Sound and Hearing

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(see also inside rear cover)

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Sound and Hearing

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For Miriam and David

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Because it is no longer possible for one textbook to cover the whole field of biology while remaining sufficiently up to date, the Institute of Biology proposed this series so that teachers and students can learn about significant developments. The enthusiastic acceptance of 'Studies in Biology' shows that the books are providing authoritative views of biological topics.

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Readers' comments will be welcomed by the Education Officer of the Institute.

1982

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Preface

Scientific enquiry into the sense of hearing is as deeply rooted in engineering and physics as in anatomy, physiology and psychology. Each approach has brought its own terminology and concepts and it is sometimes difficult for the non-specialist to obtain a clear picture of the subject. This book is a survey of several of the avenues of interest concerned with the sense of hearing and is intended to clarify some of the established principles. The book is directed to students of medicine and biology, but I think it will be of interest to engineers and possibly those involved in the creative applications of sound.

London, 1982

M.E.R.

Contents

1 Sound and Sound Waves

We use the word 'sound' to mean auditory sensation *and* its physical cause. It is the thing that is heard, occurring entirely in the mind of the listener and, at the same time, it is a disturbance in the air that exists in its own right. Sound possesses subjective qualities: tonality, loudness, discord, etc, while simultaneously having definite frequencies, intensity and velocity. It is proposed therefore, in order to avoid ambiguity, to speak of sound *waves* when discussing the physical phenomena and to reserve 'sound' for the sensory phenomena. Sound waves then, are the observable changes in the air and other media, which produce sound in the listener.

1.1 Sound waves in air

Consider the action of a loudspeaker as a source of sound waves which propagate through a gaseous medium such as air. As the cone of the speaker is driven forward the air in front is displaced forward and as it is driven back the air returns. Air molecules possess mass and so require time to accelerate under an applied force. On the forward stroke air in contact with the cone therefore moves towards the air in the next layer causing compression. On the return stroke the layers move apart producing rarefaction. The bands of compression and rarefaction transfer from layer to layer outwards from the source and constitute a sound wave (Fig 1-1).

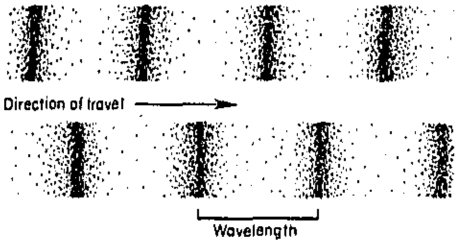


Fig. 1-1 Sound waves.

1.2 Sound waves in media

The first essential for the existence of a sound wave is a medium to support it; there can be no sound waves in a vacuum. The essential requirement of the medium is *elasticity* – the molecules must rebound after displacement. *All* substances possess enough elasticity to support sound waves.

1.2.1 Elasticity

Substances such as steel, air and rubber are obviously elastic because they behave 'elastically' with a wide range of deforming forces. Materials such as lead or wax are noted more for their plasticity. Plastic materials yield permanently under comparatively mild stresses. Nevertheless even 'plastic' materials have demonstrable elasticity if the deforming force is small enough. The transition between elasticity and plasticity occurs at the *elastic limit* for the material. The forces associated with sound waves are generally well below the elastic limit of any substance.

Measurement of elasticity Elasticity is measured directly by recording the fractional deformation caused by a known force. It is expressed as the modulus of elasticity. The quantity depends on the manner of deformation, whether, for example, the material is bent or squeezed. Since sound waves involve compression and rarefaction the relevant elastic constant is the *bulk modulus* of elasticity where:

$$\text{The bulk modulus (K)} = \frac{\text{Pressure difference (N m}^{-2}\text{)}}{\text{Fractional change in volume (dimensionless)}}$$

The units of K are thus N m^{-2}; a large value indicates that the material is relatively incompressible. The ratios of the bulk moduli for air: water: steel are roughly $1:10^9:10^{11}$.

1.2.2 The speed of sound waves

A sound wave travels steadily away from its source. The speed depends both on the elasticity and the density of the medium.

$$\text{Velocity} = \left(\frac{\text{Bulk modulus}}{\text{Density}}\right)^{\frac{1}{2}} \text{in m s}^{-1}$$

This relationship holds for gases, liquids and solids. Velocities of sound waves in various substances are given in Fig. 1–2. The important values, in connection with hearing, are those for air (around 340 m s^{-1}) and sea water (about 1500 m s^{-1}). The exact velocity depends on temperature and other factors. As a general rule sound waves travel more slowly in gases than in liquids, and more slowly in liquids than solids but there are exceptions. Hydrogen and helium support velocities greater than in some liquids; this is partly attributable to their extremely low densities.

Effects of temperature Sound wave velocity increases with temperature. For example, air at 20°C conducts sound waves 4% faster than at 0°C. This has a consequence in certain musical instruments, particularly the flute and others that work on the same principle. The note, in such instruments, derives from a vibrating column of air. The pitch of the note depends both on the length of the column and on the velocity of sound waves in it. If the temperature rises the

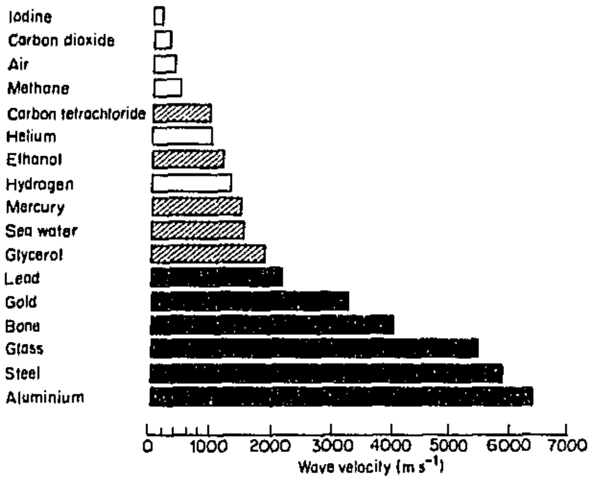


Fig. 1-2 Velocity of sound waves in various media. Gases, liquids and solids are represented, respectively, by open, hatched and filled bars.

instrument will produce a higher frequency for a given wavelength (see § 1.4.1.). Flutes are nowadays constructed to produce the correct pitch at 20°C.

Effect of amplitude The wave velocities that are usually quoted apply to sound waves of 'normal' amplitudes. Waves of very high amplitude, say in the vicinity of an explosion, travel faster: more than three times the usual rate has been recorded in these circumstances.

Effect of the shape of the medium In most cases we are concerned with an *extensive medium*, be it air or water, through which sound waves travel freely. If however the medium is confined to a tube the velocity is found to be somewhat less than the usually quoted value. This is due in part to viscous forces occurring near the walls of the tube.

Atmospheric pressure The velocity of sound waves in air is approximately independent of atmospheric pressure. An increase, say, in pressure, produces a rise both in the density of the gas and in its bulk modulus of elasticity and the changes roughly cancel.

1.3 Sound wave frequency

'Sound waves', by convention, are mechanical waves with frequencies normally audible to man. The 'standard' range is 20 – 20000 Hz although there is individual variation (see Chapter 2). Higher frequencies are called 'ultrasonic' (even though they may be audible to other species) and lower frequencies are 'infrasonic'. Extreme ultrasonic frequencies, as high as 6×10^8 Hz, can be generated by the vibrations of a quartz crystal. Extreme infrasonic frequencies are produced naturally in earth-quakes from which the waves travel through the earth's crust. Earth-quake waves have frequencies from 0.07 Hz down to 0.0003 Hz (one cycle per hour!). All such waves from the extreme ultrasonic to the extreme infrasonic are considered to have the same physical nature within the medium that supports them.

1.4 Wavelength

The length of a sound wave is the distance between successive bands of compression (or rarefaction), Fig. 1–1. The following relationship applies:

$$\text{Wavelength (m)} = \frac{\text{Velocity (m s}^{-1}\text{)}}{\text{Frequency (Hz)}}$$

The higher the velocity then, the longer is the wavelength at a given frequency. Consider a wave at 1000 Hz. The wavelengths in air, water and steel are 0.34, 1.5 and 6m respectively.

1.4.1 Wavelength and resonance

A cavity determines the wavelength at resonance, therefore the frequency at which a cavity resonates is determined by the velocity of sound and the dimensions of the cavity. We have considered the effect of temperature on the pitch of a flute. The same sort of reasoning applies to the pitch of the voice inasmuch as it depends on resonances within the throat, mouth and nasal cavities. An impressive demonstration of the consequence of a change in sound wave velocity and hence frequency is obtained when a subject speaks after inhaling helium gas. The cavities now respond at frequencies almost three times higher than normal and the voice that emerges has an unnatural squeaky quality.

1.4.2 Diffraction and wavelength

Diffraction is the phenomenon in which sound waves tend to bend round an obstacle in their path. The 'acoustic shadow' cast by an obstruction depends on wavelength. With long wavelengths diffraction is more effective and the shadow is ill defined. With shorter wavelengths there is less diffraction and the shadow is sharper. This factor is important to direction sense (Chapter 2).

1.5 Energy, power and intensity

The energy of a sound wave is carried by the mass of the displaced medium. A single wave carries forward a particular quantity of energy. A succession of waves produces a *flow of energy*, the magnitude of which depends on the amplitude and frequency of the vibrations and also on the density of the medium and the velocity of sound waves in it (Fig. 1–3).

$$\text{Energy flow } (\mathrm{W} = \mathrm{J\,s^{-1}}) \propto \underbrace{\rho}_{\text{density of medium}}\ \underbrace{c}_{\text{wave velocity}}\ \underbrace{a^2}_{\text{amplitude}}\ \underbrace{f^2}_{\text{frequency}}$$

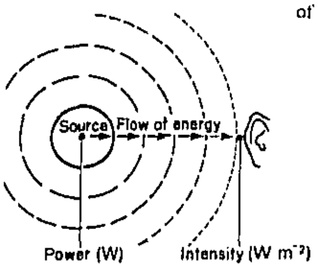


Fig. 1–3 Sound waves and energy.

The strength of a source of sound waves is described as its *power* (in watts); it is the magnitude of the flow of energy that the source can impart to the surrounding medium. Some examples of powers of orchestral instruments are given in Table 1. Considerations of power are important when assessing the likely effect of a source of sound at a given distance and when calculating the amount of energy that must be fed into the source.

Table 1 Power radiated by musical instruments at their maximum loudness (from Wood revised by J. M. Bowsher, 1975).

Source	*Power* (W)
Triangle	0.05
French horn	0.05
Clarinet	0.05
Flute	0.06
Piccolo	0.08
Double bass	0.16
Bass tuba	0.2
Bass saxophone	0.3
Piano	0.4
Trombone	6
Cymbals	10
Pipe organ	13
Bass Drum	25
Orchestra of 75 performers	70

The effect of sound waves at the receiving end is described by the *intensity* (W m^{-2}) (Fig. 1-3) or alternatively by the *pressure* (N m^{-2}). The former is the true measure of the energy flow but the latter is practically more realizable. A microphone will give a direct reading of pressure. The intensity is proportional to the square of the pressure. Increasing the power of a source by a factor of four will therefore cause the pressure to be doubled at any place in the path of the wave.

Inverse square law A sound wave travelling away from its source is imagined as an expanding spherical surface (Fig. 1-3). The total energy of the wave remains almost unchanged (losses due to friction are small in free air) but the intensity decreases with distance because the energy becomes more thinly spread. In the 'ideal' situation of a point source radiating equally in all directions the intensity is proportional to (distance)$^{-2}$. This will not hold exactly in many real life situations because of reflections of the room and the directionality of the source of sound, but it provides an approximate guide.

An application where the inverse square law definitely does not apply is when the medium is confined so that the energy is not allowed to spread. For example, in a speaking tube, (an early method of long distance communication employed in ships and large buildings) the voice is carried over large distances with relatively little attenuation.

1.6 The decibel scale

The range of audible intensities is extremely wide, extending from around 10^{-12} W m^{-2} up to 10 W m^{-2} (the latter being the intensity, for example, near the runway during a jet plane takeoff). If the intensity is increased steadily throughout the range one would experience increasing loudness but fortunately not in direct proportion to the intensity. There would be ever diminishing changes of loudness for the same increments of intensity. In other words the changes in sensation appear to be proportional to the *relative* changes of intensity (§ 2.3). Some kind of logarithmic scale of intensity is therefore appropriate to relate intensity to loudness. Acoustic calculations involving

Table 2 Decibel notation: A in terms of energy ratio; B in terms of pressure ratio. Pa (pascals) = N m^{-2}.

A	Relative intensity = $10\log_{10}\left[\dfrac{\overset{\text{intensity no. 1 (W m}^{-2})}{I_1}}{\underset{\text{intensity no. 2 (W m}^{-2})}{I_2}}\right]$ decibels (dB)
B	Relative intensity = $20\log_{10}\left[\dfrac{\overset{\text{pressure no. 1 (Pa)}}{P_1}}{\underset{\text{pressure no. 2 (Pa)}}{P_2}}\right]$ decibels (dB)

consideration of amplification and attenuation are concerned too with relative rather than absolute values. The calculations are simplified by the use of a logarithmic scale: the decibel scale (Table 2).

A quantity expressed in decibels represents an *energy* ratio. Measurements of sound levels are usually made in units of pressure, nevertheless the level (in decibels) remains the energy ratio. For example doubling of pressure is equivalent to quadrupling of intensity, hence the factor 20 (instead of 10). It is useful to memorise a few commonly used decibel quantities (see Table 3).

Table 3 Decibel quantities to remember. (Note that ratios for 3 dB and 6 dB have been rounded to whole numbers, according to common practice.)

Decibels	*Intensity ratio* (I_1/I_2)	*Pressure ratio* (P_1/P_2)
0	1	1
1	1.26	$1.26^{\frac{1}{2}}$ (=1.12)
3	2	$2^{\frac{1}{2}}$ (=1.41)
6	4	2
10	10	$10^{\frac{1}{2}}$ (=3.16)
20	100	10

1.6.1 *Absolute levels in decibels*

Although the decibel scale expresses relative energy it is used to describe absolute values by using an agreed reference standard. The reference for

Table 4 Absolute intensity levels, in decibels, of various sounds. (The values are 'A weighted' - see Chapter 5).

$$\text{Sound Level} = 20\log_{10}\left[\frac{\overset{\text{Measured pressure in Pa}}{\overset{\downarrow}{p}}}{\underset{\substack{\text{Threshold of}\\ \text{hearing (Pa)}}}{\underset{\uparrow}{2\times10^{-5}}}}\right]\ \text{dB (SPL)}$$

Jet takeoff (from 60 m)	-	130 dB
Shot gun blast	-	100 dB
Car horn at 6 m	-	90 dB
Inside sports car at 50 mph	-	80 dB
Loud thunder	-	70 dB
Normal conversation	-	60 dB
Typical room	-	40 dB
Soft whisper at 1.5 m	-	30 dB
Open country	-	10 dB

intensity is 10^{-12} W m^{-2} and that for pressure is 2×10^{-5} Pa (20 μ Pa). These are related and represent the typical hearing threshold in man at the frequency where hearing is most sensitive (see Chapter 2). When pressure readings are used, as is normally the case, we speak of the *sound pressure level* (SPL) in dB. The threshold of hearing is thus 0dB (SPL) and a jet takeoff is 130 dB (SPL). See Table 4 for other examples.

