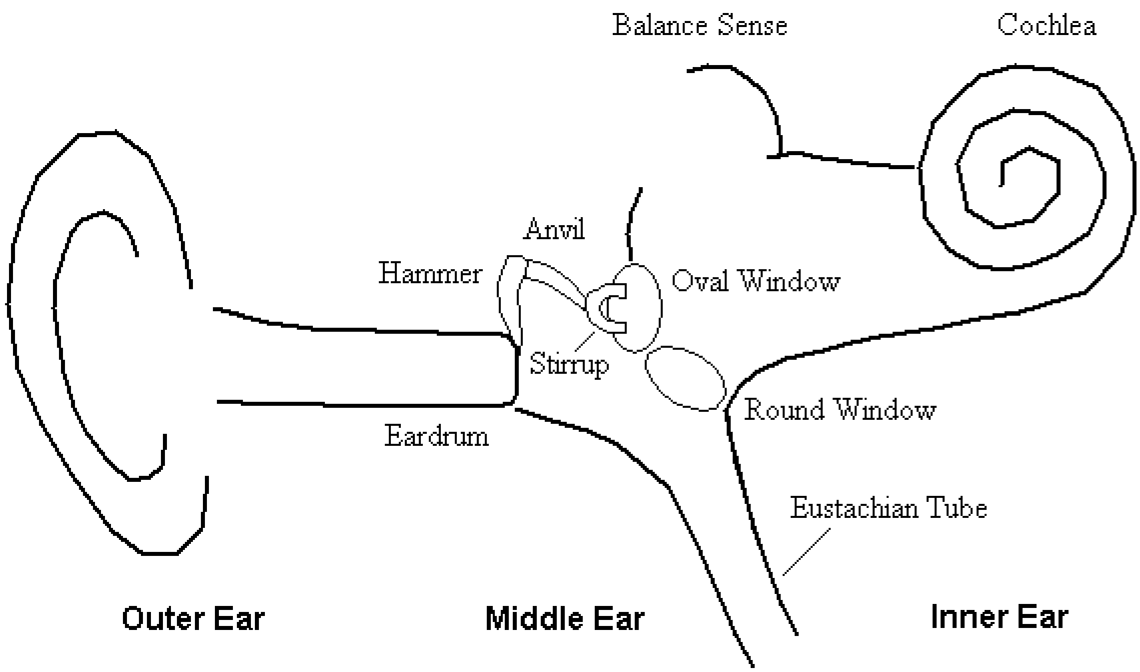
R. The Ear

We turn now to the study of the human ear. In this chapter we consider the biological components of the ear. We learn how they work in order to detect sound waves. Then, in following chapters, we look at the psychology of perception and the medical area of hearing loss, audiology.

Structure of the Ear

Fig. R-1 below illustrates the human ear. The ear is divided into three parts or sections. These are the *outer ear*, *middle ear*, and *inner ear*. The sounds enter the ear in a gas medium. We have acoustic waves in air. The waves travel to the eardrum. The eardrum is the boundary between the outer and middle ear.

Fig. R-1. Schematic of the Human Ear.



The eardrum is a membrane that vibrates in response to the incoming sound waves. It is analogous to the membrane in a microphone that oscillates in step with the sound it picks up. The eardrum transmits the vibrations to the middle ear. The middle ear consists of three tiny bones: the *hammer*, *anvil*, and *stirrup*. The vibrating eardrum vibrates the hammer. The motions of the hammer are transmitted to the anvil, and then to the stirrup. In this sequence, the bones act as a lever system. The vibrations are amplified in the process and directed to the oval window. The amplification occurs since the applied force at the oval window acts over a smaller area when compared to the area of the eardrum, the location of the input force. Muscles dampen the bones if necessary. However, sudden loud sounds may cause damage to the middle ear.

