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THE ACOUSTIC ENVIRONMENT AND ITS EFFECTS ON PEOPLE

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SESSION 18:   THE ACOUSTIC ENVIRONMENT AND ITS EFFECTS ON PEOPLE
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INTRODUCTION

This is the first of 7 sessions by various lecturers on sound
and vibration and their relevance to architecture in general and to
building design and re-modelling in particular.

As a psychologist specialising in audiology (the science of
hearing), I shall present the first part of this session dealing with
the physiology and psychology of hearing and the effects of the acoustic
environment on people, and my engineering colleague from the Commonwealth
Acoustic Laboratory, Mr. Rose, will give the second part dealing with
principles and criteria for desirable sound conditions in buildings.

Besides outlining some of the relevant basic facts, such as
are fairly readily available in the literature (see list of References
already issued and those attached), I shall try to show their special
significance for architecture in relation to man. Accordingly I shall
ensure that there is time for questions and discussions, and shall
welcome any critical and constructive comments. These notes are fairly
full, but I shall at times talk around them and deviate as seems
desirable.

THE ACOUSTIC ENVIRONMENT AND ITS RELEVANCE TO ARCHITECTURE

At the outset something needs to be said about the nature of
sounds and vibrations and their relevance to architecture.

In discussing the nature of sound, Hallowell Davis (see attached
References, 1960, pp. 29, 30) and also R.W. Young (in C.M. Harris, 1957,
Ch. 2, p. 1) both make philosophic rigmaroles about whether 'sound' is
the physical vibratory energy or the psychological audible sensation.

Whilst I am a psychologist, I firmly assert that the most scientifically valid and useful definition of sound is as a form of physical vibratory energy - a delimitation which is capable of objective, operational definition and which enables a clear distinction to be made from its effects on living organisms. However I do admit that the word "sound" is sometimes used to imply those forms of vibratory energy audible to man (compare "light" too, strictly speaking only the visible part of the full range of electromagnetic energy wavelengths). However, I shall follow common practice and usually utilise the term "sound" to comprehend all forms of vibrations whether inside or outside the audible range (including ultrasonics and infrasonics), though I may at times add the word "vibrations" to be sure.

Thus sound and vibration may be defined for scientific purposes as a form of vibratory energy constituted by an alteration in pressure, stress, particle displacement, or shear, etc. in an elastic body or mass, (whether solid, liquid or gaseous). For such vibratory energy to radiate beyond the body or mass in which it is produced, there needs to be a conducting medium. Therefore, a rocket in outer space produces no sound beyond the confines of its exterior as there is no air to serve as medium, so there is only "structure-borne noise" within the rocket. When the sound and vibration impulses progress through a medium, they cause these particles of the elastic medium to move forth and back successively, thus setting up relative compressions and rarefactions in the medium. Thus the particles of the medium oscillate in a longitudinal direction, i.e. in the same direction (positive and negative) as the progress of the sound, as indicated in the following diagram:

Direction of
Wave Front

Most sounds proceed at a uniform speed through any particular homogeneous medium, though faster in solids than in gases, so that different frequencies have different wavelengths.

THE PHYSIOLOGY AND PSYCHOLOGY OF HEARING

A) The Anatomy and Physiology of Hearing

Man's hearing system evolved over millions of years from the receptors for water-borne vibrations in primitive fish, and still shows traces of its primitive origins, e.g. fluids in the inner ear. The human acoustic receptors are paired and on the lateral sides of a mobile head. Certainly this is only a technical way of saying that we have two ears at the sides of the head, a scientific fact we being humans learned very early (together with various misapprehensions). But such technical descriptions do help us to look at hearing phenomena and relevant design problems in a new light, so that we are now more likely to design buildings to provide good acoustic conditions at ear-height rather than floor-level etc. The gross anatomy of our auditory system can be readily ascertained from introductory references (e.g. Davis and Silverman, 1960, Ch. 3; Harris, Ch. 4; or Newby, 1958, Ch.2). Here I attempt only a recapitulation of some of the salient points, using a separate coloured diagram (see also following line drawing).

Imagine a person trying to listen to another person in a noisy crowded room. As the voice of interest arrives at the listener's closer ear first, he obtains cues enabling him to turn his head towards the speaker to direct his forward orientated ears towards the speaker's voice and to obviate some of the background noise.