2 Some Properties of Hearing

The essence of hearing is the experience of *tonality*. When we hear sound waves we do not perceive the actual vibrations of the waves but there is instead a tonal quality. The relationship between tonal quality and frequency is called the *sense of pitch*. Vocal communication depends on the sense of pitch to discriminate gradations of frequency; we begin by discussing this ability.

2.1 Pitch

It may be said of an individual, usually a musician, that he has *perfect pitch*. It means that he can identify and/or reproduce the frequencies of tones with remarkable precision. Such a talent highlights the accuracy with which the sense of pitch can be used. On the other hand it may be said of another that he is 'tone deaf'. This refers specifically to lack of musical ability. He has difficulty with the enjoyment of music or he is unable to sing in tune. It does not mean that he cannot experience tonality. It does *not* mean that he lacks the sense of pitch.

2.1.1 *Complex and simple sounds*

Most sounds are complex; they consist of mixtures of tones and they usually have definite temporal structures. At one extreme the clear sounding notes of the flute, when they are analysed, are found to be combinations of a number of frequencies occurring simultaneously. At the other extreme of complexity, the elaborate sound of a spoken word is the cumulative effect of a rapid sequence of vowel sounds and consonants each element of which is made up of three or more frequencies. In a scientific study it is not practicable to analyse the fundamental properties of hearing with complex 'real life' sounds. Instead we use so-called 'simple' sounds: pure tones. These are sound waves consisting at any one time of just a single frequency, usually generated by an electrical oscillator.

2.1.2 *Frequency discrimination*

A limiting factor in the recognition of sounds is the ability to recognize slight differences of frequency. This is termed frequency discrimination and measured with pairs of pure tones (Fig. 2–1). The least change of frequency that is perceptible as a shift in pitch is called the *difference threshold* (or *difference limen* or the *just noticeable difference*) for frequency. The best frequency discrimination is found with comparatively high pitched sounds (1000–5000 Hz) where a change of 0.3% is detectable. At low frequencies the ability is not as good, for example at 100 Hz it is only 3% (see Table 5). In music a change of frequency is

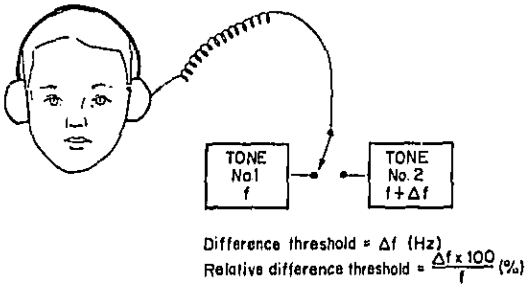


Fig. 2-1 Measurement of difference thresholds. The headphones are switched from one tone generator to another repeatedly. Tone No. 1 is of independent frequency (f) and tone No. 2 is adjusted by the subject to sound just noticably different in pitch (f ± Δf).

termed an *interval*. The smallest interval commonly used is the *semitone*, which is a change of about 6%. The semitone is the difference in sound between a note that is 'natural' and one that is 'sharp' or one that is 'flat'. An interval of one semitone is well above the difference threshold for the frequencies used in music. A musician is normally aware (sometimes painfully so) of errors of *quarter tones* (a difference of 3%), or even less.

Table 5 Difference thresholds for frequency (data from Shower, E. G. and Biddulph, R. (1931), *J. Acoust. Soc. Am.*, 3, 275–87).

	Δf	$\Delta f/f$
100 Hz	± 3.0 Hz	± 3.0%
200 Hz	± 3.2 Hz	± 1.6%
500 Hz	± 2.5 Hz	± 0.5%
1000 Hz	± 3.0 Hz	± 0.3%
2000 Hz	± 5.0 Hz	± 0.3%
5000 Hz	± 15 Hz	± 0.3%
10 000 Hz	± 40 Hz	± 0.4%

2.1.3 Auditory range

The span of sound frequencies producing tonal qualities is called the *auditory range*. The range is normally from 16 Hz up to about 15000 Hz in young adults. Children can hear frequencies up to 20000 Hz or more, while many of the elderly cannot hear beyond 5000 Hz. There is considerable variation between individuals of each age group but in general the ability to appreciate high frequencies deteriorates with advancing years.

The upper limit of the auditory range is defined simply by the inability to hear frequencies beyond it. The lower limit is less easy to pin-point; it is more a place of transition. Frequencies below 16 Hz are perceived as vibratory or fluttery sensations, rather than tones, while those above 16 Hz have a definitely tonal sound.

2.1.4 *Frequency and audibility*

The sensitivity of hearing varies across the auditory range. If different tones are sounded at the same intensity it is found that those with frequencies near the centre of the range sound louder than those towards the two extremes. Alternatively if the tones are adjusted so as to sound equally loud it is then found that greater intensities of the sound waves are needed towards the extremes of the range.

The property just described is represented by a *curve of equal loudness* (Fig. 2-2). The complete description requires a family of curves because the exact relationship depends on the general level of sound intensity; the *loudness level*. The lowest level, labelled 'barely audible' is known as the *audibility curve* because it describes the threshold of hearing as a function of sound wave frequency.

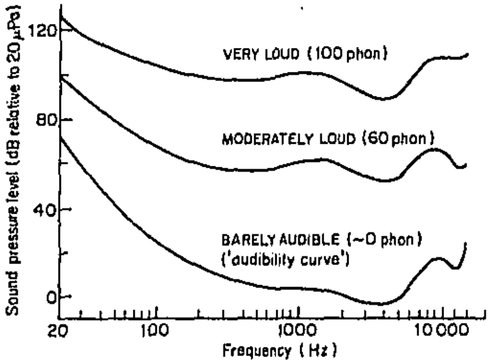


Fig. 2-2 Curves of equal loudness. The upper two curves were obtained by adjusting the intensities of various tones to sound equally loud as one of 1000 Hz. The lower curve represents the threshold of audibility as a function of frequency. Note that loudness level is given in *phons* rather than dB (see text). (After Robinson, D. W. and Dadson, R. S. (1956), *Br. J. Appl. Phys.* 7, 166.)

Notice that the slope of the curve changes with the loudness level (this is why a family of curves is needed). They become flatter with increasing loudness. If at a high level of loudness (labelled 'very loud') a tone of 100 Hz were made to sound as loud as one of 1000 Hz the intensities of the two tones would be found to be about equal, but at a lower level the intensity at 100 Hz would need to be relatively greater. For example at the lowest level ('barely audible') this discrepancy would be about 100-fold (20 dB).

An important application of the curves is in the designing of equipment for the reproduction of music and speech, since it is evident that the amount of compensation at low frequencies (bass boost) should be adjusted to suit the loudness if the tonal balance is to remain the same. More boost is required at low, than at high, levels otherwise as the loudness is decreased the sound becomes 'thin' or 'tinny', or conversely it becomes 'boomy' as the loudness is increased. A reference set of equal loudness curves is available (British Standard No. 3383 (1961)).

The reference tone and the phon scale The agreed reference tone for equal loudness curves is 1000 Hz. The 'very loud' curve, for example, was constructed using the reference tone at an intensity of 100 dB; for the 'moderately loud' curve it was 60 dB. In each case the intensities at the other frequencies were adjusted to sound equally loud. In order to specify a particular loudness level it would be quite proper to request 'that level at which the intensity at 1000 Hz is 60 dB'. The preferred way, however, is to describe the level as '60 *phons*'. The phon scale was invented to provide unambiguous description of loudness level. The level in phons is numerically equal to the intensity at 1000 Hz corresponding with that level. The intensities to other frequencies are then available from the appropriate curve.

It is emphasized that the phon scale is *not* a scale of absolute loudness. Although ascending the scale corresponds to progressive increase of loudness, no mathematically defined relationship is implied between one level and another. The scaling of absolute loudness has been attempted and presents a separate problem (see § 2.3).

2.2 Discrimination of sound intensity

Emphasis and stress are essential ingredients of spoken language and music. They often convey the meaning. They depend largely on the ability to communicate by *changes* of loudness. The capacity to discriminate small fluctuations of intensity is therefore both part and parcel of auditory experience.

2.2.1 *The difference threshold of intensity*

The limiting quantity for intensity discrimination is the *difference threshold of sound intensity* (known also as the difference limen, or just noticeable difference). It is the least increment of intensity that is perceived as a change of loudness. It can be measured by presenting a subject with a pair of sounds in succession and inviting him to judge which is louder. One of the pair is of fixed intensity and the other is variable. The test is repeated until, by the process of adjustment, the smallest discernable increment has been estimated. This method involves 'loudness memory' since a certain time elapses between the two stimuli. Another method, perhaps more sensitive, employs 'loudness modulation' – here the intensity is made to oscillate between two levels and the subject has to reduce the fluctuation until it seems almost to vanish.

It is found that the difference threshold increases with the loudness level but, for a given type of sound, the *relative* change remains remarkably constant (see Fig. 2-3). Intensity discrimination is best for the middle frequencies of the auditory range (1000-4000 Hz). Discrimination is worsened by background noise (see below); under very quiet conditions it is practicable to realize a threshold of ±10% (±0.4 dB).

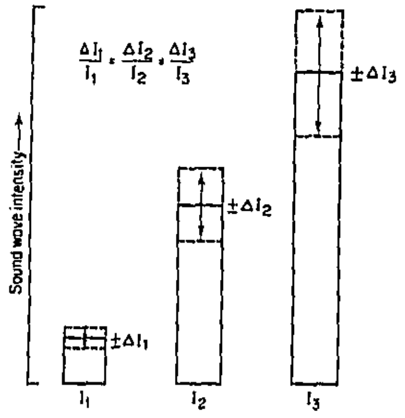


Fig. 2-3 Intensity discrimination. The difference threshold for sound intensity (ΔI) increases with the sound level (I) but the relative change ($\Delta I/I$) is almost constant.

2.2.2 *Noise and intensity discrimination*

'Noise' in the immediate context means a non-specific sound made up of a broad range of frequencies. The kind of 'rushing' or hissing sound that is loudly produced by, say, escaping gas or a waterfall. This kind of sound when produced artificially, is called 'thermal noise' or 'white noise'; the latter because it contains a similar measure of every frequency in the auditory range (and often beyond).

The presence of noise impairs the audibility of speech and other meaningful sounds. This is *masking*, the phenomenon of hearing where one sound is rendered less audible by the presence of another. Quite low levels of noise produce significant masking. It can be a nuisance but it is often beneficial, in a library for example, a low level of background noise can hide other more distracting sounds.

The masking effect of noise appears to obey the general rules of intensity discrimination provided that we *add* the intensity of the noise to that of the

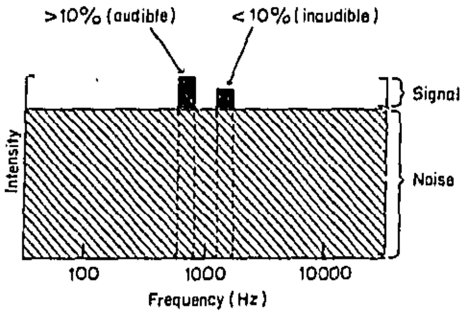


Fig. 2-4 Noise and audibility. When a meaningful sound (a 'signal') is superimposed on broad-band noise the intensities of the common frequency components effectively add together. The signal is audible only if its intensity is greater than the difference threshold (10%) for the total intensity.

specific sound when calculating the relative difference threshold. Consider the audibility of a pure tone in the presence of noise (Fig. 2-4). The frequency spectrum of the noise includes the frequency of the tone, therefore the total intensity at that frequency is the *sum* of the intensities of the tone itself and the

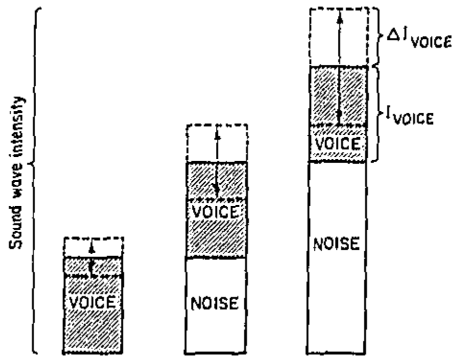


Fig. 2-5 Noise and intelligibility. The perception of speech involves appreciation of small fluctuations of intensity. The limiting factor is the difference threshold of intensity. This factor is determined by the total intensity at the frequencies common to the voice and the noise (see Fig. 2-4). Therefore, although the difference threshold remains unchanged relative to the total intensity, that for the voice alone increases progressively with the intensity of the noise (c.f. Fig. 2-3).

corresponding component of the noise. The tone will be heard above the noise *only* if it contributes more than 10% (see above) of the *total* intensity at that frequency. Otherwise the noise will completely mask the tone rendering the latter inaudible.

We can now extend the discussion to consider how noise changes the ability to appreciate *changes* of intensity, thereby affecting the intelligibility of speech. It was stated earlier that a fluctuation of intensity of 10% is just detectable under very quiet listening conditions. Under more usual conditions discrimination is worse than this. It is found that the threshold rises progressively with the amount of background noise (Fig. 2-5). In ordinary 'quietish' room conditions the threshold is likely to be about ± 25% (± 1 dB).

Signal-to-noise ratio Background noise can be a problem in the reproduction of sound and in radio and telephonic communication. The sources of noise are: electrical components (valves, transistors and resistors); recording media (tape, disc, film); and, in the case of radio transmissions, electrical disturbance in the atmosphere. The noisiness of the system is described by the *signal-to-noise* ratio; the 'signal' being the wanted part of the sound. The ratio is stated in decibels. As an example consider the background noise in sound recordings. When the earliest cylinder recordings are played today the voice is almost swamped by the surface hiss and is only just intelligible. In this case the signal is probably no more than double the intensity of the noise – in which case the signal-to-noise ratio is 3 dB, or less. For a moderately worn 78 rpm shellac record the ratio is typically about 45 dB, much better but still having noticeable surface hiss. With modern tape-cassette equipment of average quality, the signal-to-noise ratio is 60 dB or more, the noise being almost imperceptible.

2.2.3 *Masking by similar sounds*

The character of the masking sound (i.e. noise) in the case we were considering, was quite different from that of the signal (pure tone, or music). But masking occurs with any combination of sounds. For instance, when two pure tones are heard simultaneously they tend to mask each other. The effect is greatest when the frequencies are similar but still exists even when the frequencies are quite widely separated (Fig. 2-6).

As an illustration of the potency of masking imagine a choir of 100 unaccompanied voices singing the same note in unison. There is a small spread of frequency because of individual variation but the voices still mask each other substantially. If one member of the choir suddenly stopped singing, leaving the others to continue, would this be noticed by the audience? Hardly, because a single voice contributes only about 1% to the total intensity at that frequency band whereas, as we have seen, a change of 10% or more is necessary to produce a noticeable difference. It would be necessary to silence at least ten members to elicit a detectable change.

