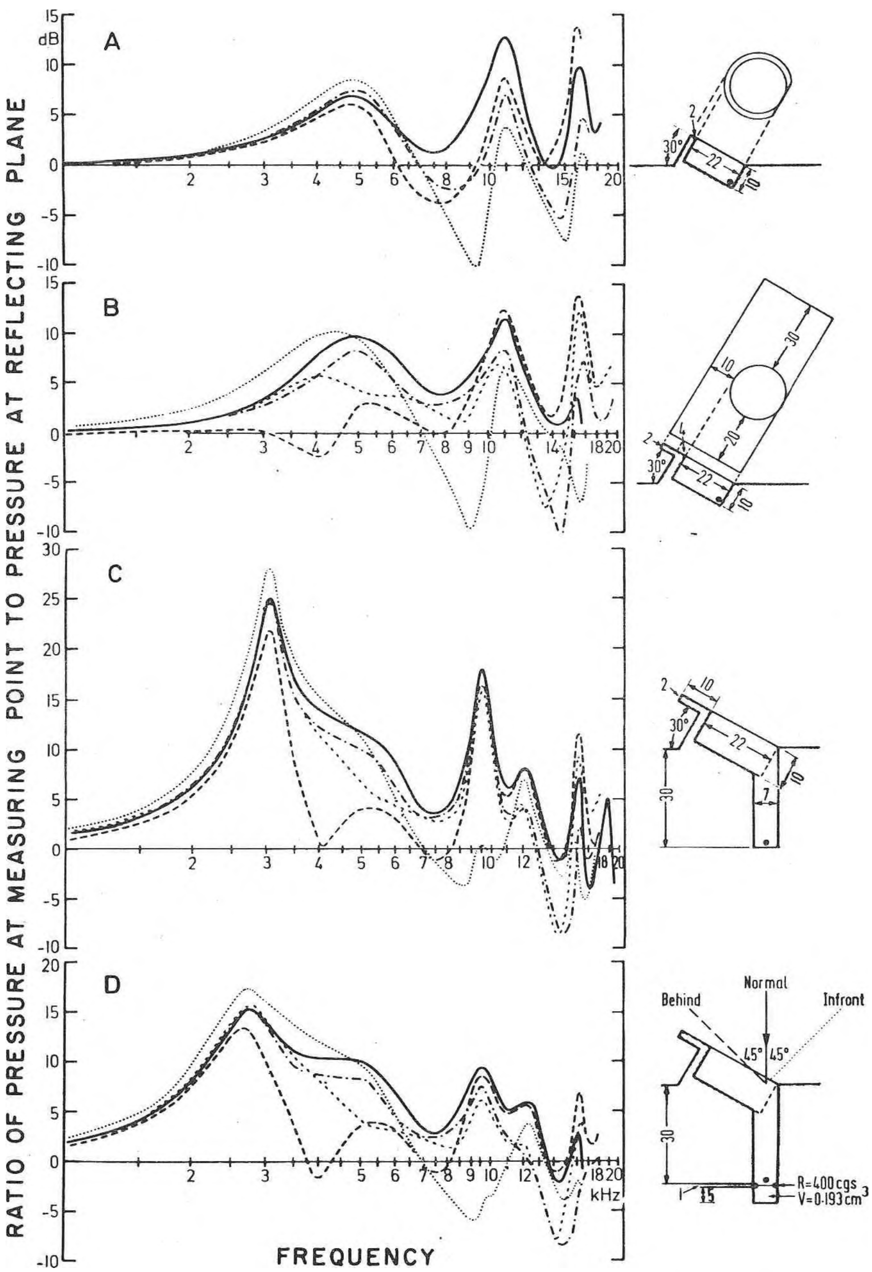

Fig. 3. Response of simple model of human ear, at four stages of development, excited by point source: with normal incidence (solid line), with source 45° in front (dotted), behind (long dash), above (dot-dash) and below (short dash). Three source positions are indicated in Panel D. Dimensions of model in millimetres. After TERANISHI and SHAW (1968), SHAW (1975).

ear canal proper. This introduces new degrees of freedom and hence additional resonances especially a new fundamental resonance at approximately 3 kHz. Finally, as shown in Panel D, the hard wall at the end of the second cylinder has been replaced by a simple acoustical network to simulate the absorption of sound at the eardrum. This model with four component parts matches the behaviour of real human ears very well up to 5 kHz but fails, as we shall see, at higher frequencies.

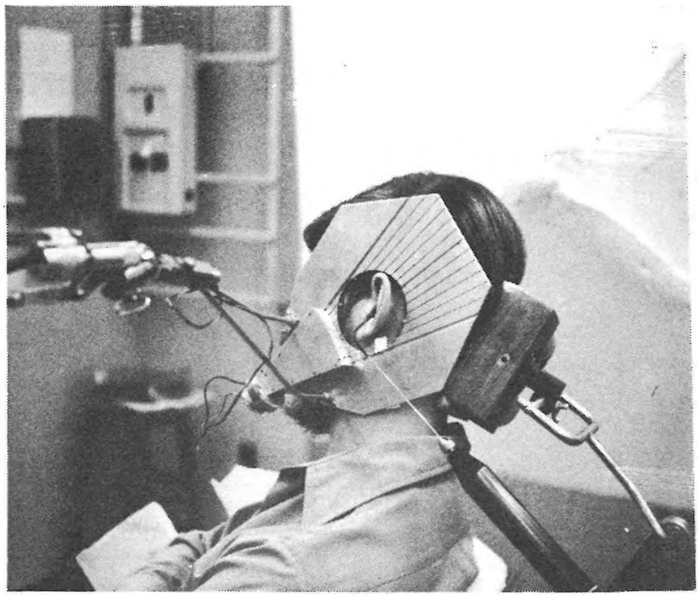

Fig. 4. Measurement of blocked-meatus response using a probe microphone (lower right) and a special source designed to generate well-defined progressive waves at grazing incidence. From SHAW (1974a, 1975).