The *eustachian tube* connects the middle-ear section to the region below the back of your mouth. This is important in order to equalize pressure. When there is no sound, the pressure on either side of the eardrum should be the same. When sound compressions and rarefactions enter, the eardrum vibrates about its equilibrium position. If you go to a higher altitude, the air pressure is less. The eardrum wants to push outward due to the lower pressure outside and greater pressure inside. However, if the outside pressure can be communicated to the middle ear behind the eardrum, a new equilibrium pressure can be established.

The reverse occurs when you come down from a higher altitude to a lower one. The increased pressure at lower altitude pushes in on the eardrum since now the average pressure behind the ear is less. When the greater outside pressure is communicated to the middle ear via the eustachian tube, the equilibrium pressure is raised.

The adjustments in pressure must not occur instantly, otherwise, the eardrum wouldn't work at all. You want the rapid changes in pressure of a sound wave to vibrate the eardrum. It does this because the pressure changes rapidly on each side as the sound vibrates the eardrum. We only want to make a correction to the pressure behind the eardrum when the overall average pressure, i.e., equilibrium pressure, changes. Therefore, the response time for the pressure adjustment is greater. It may take a few seconds or longer. When the adjustment occurs, you might hear a "pop." You might describe it as your ears "popping."

If you are "stuffed up" due a cold or allergy, your ears may have trouble adjusting for equilibrium pressure changes. The build up of pressure on either side of the ear can be quite painful, especially on airplanes. The ear is challenged on airplanes. Although attempts are made to keep cabin pressure constant, there are typically changes in the pressure when raising to higher altitudes and coming down. Smaller low-flying planes do not maintain cabin pressure as well as larger commercial jets. Some people suggest swallowing to help open passageways in the eustachian tube. Others recommend chewing gum.

The author's father-in-law (*the Colonel*) was a flight instructor during World War II. His method calls for you to cover your nose openings with your thumb and forefinger, close your mouth, and try to blow outward through your covered nose. The internal build-up of pressure helps to open the pathway in the eustachian tube.

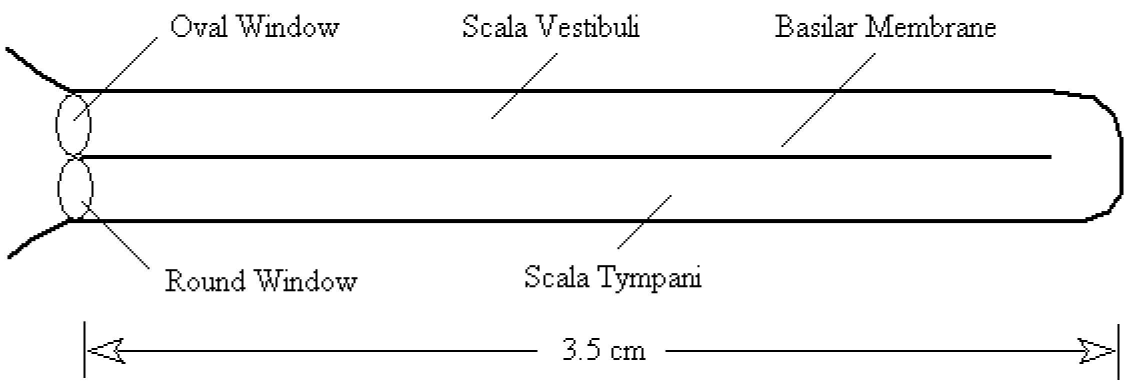
The stirrup is attached to a structure called the oval window, the boundary between the middle and inner ear. The stirrup vibrates the *oval window*. On the other side of the oval window is the inner ear with fluid. The vibrations now travel as conduction in a liquid. The pressure waves in the coiled *cochlea* (KOE-klee-uh) result in detection of sound. The inner ear also houses our sense of balance. However, the balance sense is independent of hearing. The balance structure contains semicircular canals (not shown in Fig. R-1) with another fluid which responds to our orientation. Here, fluid actually shifts around, stimulating hair cells. In the cochlea, pressure waves in the fluid stimulate hair cells.

