# Fundamentals of Hearing

### *Loudspeakers are not the final link in the listening chain, nor is the room.*

### *By Vivian Capel*

THE human ear makes all other links in the hifi chain seem crude in construction and design. An understanding of these fascinating instruments with which we have been endowed can help us identify the important characteristics of the sounds that we hear. This in turn can shed light on the art of sound reproduction and hifi.

The ear is divided into three sections: the outer, middle, and inner ear; each section has its own specific function.

## The Outer

The outer ear consists of the appendage known as the *pinna* and the ear-canal terminating in a diaphragm stretched across it, the eardrum. The pinna is provided not merely for decoration or protection, though it does both to same extent. Its convolutions produce reflections which follow the direct sound into the canal with minute delays, hence with phase differences.

The reflections differ according to the angle of incidence of the sound, so the resulting phase differences serve as a code to identify direction. The auditory section of the brain decodes this information instantly to locate the position of a sound source.

It is commonly believed that source location is entirely due to volume and phase differences existing between the two ears.. If this were so, our sound location would be limited to the front horizontal plane, as it is with conventional stereo systems. However, as we have the facility for all-around location with vertical identification as well, there is evidently more involved. This can be demonstrated by plugging one ear and trying to identify the direction of a sound source. It is still possible, though the sense of direction is reduced.

The amount of phase difference generated by there being a path difference between direct and reflected sound depends on two things: the path difference itself and the wavelength of the sound concerned. The first of these will depend on the dimensions of the pinna convolutions, and if these are small in comparison to the wavelength, the phase difference will be quite small and probably undetectable. So, logically, we will get the best sense of sound location with higher frequencies.

At mid-to-low frequencies, the wavelength of the sound becomes comparable to the head's size, so comparison of phase between the two ears may help location here. At lower frequencies, it would take pinnas (or possibly heads) of literally elephantine proportions to give good directional sense. However, this is not a major problem, as the majority of low frequency sounds have higher frequency components that we can locate satisfactorily.

## The Middle Ear

The directionally-encoded sound travels down the ear canal to the eardrum, or *timpanum* as it is also called, which vibrates in response. The next section, the middle ear, has the function of impedance matching and dynamic range compression. The well-known rule which applies in electronics as well as mechanics is that to transmit the maximum amount of energy from one system to another, the impedances must be similar. Electrical impedances can be matched through transformers, and the mechanical impedance offered by the road wheels of a car is matched to the engine torque by the gearbox.

In the case of the ear, minute air pressure variations acting on the eardrum make this a low impedance member, whereas the fluid-filled inner ear which converts the vibrations to neural signals is of a higher impedance. Matching is accomplished by three interjoined bones termed the *hammer, anvil*, and *stirrup*. The first two of these are a pair of pivoted levers that produce a leverage ratio of nominally 3:1, and the stirrup, or *stapes* as it is also called, communicates the motion of the second lever to the window of the inner ear.

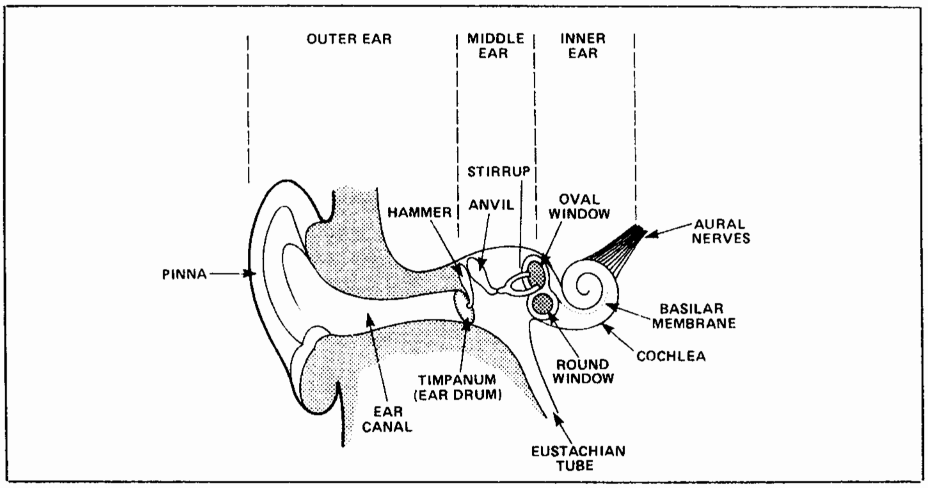

*Fig. 1 Our hearing system showing the three main sections: the outer, middle and inner ear.*

The three bones are held in position by tiny muscles. These can cause the pivot position to change, and they can also stiffen to cause a decrease in the amount of movement. Hence these can reduce the sensitivity of the whole ear progressively as the sound level increases. This enables the ear to handle an enormous range of sound levels, the loudest being one trillion times the faintest, or 120dB. We can accommodate all the natural sounds we are ever likely to encounter, from the rustling of leaves to a thunderclap, but we have problems with man-made sounds such as explosions, jet engines and machine tools, to name but a few.