To obtain precise information at the higher frequencies it is necessary to study the ear in isolation. The progressive wave source shown in Fig. 4 has been designed to operate sufficiently near to the ear that head diffraction effects are virtually eliminated while maintaining just enough clearance to prevent significant interaction between source and ear. This special source produces clean progressive waves at grazing incidence the direction of which, with respect to the ear, can be varied by changing the source orientation in the circumaural plane. The response of the ear is measured with a probe microphone whose orifice is located at the centre of a carefully fitted plug filling the ear canal entrance. At frequencies up to 10 kHz or more the polar diagram of the ear when measured under this blocked-meatus condition has been found to be almost identical with that measured at the eardrum position.

The blocked-meatus response curves for a single subject are shown in the upper panel of Fig. 5. As can be seen, there are astonishingly large variations in response with angle of incidence at frequencies greater than 5 kHz: rarely

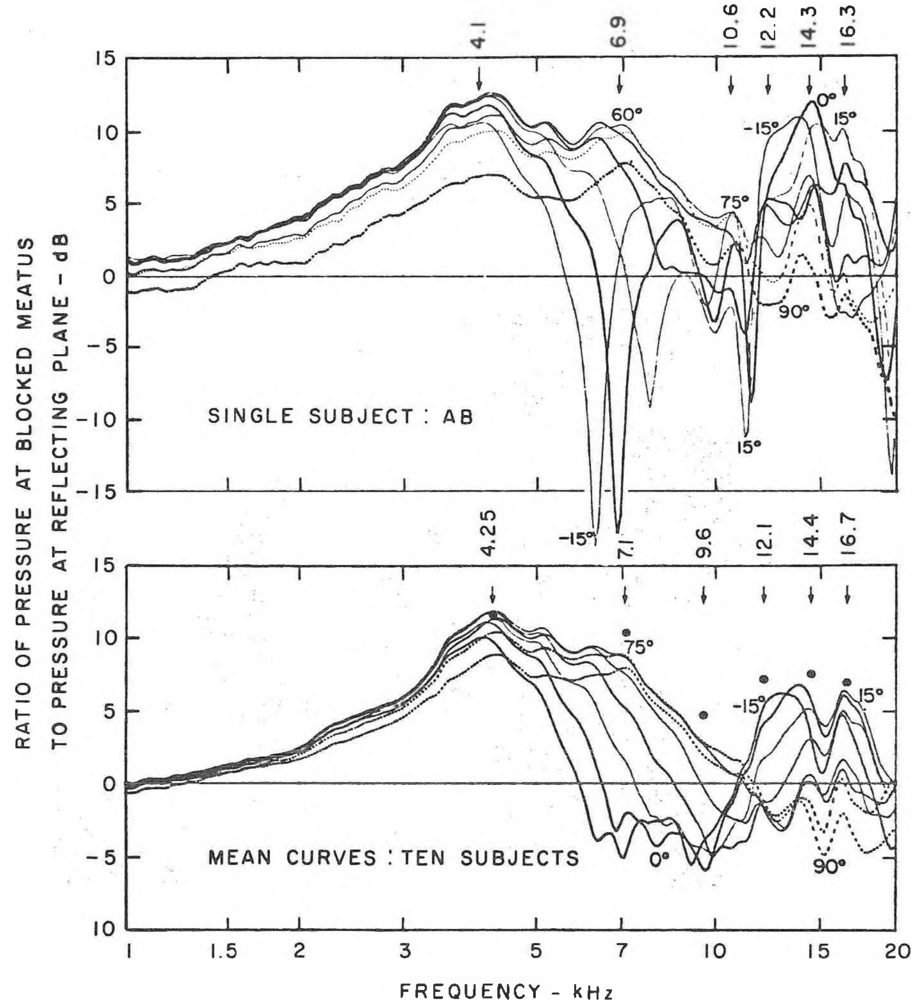

Fig. 5. Upper panel: Blocked-meatus response curves for single subject at eight angles of incidence (-15° to 90°). Source is in front of ear at 0°, above at 90°. Lower panel: Mean curves for group of ten subjects. Arrows indicate mode frequencies. After SHAW (1974a, 1975).

less than 10 dB and at some frequencies as great as 25 dB. Each ear has its own characteristic family of curves but different ears also have much in common as shown in the lower panel of Fig. 5. This family of curves was obtained by averaging the data for ten subjects, a procedure which eliminates idiosyncracies such as the deep minima but enhances those features which are common. Notice that with sound waves approaching from above - angles of incidences between 60° and 90° - the average response remains strong between 6 and 9 kHz but is weak between 11 and 16 kHz. With frontal incidence, however, - angles of incidence between -15° and +15° - the situation is reversed: the excitation is weak between 6 and 9 kHz but strong between 11 and 16 kHz.