The Inner Ear

To acquire an understanding of the cochlea of the inner ear, we will enlarge it in stages. However, first we unwrap it. The unwound cochlea is about 3.5 cm in length (one inch and a half). Magnifying the unwrapped cochlea gives the result in Fig. R-2 below. Sound enters at the oval window. The oval window transmits the sound waves into the upper cochlear chamber called the *scala vestibuli*.

The oval window is an oval opening covered with a membrane on each side. It is exaggerated (too large) in Fig. R-2. The window itself does not take up the entire end of the upper chamber. Sound travels down the scala vestibuli, crosses and is detected along the basilar membrane (the place depending on the frequency), and remnant sound waves travel through the *scala tympani*, the lower chamber to the round window.

Fig. R-2. Unwound Sketch of the Cochlea.



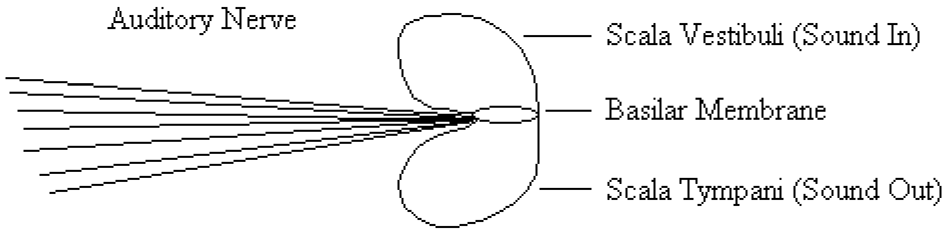
Sound Travels Down the Top Chamber, Around the End, and Back Up the Bottom Chamber.

The *round window* is a small round opening covered with a membrane on each side. It is located at the end of the path that the sound takes. It gives way to the pressure vibrations, preventing strong reflections that would occur if the end of the path were a solid wall. The size of the round window is exaggerated in Figs. R-1 and R-2. It does not take up the entire end of the lower chamber.

The *basilar membrane* lies between the upper and lower chambers in Fig. R-2. The sound is detected here. The basilar membrane is stiff at the left end near the oval window. This causes high frequencies to be detected there. Stiff structures vibrate more quickly than supple ones. The right end of the basilar membrane is not as firm and responds more readily to low frequencies. The slight disturbance of specific regions of the basilar membrane detects the different frequencies. The basilar membrane connects to nerves along its length. A cross section of the unwound cochlea found in Fig. R-3 shows this bundle of nerves called the *auditory nerve*.

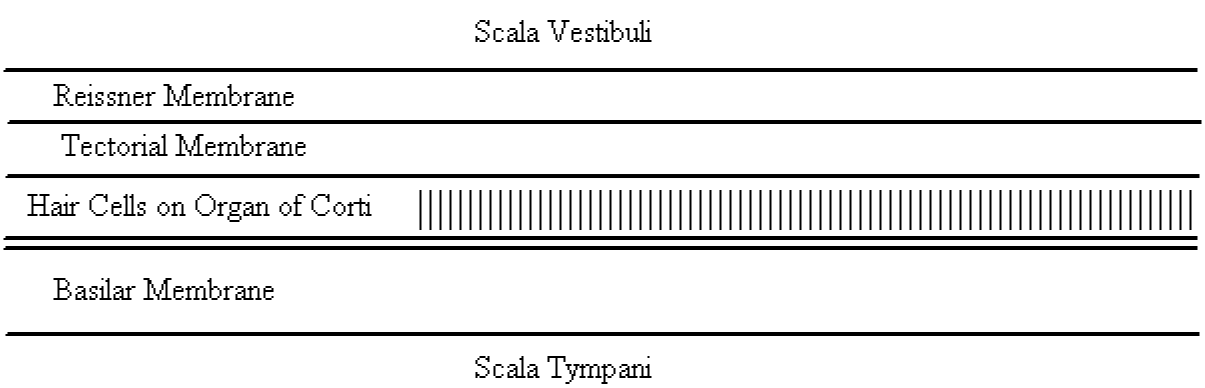
Fig. R-3 is a cross section of a cochlea that has been unwrapped. Think of the cochlea now as a hot dog with threads coming out from the left middle side throughout its entire length. Then cut the hot dog in half and look at the end that is cut. This is what you are seeing in Fig. R-3. To get the original cochlea you need to put the other piece back and roll it up. In Fig, R-3 you can look down the top and bottom chambers of the cochlea. The basilar membrane lies in the middle region. However, some structures in the middle have been omitted so far. To investigate further the structure of this central region of the cochlea, we magnify once again.