The sound of the voice enters the ear canals which are approximately 2.4 cm. long (for convenience, now let us use the singular). It is funnelled towards the eardrum or tympanic membrane (T.M.) which it sets vibrating sympathetically, especially if the eustachian tube from the throat has been opening periodically, enabling the air pressure inside the middle ear to equal that outside in the ear canal. The moving tympanic membrane sets vibrating the first of the tiny attached and suspended conducting bones or ossicles, namely the malleus (or hammer), which transmits its vibrations to the jointed incus (anvil), and then the stapes (or stirrup). The footplate of the stapes is seated in an 'oval window' cavity in the mastoid bone of the skull, so that its vibrations are transmitted through the membrane covering the window to the vestibular fluids inside the cavities for the inner ear and the semi-circular canals (concerned with balance). At
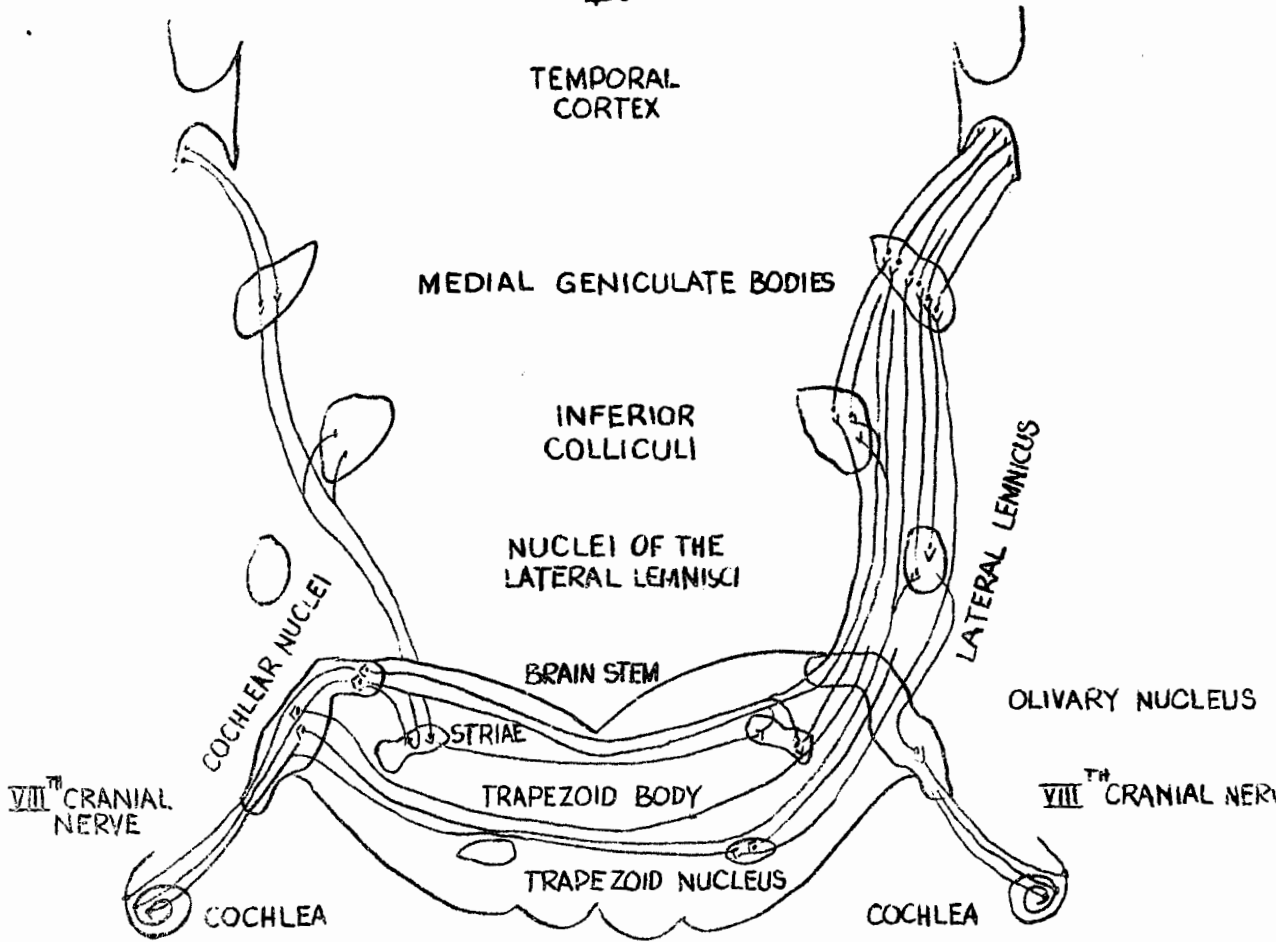
TEMPORAL
CORTEX