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Let us digress for a moment to mention the highly original work by BLAUERT (1969). When he presented his subjects with 1/3 - octave bands of noise produced by sources in five different symmetrical configurations he found, as would be expected, that the sound was always localized in the median plane. Contrary to expectation, however, the perceived direction was found to depend not on the source configuration but on the frequency of the noise band. Moreover, at each frequency, the perceived direction tended to coincide with that at which the acoustical response of the ear was at a maximum. It is reassuring to note that Blauert's observations are generally in harmony with the data presented

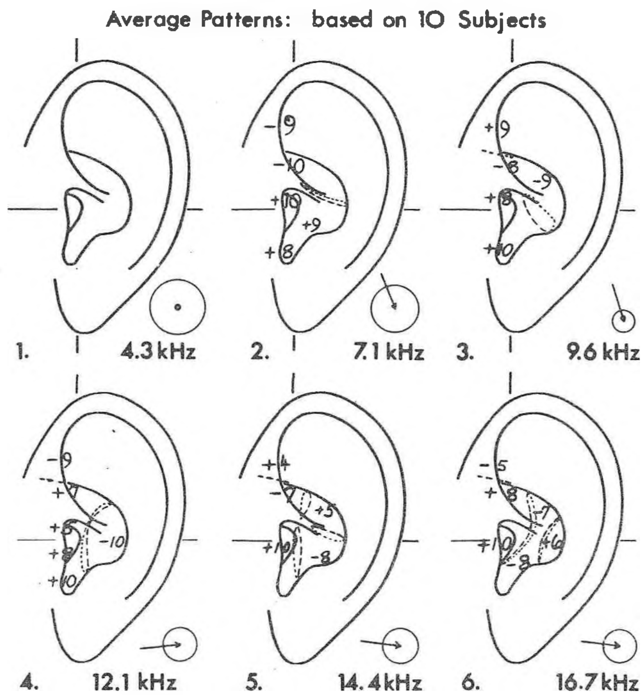

Fig. 6. Average pressure distributions and resonance frequencies of six modes measured with ear canal closed at entrance. Circles indicate relative degrees of excitation. Arrows show directions of maximum response. After SHAW (1974a).

in Figs. 2 and 5. For example, the 8 kHz band was most often localized above the head. Also, in retrospect, it appears that Blauert's work is strongly supported by a contemporaneous study of "in-head localization" (TOOLE, 1969). Finally one should mention the experiments of FISHER and FREEDMAN (1968) who showed that their subjects could localize quite well with artificial pinnae coupled to their ear canals but performed more accurately with their own pinnae. This observation is in qualitative agreement with the degree of similarity between ears indicated in Fig. 5.

The central feature of the human pinna is its network of cavities whose dimensions are comparable with the wavelength of sound at high audible frequencies. It seems natural then to propose the eigenmodes of the system as the key to its acoustical function recognizing, however, that these modes may be broadly tuned and therefore hard to separate experimentally since the concha is open to the sound field. The overlapping of the tuning curves does indeed make resolution difficult in some cases but it has been found that sufficient separation can generally be achieved if full advantage is taken of differences in directionality. The essential characteristics of six modes under blocked-meatus conditions are shown in Fig. 6. The first mode at 4.3 kHz is a simple depth resonance with uniform pressure across the base of the concha. The other modes are mainly transverse. The second mode at 7.1 kHz and the third at 9.6 kHz are best excited at 75° elevation but the second is more strongly coupled to the sound field than the third. Notice that the pressure distributions of modes 2 and 3 are similar apart from the sign of the pressure in the fossa: they form a doublet. Modes 4, 5 and 6 also form a group since all three are strongly excited from the front.

Once we have identified the eigenmodes of an acoustical system we can broaden our understanding of the system by constructing models which are acoustically similar but dissimilar in other respects. In Fig. 7 we compare a simple model (Panel A) in which only one mode has been tuned with a more refined model (Panel B) which has just sufficient complexity to produce five modes with approximately the same mode frequencies, pressure distributions, directionality and excitation as the average human ear. As the first refinement, we replace the cylindrical cavity by one that is rectangular in form. The first order transverse modes are then resolved in the frequency domain and aligned with the major and minor axes of the cavity as seems to be required by the directionalities of the modes. Tuning the first horizontal mode (Mode 4 in Fig. 6) is readily accomplished by adjusting the breadth of the cavity. When we attempt to tune the first vertical mode, however, we quickly discover that any reasonable choice of cavity length gives a resonance frequency which is much too high. To bring the frequency down it is necessary to follow nature by introducing a horizontal barrier (the crus helias) which diverts the airflow towards the rear of the cavity thereby increasing its effective length. Finally we require a resonant channel (the fossa) to produce an additional degree of freedom and hence two modes (Modes 2 and 3 in Fig. 6) where there would otherwise be only one.