If the middle ear were a completely sealed cavity, differences of atmospheric pressure would cause the eardrum to be stretched inward or outward, depending on the atmospheric pressure. This would displace the three connecting bones and upset the sound comprehension. The *Eustachian tube* connects the middle ear to the back of the throat, and so maintains atmospheric pressure on the inner surface of the eardrum.

## The Inner Ear

The final bone of the trio, the stirrup, transmits the sound vibration to the window of the inner ear. This is shaped like a snail's shell; hence it's name, the *cochlea.* It is really a long tube rolled up in a spiral. To understand what it does, we will imagine that it is unrolled. A horizontal membrane divides the tube into an upper and lower compartment, except at its end where there is a short gap. The membrane is termed the *basilar membrane,* the upper compartment the *scala vestibuli,* the lower one the *scala tympani,* and the end gap the *helicotrema.*

The whole tube is filled with fluid and is sealed at the far end so that a complete path is formed along one half, through the helicotrema and back along the other half. The top half has at its entrance a diaphragm termed the*oval window,* while the bottom one terminates at the *round window.*

When pressure variations are communicated to the upper oval window by the stirrup, they travel along through the fluid to the far end, down through the helicotrema gap and back along the lower chamber to the round window. As fluid is incompressible, the round window serves to absorb the pressure variations and dissipate them to the air in the middle ear.

Now as those vibrations travel along the upper chamber they pass through thousands of very sensitive hair cells on the upper surface of the dividing membrane. These are linked to the nerve fibres that are connected to the auditory part of the brain, and their movements produce the neural signals along the fibres.

Total length of the membrane average 31mm, and frequency response is distributed along its length; the region near the entrance is sensitive to the high frequencies and the region near the end to the low frequencies. The audio spectrum is divided into 24 bands with 1/3 octave spacing, each with its own nerve path to the brain. Centre frequencies of each band start at 50Hz for band 1 up to 13.5kHz for band 24.

Cutoff outside each bad is not sharp but gradual, especially on the high side, although it is steeper on the low. Thus there is some overlap which fills in, should any band become inoperative for some reason. Each band occupies a definite position along the basilar membrane with physical spacings of 1.3mm; spacings are termed *barks,* one bark being the space from one band to the next.

## Frequency Response

The frequency response of the "typical" ear is shown in Figure 3. As can be seen, the response is by no means levels, and varies considerably with absolute sound intensity.

The figure shows the levels at which pure tones of given frequency appear to equal the loudness of a 1KHz reference tone, averaged over a large group of people in the 18 to 25 age range; these curves are now accepted as an international standard.

The most sensitive region at all sound levels is around 4kHz, with lifts in response at around 400Hz (for higher sound levels) and 12kHz. The response at very low levels to bass and treble is comparatively much lower than at the higher levels, in particular at the bass end. This explains why some amplifiers have loudness controls to lift the bass response at low levels. The better amplifiers will have loudness contours dependent on the volume control setting.

As with most other abilities, there is a decline in the sensitivity of hearing with age. Over the age of 30, the high frequency response falls off at an increasing rate, and at age 60, the response is some 15dB down at 3kHz as compared to the age of 20. At 6kHz the response is even lower, at around 25dB down. Thus progressive loss is known as *presbycusis.*