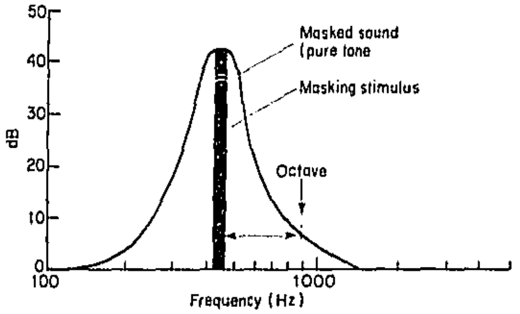


Fig. 2-6 The *masking stimulus* in this experiment was a constant, narrow band of frequencies of fixed intensity. The *masked sound* was a pure tone whose frequency and intensity could be varied. The object of the experiment was to find the threshold of the masked sound in the presence of the masking stimulus. The ordinate gives the elevation of threshold above that obtained when the masking sound was absent and thus provides an index of masking. Notice that the masking is high when the frequencies are similar but declines steeply as they are separated. When the separation is one octave or more the masking has little effect. (Curve redrawn from Egan, J. P. and Hake, J. W. (1950), *J. Acoust. Soc. Am.*, 22, 622.)

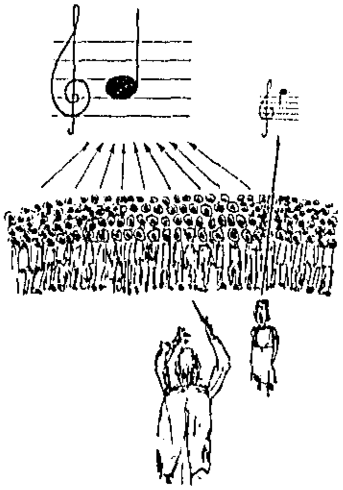


Fig. 2-7 Frequency selectivity of hearing (see text).

2.2.4 *The lack of masking by dissimilar sounds*

We will now look at masking from another point of view and describe circumstances where it is relatively ineffective. From common experience we know that quite weak sounds can easily be heard in the presence of strong ones provided that the frequencies of the different sounds are separated. Extending the musical illustration: if a soloist joins the 100-strong choir but singing the note one octave higher, then this single voice will normally be distinctly heard above the rest (Fig. 2-7). Or consider the sound at a football match, when it is possible to hear the referee's whistle above the cheering of several thousand spectators.

The phenomenon is quantitatively represented by the curve for masking in Fig. 2-6. Evidently the range of frequencies for effective masking is quite narrow; once outside this range the threshold of detectability of another sound falls steeply with frequency. At a separation of one octave or more the threshold is practically independent of the masking sound. In other words, the sense of hearing displays *frequency selectivity*. This property is surely more remarkable than masking. It demonstrates that sounds of substantially different frequencies do not interfere and suggests, as will be shown to be the case physiologically, that the sensory information in each narrow band of sound wave frequencies is channelled separately to the brain.

2.3 How loud?

It is in our nature to recognize changes of loudness but not to quantify loudness in absolute terms. We know when a sound is too soft, too loud or just right but we cannot state, with any confidence, that a given level of intensity causes, say, three times rather than five times the loudness of another. Despite this difficulty it would be useful for scientific purposes to have some kind of numerical scale of loudness. Several studies have been conducted with such an

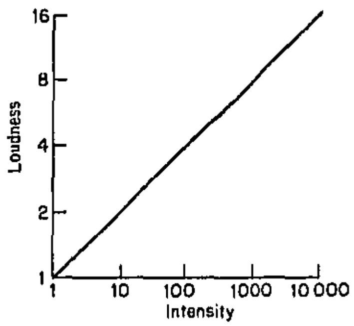


Fig. 2-8 A scale of loudness (see text).

objective. A straightforward test was employed. The subject was asked to adjust the intensity of a tone until it seemed either twice as loud or half as loud as before. The test was repeated at various intensities. The fundamental problem is to know what the experience of 'twice as loud' is like, and the different research groups arrived between them at a variety of conclusions concerning the intensity factor. All agreed, however, that in order to change loudness by a factor of two, it is necessary to alter the intensity by a factor greater than two. One result that has been widely accepted states that doubling (or halving) of loudness requires a ten-fold change of intensity. A graph constructed on this basis is given in Fig. 2-8.

To illustrate the property we will return to the concert hall and the singing voices. Imagine we are suspended, like a microphone, over the auditorium about equidistant from each performer and from each member of the audience. For simplicity it is assumed that every voice in the hall is capable of producing a similar power. According to the 'ten-fold relationship', the 100-strong choir should produce four times the loudness of a solo voice. If an audience of 1000 people join in singing lustily, the loudness should rise to eight times that of a solo voice. As a larger example, consider a sports stadium containing 100 000 spectators. To an observer at the centre of the arena, the sound of the roar of the crowd should sound 32 times as loud as a single voice. The reader must decide from personal experience whether or not these predictions are reasonable.

2.4 Hearing in mammals other than man

The assessment of hearing in mammals has been carried out using: (*i*) The neurophysiological method; (*ii*) the reflex response method, and (*iii*) the behavioural method.

The neurophysiological (or electrophysiological) approach requires the monitoring of electrical activity of the ear or brain in response to sound waves.

The reflex response approach exploits a reaction to a sound stimulus, for example, some animals flick both ears in response to sound (the pinna, or Preyer, reflex). Signs, such as changes in heart rate or in the pattern of breathing, have also been used as indices of hearing.

The behavioural method involves the animal in some kind of training programme in association with an auditory stimulus, either in order to set up a conditioned response or to teach it to expect a reward for a correct response. This method is the more arduous for the experimenter but provides the better indication of auditory *ability*.

The majority of work on the hearing capabilities of animals has been concerned with auditory range. We will concentrate on that aspect.

2.4.1 Auditory range

The frequency spans of hearing ability for a selection of mammals are given in Figs 2-9 and 2-10. The relative sensitivity as a function of frequency is given in each case, as derived from the audibility curve.

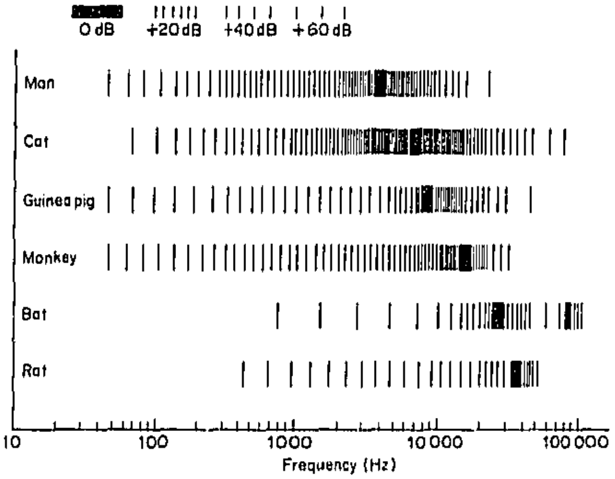


Fig. 2-9 Frequency sensitivity in land mammals. The 'best frequencies' in each case are indicated by a solid bar and normalized to 0 dB. The relative threshold at other frequencies is indicated by the bar spacing (see key). (Notice that the bat (greater horseshoe bat) has two sets of best frequencies). (data from various sources.)

The most significant part of the auditory range is that region where sensitivity is greatest, and referred to as the '*best frequency*'. In man this is around 4000 Hz (see also Fig. 2-2). This is low compared with some other mammals. In certain species the greatest sensitivity evidently occurs at frequencies beyond the upper limit of human audibility.

The 'best frequency' in each species is towards the high frequency end of its auditory range. In comparative hearing it is sensitivity to high frequencies that has excited the most interest. The ability to hear *very high* frequencies (beyond 40 000 Hz) among the vertebrates is special to mammals. Birds cannot detect frequencies beyond about 20 000 Hz and in reptiles the upper limit is probably no more than 10 000 Hz. The majority of mammals that have been tested responded to tones in excess of 40 000 Hz, some above 60 000 Hz and a few beyond 100 000 Hz. That is not to say that *all* mammals have this special ability. It should be stated that, for reasons of experimental convenience, most of the species examined so far have been small in size (with the exception of water mammals). Of the larger species, man has a relatively low upper limit (typically about 15 000 Hz).

The limitations of hearing ability in the larger land mammals is comparatively little known. The prospect of testing a lion or a rhinoceros or even a cow or a horse is understandably a daunting one. Nevertheless in a recent study the auditory range was obtained for a young elephant and it was found to be unresponsive to tones in excess of about 10 000 Hz. This suggests that size, especially head size, is the determining quantity for sensitivity to high frequencies (see also below) but many more species need to be examined before one can decide with confidence whether the attenuated auditory range in man is a peculiarly human (and elephantine) failing or a consequence of physical dimensions.

Water mammals, as a group, enjoy an impressive ability to detect high frequencies in water-born sound waves. The best-frequency of the bottle-nosed dolphin is around 60 000 Hz. Lest it might be supposed that the medium is in some way responsible it should be noted that for a human under water the best frequency is rather lower than it is in air (Fig. 2-10).

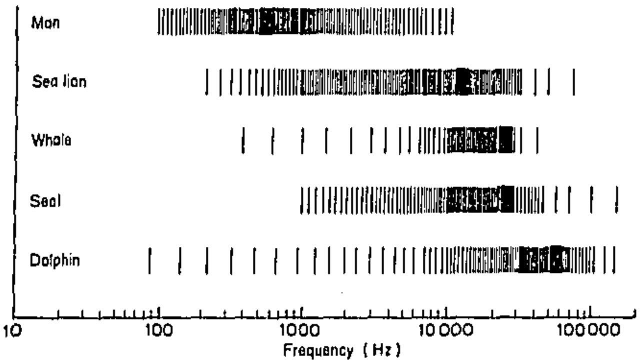


Fig. 2-10 Underwater hearing in water mammals (and man). Conventions as in Fig. 2-9. (From data quoted by Popper, A. N. (1980). In *Cetacean Behaviour: mechanisms and functions*. Ed. L. M. Herman. John Wiley & Sons, New York.)

2.5 The significance of high frequencies in hearing

The ability to hear high frequencies is involved in direction sense. The head tends to shield the ear furthest from the source and the resulting disparity between the intensities at the two ears indicates the direction of the sound waves. This is not the complete basis of auditory localization but it is an important part. The significance of high frequency hearing ability is because the diffraction of soundwaves round the head decreases with wavelength. The 'acoustic shadow' cast by the head on the further ear, becomes deeper with increasing frequency.

Sense of direction is relevant to vocal communication and it is significant that the essential frequencies of human speech and also the more urgent cries of other mammals are relatively high in their respective auditory ranges, corresponding with the region of the 'best frequency'. Many sounds in nature, whether vocal or otherwise, contain components of high frequency which can provide auditory clues to the direction of their source.

The size of the head is another factor that determines the degree of acoustic shielding. The smaller the head the shorter must be the wavelength for equivalent inter-aural difference of intensity. This, it has been suggested, is why small mammals have ability to detect particularly high frequencies and why, as has been found in mice, certain kinds of vocal communication, notably distress calls, are carried on at ultrasonic frequencies.

Echo-location is a specialized adaptation of sound wave production and hearing, employed by certain species of bats and water mammals. They emit bursts of sound waves and from the echoes can navigate and catch prey, apparently obtaining a picture of the immediate surroundings from the acoustic reflections. The pulses produced by bats depend on the species and they usually contain components in the range 60 000 Hz to 100 000 Hz. Dolphins have an especially elaborate repertoire of echo-locating pulses: the bottle-nosed dolphin can vary the frequency contained in the pulse from 35 000 Hz to 130 000 Hz. Hearing ability in such species is evidently suited to receive the high frequency components of the pulses. In echo-locating bats the audibility curves are sharply tuned – the species represented in Fig. 2-9 has two 'best frequencies' the higher one presumably related to echo-location is very sharply tuned at 83 000 Hz.

The limiting factor in the resolution of small objects by echo-location is wavelength. Effective reflection of sound waves does not occur if the wavelength is longer than the object in question. Hence the significance of high frequencies. For example, in order to detect an insect of wingspan 5 mm the wavelength must be 5 mm (0.005 m), or less, necessitating a frequency (in air) of 68 000 Hz, or more. Wavelength under water at a given frequency is about four times longer than in air, therefore correspondingly higher frequencies are needed to detect an object of a given size.

3 Transmission of Sound Waves in the Ear

The previous chapter dealt with hearing from a psychological standpoint. We now turn to physiology and seek the mechanisms underlying auditory experience. The traditional physiological approach to a system of the body is to find the properties of the component mechanisms individually and then reconstruct the overall behaviour from the sum of the parts. In the case of the ear and hearing there are distinctly different regions that work in series. The *outer ear* channels sound waves to the ear drum; the *middle ear* in which the vibrations of the ear drum are intensified and focussed onto the inner ear; and the *cochlea*, the part of the inner ear which houses the organ of hearing.

3.1 The outer ear

The principal parts of the outer ear are the *pinna* ('feather'), the *concha* ('shell') and the *ear canal* (see Figs 3–1 and 3–2). The pinna is important for direction sense, especially in those animals where it is large and under muscular control. The concha is a bowl shaped cavity which forms the entrance to the ear canal. Concha and ear canal modify the sound in a positive way and so influence the frequency sensitivity of hearing.

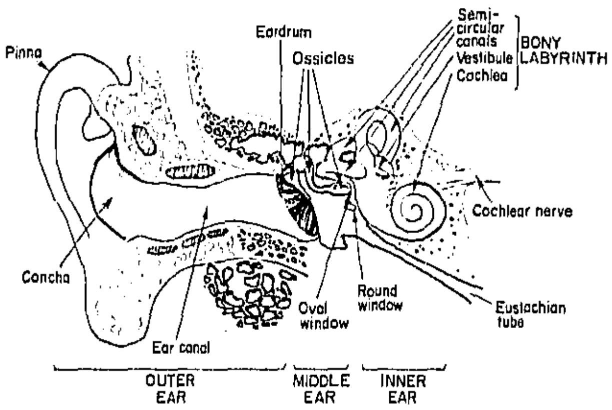


Fig. 3-1 The parts of the ear. (Adapted from Davies, H. (1959). In *Handbook of Physiology*, Vol. 1, American Physiological Society, Washington.)

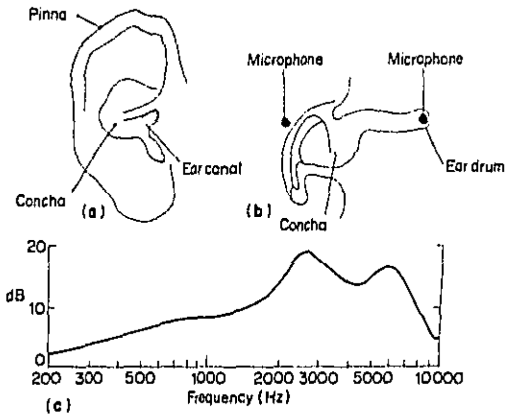


Fig. 3-2 The outer ear. (a) external view; (b) internal chambers (horizontal section) and the positions of microphones to measure frequency response; (c) frequency response of the outer ear measured at the ear drum. The sound source was directly in line with the ear canal. The graph gives the difference in pressure between a microphone outside the ear and the one inside. (After Shaw, E. A. G. (1974). In *The Auditory System. Handbook of Sensory Physiology*, Vol. V, part 1. Eds. W. D. Keidel and W. D. Neff. Springer, Berlin.)