To complete our refined model we must add a representation of the ear canal and a terminating impedance which simulates the load presented by the human eardrum as shown in Fig. 7, Panel C. Notice that there are now eight resonances between 2.6 and 15.7 kHz where there were only five before. Mach would surely see this as strong support for his view that the pinna served as a resonator for high frequency sounds. The grouping of modes with similar directionality is equally striking: It suggests perhaps that specific roles are associated with each of three frequency bands: Lateral discrimination linked with the 2-6 kHz band (see Fig. 2), the detection of sources above the head linked with the 6-10 kHz band, and the detection of sources in front of the head linked with the 12-16 kHz bands. Here, then, is a physical basis for large systematic variations in the timbre of broad-band sources moving over and around the head. And there is agreement with ROFFLER and BUTLER's experimental finding

(1968) that "to localize sounds in the median sagittal plane requires that the sounds be complex and that they contain frequencies of 7000 Hz and above." One should also mention the recent studies of GARDNER and GARDNER (1973). These authors, improving upon the technique of pinna modification initiated by Bloch, found that localization accuracy progressively deteriorated as the cavities of the pinna were filled with a rubber compound. Even the scapha (the channel at the rear of the pinna extension) was found to have a minor effect on the accuracy of localization in the median plane.

It is tempting to conclude this chapter with the broad observation that the timbre theory of localization is now supported by an abundance of evidence, both psychophysical and physical but, as so often happens in science, there are pieces of the puzzle which do not quite fit. Just three years ago SEARLE et al (1976), having analyzed a large number of localization experiments in terms of statistical decision theory, concluded that localization cues related to differences in characteristics between the two ears - interaural pinna-disparity - were stronger than the monaural cues. If their findings are accepted, then the second century of research on sound localization is evidently off to a good start.

The small bones of the middle ear - the malleus, the incus and the stapes - which link the eardrum to the oval window of the cochlea, are maintained in a state of equilibrium by an array of ligaments and muscles. This somewhat variable connection is part of an impedance matching device, a lever system coupling two pistons which differ greatly in area and acoustical loading. Thanks to the work of ONCHI (1961), MØLLER (1961), ZWISLOCKI (1962) and others during the past twenty years we now have highly developed acoustical networks describing the operation of the middle ear in considerable detail. These appear to work well up to about 1 or 2 kHz.

Quite recently it has been found necessary to reexamine the role of the eardrum itself in relation to the middle-ear system. In particular, we have to come to terms with the fact that the eardrum appears to absorb approximately 50% of the incident sound energy at frequencies as high as 8 to 10 kHz which is much larger than would be expected if the eardrum were rigidly coupled to the middle ear. It was the development work on ear simulators for the calibration of insert earphones which forced us to pay attention to this discrepancy (ZWISLOCKI, 1971; SHAW, 1974b).

It is now clear that the eardrum behaves as a simple elastic shell at low frequencies (FUNNELL, 1975) but breaks up into isolated zones vibrating almost independently as the frequency rises (TONNDORF and KHANNA, 1972). As a first approximation, as shown in Fig. 8, we can think of the eardrum as a pair of pistons, one approximately four times as large in area as the other, tightly coupled up to 1 or 2 kHz but operating independently at the higher frequencies. It is the smaller piston which is directly connected to the malleus and, hence, this alone which drives the ossicular chain at high frequencies. To represent such behaviour in an acoustical network we must introduce an ideal transformer which is switched out of operation at high frequencies by a frequency-dependent impedance. In effect, the middle ear transformation ratio is reduced at high frequencies and a substantial fraction of the input energy never reaches the ossicular chain. It must also be assumed that the larger piston,

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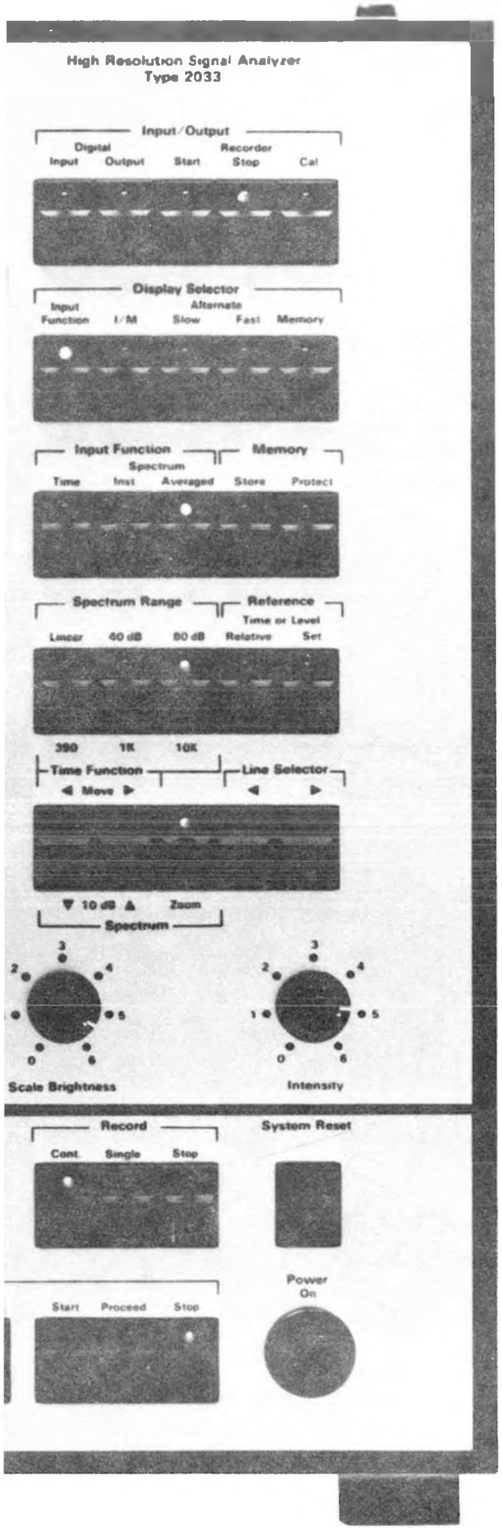

