What's this 'ear?

Anyone who has ever designed a synthesiser or other electronic musical instrument will, no doubt, have at some time cursed our remarkable sense of pitch, which puts so many design constraints on the oscillator system. Dr. R A Henson of The London Hospital explains just how the human sense of pitch works and turns up quite a few interesting pieces of information.

THE PITCH of a sound means its position on a scale of frequencies. Pitch sense is involved in perceiving all complex sounds: for example human speech has its set of pitches. In this article, I consider the way pitch relates to music.

In general, the pitch of a tone depends on its fundamental frequency, which determines whether it stands high or low on the musical scale. We tell one tone from another by their different fundamentals. Music is made up of a succession of tones and combinations of tones that are perceived, analysed and coded by the nervous system in ways to be explored, but questions of tuning and scales and how well we can hear them must be dealt with first.

Orchestral pitch is agreed nowadays as 440 Hz for A', that is, the note A above middle C. It became necessary to agree this internationally because different pitches were used in different places and because a progressive heightening of pitch in the 19th century led to A' as high as 461 Hz in some places. Musical scales are sets of pitches arranged in such a way that they contain a maximum of consonances, where various tones tend to blend pleasingly, and a minumum of dissonances, where they do not. Tuning in 'equal temperament' has held the field in western music for three centuries because, unlike the earlier 'perfect temperament', it makes possible the use of all 24 keys (C major, C minor, C sharp and so on) without retuning. In equal temperament the octave is divided into 12 logarithmically equal steps of frequency, each to a frequency 5.9 per cent greater than the step below. The steps, called semitones, are each divided into 100 further equal steps or cents, and an octave covers 1 200 cents. This method of tuning is imperfect and less accurate than the earlier forms. As Balbour, the eminent American composer and organist wrote, "all players and singers are playing false most of the time . . . these are errors of equal temperament."

Have we an inbuilt tuning system? Training and early exposure to musical stimuli make this question impossible to answer with any assurance. However, we can say that the western musician's internal pitch scale corresponds to equal temperament but with a slight tendency to sharpen all notes relevant to the tonic or keynote; the target pitch for notation is a shade sharper than equal temperament.

Normal Capability

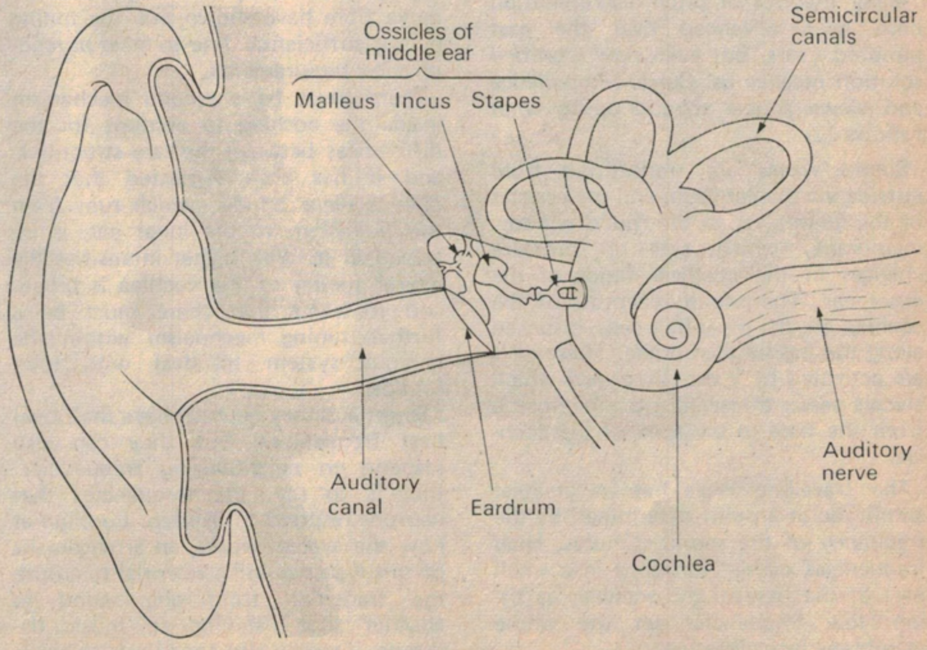
How much of the normal range of frequencies is actually heard depends on the age of the hearer and also on what is meant by 'hearing' a frequency.

Some organ pipes are felt rather than heard.

The figures commonly given are 16 – 20 000 Hz for young people and 20 – 16 000 Hz for adults. Hearing is most sensitive for frequencies between 1000 and 3000 Hz, being much reduced in the extreme lower and higher ranges. People's ability to discriminate in pitch ranges from those who are tune- or tone- deaf to those with absolute pitch sense. Though it is highly developed in some, there is no experimental evidence that they can do better than discriminate between quarter tone intervals consistently. The ability to detect small changes of frequency diminishes sharply above 4000 Hz.

A sense of relative pitch is necessary for hearing or singing a simple tune. Most of us perceive and remember music in terms of changing sequences of notes rather than in orchestral or other pitch vlaues. Absolute or perfect pitch is the ability to name a sounded note or identify its frequency, or to do both this and to sing a given note accurately straight off.