3.1.1 'Tuning' in the outer ear

Acoustic properties of the outer ear have been determined by comparing the sound waves arriving at the ear with those reaching the ear drum. The method employs two microphones, a very small one inserted in the ear canal and another just outside the ear (Fig. 3-2b). Using pure tones it has been found that the outer ear is 'tuned' to sound waves having frequencies in the range 2-7 KHz. In effect these frequencies of sound are selectively amplified. There are two maxima; at 2500 Hz and at 6000 Hz (Fig. 3-2c). This property of the outer ear accounts, in part at least, for the greater sensitivity of hearing at those frequencies important for the perception of speech.

The nature of the tuning is the same as that in any air-filled tube which is closed at one end and has a disturbance applied to the other. Standing waves occur at those frequencies where the wavelength in air is about four times the length of the tube. This amounts to amplification at these frequencies. This phenomenon applies to the flute, the 'flue' pipe of a church organ and accounts for the sound obtained by blowing across the top of an empty bottle. The sharpness of tuning in such a system is not acute, therefore sounds over a range of frequencies about the central value are accentuated.

The concha and ear canal behave as separate cavities whose individual properties add together. The concha alone, if it were a tube closed at one end, would accentuate frequencies around 5000 Hz. The ear canal alone would accentuate those around 3000 Hz. (Calculations upon which these predictions are made take into account certain 'end corrections' – the effective length of a tube being longer, in relation to its acoustic properties, than the actual length.) The result of combining the two chambers was tested on a simple model. There were two maxima corresponding with the result obtained in the real ear. Concha and ear canal have complementary properties, therefore. The combined effect is to amplify sound waves over a broad range of frequencies.

When comparing the hearing abilities of different species, the dimensions of the outer ear provide significant clues. Figure 3-3 shows dimensions of the cavities in man, cat and guinea-pig. The decreasing size corresponds with the increase in the frequency of maximum sensitivity.

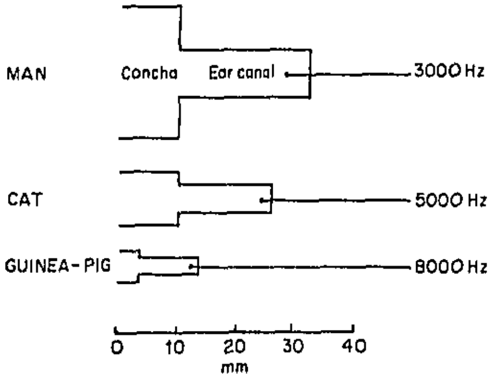


Fig. 3-3 Sizes of the concha and ear canal in different species with the frequency of maximum response (calculated from the length of the ear canal). (Dimensions taken from Shaw, E. A. G., 1974.)

3.2 The middle ear

The middle ear is an air-filled chamber containing a mechanical linkage by means of which airborne vibrations of sound, collected by the ear drum, are impressed on the watery fluid of the inner ear (Fig. 3-1). The air in the middle ear is maintained at atmospheric pressure via the eustachian tube (Fig. 3-1). The moving parts of this linkage are three bones known collectively as the *auditory ossicles* and individually as *malleus* (hammer), *incus* (anvil) and *stapes* (stirrup) (Fig. 3-4).

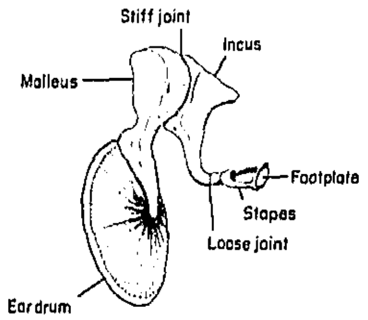


Fig. 3-4 The auditory ossicles. (After BÉKÉSY, G, 1957.)

3.2.1 Mechanical transmission

In response to sound waves, the ear drum acts on the malleus. The head of the malleus behaves as a pivot and its rotatory movement is coupled to the incus. Malleus and incus are joined firmly together and rotate as a single unit. The motion is transferred to the stapes which exerts plunger-like compression on the contents of the cochlea. The cochlea has two openings to the middle ear: an *oval window*, which is closed by the footplate of the stapes, and a *round window* which is closed by an elastic membrane. In order for sound to be detected there must be *displacement* of the fluid of the cochlea (the details will be given in Chapter 4).

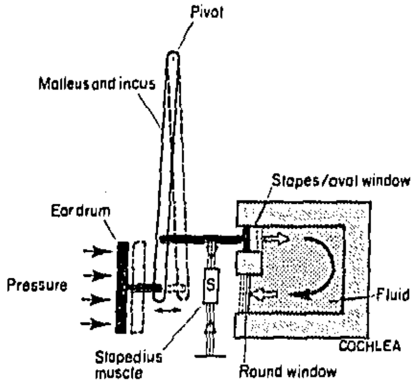
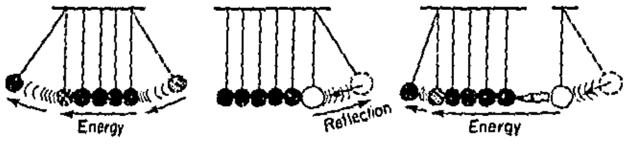


Fig. 3-5 Schematic model to illustrate the mechanism of the middle ear.

The function of the membrane of the round window is to accommodate the displacement by virtue of its distensibility. The system of ossicles magnifies the pressure of sound waves and concentrates it onto the oval window. Energy collected over the surface of the ear drum is transferred to the much smaller area of the footplate of the stapes. In addition the stapes is attached nearer to the pivot of the system than is the ear drum and thereby derives mechanical advantage with regard to force (see Fig. 3–5). The two factors combined produce an estimated 20-fold amplification of pressure.

3.2.2 The significance of force amplification

Damage to the middle ear mechanism results in severe impairment of hearing. In these circumstances airborne sound waves can exert an effect only by acting directly at the round and oval windows. This situation highlights the importance of the normal middle ear mechanism. When sound waves strike the round or oval window they are in effect striking a water surface and most of the energy is reflected – only a tiny proportion is absorbed. The moving mass of gas has a very low inertia compared with the fluid of the inner ear. The effect of the ossicles is equivalent to increasing the density of air by twenty times, thereby creating a more efficient transfer of energy to the inner ear: a better *impedance match* (see Fig. 3–6).



(a) Perfect match (b) Mismatch (c) Partial match

Fig. 3–6 Model to illustrate the concept of energy transfer and impedance matching in the middle ear. The model employs a 'Newton's cradle' consisting of a system of identical steel balls suspended in contact. (a) If a ball at one end is swung to collide with the rest, it comes to rest immediately; the energy is completely transferred through the system to the ball at the other end. This illustrates perfect impedance matching. (b) If a much lighter ball, a table tennis ball say, is made to collide with the system, it bounces off leaving little, if any, motion in the steel balls. This represents a hopeless mismatch of impedance. (c) Matching can be improved by interposing a pointed rod, say a sharpened pencil, to increase the force. It is found that significant transfer of energy now occurs.

Another relevant factor is the requirement to produce a difference of pressure between oval and round windows. If this were not so, as in the case of the damaged middle ear, then both windows would receive the same airborne sound waves and so experience identical pressure fluctuations simultaneously. This would minimize the displacement of cochlear fluid and hence the detection of sound. A proportion of the deafness due to loss of middle ear function is attributable to this factor. Hearing in such patients has been considerably improved by introducing a sound shield over one of the windows to facilitate a pressure difference.

3.2.3 Muscles of the middle ear

Jointing between the auditory ossicles is under muscular control. There are two muscles and they pull at strategic places in the mechanical transmission system: the *tensor tympani* muscle, attached to the malleus, and the *stapedius* muscle that pulls at the neck of the stapes (Fig. 3–7). The primary purpose of the tensor tympani is to control the angular relationships between the ear drum and the system of ossicles; it provides postural adjustment to compensate for movement of the body and inclination of the head. The purpose of the stapedius is to regulate the freedom of movement of the ossicles and thereby influence the transmission of sound in the middle ear (see also Fig. 3–5). The stapedius muscle, in particular, responds directly to sound: it has an 'acoustic function'.

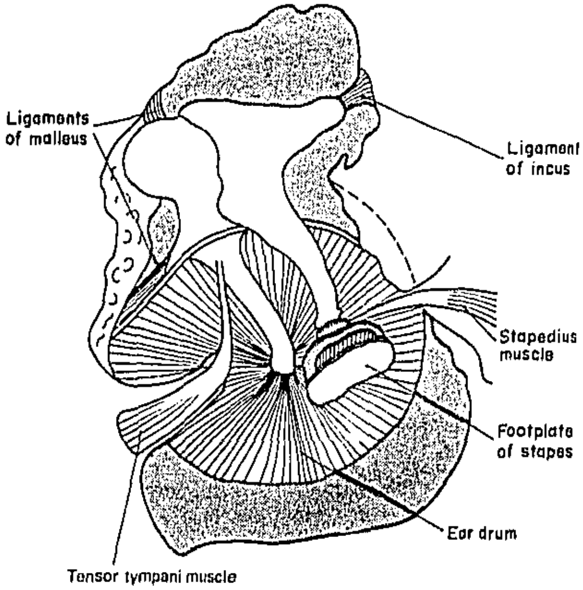


Fig. 3–7 Muscles of the middle ear. The tensor tympani is attached to the handle of the malleus. When it contracts the eardrum is pulled *towards* the middle ear. The stapedius is attached to the stapes and pulls it sideways. Contraction of the stapedius muscle stiffens the transmission mechanism.

The tensor tympani is influenced mainly by factors other than sound (head position etc); its function is therefore regarded as 'non-acoustic'.

3.2.4 The stapedius reflex

The stapedius muscle contracts in response to sound, especially intense sound. The response is known as 'the acoustic middle ear muscle reflex' or alternatively as 'the stapedius reflex'. It is a mechanism by means of which the sensitivity of hearing is adjusted. The reflex was observed originally by watching the middle ear muscles through a hole in a patient's perforated ear drum. When a loud sound (80 dB or more) was applied the stapedius muscle was seen to contract. The reflex is *bilateral* since a sound applied to either ear produced the reflex in the observed ear. The stapedius reflex has been observed and measured in several species of mammal as well as in man.

Protective function of the reflex? It had been supposed for some time that the primary purpose of the stapedius reflex is to protect the inner ear against damaging vibrations of intense sounds. This is an attractive idea which must have a degree of validity, but is difficult to accept as the complete *raison d'être* for the evolutionary development of the reflex and estimates of the amount of attenuation that the reflex can produce suggest that it cannot afford a great deal of protection. Modern experience shows how easy it is for hearing to be permanently damaged by exposure to noise despite the reflex (Chapter 5). Furthermore there is a delay of about 30 msec (in man) between the onset of a sudden loud sound and the initiation of contraction of the stapedius muscle, consequently there is no protection at all against impulsive sounds. An alternative purpose for the reflex, according to recent work, is in the discrimination of vocal sounds. The idea derives from consideration of the frequency sensitivity of the reflex and the nature of the disability associated with loss of the reflex.

Frequency sensitivity of the reflex The stapedius reflex is a sustained contraction of that muscle related to the level of sound intensity. The effect is to stiffen the movements of the auditory ossicles and so attenuate the transmission of ongoing sound waves but the attenuation is not the same at all frequencies. The intensity of low frequency sound is reduced more than high frequency sound. Sounds above 2000 Hz are hardly attenuated at all but those below 1000 Hz are substantially affected. The result is to diminish the loudness of the deeper components of the voice.

Antimasking and speech perception In order to recognize speech sounds there must be good sensitivity of hearing for the range 1000–3000 Hz but the most intense components of the human voice are at 400–500 Hz. In the absence of the stapedius reflex the low frequency sound tends to mask that at higher frequencies and so impair speech perception. Normally the contraction of the muscle leads to attenuation of the low frequencies; it therefore exerts an antimasking action.

Support for this notion was obtained in subjects with Bell's palsy, a temporary ailment in which the muscles of one side of the face, including the stapedius, are paralysed. This condition gives the opportunity to compare hearing with and without the benefit of the stapedius reflex, in the same person.

The effect of masking was determined as follows: subjects with Bell's palsy were invited to detect tones of relatively high frequency against a background of intense low frequency sound. The high frequencies were in the range 2000–8000 Hz and therefore included those important for speech discrimination. The low frequency was about 500 Hz and thus represented the stronger components of the human voice. Masking was found to be particularly severe when using the afflicted ear. The result indicated that, in the normal ear, the stapedius muscle has an antimasking action.

These investigators employed also a more direct approach in which they tested speech perception with and without the paralysis of the reflex. The subject was asked to discriminate monosyllabic speech sounds presented at different intensities (see Fig. 3-8). At moderate levels of loudness (60–80 dB) it was found that discrimination with the 'bad' ear was about the same as with the good ear. At high levels (90–115 dB) however, discrimination using the affected ear was worse than with the other ear (or than with the same ear after recovery). These results suggest that the stapedius muscle is important in the perception of spoken language particularly at high intensities.

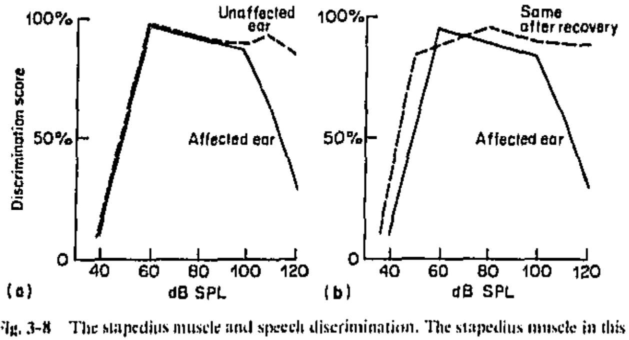


Fig. 3-8 The stapedius muscle and speech discrimination. The stapedius muscle in this patient was temporarily paralysed (Bell's palsy). The ability to discriminate monosyllabic speech sounds was measured at different intensities. At high intensities discrimination using the affected ear was evidently worse than with its fellow (tested on the same occasion) and worse than with itself tested after recovery. (After Borg, E. and Zakrisson, J. E. (1975). In *Sound Reception in Mammals*. Eds. R. J. Bench, A. Pye and J. D. Pye. Academic Press, London.)

Hearing during speaking The stapedius muscle has been observed to contract while a subject is himself making vocal sounds. This is believed to be part of the process of vocalization rather than a response to the sound of the voice, because contraction begins *before* the sound. The muscle was observed to contract at all levels of vocal intensity. It appears therefore that the stapedius muscle is active all the time we are speaking, however softly, thus selectively attenuating the lower frequencies of the voice. It has been suggested that this helps one to hear, and therefore respond to other voices heard simultaneously with one's own. Evidently this aspect of the control of ossicles is not dependent on a high level of sound. Perhaps it is the main 'reason' for the stapedius muscle.