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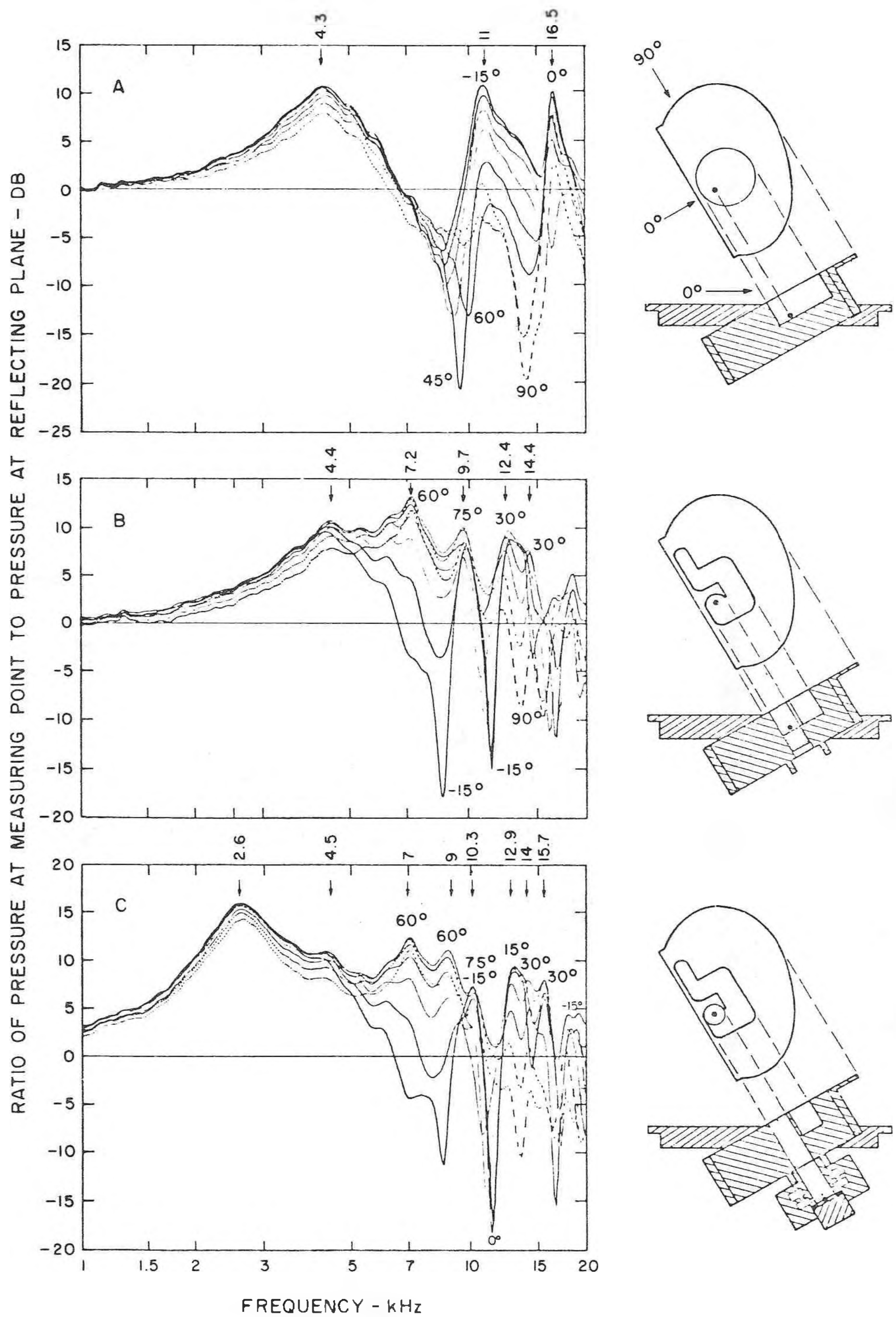

Fig. 7. Response of model ear at three stages of development when excited by progressive-wave source. Arrows indicate mode frequencies. Source is in front of ear at 0°, above at 90°. Panel A: Cylindrical concha. Panel B: Refined concha. Panel C: Refined concha, cylindrical canal and eardrum impedance simulator. After SHAW (1979b).

representing the isolated zones of the eardrum, is well damped at high frequencies by a mechanism which has yet to be determined.