MEDIAL GENICULATE BODIES

INFERIOR
COLLICULI

NUCLEI OF THE
LATERAL LEMNISCI

BRAIN STEM

STRIAE

TRAPEZOID BODY

TRAPEZOID NUCLEUS

COCHLEAR NUCLEI

LATERAL LEMNISCUS

OLIVARY NUCLEUS

VIIITH CRANIAL NERVE

VIIITH CRANIAL NERV

COCHLEA

COCHLEA

FIG II: THE CENTRAL AUDITORY CONNECTIONS

CARTILAGE   MASTOID CELLS   ONE OF THREE
SEMI-CIRCULAR CANALS

VESTIBULE

VIIITH CRA
NERV

MALLEUS

INCUS

PATH OF SOUND
WAVES

COCHLE
(WITH MEMBRANO
(LABYRINTH REM

EXTERNAL
AUDITORY
CANAL

STAPES
(IN OVAL
WINDOW)

ROUND
WINDOW
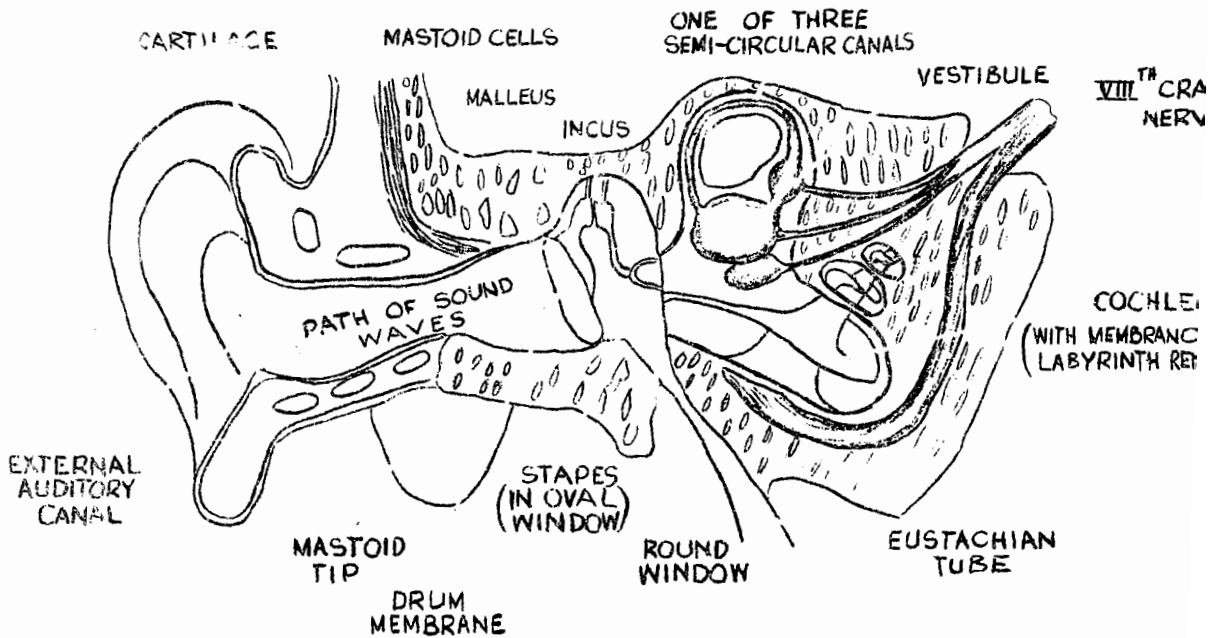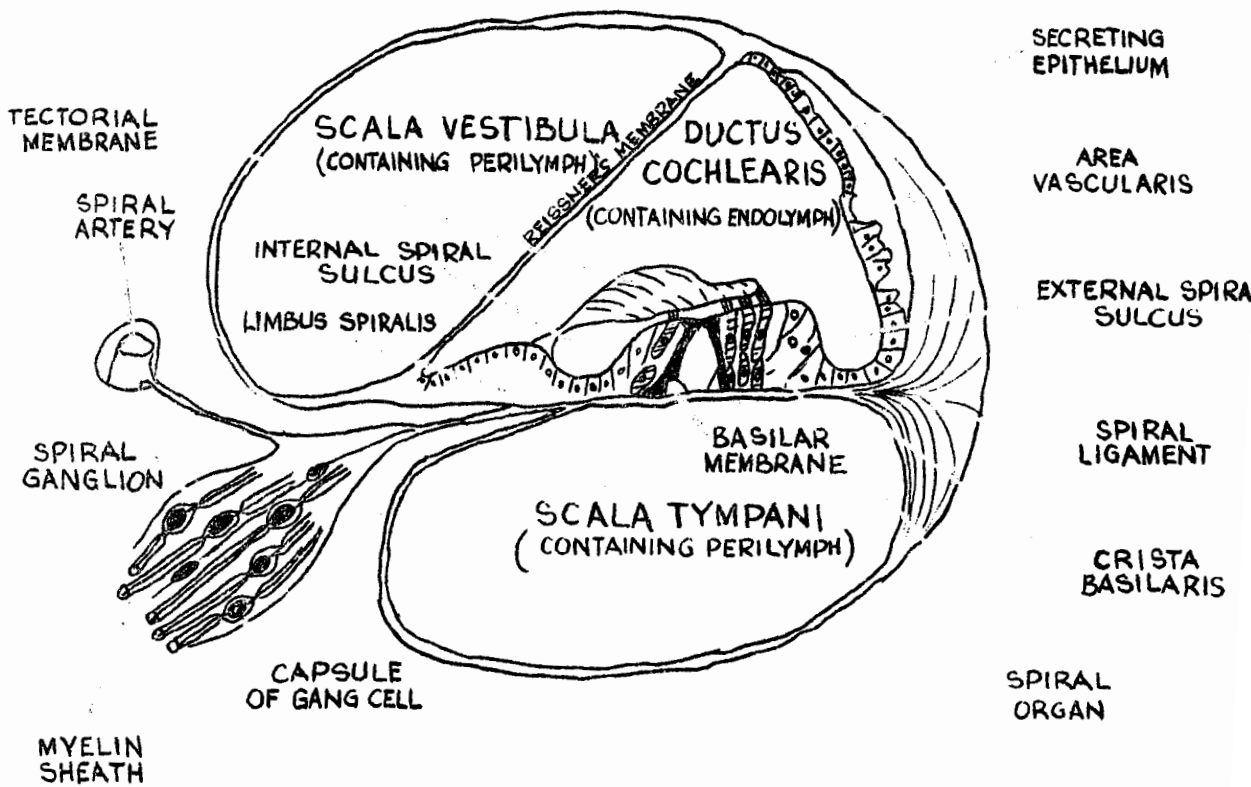
EUSTACHIAN
TUBE

MASTOID
TIP

DRUM
MEMBRANE

FIG I: THE OUTER EAR, MIDDLE EAR AND INNER EAR

high intensities, tiny muscles in the middle ear contract to stiffen the drum and the ossicular chain, and also probably allow the footplate of the stapes to rock from side to side (instead of longitudinally), i.e. somewhat less severely than they otherwise might, thus constituting a protective mechanism. The area of the tympanic membrane is 70 square c.m. as against only the 3.2 square c.m. of the footplate, thus giving an increase in pressure of 27 decibels. Were it not for these impedance-matching middle ear mechanisms, most of the air-borne vibrations would bounce off the membrane covering the inner ear fluids just as they are reflected off water. This air-fluid impedance matching mechanism gradually evolved after animals emerged from the seas on to the land, and was necessary for auditory efficiency in air.