3.3 Bone conduction

If the stem of a vibrating fork is held firmly against the forehead, or any other accessible part of the skull, the sound is heard by *bone conduction*. This phenomenon is the basis of certain diagnostic procedures (see Chapter 5). Sound waves travel through the flat bones of the skull, and also through the soft tissues both inside and outside of it, finally reaching the temporal bone, which houses the inner ear. Vibration of the temporal bone has a direct action on the organ of hearing, by-passing to some extent, the middle and outer ear (herein lies the diagnostic importance).

It should not be concluded that bone conduction works only by a direct route to the inner ear. It has been shown that the vibrations of the temporal bone produce sound waves also in the external ear canal and furthermore, that the ossicles are independently shaken into motion. The final result of bone conduction is viewed, therefore, as a cumulative effect on the organ of hearing of simultaneous activation of outer, middle and inner ear.

Bone conduction plays a part, although a small one, in normal hearing by airborne sound. Sound waves, even in air, set the skull into vibration and so produce a proportion of the final sound. The transfer of energy between air and skull is rather inefficient and the threshold of hearing by this route alone is some 60 dB above that by the normal ear.

4 Sensory Mechanisms of Hearing

The fundamental perceptions of hearing are loudness and pitch. In behavioural terms these represent the capacity to assess, simultaneously, acoustic energy and frequency. In this chapter we examine the physiological mechanisms that provide the basis of this ability.

4.1 The organ of hearing

Reception of sound waves is one of the functions of the *inner ear* which contains the organs of position and acceleration sense as well as that of hearing. These organs are housed within a system of fluid-filled, interconnecting tunnels in the substance of the skull – the labyrinth (Fig. 3–1). In man and other primates the labyrinth is buried deeply in bone and it is impossible to make out anything of its form by inspecting the internal or external surfaces of the skull. The familiar representation of the labyrinth (Fig. 3–1) is the equivalent of a plaster cast of the interior – the shape represents a *cavity* in the bone and not an actual bony structure.

4.1.1 The cochlea

The auditory portion of the labyrinth is known as the *cochlea*. It is a spiral tunnel (Fig. 3–1) and the name is descriptive of its shape (cochlea = snail shell). It is well to appreciate how tiny the cochlea actually is considering its complexity. In man the entire structure would occupy just about half the space in a cube of side 10 mm.

The amount of coiling differs between the mammalian species and the 'cochlea-like' organ of birds and reptiles is not coiled at all. The coiling provides compactness for the relatively long chamber and permits centralization of the nerve and blood supply to the organ. There is a lingering debate as to whether or not the spiral shape is of importance acoustically. It is generally believed to be of no great importance since, as we shall see, the principal functions of the cochlea have been adequately explained in terms of a straight chamber of similar dimensions. In accordance with this view and to simplify description the device of 'unrolling' the cochlea will be used (Fig. 4–1). It must be remembered that the conventional terminology relates to the coiled structure.; the end of the cochlea in contact with the middle ear is the *base* (or *basal end*) and that at the far end, the top of the spiral, is the *apex* (or *apical end*); and a general region of the organ is identified by its relationship to a 'turn' of the cochlea; for example the 'basal turn', or the 'apical turn'.

The principal vibrating parts of the cochlea are the *oval window*, the *round window* and the *basilar membrane* (Fig. 4–1b). The oval window is closed by the

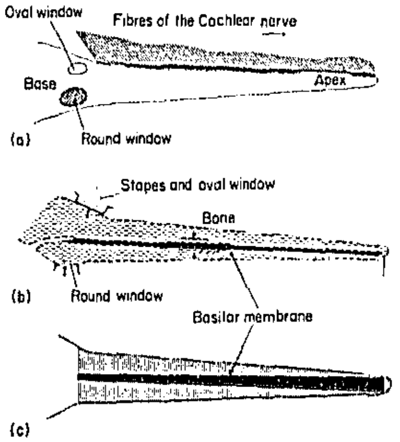


Fig. 4-1 The 'unrolled cochlea'. (a) 'Plaster cast' of the cochlear canal. (b) Side view of basilar membrane showing the principal vibrating parts. (c) Plan view of basilar membrane.

footplate of the stapes and the round window is closed by a flexible diaphragm; the fluid content of the cochlea is thus sealed from the middle ear. The windows are the only non-rigid places in the hard bone of the labyrinth. The basilar membrane is an elastic longitudinal partition which supports the auditory receptor cells. The membrane divides the cochlear, hydrodynamically speaking, into two compartments. The upper compartment is in contact with the oval window (and stapes) and the lower with the round window (and tympanic cavity).

As the stapes vibrates against the fluid of the cochlea so the basilar membrane and round window are caused to vibrate in sympathy – presently this process will be discussed in detail. A small opening, the *helicotrema*, at the apical end of the cochlea allows fluid to leak between the upper and lower compartments and so prevent the build-up of any sustained pressure difference. Finally, a very important feature: the width of the basilar membrane is not uniform but tapers down from the apical to the basal end of the cochlea (Fig. 4-1c). Notice that the taper of the basilar membrane is in the *opposite* direction to the taper of the cochlea.

4.1.2 The auditory receptors

A sensory receptor is a biological device, often a single cell, that is specialized to transduce a particular kind of energy (in this case the energy of mechanical vibration) into nerve impulses.

The receptors of hearing are *hair cells*. They are deployed along the entire length of the basilar membrane. There are two populations: the *inner* hair cells, so named because in the coiled cochlea they are towards the inside of the 'turns', and the *outer* hair cells (see Figs. 4–2 and 4–3). There is a single rank of inner hair cells. Outer hair cells are more numerous; in man there are three ranks at the basal end and five ranks at the apical end.

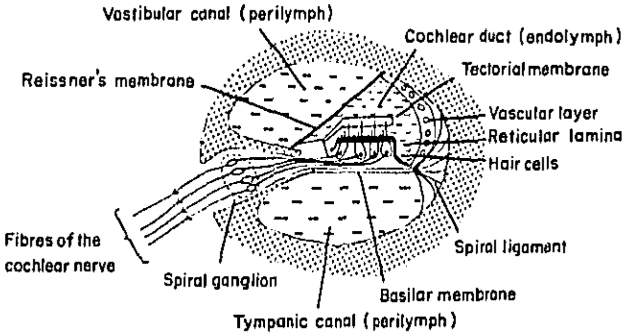


Fig. 4–2 Transverse view of the cochlea. Note that vestibular and tympanic canals are filled with *perilymph* but the cochlear duct contains *endolymph*.

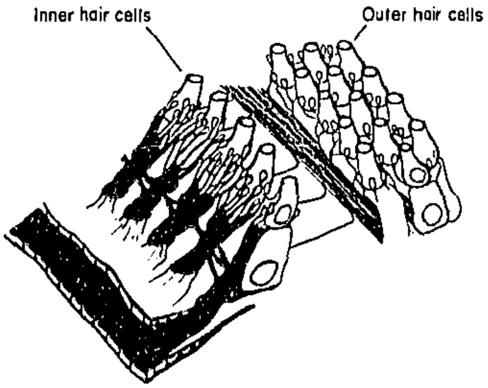


Fig. 4–3 Deployment of the hair cells. Each inner hair cell has its own separate and profuse innervation. The nerve supply to individual outer hair cells is comparatively sparse but there is convergence of several cells onto each nerve fibre. (After Spoendlin, H., 1978, in *Evoked Electrical Activity in the Auditory Nervous System*, eds. Naunton, R. F., and C. Fernandez, Academic Press, London and New York.

The hairs, or *stereocilia*, penetrate through the *reticular lamina* into the space above (Fig. 4-2). The tips of the longest stereocilia are embedded in the gelatinous *tectorial membrane* (tectum = roof).

The fluids of the cochlea are distributed between three longitudinal compartments: the *vestibular* and *tympanic* canals, which are interconnected at the helicotrema and contain *perilymph*; and the *cochlear duct* which encloses the sensory structures and contains *endolymph*. Perilymph resembles the cerebrospinal fluid that bathes the brain and spinal cord – its main cation is sodium. Endolymph is found only in the labyrinth, it is remarkable in that, although an extracellular fluid, its major cation is potassium.

The real boundary between endolymph and perilymph is the reticular lamina. The basilar membrane is permeable to small ions such as sodium and potassium but the reticular lamina is not. The environment of the bodies of the hair cells is therefore similar to ordinary extracellular fluid while the stereocilia are alone exposed to endolymph.

Nerve fibres from the hair cells enter the *spiral ganglion* and continue as axons of the *cochlear nerve*. Each inner hair cell is separately innervated, in effect it has a 'private line' in the cochlear nerve. In contrast the outer hair cells share 'party lines' – a single nerve fibre links up ten or so cells. Summation in the cochlea therefore occurs between outer hair cells but not between inner hair cells.

Other significant structures are the spiral ligament, which holds the basilar membrane in place, the *vascular layer*, that maintains the endolymphatic environment, and *Reissner's membrane* which separates the perilymph in the vestibular canal from endolymph in the cochlear duct (Reissner's membrane, like the reticular lamina, is impenetrable to small ions).

The total assembly, made up of hair cells, basilar and tectorial membranes, together with the other supporting structures, is the organ of hearing and named the *organ of Corti* after the anatomist Alfonzo Corti (1822–1888). The region, triangular in cross section, containing the organ, and bounded by the Reissner and basilar membranes, is referred to as the *cochlear partition*.

4.2 The detection of sound waves

4.2.1 Properties of stereocilia

We can look more closely at the hair cells. Each has a large number of stereocilia, about 100 in man, arranged in rows with the tallest hairs at the back and grading down to the shortest in the front row (Fig. 4–4). The individual stereocilia have a core of protein filaments rooted in the cell body. The protein has been identified as *actin*, similar to that in the thin filaments of skeletal muscle.

The mechanical properties of stereocilia have been studied in hair cells of the semicircular canals of the frog. They appear not to be bendy and hair-like as was once believed but stiff and rod-like and rather brittle. These properties are due to the protein core. The stiffness is appropriate for the faithful detection of vibrations of the basilar membrane.

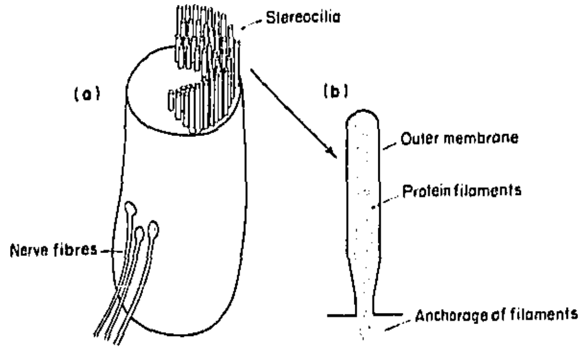


Fig. 4-4 Stereocilia (hairs) of an auditory receptor cell. (a) The arrangement of stereocilia in rows and graded in length. In man each cell has around 100 hairs of lengths 3–6 μm in four rows. (b) A stereocilium. The core is a bundle of protein filaments rooted in the cell body. The outer membrane is continuous with that of the cell body. (Described by Flock, A., 1977, in *Psychophysics and Physiology of Hearing*. Eds. E. F. Evans and J. P. Wilson. Academic Press, London and New York.)

There appear to be connecting strands between adjacent hairs since probing one of the longest stereocilia caused the shorter ones to move as well (Fig. 4–5). Further evidence of these strands has been obtained by electron microscopy of hair cells both in semicircular canals of the frog and in the mammalian cochlea. The existence of a mechanical linkage between the stereocilia explains the puzzle of why only the longest ones reach up to the tectorial membrane.

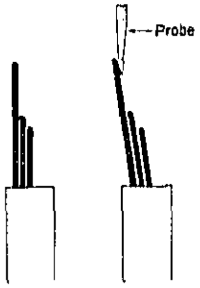


Fig. 4-5 Evidence for mechanical coupling between stereocilia. Experiment on hair cells in the frog. When a fine probe was applied to one of the longer hairs the shorter ones were caused to be displaced. (Described by Flock, A., 1977.)

4.2.2 Excitation of hair cells

The effective local stimulus to a hair cell is a sideways (shearing) displacement of the stereocilia. No one has yet seen a hair cell responding naturally to sound waves but a simplified reconstruction of the probable mechanism can be made from local knowledge (Fig. 4-6).

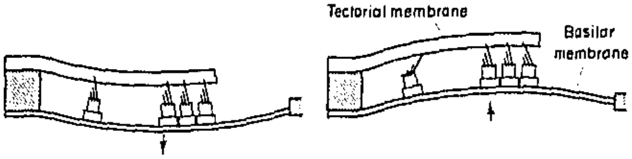


Fig. 4-6 Deflection of the stereocilia by sound waves. At the left side, towards the anchorage of the tectorial membrane, the relative motion of the two membranes resembles that of a *hinged parallelogram*; the stereocilia will be deflected to the left *and* to the right during each cycle of vibration. On the right side, beyond the centre of the basilar membrane, hair cells will experience shearing due to *stretching* of the basilar membrane relative to the tectorial membrane, and shearing will be in one direction only. In real cochleas the position of the hair cells differs between species, in some the organ of Corti is well to the left (in terms of this model) while in others it is centrally placed. (Developed from WHITFIELD, 1967.)

The question of how the shearing action causes nerve impulses is a bigger problem. We will consider a recent hypothesis. It has been proposed that the process involves modulation of the flow of ions through the bounding membranes of the stereocilia. It is assumed that the membranes of the stereocilia are freely permeable to ions and that the reticular lamina is impermeable to these ions. The total surface area of stereocilium membrane exposed to endolymph depends on the closeness of packing of adjacent stereocilia. When the stereocilia are upright there is minimum ionic flow but when they are sheared in the appropriate direction the spaces widen and the ionic flow increases. Calculations give the effective increase of surface area as 30–60% (Fig. 4–7a). The increased ionic flow tends to depolarize the hair cell (receptor potential) and generate impulses in their cochlear nerve fibres (Fig. 4–7b).

A significant property is that a standing potential exists such that endolymph has a substantial positive charge relative to perilymph and the surrounding tissues. The function, if any, of this '*endolymphatic potential*' has long been a subject for speculation. In the light of the present hypothesis it would have the function of increasing the electrical gradient for ionic flow above that of the normal resting potential of the hair cell, thereby enhancing the sensitivity of the cell in the translation of vibrations to nerve impulses.