How well is the ear matched to the sound field? To answer this question WEVER and LAWRENCE (1954) compared the characteristic impedance (ρc) of air with that of water making allowance for the impedance transforming function of the middle ear. Implicit in this approach is the assumption that one is dealing with a system whose dimensions are much greater than the wavelength of sound in each of the two media, an assumption which is clearly unjustifiable in the present case (see SCHUBERT, 1978; KILLION and DALLOS, 1979). Another approach, which leads to a rather precise answer, is by way of the acoustical reciprocity principle which was shaped, in part, by RAYLEIGH (1973, 1976). By performing a mental experiment in which the external ear is first a receiver and then a transmitter we can express the power absorbed by the ear, when immersed in a diffuse sound field, essentially in terms of two impedances (SHAW, 1976). These are the load impedance, that is to say the eardrum impedance, and the impedance looking outward from the load, predominantly the radiation impedance. (Where there are appreciable radiation losses the response is multiplied by a radiation efficiency factor which for the human ear is probably greater than 80% at most frequencies.) We cannot of course measure the radiation impedance of real human ears but we can make such measurements on models and replicas using an impedance tube. We can go a stage further and express the performance of the ear as a sound collector in terms of its absorption cross section, the parameter universally used in radiation theory. For the ear, the absorption cross section in a diffuse sound field can be defined as the size (cross sectional area) of the transparent sphere which, when placed in the same sound field, would intercept the same amount of power as the ear. Such measurements and calculations have been carried out for the model ear described earlier. The results are shown in Fig. 10.

Consider first the absorption cross section at the eardrum. According to the upper graph of Fig. 10, below 1 kHz the absorption cross section decreases rapidly with decreasing frequency and soon becomes exceedingly small. This is hardly surprising since three adverse factors come into operation in rapid succession. First, the external ear provides negligible pressure gain much below its principal resonance frequency which means, acoustically speaking, that the eardrum is simply a small piston mounted in a spherical surface. Second, the wavelength of sound, already large compared with the circumference of the piston, soon becomes large compared with that of the sphere. Third, the load carried by the piston is an impedance whose magnitude rises with decreasing frequency while its power factor falls. Above 1 kHz the situation is quite different. As shown in Fig. 10, at the principal resonance frequency of the external ear ($\sim$2.6 kHz), the power absorbed at the eardrum is that which would pass through a sphere approximately 6 cm^2 in cross section (radius 1.3 cm) immersed in the same diffuse sound field. This is 40% of the limiting value. At higher frequencies, the absorption cross section declines in absolute value while passing through a series of minor peaks at the mode frequencies but always stays quite near the theoretical limit of $\lambda^2/4\pi$ imposed by radiation theory. In fact, at 9 kHz, the absorption cross section (1 cm^2) almost reaches that limit.

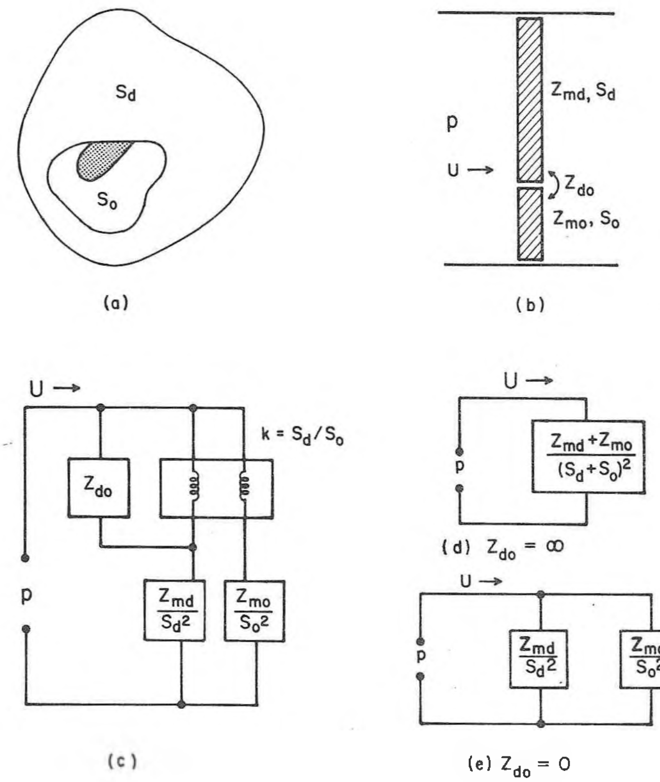

Fig. 8. Compound-eardrum concept: (a) S_o rigidly attached to malleus, S_d independent of S_o at high frequencies; (b) Rigid pistons S_d and S_o coupled by frequency-dependent impedance Z_{do}; (c) Network representation with ideal transformer; (d) Low frequency behaviour; (e) High-frequency behaviour. From SHAW (1977).

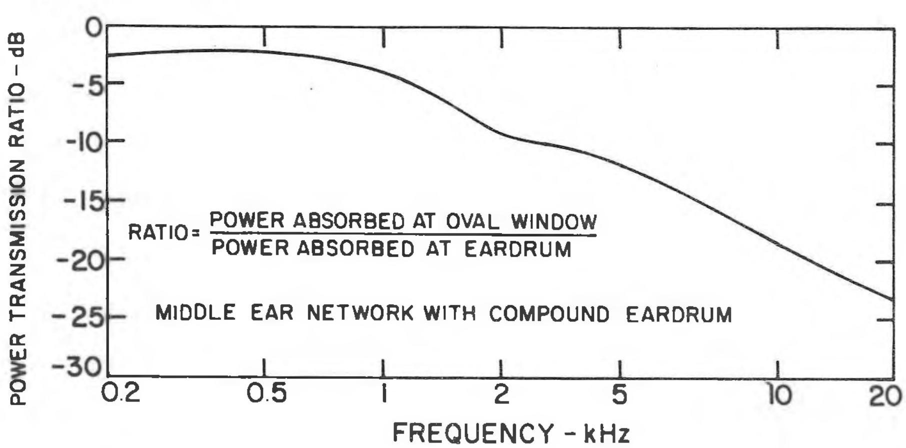

Fig. 9. Power transmission ratio of average human ear calculated from Zwislocki-style middle-ear network with compound-eardrum representation. From SHAW (1979a).