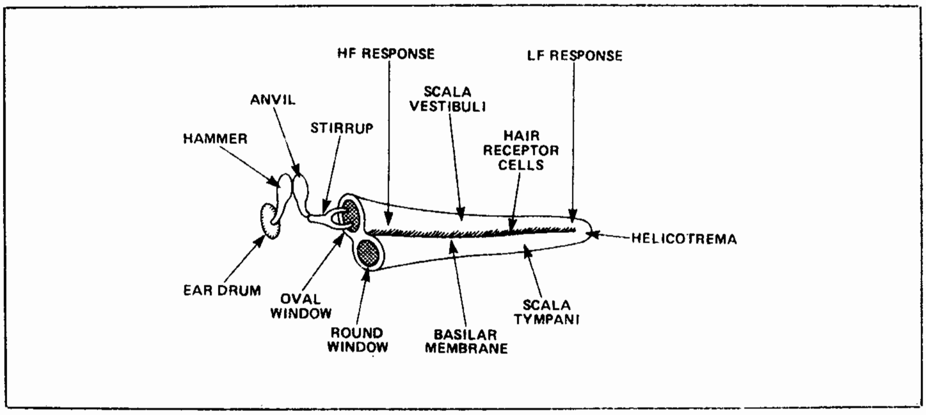

*Fig. 2 Diagram of basic components with cochlea straightened out to show various features.*

### Warning Rock Fans...

Permanent damage can be inflicted on your ears by overexposure to loud sounds. Short periods of overindulgence produces a temporary loss of sensitivity, after which your hearing will recover. However, if you listen to such a sound for a long enough time, permanent damage will occur, and the safe time depends on the level of the sound.

There are maximum permitted times for which workers can be exposed to industrial noise; these vary internationally. For example, eight hours of exposure might be permitted for a level of 90dB, with a halving of the time for each 3dB increase in level.

Damage can be greater if the noise contains impulsive components caused by percussive sources. However, irrespective of the frequency or nature of the noise which produced the damage, the effect is always the same: a reduction in sensitivity centred around 4kHz, the frequency region for speech. Lower and higher frequencies are less affected, if at all. As the damage increases with further exposure, the band of affected frequencies broadens until it sometimes reaches down to 1kHz.

The effect of listening to loud rock music can now be appreciated. Unlike classical music where loud peaks are interspersed with quiet passages, rock music is usually reproduced at a continuously high level, often at well over 100dB. Furthermore, the percussive beat adds its toll.

### Listening Levels

At what volume should orchestral music be reproduced? If it is too quiet, it lacks colour and interest, while if too loud, as is more often the case, it sounds unnatural. One reason for this, even if the amplifier can handle the peaks, is those aural response curves. The frequency balance is distorted a very high levels just as much as at the low ones. For optimum fidelity, the sound pressure level at the ears should be about what it would be in the concert hall.

What sort of levels could we expect there? A lot depends on the acoustics, the size of hall and the position of the listener. In a typical concert hall, from a centre position in the 11th row, peaks of 86dB were measured during an orchestral concert. On another occasion, in the 9th row, 90dB was clocked. From a similar position, during a large scale orchestral and choral work, a peak of 94dB was recorded.

Those peaks were rare and momentary. The quietest passages were pianissimo strings which measured 45dB and were just audible. Woodwind solos were in the 60dB range, while most of the orchestral playing was in the 60–80dB region. Thus a dynamic range of some 45dB was called for, which is well within the range of hifi producers; in fact, many exceed this.

If you are keen on getting the level right, a sound level meter should be used. Not all are expensive; some are available without the sophistication of professional instruments. However, if you feel indisposed to shell out for one of these, a few common sound pressure levels might help to get things into perspective: a soft whisper at 1 metre is 45dB, a vacuum cleaner at 1 metre 75dB, inside a cruising bus 70dB, a whistling kettle at 1 metre 85dB, and a pneumatic drill at 1 metre 110dB.

### Decibels

The decibel, or dB, expresses a logarithmic ratio between two numbers. In sound pressure levels, it is the ratio between the sound being measured and a reference standard which is the accepted threshold of hearing, 20 microPascals, or 200 microdynes per square centimetre. Being logarithmic, it more closely expresses