Thus the vibrations are transmitted through the oval window into the vestibule between the caverns or galleries of the semi-circular canals (concerned with balance) and those of the cochlea (concerned with hearing). When the perilymphatic fluid of the vestibule is pushed by the stapes into the vestibular gallery, it readily compresses through Reissner's membrane the scala media (or middle gallery) which contains endolymph and hence forces down the other containing membrane, the basilar membrane, which is relatively free to bulge into the lower gallery, the scala tympani, which has a release outlet at the round window, back below the oval window. (See accompanying diagrams or Davis & Silverman, pp. 62 and 70, or Newby, pp. 20, 22, and 24. In examining diagrams of the inner ear, it should be remembered that it is not really an object, but rather a series of cavernous tunnels, containing fluids, the endolymph in the outer parts of this being labyrinth, and the perilymph inside the enclosed sac-like system, the inner membranous labyrinth.)

High pitched tones produce the maximum vibration of the basilar membrane at its basal or outermost end, whereas somewhat lower tones produce their greatest effect further in towards the apical end of the cochlea (place mechanism), though tones below about 500 cps have more generalised effects (volley mechanism). The vibration of the basilar membrane causes the base of the receptor hair cells embedded in it to move in a shearing fashion relative to the tectorial or roofing membrane which they join above. This shearing movement on the hair cells of this Organ of Corti produces, by a complex physico-electrical amplifying mechanism, neural impulses in the complex nerve endings supplying the hair cells. (A good account of these cochlear mechanisms is given by Davis and Silverman, 1960, pp. 67-79.)

SECRETING
EPITHELIUM

TECTORIAL
MEMBRANE

SCALA VESTIBULA
(CONTAINING PERILYMPH)

DUCTUS
COCHLEARIS

REISSNER'S MEMBRANE

AREA
VASCULARIS

SPIRAL
ARTERY

(CONTAINING ENDOLYMPH)

INTERNAL SPIRAL
SULCUS

LIMBUS SPIRALIS

EXTERNAL SPIRA
SULCUS

SPIRAL
GANGLION

BASILAR
MEMBRANE

SPIRAL
LIGAMENT

SCALA TYMPANI
(CONTAINING PERILYMPH)

CRISTA
BASILARIS

CAPSULE
OF GANG CELL

SPIRAL
ORGAN

MYELIN
SHEATH

Diagrammatic Cross-section of the Cochlear Canal

The neural impulses from the cochlea, varying in tonotopic patterning, and rate and widespreadness of firing, proceed along the first-order neurone axons constituting the auditory part of the Eighth cranial (or acoustic) nerve cable. They cross the first synapses (or connections) to the second order neurones constituting the cochlear nuclei in the brain stem, and then by three more successive synapses up to the auditory cortices near the surfaces of the brain in the temporal lobes. Note that the neurones from _each_ ear have some neural projections to _both_ sides of the brain. By complex neural mechanisms in the brain which are not fully understood, the nerve impulses are decoded by us so that we can perceive and then react appropriately to sounds – at least with experience and training which enables connections to be made with other sensations and with movement responses.

B) The Psychology of Hearing

Some indication of the complexity of the psychology of hearing can be gained from the referred chapters by Licklider in S.S. Stevens (1951) which are already partly outdated. Briefer accounts are given by Davis and Silverman (1960, Ch.2 pp.29-60) and by Van Bergeijk (1961, a handy paperback). Here I can only mention some of the key facts and also some points usually overlooked in most audiology tests. (Incidentall 'audiology' is the newly integrated discipline of the sciences of hearing, which has given rise to professional audiologists, especially in the U.S.A.)

Human hearing acuity over a wide range of frequencies is substantially present at birth, although certain hearing aptitudes, such as auditory memory span, do not fully mature until at least 8 years of age, and of course the learning of specific auditory skills in relation to other languages, music, etc. can continue throughout life until considerable decline in auditory aptitudes occurs towards old age.

Hearing and vibration sense are alerting, orientating, distance senses which keep us in touch with our environment even to some extent when we are asleep, and which provide ones enabling us to orientate the body and turn the head towards the stimulus so that we can bring other senses, such as vision, to bear. Hearing operates all round the head, and we have only partial central mechanisms to limit its operations (we cannot suspend hearing naturally by means of any bodily mechanism

analogous to eyelids). Thus the architect is often required to design structures to help guard sleep against noise. Moreover we use vocal-auditory symbol systems for communication.