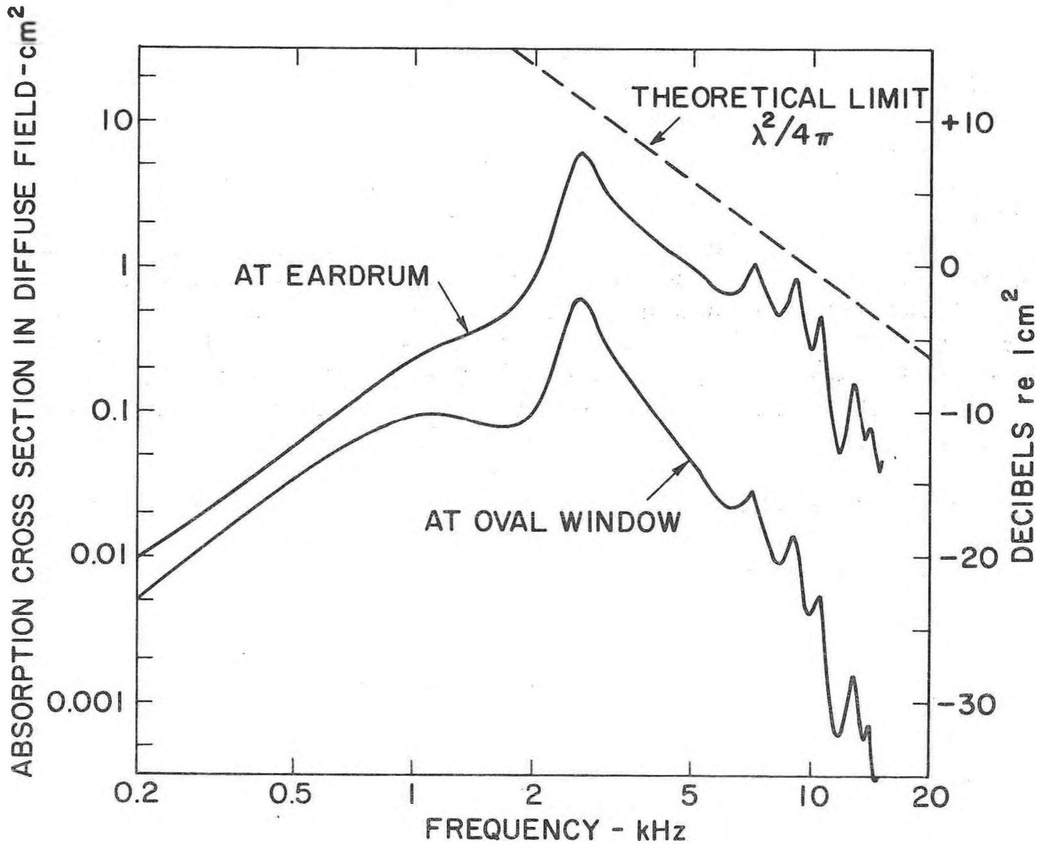

Fig. 10. Calculated absorption cross section of external ear physical model when terminated by middle-ear network with compound eardrum representation: (a) at eardrum, (b) at oval window of cochlea. From SHAW (1979a).

Viewed in isolation, the external ear is clearly an impressive sound collector at the higher frequencies. Unfortunately, as we have seen, only a small fraction of the high frequency energy reaching the eardrum appears to be transmitted to the oval window of the cochlea. Hence, if our understanding of eardrum and middle-ear function is correct, the inner ear receives barely 10% of the energy available from the sound field at the principal resonance frequency ($\sim$2.6 kHz) and only 0.5% at 10 kHz.

My final vignette is inspired by a problem which caused confusion and consternation for three decades: the lack of agreement between psychoacoustic measurements with earphones and in the free field. It is now established beyond reasonable doubt that the elevated low-frequency hearing-threshold-levels measured with conventional earphones are contaminated by the masking effect of physiological noise generated when the ears are enclosed. This noise is most likely due to relative movement between the earphones and the head which is kept in vibration by the pump action of the heart and by general muscular activity. Above 1000 Hz the differences between the minimum audible field (MAF) and minimum audible pressure (MAP) can be readily explained by sound pressure transformations in the ear and around the head. Building on this knowledge and making use of various data which have become available in recent years, KILLION (1978) recently presented a revised estimate of the minimum audible pressure from 100 Hz to 10 kHz with tentative extensions at either end. (The minimum audible pressure, as defined by SIVIAN and WHITE in 1933, is the sound pressure level measured at the eardrum for a median normal subject at hearing threshold.) In Fig. 11 we approach the subject in a slightly different way. The solid curve and points are various experimentally determined average pure-tone hearing-threshold levels processed and translated into sound pressure levels at the eardrum so that they can be directly compared. As can be seen, there is reasonable agreement but some minor discrepancies remain which is hardly surprising considering the probable errors in the original measurements, the data processing and the translation procedures. We are, however, bound to ponder the significance of the peak in hearing threshold level at 2.6 kHz which is indicated in Fig. 11. If more sound pressure is, indeed, required at the eardrum to bring the median subject to threshold level at this peak than is required at frequencies on either side, then there must be a mechanism in the middle ear or beyond which, on average, counterbalances the principal resonance of the external ear.