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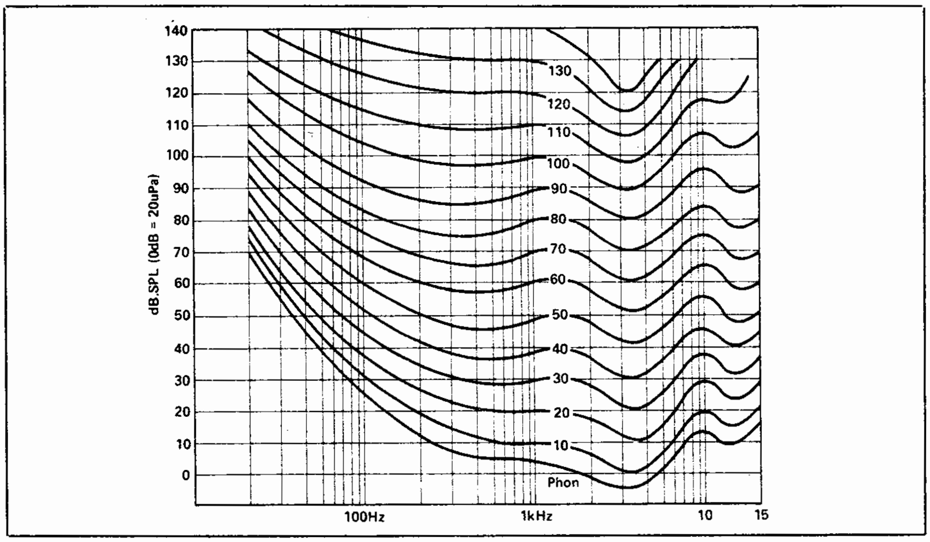

*Fig. 3 Equal loudness contours. These show the amount of sound pressure required to produce sensations of equal loudness at various frequencies and volume levels. They are therefore the inverse of a frequency response curve.*

the ear's perceived sound levels because of the ear's sound level compression. A difference of 1dB is said to be the absolute minimum that can be detected, though some people can detect less in the midrange; a level of 3dB is a more usual level before a difference is detected. Doubling the sound pressure produces a 6dB increase in the log scale, but a subjective doubling of the loudness requires an increase of some 10dB, or about three times the SPL.

## Identifying Sounds

How is it that we can identify sounds, especially musical instruments that are playing the same note? The standard explanation is that we do it by means of harmonics and overtones.

When a string or column of air in an instrument vibrates, in addition to the fundamental vibration there are harmonics at twice, three times, four times the fundamental frequency and so on. As well, the various parts of the instrument vibrate at resonant frequencies which may be harmonically unrelated to the note being played. All these harmonics and overtones produce a characteristic pattern or *formant* which is different for each instrument and gives it its special tone.

Harmonic analysis reveals that the pattern changes considerably with some instruments between their lower, middle and upper registers. The flute, for example, has few if any harmonics in its upper register, being perhaps one of the purest of instruments, yet in its lower range it can have up to ten. The bassoon has an upper register that is fairly conventional, with a strong fundamental and a series of harmonics of diminishing amplitude, but its middle compass has a weak fundamental and a second harmonic that is usually

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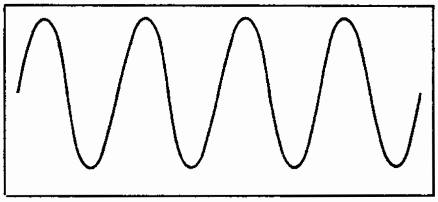

*Fig. 4 Format of glockenspiel: a pure tone with low harmonic content; very difficult to identify without starting transients.*

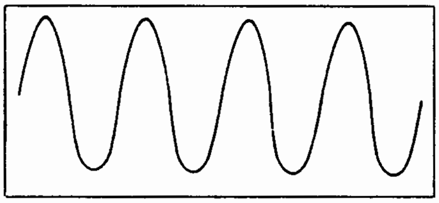

*Fig. 5 Piano played pp: mainly second harmonic with fundamental as seen from broader negative half-cycles.*

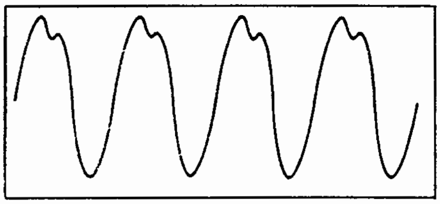

*Fig. 6 Piano played mf: stronger second harmonic with others, mainly even.*

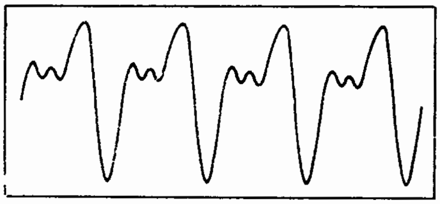

*Fig. 7 Trumpet: stronger harmonic content then piano note but not dissimilar, when starting and finishing sections removed. Harder sound than piano.*

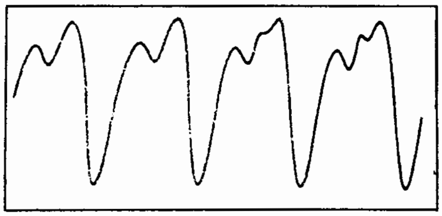

*Fig. 8 French horn: mellower tone then trumpet, but similarity in waveform can be seen.*