There remains a problem in that, according to this hypothesis and the model in Fig. 4–6, certain hair cells should not be excited (those to the right of the mid-line). The model is probably an over-simplification and should include longitudinal and oblique vibrations of the basilar membrane as well as

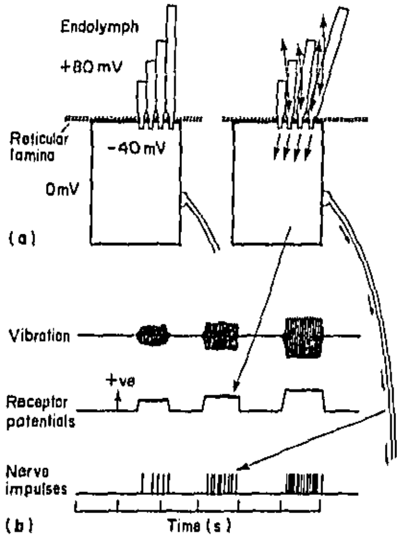


Fig. 4-7 Generation of nerve impulses by hair cells. (a) Hypothetical mechanism (based on Malcolm, R., (1974). *J. gen. physiol.*, 63, 757–72). (b) Experimental observations (schematically represented). Showing receptor potentials recorded from a hair cell and impulses recorded from a fibre of the cochlear nerve. Notice that impulse *rate* (somewhat irregular) is related to the *intensity* of the sound wave.

transverse ones, in which case other opportunities for opening of the spaces between stereocilia would exist.

The rate of nerve impulses depends primarily on the *amplitude* of displacement of the stereocilia. There is no clear-cut relationship between impulse rate and the frequency of the sound wave (except at very low sound-wave frequencies). The perception of *loudness* is regarded as a function of the rates of nerve impulses from a given group of hair cells.

4.3 The cochlea and the sense of pitch

The sense of pitch is the most specialized gift of hearing. To account for it in physiological terms we should first recognize that pitch is an *absolute* rather than a relative experience. A particular note in music always has a similar quality of tone and can be recognized and even identified. This is a different kind of affair from visual brightness, touch, or loudness, all of which are relative experiences and we cannot quantify them with any confidence.

4.3.1 The place principle

Why is pitch experience so unvarying? One can find parallels of constancy in other types of sensory discrimination. Consider tactile localization. If a part of the finger is touched we 'know' the place exactly. This may seem very obvious – even a truism – until we try to explain it. The reason why we feel 'touch' is because a particular region of the brain has evolved to provide us with *that* perception and because nerve fibres from receptors in the skin are in effect, linked with *that* part of the brain. Moreover, when impulses are generated at two different places on the skin they are transmitted along different nerve fibres and the brain can tell them apart. We therefore experience simultaneously both 'touch' and, say, 'finger tip'. It is quite evident that tactile localization depends on the existence of permanent connections between receptors in the skin and nerve cells in the brain. A parallel may be drawn with the experience of visual localization where we have the simultaneous perceptions of both light and position.

What has this to do with the sense of pitch? There is a part of the brain that is associated with sound. Impulses reaching that part are 'heard' rather than seen or felt. There are permanent connections from the hair cells of the cochlea, by way of the cochlear nerve (and other relay stages) to the auditory region of the brain. We have no sense of 'position' in the cochlea in the meaning that is used for touch or sight (directional sense is a different matter) but we *do* have the sense of pitch. It is proposed that instead of 'position' the brain has substituted the experience of 'tone'. The quality of the tone – the pitch – is determined by which of the hair cells, and therefore which of the nerve fibres, has been stimulated. This is the background to the concept of the *place principle*.

There is support for the place principle from behavioural studies. Localized damage can be inflicted on the organ of Corti such that a circumscribed region is destroyed while the remainder continues to function normally. In animals this has been carried out deliberately by surgery. In man it can happen accidentally by long term exposure to intense noise. The individual is left with a *tonal gap*; his hearing is normal except for a band of frequencies intermediate in the auditory range (see Chapter 5). In experiments on cats it was found that damage inflicted within the basal region of the cochlea caused deafness to high frequency tones while that to the apical regions affected the hearing of low frequency tones. Lesions at intermediate sites produced loss of hearing for intermediate bands of frequency.

4.3.2 A model of the basilar membrane

There are two ways in which frequency analysis might come about in the cochlea: either the hair cells themselves are frequency sensitive *or* it is a property of the structure that supports them. In the mammal the latter seems to be the case.

The idea of Helmholtz The beginning of the modern theory of the cochlea is due to Herman von Helmholtz and published in 1863. Having observed that the basilar membrane tapers along its length, he reasoned that its behaviour might be like a set of transversely stretched strings each tuned to a different note. Helmholtz suggested that sound vibration put the 'strings' into sympathetic vibration such that each responds to the frequency component of the sound waves to which it is tuned, rather as a piano when the dampers are raised. High frequencies would be represented towards the base and low frequencies towards the apex. The vibrating parts of the membrane would, presumably, excite the sensory receptors adjacent to them. Pitch would be perceived according to which particular auditory nerve fibres were excited. The only difference between Helmholtz's idea and the modern view is in the manner of vibration. According to Helmholtz the vibration of a place on the membrane was like a string freely resonating. Subsequent study, as we shall see, has indicated another kind of vibration.

The model of Békésy A practical approach to an understanding of the cochlea was made by Georg von Békésy, beginning in the 1920s. He constructed models of the basilar membrane to see how it would work. His simplest model is shown in Fig. 4-8. The idea to be tested was whether or not a tapering membrane has adequate frequency selective properties. Theoretical considerations had suggested to him that it might. Békésy proposed that the basilar membrane behaves as a simple sheet of elastic tissue held under uniform tension.

Sound waves set up in the fluid caused vibrations in the 'basilar membrane' of the model. The vibrations were very small and not easily seen but their location

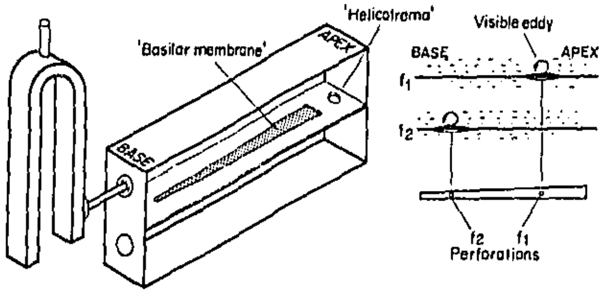


Fig. 4-8 Model of the basilar membrane. The membrane is represented by a rubber diaphragm adhering to a tapering slit in a metal plate. The metal plate and diaphragm form a partition between the two fluid compartments. Oval and round windows are simulated with other diaphragms. The system is driven by an electrically maintained tuning fork. The chambers are filled with plain water. (Reissner's membrane is not represented here but in other versions of the model, where it was included, there was no essential difference in mechanical performance.) The behaviour of the model was visualized by the addition of carbon particles which were thrown into an eddy at the site of maximum vibration ($f_1 < f_2$). The membrane was later found to be perforated at these sites. (After Békésy, G. von, 1960, *Experiments in Hearing*, McGraw-Hill, New York, Toronto, London.)

was revealed by adding carbon particles to the fluid. Where the membrane was at rest the carbon lay on it as a black dust but where it vibrated the particles were thrown upwards in an eddy. It was found that the place of the eddy depended on frequency. The eddy moved towards the wider end ('apex') when the frequency was reduced and towards the narrow end ('base') when it was increased. If a particularly thin and delicate membrane was used for experiment it was discovered later that tiny perforations had been caused at the sites of the eddies.

These experiments showed that a simple tapering elastic membrane has frequency sensitivity consistent with the place principle.

Explanation of the model We can reach an intuitive understanding of the model if the following three premises are accepted.

(*i*) *Pressure on the membrane* When a force is impressed on the fluid of the cochlea at a single place (say, the oval window) the resulting pressure change throughout the fluid is virtually instantaneous. We therefore envisage the pressure acting on the basilar membrane to be uniform over its entire surface.

(*ii*) *Distension of the membrane* The bulging of the basilar membrane caused by downward (or upward) pressure will increase with the width of the membrane (assuming that the transverse tension is everywhere the same). This is a rather sharp effect since, as Békésy has stated, a fluid pressure acting on an elastic sheet under constant tension causes a distension (bulge) the amplitude of which increases as the *fourth power* of the width.

The distensibility of any elastic structure may be described by its *stiffness*. The definition of stiffness is: elastic restoring force/unit displacement. The basilar membrane of the model has therefore a *gradient of stiffness* increasing from the wider towards the narrower end. Stiffness could be graded also by varying the tension. A parallel-sided sheet could be given a similar stiffness gradient by increasing the transverse tension from apex to base – but this appears not to be the way that the gradient is achieved in the cochlea. The point here is that stiffness is a unifying concept from which the behaviour of the structure may be predicted irrespective of how the stiffness is produced.

(*iii*) *Speed of response* The stiffer a system the more faithfully will it follow fluctuations in the applied force. With rapidly changing pressure the displacement of a narrow (i.e. stiff) region of the membrane will lead that of a wider (less stiff) region.

We are now suitably equipped to re-examine the behaviour of the model.

Response to slow changes Consider what will happen when the stapes of the model is pushed slowly inwards (Fig. 4–9). The fluid in the upper compartment will press equally over the entire membrane which will therefore bulge downwards. The amplitude of the bulge increases steeply from base to apex (because of the fourth power relationship). If the stapes is now pulled slowly outwards there will be the mirror image of the previous displacement. Repeating the process continuously will cause the whole membrane to flap up and down in sympathy with the movements of the stapes, the envelope of the displacement having its maximum amplitude towards the apical end. We have reproduced the circumstances of low frequency sound waves.

Response to rapid changes If the stapes is pushed inwards abruptly (Fig.

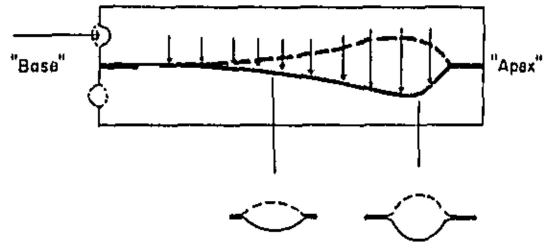


Fig. 4-9 Response of the model (greatly exaggerated) to slowly applied pressure (see text). (Assume that flow via the helicotrema is negligible over the time of the test cycle.)

4–10) the effect will *not* be simultaneous over the whole membrane. The stiffer regions will respond first. Therefore a wave of displacement will travel along the membrane according to the stiffness gradient. If the stapes is now jerked outwards then the corresponding sequence will occur with upwards displacement; again the less stiff parts will lag behind. If now, in imagination, we repeat the process continuously as a rapid sinusoidal oscillation, it should be apparent that

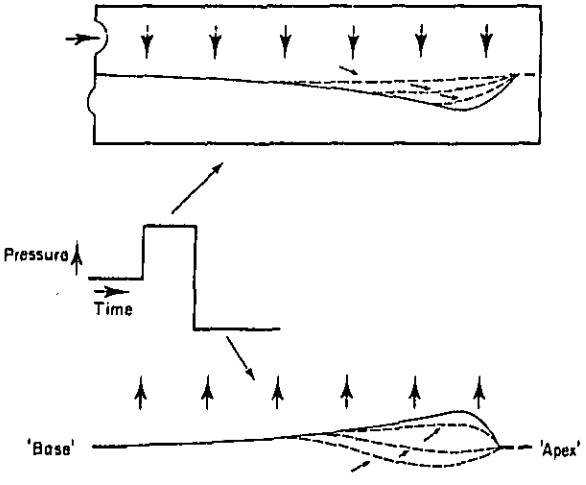


Fig. 4-10 Response of the model to rapidly applied pressure. Displacement of a less-stiff region lags that of the stiffer one adjacent to it. Therefore the displacement *travels* along the membrane (see text).

the less stiff end of the membrane does not have time to react fully within a half cycle. Consequently the maximum of the envelope of vibration shifts away from the apical end. As the frequency is raised still further the position of the maximum is drawn still closer to the stapes.

The study was transposed by Békésy from the model to the real cochlea in probably the most celebrated experiments in auditory physiology. He found that the pattern of vibrations seen in the model could be observed directly in the basilar membrane of the human cadaver. More recently, in experiments on animals, further confirmation has been obtained for the living cochlea (Fig. 4-11).

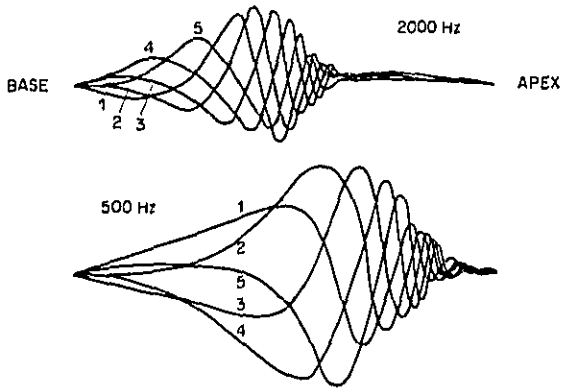


Fig. 4-11 Vibration of the basilar membrane *in vivo*. Response to pure tones recorded in the cochlea of the chinchilla (a relative of the guinea-pig). Each line indicates the relative longitudinal displacement of the membrane at an instant of the sinusoidal vibration cycle, numbered in sequence. (The curves were computed from changes in electrical potential (cochlear microphonic) associated with displacement of the membrane.) Notice the travelling waves and the shift in the position of the maximum with frequency. (Eldredge, D. H., 1978, in *Evoked Electrical activity in the auditory nervous system*. Eds. R. F. Naunton and C. Fernandez. Academic Press, London and New York.)

It is concluded that the frequency dependent property underlying the sense of pitch results from the mechanical properties of the basilar membrane in which are generated *travelling waves* which progress from the apical to the basal end and whose place of maximum amplitude is a function of their frequency.

4.3.3 Measurement of the amplitude of vibration

A recent method for measuring the magnitude of the vibrations in the cochlea employs a discovery of nuclear physics, the Mössbauer effect; it is described in

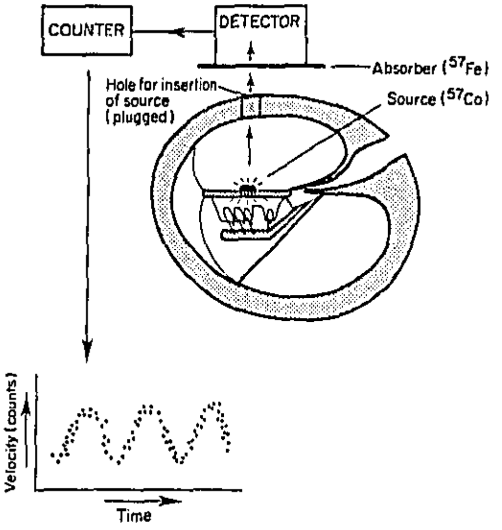


Fig. 4-12 Measuring the amplitude of vibration of the basilar membrane. A minute source of gamma radiation is attached to the membrane. The radiation passes through an absorber that is selective for a narrow band of radiation energy. Vibration of the basilar membrane produces fluctuations of the count rate from which amplitude and velocity of the vibration can be calculated. (Described by Rhode, W. S., 1971, *J. Acoust. Soc. Am.*, 49, 1218–31).