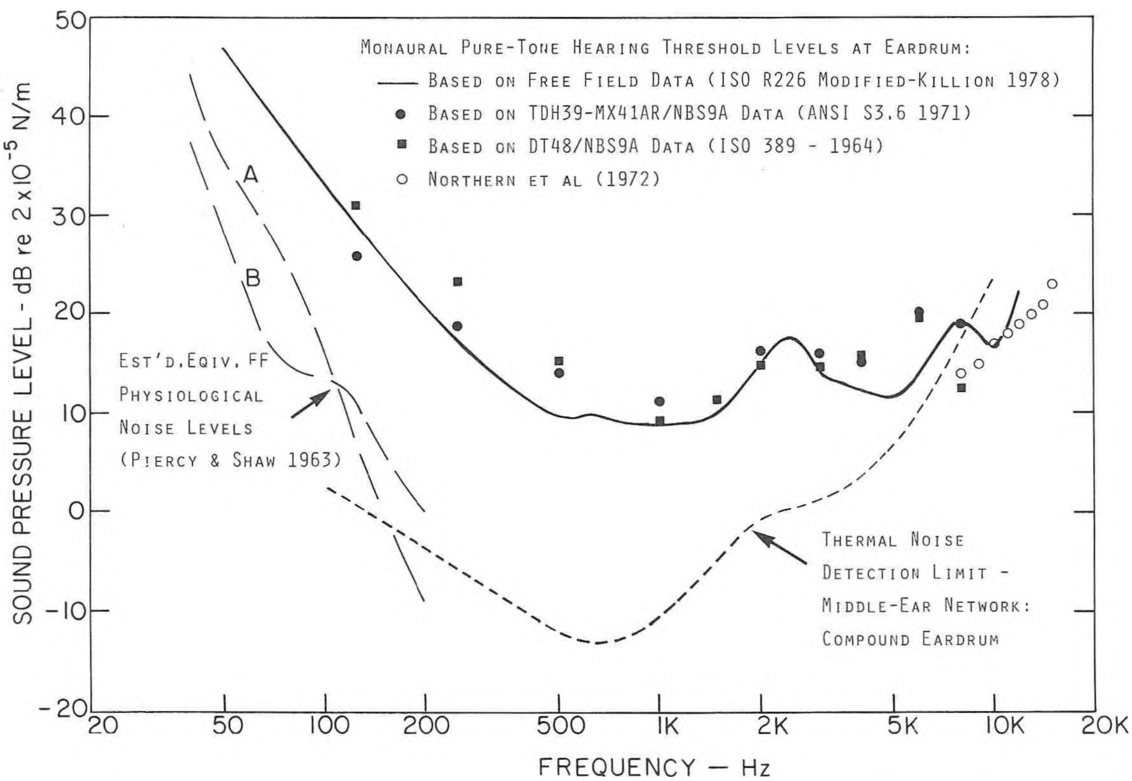

Fig. 11. Comparison of various standard values of monaural pure-tone hearing-threshold level presented as minimum audible pressure at the eardrum with estimated free-field physiological noise levels (broken lines) and calculated thermal-noise detection-limit (dotted lines). Transfer of free-field and earphone-coupler levels to eardrum position: according to KILLION (1978).

THE ELUSIVE CONNECTION

The reality of physiological noise generated within earphone enclosures was clearly demonstrated in two papers presented in 1962 (RUDMOSE, SHAW and PIERCY). As a corollary, it seemed likely that the head vibrations which generated noise within an enclosed ear should also set the middle ear into vibration, thus producing low-level masking even when the ear was open to the sound field. To estimate these noise levels a colleague and I set up a special measurement of the "occlusion effect". The results, which were presented at a meeting in 1963 (PIERCY and SHAW), are indicated by the broken lines at the left of Fig. 11. As can be seen, at 50 Hz the estimated third-octave band equivalent levels of physiological noise in the free field are not much lower than the hearing threshold levels which suggests that the sensitivity of the ear at very low frequencies may well be adapted to this built-in noise.

What can be said about the internal noise of the ear at higher frequencies? In 1948, DE VRIES concluded that "the Brownian movement of the inner ear is close to the threshold actually observed whereas the Brownian motion of the air at the eardrum is below the audible threshold." Now that we have acoustical networks to represent the human hearing system up to the oval window, we are in a position to calculate the thermal noise levels by applying the Nyquist noise generator theorem. The calculation confirms that most of the noise appearing at the oval window is associated with the input impedance to the cochlea not with the external ear. Knowing the integration time of the ear (GREEN and McKEY, 1959) we can then calculate the detection limit for pure tones in the presence of thermal noise. As shown by the dotted line in Fig. 11, this limit is nearly 20 dB below the observed median normal hearing threshold level at 500 Hz. At 5 kHz, however, the ear is evidently operating near the thermal limit. When the lines cross as they appear to do in the vicinity of 8 kHz, it is time to remind ourselves that such perfect agreement between theory and experiment is uncharacteristic of auditory acoustics and, therefore, to be viewed with the deepest suspicion! It seems safe to conclude that the last words on the external- and middle-ear systems have yet to be written and that the nature of the connection between the sound field and the inner ear will remain somewhat elusive for some time to come.

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