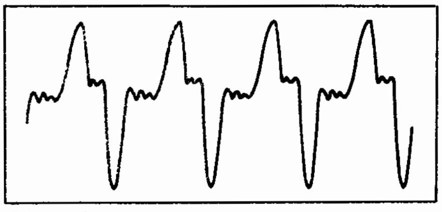

*Fig. 9 Clarinet: distinctive pattern consisting of strong fundamental with strong odd harmonics in large number.*

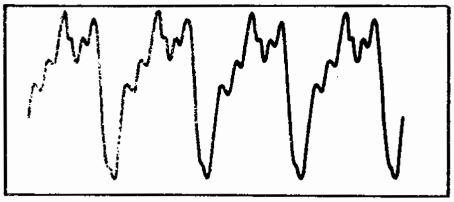

*Fig. 10 Violin: large number of harmonics both odd and even gives rounder, less incisive tone than clarinet. Yet without starting and finishing portions, it is difficult to distinguish them.*

stronger, with the following ones irregular in strength. The low register is different again with a weak fundamental and harmonics increasing in amplitude as high as the fifth.

Also, many instruments have quite a different harmonic pattern when played loudly to when played softly; the piano is an example. Yet with all this, we can still recognize the instruments whatever their register and level.

Clearly, something else must be responsible for giving the characteristic sound in addition to harmonic content. Another factor which has been suggested is the "shape" of the sound; that is, the way it starts, decays and finishes. Percussive instruments produce very steep starting transients, but quickly decay to inaudibility. The attack of the bow on stringed instruments is quite different, and the notes can be sustained or increased in volume at the will of the player, and the cessation is abrupt as the bow is lifted. Further complications are vibrato, whereby the performer makes small and rapid changes in pitch, and tremolo, which is mainly amplitude variations.

## Experiment

To test the validity of this theory, I set up an experiment with the cooperation of a small amateur orchestra. Six instruments were chosen that were all unalike in tone: trumpet, French horn, glockenspiel, B-flat clarinet, violin, and piano. Each instrument played in turn an ascending scale of C major starting at middle C. Each note was played deliberately and slowly, with no vibrato or tremolo, and was duly recorded on a reel-to-reel tape recorder.

Next, each note was edited; the start and finish were edited out, leaving only the middle portion, and the order of the instruments was rearranged.

Finally, members of the orchestra, members of a choir that performed with it, and some hifi enthusiasts were asked to try and identify the instruments from the doctored recording. In view of the knowledge and familiarity with the sound of the instrument, only 25 percent got it right.

The editing gave the glockenspiel a pure clear tone very much like the flute. Horns were the easiest to identify, and the piano turned out to have a strange tone rather like a brass instrument.

So, the conclusion is that stating transients in particular, and the decay and termination in addition, play an important part in the recognition of musical sounds. This emphasizes the need for good transient response and avoidance of transient distortion in sound systems.

## Listening Fatigue

After a spell of listening to music, various symptoms may arise. These can range rom a mild feeling of having heard enough to feelings of unease and actual irritation. It may not be associated with the sounds actually heard, but these nevertheless are the cause.

What causes listening fatigue? Distortion is one problem. Even harmonics can be tolerated in quite large doses, because they are harmonious with the fundamentals. Odd harmonics are dissonant, and small amounts can be unpleasant. Crossover distortion associated with Class-B amplifiers consists mostly of third harmonics. Although reduced to very low levels by sophisticated design, it can still have an effect, though to a lesser extent.

Another case is intermodulation distortion. Here, harmonically unrelated spurious frequencies are generated by the interaction of two signal frequencies. Complex waveforms consisting of many frequencies can generate an abundance of spurious ones, nearly all discordant. This too can result in fatigue.

A further cause is excessive high frequency response. Peaks in the treble can over-emphasize the natural harmonics of the musical instruments. The effect may be an apparent brilliance which is not unpleasant, but even stimulating to start with, yet can soon produce fatigue symptoms.

An interesting fact is that female voices are less likely to produce listening fatigue than male ones. A possible explanation for this is the harmonic content of the female voice. Although the female voice is pitched higher than the male, it has less harmonics and thus a purer tone.

We do not know all the mechanisms and psychological effects that are involved between the outer ear and the sensations of sound produced in the brain, but the outline presented here should help us appreciate the equipment with which we have been endowed and how it relates to reproduced sound. ■