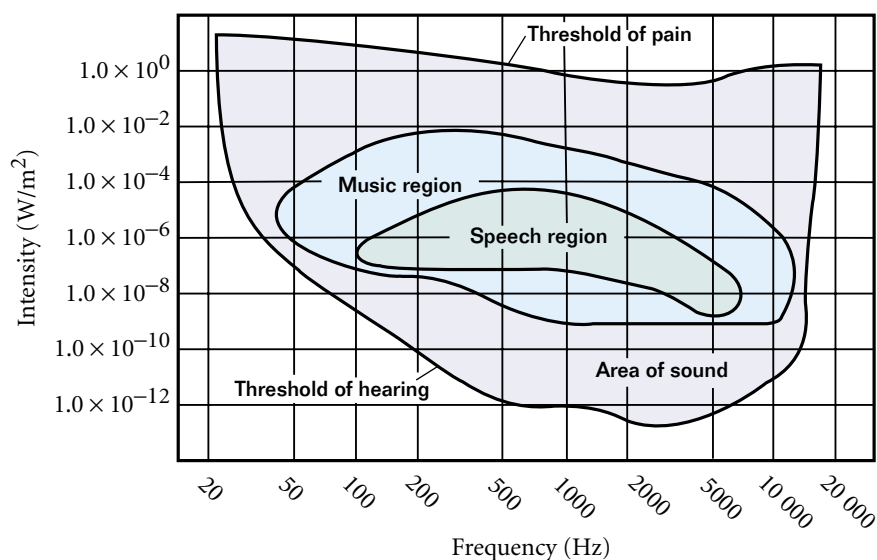


Figure 9

Human hearing depends on both the frequency and the intensity of sound waves. Sounds in the middle of the spectrum of frequencies can be heard more easily (at lower intensities) than those at lower and higher frequencies.



Intensity and frequency determine which sounds are audible

As you saw in Section 1, the frequency of sound waves heard by the average human ranges from 20 to 20 000 Hz. Intensity is also a factor in determining which sound waves are audible. **Figure 9** shows how the range of audibility of the average human ear depends on both frequency and intensity. As you can see in this graph, sounds at low frequencies (those below 50 Hz) or high frequencies (those above 12 000 Hz) must be relatively intense to be heard, whereas sounds in the middle of the spectrum are audible at lower intensities.

The softest sounds that can be heard by the average human ear occur at a frequency of about 1000 Hz and an intensity of $1.0 \times 10^{-12} \text{ W/m}^2$. Such a sound is said to be at the *threshold of hearing*. (Note that some humans can hear slightly softer sounds, at a frequency of about 3300 Hz.) The threshold of hearing at each frequency is represented by the lowest curve in **Figure 9**.

For frequencies near 1000 Hz and at the threshold of hearing, the changes in pressure due to compressions and rarefactions are about three ten-billionths of atmospheric pressure. The maximum displacement of an air molecule at the threshold of hearing is approximately $1 \times 10^{-11} \text{ m}$. Comparing this number to the diameter of a typical air molecule (about $1 \times 10^{-10} \text{ m}$) reveals that the ear is an extremely sensitive detector of sound waves.

The loudest sounds that the human ear can tolerate have an intensity of about 1.0 W/m^2 . This is known as the *threshold of pain* because sounds with greater intensities can produce pain in addition to hearing. The highest curve in **Figure 9** represents the threshold of pain at each frequency. Exposure to sounds above the threshold of pain can cause immediate damage to the ear, even if no pain is felt. Prolonged exposure to sounds of lower intensities can also damage the ear. For this reason, many musicians wear earplugs during their performances. Note that the threshold of hearing and the threshold of pain merge at both high and low ends of the spectrum.

Did you know?

A 75-piece orchestra produces about 75 W at its loudest. This is comparable to the power required to keep one medium-sized electric light bulb burning. Speech has even less power. It would take the conversation of about 2 million people to provide the amount of power required to keep a 50 W light bulb burning.