Human hearing is extremely sensitive, so that we can almost detect the Brownian movements of the molecules of oxygen, nitrogen etc. of the air impinging on our eardrums. Human beings up to about middle age can perceive as tones frequencies ranging from about 20 to 20,000 cycles per second, though the ear is relatively less sensitive to energy in the lower frequencies. (Middle 'C' is about 250 c.p.s.) Much of the information about the range of human hearing is conveniently conveyed in a graph of what is called "the auditory area" (see attached diagram). The intensity of environmental sounds is usually measured on a decibel-scale, a logarithmic scale convenient for comprehending the tremendous range of intensities to which we can respond. Thus:

1 decibel (abbrev. db) = 1/10 bel[**][*]

.˙. Whereas the <u>power</u> ratio of two sounds in bels is given by:

$$N \text{ (in bels)} = \log_{10} \frac{\text{Power of the Particular Sound}}{\text{Power of the Reference Base Chosen}}$$

.˙. $$n \text{ (in decibels)} = 10 \log_{10} \frac{\text{Power of the Particular Sound}}{\text{Power of the Reference Base Sour}}$$

However it is usually more convenient to express sound intensities in terms of <u>pressure</u>. But as:

$$\text{Power} = (\text{Pressure})^2 \times \text{Constant}$$

.˙. The intensity of a particular sound in decibels Sound <u>Pressure</u> Level is given by:

$$\text{S.P.L. db} = 20 \log_{10} \frac{\text{Pressure of the Sound}}{\text{Reference Pressure Base}}$$
(Usually 0.0002 dynes/cm^2)

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[*] "The <u>bel</u> is the fundamental division of a logarithmic scale for expressing the ratio of two amounts of power, the number of bels denoting such a ratio being the logarithm to the base 10 of this r

[**] "The <u>decibel</u> is one-tenth of a bel, the number of decibels denoting the ratio of two amounts of power being 10 times the logarithm to base 10 of this ratio." (Amer. Standards Definitions)
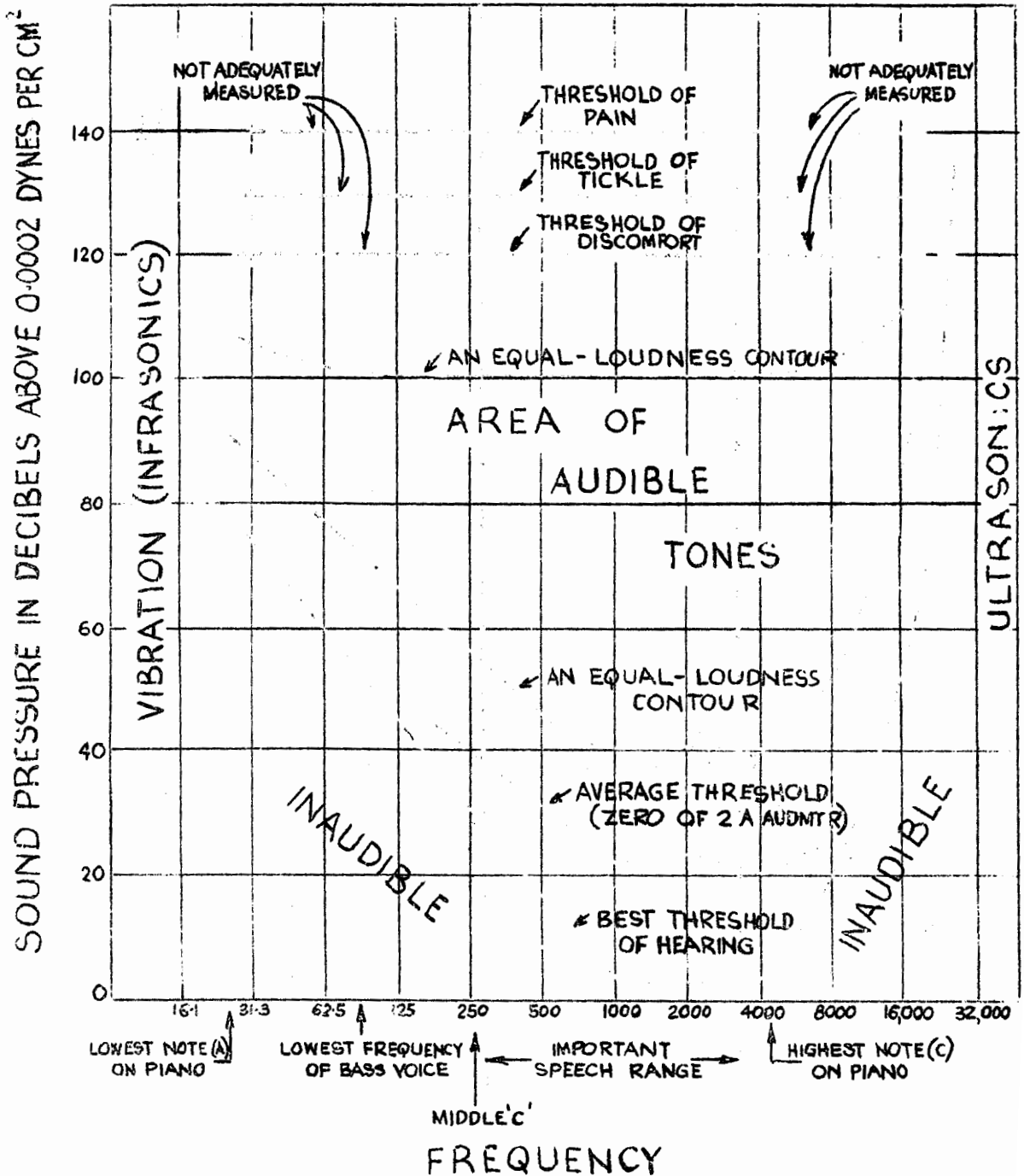
The Area of Audible Tones (The Auditory Area)
(Modified from Newby, 1958, p. 14, and H. Davis, 1947 edn.)