Possessors of absolute pitch appear to have an inbuilt pitch grid against which to measure the incoming sounds. ▶



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There has been a prolonged debate about whether absolute pitch is innate or acquired, but the present majority view is that both heredity and environment play their parts. Absolute pitch may be the normal manner in which we deal with frequency, but this is trained out of us by our musical environment, which depends on relative pitch. Certainly, absolute pitch can be learned in early childhood, but while pitch perception can be improved in adults by training, no-one has been able to train adolescents and older people who had little original ability in pitch naming. It is likely that highly developed pitch naming almost always derives from reinforcement of a child's behaviour by an adult.

Perfect pitch is an advantage in some aspects of practical musicianship, but it also carries handicaps. For example, a singer has to transpose consciously when a key is changed. Interestingly, all normal people can retain information on absolute pitch for periods ranging from ten seconds to a few minutes, but the information is then discarded.

The Peripheral Analyser

The capacity of the human ear to analyse sound waves is truly remarkable. Perception of musical sounds depends on several factors, including identification of the pitch, duration, intensity and rhythm of a series of tones, and this requires an efficient peripheral analyser of the sound waves produced. Here we are concerned solely with the problem of pitch perception.

Many theories of pitch discrimination have been advanced over the past hundred years, but even now a unified solution escapes us. Current knowledge and views appear to add up to what follows . . .

Sound waves are transmitted from outside via the ear drum and the ossicles of the middle ear to the round window membrane, which sets up pressure changes in the cochlear fluids of the inner ear. The sound receptors of the cochlea are the inner hair cells, disposed along the basilar membrane. These cells are activated by a travelling wave which always passes throughout the membrane from the base to the apex of the cochlea.

The travelling wave has its greatest amplitude at a point determined by the frequency of the sound stimulus. High frequencies cause vibrations in a small part of the base of the cochlear partition; low frequencies set the whole membrane into vibration.

The place where the inner hair cells are activated may well account for the perception of high frequencies, and this idea is supported by the fact that people with disease at the base of the cochlea are deaf to high tones. But this theory does not explain how we perceive low tones, and it has been suggested that low frequencies are represented by the rate of nerve impulses engendered by the stimulus.

The cochlear nerve fibres, which join the ear to the brainstem, cannot carry more than 500 to 600 Hz, and this led to the 'volley' theory. This was that groups of fibres could carry frequency information, so that the stimulus frequency is represented in the combined pattern of nerve impulses produced.

This idea is acceptable in a general sense, but there are objections to it on physiological grounds, especially where frequencies over 3 kHz are concerned. Perhaps the place and frequency patterns in time all play their parts in pitch perception. Harmonics may help in identifying the fundamental lower tones, for if a set of overtones is sounded, without the fundamental, the listener's ear supplies it and he hears it just the same.

Second Mechanism

This first stage of analysis by the basilar membrane is not enough to account for the fine degree of pitch discrimination achieved by the human ear. Studies on the mechanical tuning of the basilar membrane have shown that it acts as a heavily damped, broadly tuned structure; on the other hand, recent recordings of the activity of a single auditory nerve fibre have shown that the tuning here is sufficiently fine to meet psychophysical requirements.

There must be a second mechanism inside the cochlea to account for the differences between the two structures, and it has been suggested that the olivocochlear bundle, which runs from the brainstem to the inner ear, is involved in it. With higher intensities the neural tuning of the cochlea is broad, and it seems that there must be a further tuning mechnaism within the nervous system to deal with loud sounds.

Single auditory neurons have their own best frequencies, but they can also respond to neighbouring frequencies: that is to say, the frequencies that neurons respond to overlap. Looking at how the system works, an arrangement of this type would be essential to ensure the transition from one sound to another that listening to music demands; it would also contribute towards the appreciation of loudness.

Psychophysical studies suggest the frequency selectivity is achieved in man by the equivalent of a bank of overlapping filters, a system that would separate the individual components of a complex signal for analysis. Psychophysical measurements, known as critical bands, have been used to find the effective bandwidths of the human auditory system. It appears that these critical bands range from 200 Hz wide at 1 kHz to 2 kHz wide at 10 kHz.

Such a mechanism could explain why we hear the normal differences in tuning or sounding instruments or voices as the same note or tone. Tonal material that is not relevent to the task on hand is inhibited, a process called tuning or sharpening. The exquisite sensitivity of the human ear is shown by the way in which we can separate simultaneously-heard tones with shared harmonics. So far we have been unable to sort out the mechanisms that produce these psychophysical effects.

A central pitch processor should transform incoming nervous impulses bearing information on pitch into patterns, so that all stimuli of the same periodicity are represented in the same way. This would produce individual sensations for different pitches.

We have already seen the need for an auditory system capable of categorical assessment and of dealing with tones of neighbouring frequency or shared harmonics. The nervous system meets this need in ways we do not understand. The auditory system must integrate stimuli presented to both ears, and its ability to do this is shown by the way harmonic components fed simultaneously into both ears combine so that the subject hears the fundamental.

Conventional neuroanatomical and neurophysiological studies have given little information about central pitch processing, although the complex pathways of hearing in the brainstem have been thoroughly investigated. Auditory nerve fibres from both inner ears stream up the brainstem on both sides after their first relay point in the cochlear nuclei. It appears that these fibres relay at four or more points in the brainstem nuclei before they reach the auditory cortex of the brain.

The final relay is in the thalmus, and from it auditory information flows to the auditory cortex. Apart from the complexity of the nuclei and linking tracts, investigations are made difficult because if anaesthetics are used, then evoked auditory responses in man and experimental animals are not normal, but, of course, more of these abnormal responses are obtained under anaesthesia. than otherwise.