The method depends on very special circumstances concerning the absorption of gamma rays: the Mössbauer effect. Ordinarily when gamma radiation enters a substance it loses energy in collisions with atomic nuclei. Mössbauer discovered a case when this is not so. If the energy spectrum of the gamma radiation matches *exactly* the transitional energies of the nuclei of the absorber then the radiation suffers no loss of energy (nuclei, like electrons, can exist only in certain well defined energy levels). To achieve the required conditions experimentally the nuclei of the radioactive source must be identical with those of the absorber. A suitable matched pair is ^{57}Co and ^{57}Fe. The cobalt nuclide decays to become the iron nuclide which is then the source of gamma radiation.

In order to study the phenomenon Mössbauer needed to alter the energy of the gamma radiation by tiny amounts. He found that imparting a velocity to the source is enough to 'detune' the system. Moving the source towards the absorber increased the energy and moving it away decreased the energy (the Doppler effect). The Mössbauer effect is so sensitive that source velocities as low as 1 mm s^{-1} can be detected.

Fig. 4-12. The technique involves adhering a tiny radioactive source to the surface of the basilar membrane. Under the special conditions that define the Mössbauer effect, the velocity of the source as it vibrates with the membrane can be detected from the outside of the cochlea. The method is very sensitive and has provided extra confirmation of frequency localization along the cochlea. It has also given absolute values for the amplitude of vibration of the basilar membrane at normal levels of sound intensity. Studies have been carried out on a primate (squirrel monkey) in which it was found that with a sound intensity of 80 dB (a loud sound by human standards) the maximum displacement was only about 10 nm (this is similar to the diameter of a medium-sized protein molecule such as haemoglobin). At an intensity close to the threshold of human hearing the displacement was only 0.001-0.006 nm!

4.4 The neural mechanism of pitch perception

Frequency analysis of sound waves has thus far been described from, as it were, within the cochlea. We now step outside to see how the cochlea carries the analysis forward to the brain.

The experimental method is to record impulses from a single fibre of the cochlear nerve while at the same time altering the frequency of the test tone. It has been found that a given individual fibre responds selectively to a narrow band of frequencies. If several fibres are observed, one at a time, it is found that the frequency range for the response differs from fibre to fibre.

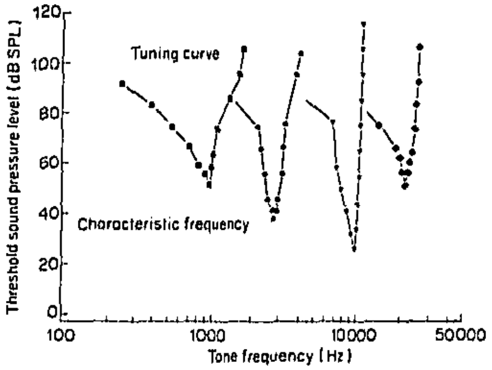


Fig. 4-13 Recordings were made from individual fibres of the cochlear nerve of the guinea-pig, and the threshold of sound wave pressure for the generation of nerve impulses, measured at different frequencies. Each curve represents an individual fibre. Evidently an individual fibre is sensitive only to a restricted band of frequencies. (Adapted from Evans, E. F., 1972, *J. Physiol. Lond.*, 226, 263-87.)

A fibre of the cochlear nerve can be represented by its tuning *curve* (Fig. 4–13) which describes the threshold of sound wave intensity as a function of tone frequency. This indicates the sharpness of tuning. The tip of the curve denotes the condition for greatest sensitivity (the characteristic frequency) for that fibre. When tuning curves for a large sample of fibres were assembled it was found that, collectively, their characteristic frequencies span the auditory range. We can therefore construct the curves for a population of cochlear nerve fibres (Fig. 4–14). Almost a fibre for every frequency. These properties provide the neural basis for the seemingly absolute nature of pitch perception. A given fibre from the organ of Corti (or small group of fibres) has a permanent association with a specific narrow band of sound frequencies. Whenever that fibre transmits impulses, at whatever rate within the working range, we the listener perceive a sound, or component thereof, having that definite and identifiable tonal quality that we call its pitch.

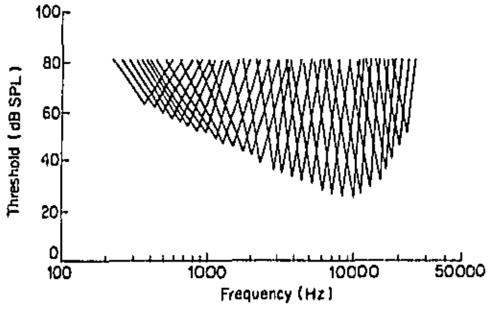


Fig. 4–14 The neural basis of pitch perception. Schematic representation of the tuning curves for a population of cochlear nerve fibres.

5 Living with Sound

5.1 The problem of noise

A suitable definition of noise is *unwanted* sound. It is sound that interferes with thought or communication. The effects of noise range from plain annoyance to the permanent damage to hearing ability. Excessive noise in a work environment reduces the individual's efficiency. Too much noise in residential surroundings impairs the quality of community life. Noise is therefore a matter both of industrial and public health.

5.1.1 The measurement of noise

A noise is described by its *intensity*, its *tonal composition* and its *temporal structure*.

The primary assessment of noise is the *sound level*. A sound level *meter* consists essentially of a microphone, an amplifier and a display calibrated in decibels (Fig. 5–1). The instrument has circuits that '*weight*' its frequency response to resemble that of human hearing. The appropriate weighting to apply depends to some extent on the intensity of the sound and is derived from the equal loudness curves (Chapter 2). Sound-level meters usually provide the user with a choice of 'A-weighting' or 'C-weighting' (Fig. 5–2), but the measurement of noise (as distinct from music or speech) is, by convention, always carried out using A-weighting.

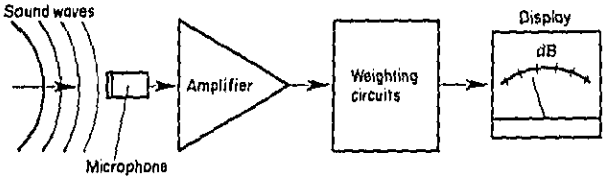


Fig. 5–1 The parts of a sound level meter.

When quoting a value for sound level, whether noise or otherwise, it is necessary to indicate the kind of weighting used. Thus 75 dB using A-weighting is written 75 dBA, or 75 dB(A). Examples of sound levels in dBA were given in Table 4.

The effect that a noise has on us is determined to a large extent by its tonal composition. If the source produces frequencies in the range 1000–4000 Hz the

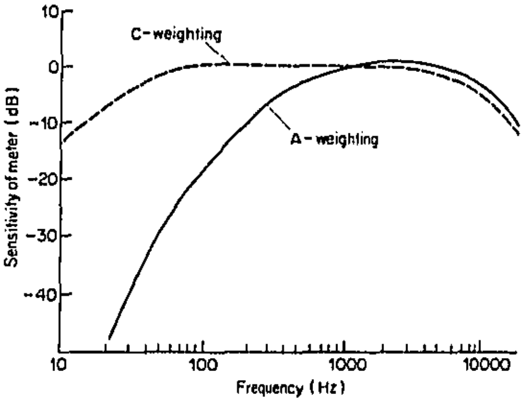


Fig. 5-2 Weighting characteristics of sound level meters. 'C-weighting' is intended to resemble the frequency sensitivity of human hearing at high intensities and 'A-weighting' at low intensities. For the measurement of noise, however, 'A-weighting' is used at all intensities.

sound will tend to mask speech and so impair conversation. If the noise is confined to very high or very low frequencies the annoyance will take on other forms. Knowledge of the frequency composition of a noise, the *noise spectrum*, is an important part of the description; it can also assist in the diagnosis of the cause of the noise or in the design of appropriate acoustic insulation. Examples of various noise spectra are given in Fig. 5-3.

The description of a noise should also indicate its time course. There are four categories. (*i*) *Steady noise* (the hum of electrical machinery or the sound of a waterfall); (*ii*) *Fluctuating noise* (traffic sounds, a neighbour's radio); (*iii*) *Intermittent noise* (construction work, aircraft overflight, domestic appliances); (*iv*) *Impulsive noise* (hammering, pile driving, explosions). This form of description can be presented as a *graphic time history* (Fig. 5-4).

5.1.2 Effects of noise on hearing ability

Distinction is made between relatively mild and reversible effects of noise (auditory fatigue) and permanent injurious effects.

Auditory fatigue Continuous exposure to sound of intensity 75-85 dBA causes a temporary impairment of hearing known as auditory fatigue. The condition is manifest by an increase in the threshold of hearing referred to as *temporary threshold shift* (TTS). When a person enters a noisy environment and remains there, his hearing threshold starts to rise and continues rising for several hours finally attaining a plateau level the height of which depends on the

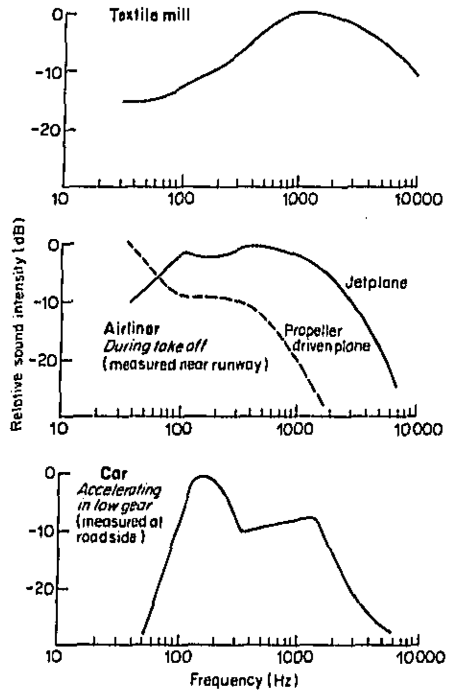


Fig. 5-3 Noise spectra. (data from various authors) The curves have been normalized at the peak values (0 dB) and therefore indicate the *relative* intensity at each frequency.

ambient noise intensity. On leaving the environment the threshold begins to fall but it may take 24 hours or so before it has returned to 'normal' (Fig. 5-5). For example, in a car travelling at speed the noise can be 80 dBA or more. A few hours of this is sufficient to generate a substantial and long-lasting threshold shift. Nor is it necessary that a noise be continuous; intermittent sounds of minutes or even seconds duration have a cumulative effect. It would seem that modern life affords little opportunity to experience the maximum potential of hearing sensitivity.

Permanent damage Routine exposure to noise of 90 dBA or more causes irreversible impairment of hearing. A particularly informative study was carried out on workers in a jute weaving mill where the clatter of the looms was more than 95 dB. Some people had been employed in this environment for 50 years or

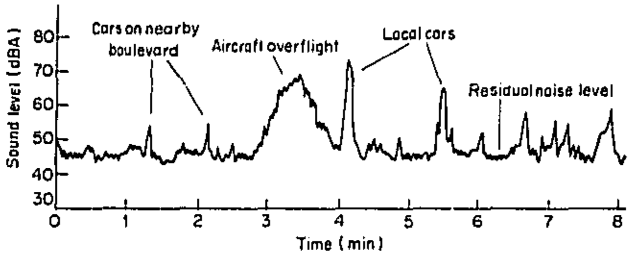


Fig. 5-4 Graphic time history of sound level. Example from an analysis of urban noise. (From Goldstein, J., 1978, in *Noise and Audiology*, ed. D. M. Lipscomb, University Park Press, Baltimore.)

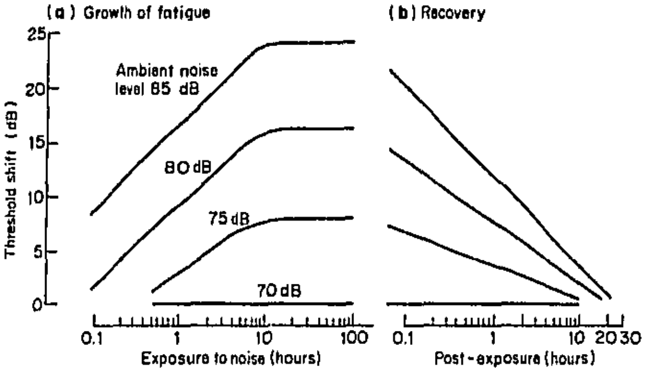


Fig. 5-5 Auditory fatigue (see text). (Based on Melnick, W., 1978, in *Noise and Audiology*, ed. D. M. Lipscomb, University Park Press, Baltimore.)

so and there was no reason to believe that the noise had changed over this period. It was found that the workers had a characteristic defect of hearing called *tonal gap*. Their hearing was affected over an *intermediate* band of frequencies centred at 4000 Hz. The defect was already evident in those exposed for only one or two years and became progressively worse with further years. It was profound after 25 or more years (Fig. 5-6). Members of the latter group had significant difficulty in the perception of speech.

This kind of damage to hearing is called 'industrial deafness' or *noise-induced hearing loss*. It usually has its maximum effect around 4000 Hz because the transmission of sound waves by the outer and middle ear has maximum

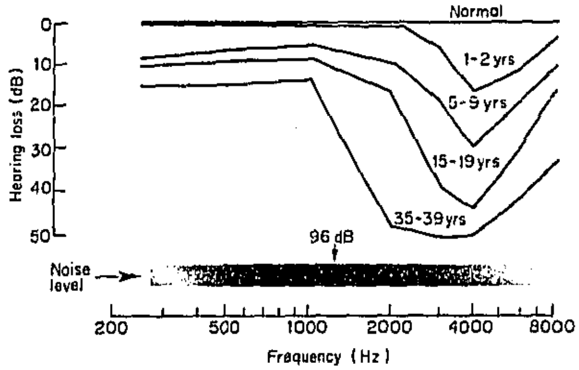


Fig. 5-6 Noise-induced hearing loss (Industrial deafness). The curves give abnormalities of the auditory thresholds among workers in a jute-weaving mill. Note that the data represents the average *deviation* from normal in each group. 'Normal' hearing is depicted by the horizontal line at 0 dB. This is an example of the use of 'pure tone' audiometry (section 5.3.1). The shaded bar indicates the spectrum of the noise in relation to the hearing loss (see also Fig. 5-3). (after Taylor, W. *et al.* (1965). *J. Acoust. Soc. Am.*, 38, 113-20).

efficiency around this frequency. Consequently the latter components of the noise are amplified selectively although the maximum intensity may be at considerably lower frequency (in the jute mill the maximum was at about 1500 Hz).

5.1.3 The nature of the damage

Noise-affected ears in man and animals have been examined post mortem. There was a loss of hair cells from the part of the organ of Corti corresponding to the frequencies of deafness. Thus in patients with a history of industrial deafness a damaged region was found near the basal end of the cochlea (see section 4.3.1). Outer hair cells seem to be more vulnerable than inner hair cells. However there was usually no damage to the basilar membrane or to the structures of the outer and middle ear. It seems that the latter are harmed only by extremely intense sounds of 160 dB or more. In some cases there was a complete absence of hair cells over a restricted region of the organ of Corti while the remainder of the organ appeared normal.

On the basis of such studies it has been proposed that excessive exposure to intense sounds produces the following sequence of changes: (*i*) large amplitude vibration of the basilar membrane damages the pillars (supporting cells) of the organ of Corti; (*ii*) outer hair cells in that vicinity degenerate; and (*iii*) inner hair cells degenerate. The nerve fibres that innervate the hair cells degenerate in association with these changes. It has not yet been established whether the neural degeneration happens earlier or later than that of the hair cells.