Most environmental sounds are measured in decibels re 0.0002 dynes/cm^2, usually called <u>decibels Sound Pressure Level, or db S.P.L.</u> The human ear at its most sensitive areas for frequencies from about 1000 to 5000 cps can detect minute sound energies of only a few db S.P.L., such energies at which sounds can just be sensed being called <u>acuity thresholds,</u> though they are more conveniently measured under the earphone of a pure tone audiometer with a different calibration (called <u>decibels hearing loss,</u> 0 decibels hearing loss being almost 20 db S.P.L. for frequencies from about 1000 to 6000 c.p.s.). The ear can also respond to sounds up to extremely high intensities, though eventually "discomfort" is experienced, and at about 130 decibels S.P.L. over most of the audible frequency range, "tickle" is felt as the nerve endings for touch in the ear are stimulated; and at about 140 db S.P.L., "pain" deep in the ear is experienced as the relevant nerve endings are stimulated. Thus is the auditory area bounded at its upper level for all of us, however deaf we may be.

To scale the sensation of loudness, the 'phon' units and the 'sone' units have been developed, such that:-

The Loudness to a normal listener of a 1000 c.p.s.
Tone at 40 db S.P.L.   =   40 phons

                =   1 sone

It is useful to remember that over much of the audible intensity range, an increase of 10 decibels S.P.L. (i.e. 10 times the power, or about three times the pressure) seems about twice as loud, i.e. one extra sone. As sound intensities are usually measured on physical sound level meters in db S.P.L. and as we are less sensitive to low frequencies, much effort has been devoted to devising methods of analysing, measuring, and adding components of sounds so as to arrive at estimates of their loudness. Several methods have been devised (see Broch in Bruel and Kjaer's Technical Review No. 2, 1962, and Great Britain's Dept. S.I.R. Review, 1961), though an international standard has not yet been decided on. One method (Kryter's) tries to scale the perceived 'annoyance' of sounds rather than their loudness, though other factors affect annoyance besides intensity and frequency composition. Actually the usual aim is to try to predict people's reactions to noises, and it is becoming increasingly clear that valid predictions cannot be made solely on the basis of derivations from frequency and intensity measures alone. The perceived significance of the sound to the listener is important, and this is affected by hearing and experience, sociological variables, etc.