Fig. R-3. Cross Section of Unwound Cochlea.



The central region of the basilar membrane is blown up in Fig. R-4 below. The basilar membrane supports the *organ of Corti* (CORE-tee) which contains over 20,000 hair cells. As one region of the basilar membrane responds to a specific frequency, those hair cells in the vicinity move as a result of the disturbance of the underlying section of the basilar membrane. The moving hair cells get "tickled" by the *tectorial membrane*. Each hair cell is connected to a nerve member of the auditory nerve. The stimulated hair cells send electrical impulses to the brain by way of the auditory nerve. The louder the sound, the greater the movement, and a more intense electrical signal is sent along the auditory nerve. The *Reissner membrane* is a protective covering. Note the neighboring scala vestibuli and scala tympani in Fig. R-4.

Fig. R-4. Enlarged View of Basilar-Membrane Region.



The position of the stimulated hair cell along the basilar membrane determines the frequency perceived by the brain. Remember that the basilar membrane has various degrees of stiffness. Different sections of the basilar membrane move for different incoming frequencies. The stiffer parts near the oval window respond to higher frequencies while the more supple sections at the far end move under the influence of low frequencies.

In order for the ear to be able to detect frequencies as low as 20 Hz and as high as 20,000 Hz, the various frequencies detected are spaced in a special way. Imagine dividing the length of the basilar membrane into 10 equal steps. Figs. R-5a and R-5b illustrate two spacing rules. The spacing in Fig. R-5a is *arithmetic* or *linear*. You add the same amount every step of the way as you proceed from right to left. In Fig. R-5a we add 20 for each step. After 10 steps, we have moved 200 units. Since we started with 20, the final value is 220. The range is not very great.

Fig. R-5a. Linear Spacing Greatly Restricting Range.

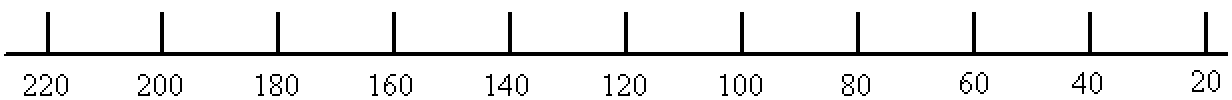
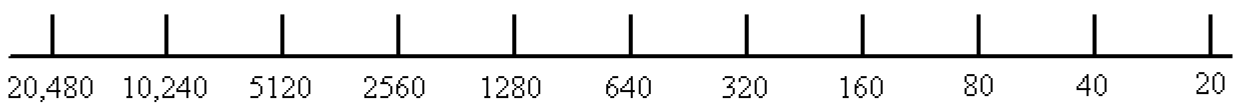


Fig. R-5b. Nonlinear Spacing of Frequency Detection Along Basilar Membrane.



On the other hand, the spacing in Fig. R-5b is *nonlinear*. Equal spacings do not correspond to equal increments. The particular nonlinear spacing in Fig. R-5b is *geometric* since every time you make a step, you multiply by a fixed number instead of adding a fixed amount. In Fig. R-5b, we multiply by 2 for every step, i.e., double each previous value. Let each vertical line in Fig. R-5b represent a bundle of hair cells on the organ of Corti. The many more hair cells that lie between these localized groups are omitted for ease of analysis. Then the numbers are the frequencies detected along the basilar membrane.

The social scientist Malthus drew attention to the concepts of arithmetic and geometric rates in his analysis of population around 1800. He proposed that population growth is geometric but improvements in food supplies are arithmetic as time goes on. Consider a chess board as another example. If you put 1 penny on the first square, 2 on the second, 4 on the third, and so on, roughly how much money would you need for the 28th square? How much for the 38th square?