5.1.4 Noise dosage and hearing conservation

The damaging effect of noise on hearing is progressive and is compounded of the duration of exposure and the intensity. This has led to the concept of noise 'dosage' which provides the basis for guidelines (in the U.K.) and legislation (in the U.S.A.) for hearing conservation in industry. *Continuous* noise of 90 dBA or more if experienced routinely is a potential hazard. Using this level as the starting point, the safe periods for exposure to a range of intensities have been estimated (Table 6). The maximum level for any period of exposure of the unprotected ear is 135 dBA. The use of ear protectors is encouraged to reduce the intensity at the ear; the more efficient of these give attenuation of 30–40 dB (at 1000–2000 Hz). In the case of impulse noise (e.g. riveting machines, drop hammers) the dose is calculated as the number of impulses per day at the existing sound level.

Table 6 Levels of noise which indicate a serious hazard to hearing. (From *Noise and the Worker*, Health and safety at work, No 25. HMSO, 1971.)

Exposure duration (hours day^{-1})	*Maximum sound level* (dBA)
8	90
4	93
2	96
1	99
1/2	102
1/4	105

Some leisure pursuits impose a risk to hearing. The noise in an indoor swimming bath on a busy day can exceed 100 dBA. The sound levels of certain power-driven tools used in the home and garden (motor mowers, chain saws, electric hedge trimmers, circular saws, etc.) can reach 95 dBA. Finally, the well known, but usually disregarded, hazard in amplified music at dance halls and private functions, where sound levels are commonly in excess of 105 dBA and levels of 120 dBA are not unusual.

5.2 Tinnitus

Tinnitus is a very private kind of noise. Many of us, from time to time, experience sounds that have no external cause. In most cases it is a simple sound, often a pure tone, that comes and then vanishes and is forgotten. This is mild tinnitus as experienced by at least 20% of the population. In a few percent the experience is persistent and may be more complex. In some the noise is so unyielding and sometimes so loud that it is hardly bearable.

The nature of the sounds of tinnitus is difficult to investigate. In most sufferers they are completely subjective and one has only the patient's verbal description to go on. Recently, however, the sounds have been rendered 'audible'. The technique employs an electronic music synthesizer – a device that can be made to imitate almost any sound. By a process of trial and error the patient matches the sound from the instrument to that in his head, and the result is sound recorded. Playing through a selection of such recordings reveals the variety in the sounds experienced by different sufferers. In some the tinnitus has a continuous rushing sound like a loud waterfall. Sometimes it is more of a hissing sound perhaps with a high pitched whistle superimposed. In others it is a jangle of tones similar to a radio-jamming transmission. Some hear a regular thumping or tapping corresponding with the heart beat. Severe tinnitus is commonly an accompaniment to deafness (although it can occur with normal hearing). It is experienced by military personnel after exposure to gun fire. Some drugs cause tinnitus, for example aspirin in high dosage; in this case the sound vanishes after the drug is withdrawn. BALLANTYNE (1977) recalls some famous tinnitus sufferers: Beethoven was driven to distraction by his tinnitus; Schumann heard the note 'A' continually; Smetana who also became deaf actually reproduced his tinnitus musically in his first string quartet – as an expression of his private torture. It is quite evident that deafness can be far from peaceful.

The pathology of tinnitus remains speculative. There are probably various local causes judging from the repertoire of sounds among different sufferers. Some of the sounds presumably arise from spurious discharge of specific groups of nerve fibres – this would be in keeping with the place principle. The 'rushing' noises could result from the removal of neural inhibition, due to nerve degeneration. The regular thumping sounds could have a vascular origin due to abnormal proximity of a blood vessel at some stage of the auditory pathway.

Severe tinnitus is a very distressing condition. It is not only its loudness, indeed in some it is relatively quiet. Rather it is the sheer relentless continuity of the sound completely beyond the control of the sufferer. There is no reliable treatment for the condition but there are ways of alleviating it. It has been found that continuous external sounds can help. A current type of therapy is to introduce broad band noise ('white noise') into the ear using a hearing aid type of insert; this tends to mask the tinnitus and also provides a controllable factor for the sufferer which appears to be of psychological benefit.

Perhaps the main point of this section is to make the reader sympathetically aware of a serious problem that some have to live with.

5.3 Deafness

We have already considered some aspects of deafness. Now we examine the subject more generally. Impaired hearing is very common. One adult in six has some kind of difficulty and at least one in 30 has a substantial handicap. The numbers are smaller in the younger age groups that in the over-70s but they are sizeable at all ages. We tend to describe all people with a hearing problem as 'deaf' but this term is best reserved to describe *total* absence of hearing. Poor hearing is best described as a *hearing loss*.

5.3.1 Testing the hearing

Voice tests Hearing difficulties usually have to do with inadequate reception of speech. The first step in the diagnosis is to assess the disability. This would usually be carried out initially by the medical practitioner (otologist). He speaks or whispers to the patient from various distances and from the responses he can gauge the severity of the problem. In the days before modern audiometry, otologists were particularly adept in the performance of voice tests.

Speech audiometry This is a development of the voice test. It is normally performed, as are other forms of audiometry, by an audiologist or audiological technician, a non-medical specialist in the assessment and conservation of hearing. The patient listens to a recorded voice and is asked to repeat each of a string of words (e.g. ride, rise, rub, slip, smile, strife, such, then, there, etc, etc). The test is repeated at different sound levels. The index of hearing ability is the sound level in decibels at which 50% of the words are correctly repeated. The test is calibrated by using subjects with normal hearing. If the patient achieves a 50% score but with a sound level of, say, 20 dB higher than normal, he is described as having a 'hearing loss of 20 dB' with speech audiometry.

Pure tone audiometry The most widely used test of hearing is the analysis of the patient's threshold of hearing as a function of frequency. The result is

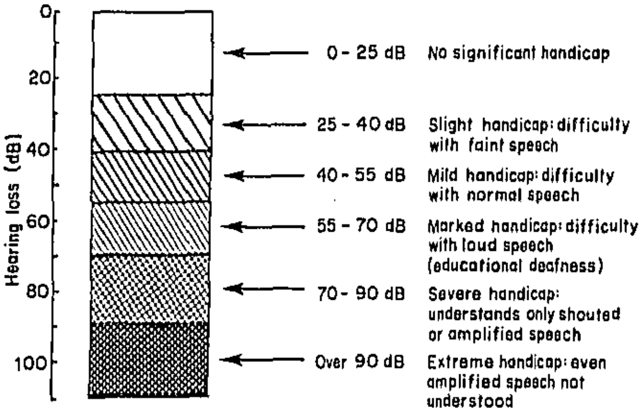


Fig. 5-7 Severity of handicap. Hearing difficulty correlated with hearing loss. (Average hearing loss at 500, 1000 and 2000 Hz obtained by pure tone audiometry). 'Educationally deaf' children require special education if they are to learn to talk. (After Shepherd, I., 1978, *Brit. J. Audiology*, 12, 3.)

presented as an *audiogram* in which the threshold at each test frequency is given as a deviation from the 'normal' (Fig. 5-6). One use of the audiogram is to 'tailor' a hearing aid to compensate for a patient's specific hearing deficiencies.

5.3.2 Grading of handicap

The severity of the problem imposed by impaired hearing depends on the extent of the hearing loss at the frequencies associated with the perception of speech. A hearing loss of less than 25 dB at these frequencies does not cause significant difficulty and is regarded as unimportant. The problem becomes real when the loss exceeds 40 dB and is marked at 55 dB or more. Children in this last category are 'educationally deaf' (see Fig. 5-7).

The hearing difficulty of the elderly (presbycusis) is due to loss at high frequencies. This can be appreciated by a person with normal hearing, by simulating the effect with an electrical filter, equivalent to turning down the 'treble' control on a radio. This tends to muffle the clarity of the voice. Conversely, if frequencies below 1000 Hz are attenuated but higher frequencies are not, as occurs in certain other hearing disorders, there is hardly any loss of clarity in the hearing of speech.

5.3.3 Discovering the cause

Assume that patient has a hearing loss that is abnormal for his age group and that there is no obvious blockage of the ear canal or damage to the ear drum. The otologist seeks to determine whether the trouble arises in the middle ear, in the cochlea, or somewhere in the auditory pathway. The corresponding disorders are known, respectively, as *conductive*, *sensorineural*, and *retrocochlear* hearing loss. Types of conductive hearing loss can be treated by surgical intervention. For example, if the stapes becomes fused to the oval window because of abnormal growth of bone (otosclerosis) it can be removed (stapedectomy) and replaced by an artificial stapes. Retrocochlear hearing loss may be caused by a tumour pressing on the auditory nerve – this too might benefit from surgery.

Tuning fork tests A long established and still important group of tests for preliminary diagnosis employs tuning forks. These are used to compare the patient's ability to hear by air and bone conduction and to compare the performance of one ear with the other. The best known are the *Rinne test* and the *Weber test* which differentiate between conductive hearing loss and the other categories (see Fig. 5-8).

Acoustic impedance measurements If conductive hearing loss has been diagnosed it is then necessary to find out which of the elements of the middle ear is faulty. A recent method records the acoustic impedance at the ear drum. The essence of the method is as follows. Two tubes are inserted into the ear canal, which is otherwise occluded. One tube is used to feed sound waves to the ear canal and the other, which leads to a microphone, is used to measure the resulting pressures (there is often a third tube through which static pressure can be applied). The purpose is to measure the freedom of movement of the ear

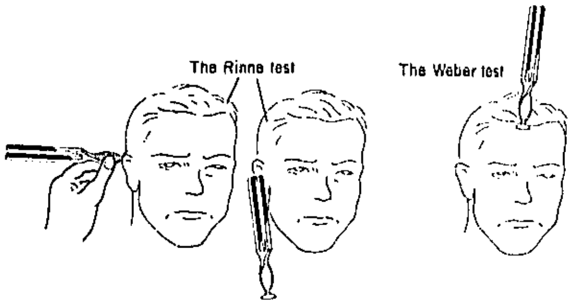


Fig. 5-8 Tuning fork tests. *The Rinne test*. The fork is struck and its base is applied at the mastoid process. It is heard now by bone conduction. As the vibrations die down the patient signals when he can no longer hear them. The fork is then transferred quickly to a position 2 cm in front of the ear canal when, if transmission in the middle ear is normal, the sound should be heard again ('Rinne test positive'). If not, the test is pronounced 'negative' indicating conductive hearing loss. *The Weber test*. The fork is applied to the head at the midline. Normally (or if both ears are equally affected) the sound will seem central. With *conductive hearing loss* the sound seems to be on the *side of the affected* ear. With *sensorineural hearing loss* the sound appears to be on the *side of the better ear*.

The explanation of the Weber test is to do with masking. With conductive hearing loss there is less masking in the affected ear from environmental sounds, therefore hearing in that ear by bone conduction is heightened.

drum. If there is obstruction in the middle ear then pressure in the outer ear will respond more sharply than normal to the applied changes. This is measured as raised impedance. The impedance changes depend on the frequency of the sound waves and the precise nature of the defect in the middle ear. Clinical experience with the method is now accumulating and otosclerosis, for instance, can be distinguished from other middle ear conditions.

Electrical recording In cases of sensorineural and retrocochlear hearing loss it is valuable to examine the electrical activity of auditory function. Much progress has been made here through the technique of *averaging* a large number of responses to a repeated stimulus. In this way, with electrodes applied to the surface of the skin at appropriate sites, it is practicable to detect and separately identify, activity in the cochlea, the auditory nerve and the cerebral cortex. The method can help to locate a lesion that is affecting hearing. It is also of particular value for assessing the integrity of the auditory system in babies and young children, since it makes little demand on their cooperation.

Special symptoms The hard of hearing commonly complain about loud sounds. 'Please don't shout!' is a standard plea. The threshold of hearing is high but thereafter increasing intensity causes a rapid growth of loudness. This is '*recruitment*' of loudness and is associated with damage to the organ of Corti (sensorineural hearing loss). An explanation of recruitment is that the damage initially affects the outer hair cells leaving the inner hair cells working normally. The former normally function at low intensities and the latter join in at high intensities.

Another symptom in some types of sensorineural hearing loss is *diplacusis binauralis*, a curious phenomenon in which a tone of a given frequency presented to one ear produces a different pitch than when presented to the other ear. In some cases the discrepancy is as much as a semitone.

In certain patients the hearing loss is associated with *abnormal adaptation*. The test is to apply a continuous pure tone at a level just above the auditory threshold. If adaptation is abnormal the tone fades rapidly and must be intensified in order to be heard again. This indicates a lesion in the nerve supply to the cochlea, thereby causing a retrocochlear hearing loss.

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Audio tape

'The sounds of tinnitus' available from the British Tinnitus Association, 105 Gower Street, London WC1E 6AH.

Index

(continued from inside front cover)

91 **Boreal Ecology** Pruitt
92 **Nitrogen Fixation** Postgate
93 **Haemoglobin** Maclean
94 **Principles of Human Nutrition** Taylor
95 **Structure and Function of Viruses** Horne
96 **Plant Growth Analysis** Hunt
97 **Man - Hot and Cold** Edholm
98 **Plant Physiological Ecology** Etherington
99 **The Physiology of Diving in Man and other Animals** Hempleman & Lockwood
100 **Cellular Recognition Systems in Plants** Heslop-Harrison
101 **Sulphur in Biology** Anderson
102 **The Biology of Helminth Parasites** Lyons
103 **Sex Hormones and Behaviour** Slater
104 **Biological Clocks** Brady
105 **Liver** Horner Andrews
106 **Aquaculture** Reay
107 **Pollen and Allergy** Knox
108 **Animals under Stress** Archer
109 **Lizards - A Study in Thermoregulation** Avery
110 **Sexual Incompatibility in Plants** Lewis
111 **Microorganisms and Man** Noble & Naidoo
112 **Life at High Altitude** Heath & Williams
113 **The Nature of Toadstools** Ingold
114 **Nerves, Brains and Behaviour** Messenger
115 **Vocal Communication in Birds** Catchpole
116 **Influences on Animal Growth and Development** Batt
117 **Collagen; the Anatomy of a Protein** Woodhead-Galloway
118 **Social Behaviour of Animals** Deag
119 **Medical Mycology** English
120 **The Respiration of Higher Plants** Opik
121 **Ecology of Insect-Plant Interactions** Edwards & Wratten
122 **The Ecology of Streams and Rivers** Townsend
123 **The Biochemistry of Pollution** Ottaway
124 **Light and Plant Life** Whatley
125 **Lipids and Polysaccharides in Biology** Furth
126 **Bioenergetics of Autotrophs and Heterotrophs** Anderson
127 **Invertebrate Respiration** Wells
128 **Immunobiology** Inchley
129 **Growth Regulators in Crop Production** Luckwill
130 **Evolution and Pollution** Bradshaw & McNeilly
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132 **Biological Control of Pests and Weeds** Samways
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