Regarding speech and hearing, it should be noted that although we can vocalise over most of the range of frequencies we can hear (a linkage probably due to evolutionary selection), the range of frequencies important for perceiving speech is only from about 300 to 3000 cps.

THE EFFECTS OF SOUNDS ON PEOPLE

The possible effects of sounds on people are very diverse (see Kryter, 1950 and Harris, 1957). I have categorised such possible effects as follows:-

A CLASSIFICATION OF THE POSSIBLE EFFECTS OF NOISE ON MAN

A) EFFECTS ON ANATOMICAL STRUCTURES

1) Vibration of bodily structures, heating effects, permanent damage to semi-circular canals, etc.

2) Damage to middle ear - noise of 160 db S.P.L. (i.e. 0.02 atmospheres) will immediately rupture the tympanic membrane (Parrack).

3) Damage to cochlea (temporary and permanent) - damage risk criterion for continuous wide-band noise 8-hrs/day for years is about 90 db S.P.L./octave.

B) EFFECTS ON MAJOR PHYSIOLOGICAL PROCESSES

1) Pain in the ear - at over 140 db S.P.L.

2) Upsetting bodily orientation. At over 135 db S.P.L. there may occur nausea, vomiting, nystagmus, apparent shifting of visual field, feelings of forced movement, and loss of balance.

3) Effects on blood pressure, pulse rate etc.

C) POSSIBLE EFFECTS ON MENTAL AND MOTOR BEHAVIOUR

1) Interference with Activities:

a) Speaking and listening communication (usually above about 50 db S.P.L.)

b) Working
c) Relaxing
d) Sleeping
e) Reading
f) Convalescing
g) Travelling, etc.

2) Disturbance of Attitudes, Feelings etc.:

Noise may contribute to:

a) Annoyance
b) Fear of: (i)   bodily injury;
                     (ii) economic and status loss.
c) Accentuation of stress illnesses:
                     (i)   psychosomatic stress diseases, e.g.
                              ulcers, asthma, etc.;
                     (ii) neuroses and psychoses.

3) Provocation to Action in Response to the Noise:

a) Leaving or avoiding the noise field
    e.g. moving residence.

b) Attempting to Block Out the Noise
    e.g. planting tree barriers, closing windows,
    putting in double windows, etc.

c) Antagonistic Action to the Noise-Maker

        (i)   Grumbling and discussion within local groups
        (ii) Complaints to local authorities
        (iii) Complaints to State or Federal Authorities
        (iv) Threats of legal action
        (v)   Vigorous legal action
        (vi) Sabotage.

        Some key facts and gross criteria pertinent for engineering
and architectural design may be summarised as follows.

        Very intense sounds (beyond about 90 db S.P.L. overall, i.e.
beyond deafness risk level), can over a period damage hearing,
especially for relatively high frequencies, and may at extremes vibrate
surfaces of the body and cause momentary giddiness.

Moderately intense sounds (beyond about 50 db S.P.L. overall
up to 90 db S.P.L.) do not damage hearing but may interfere with other
activities, e.g. sleeping, speaking, etc. The level of noise within the
three octave band range from 600 to 4,800 cps that will interfere with
ordinary face to face conversation is about 60 db S.P.L. overall (i.e.
speech interference level for medium speech) and architects must take
account of the still lower speech interference level for soft speech as
an upper limit in planning offices. Incidentally noise does not seem
to affect work output much, unless it involves communication or stimulat
adverse emotional response (see Kryter, pp. 8-17).

Low intensity sounds (from threshold to about 50 db S.P.L.) do no
damage hearing or directly interfere with our activities, but they may
cause emotional responses, sometimes quite intense, e.g. those to a
twig snapping, or a whispered compliment or insult. Thus man responds
not only to the intrinsic qualities of the physical characteristics of
sounds, but he also tends to learn to attribute significance to sounds
and to respond to their meaning to him.

In planning the acoustic aspects regarding buildings, architects
must consider the outside acoustic conditions, the activities to be
carried on inside the building, and the likely characteristics of the
occupants, and he must then plan conditions to satisfy the vast majority
of the occupants, subject to economic considerations. How to analyse
and measure sounds, the specification of more detailed criteria and how
to plan in relation to them are the subjects of the following lecturers
in this series.

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