A slightly smaller range of frequencies to consider spans from 30 Hz to 16,000 Hz. This stays away from the extremes 20 Hz and 20,000 Hz. The lowest note on the piano is about 30 Hz, while the highest note is approximately 4,000 Hz or 4 kHz. Frequencies beyond 4 kHz sound real shrill. See Fig. R-6 below for frequencies listed from 30 Hz to 16 kHz. We double at each step as before. Note that when we double 60, we write 125 instead of 120. We do this because doubling 125 gives the nice number 250, which we can double to get 500. The spacing in Fig. R-6 represents the spacing of the frequencies as detected along the basilar membrane. Remember that the "k" is shorthand for 1000.

Fig. R-6. Two Ranges of Frequencies.

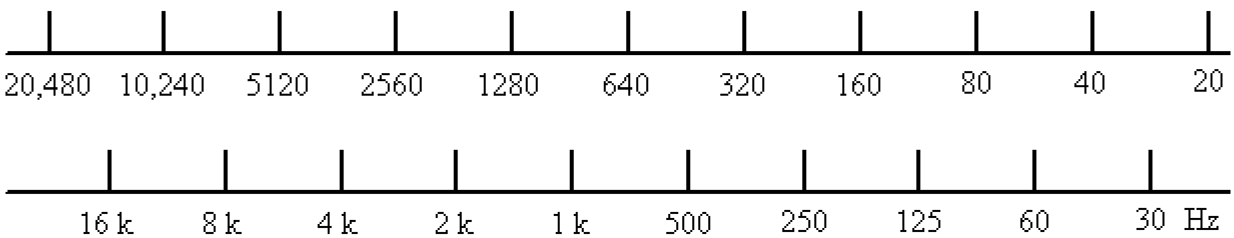
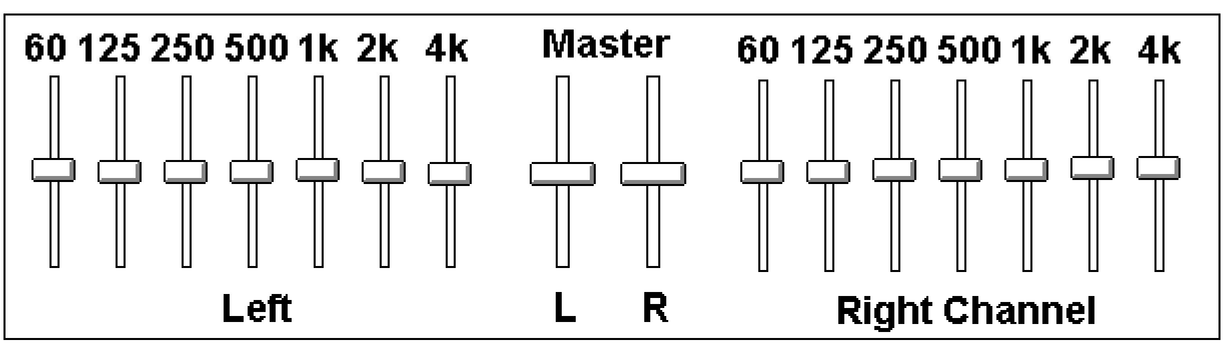


Fig. R-7 illustrates the equalizer we encountered earlier. Compare the numbers on the equalizer with our new series of frequencies in the lower line in Fig. R-6. The seven-band equalizer offers 7 frequency bands in which you can enhance the sound from your source. The equalizer can be considered as part of the 2nd stage in sound reproduction.

We learned about the functional similarity between the amplifier and filter. Both are modifiers. An active filter in an equalizer also incorporates an amplifier as part of the filter circuit itself. The center frequencies of the equalizer bandpass filters are arranged in jumps corresponding to the spacing of frequencies along the basilar membrane. The frequencies span the pitches on the piano except for the lowest octave.

Fig. R-7. Equalizer.



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