3. HUMAN RESPONSE TO SOUND

3.1 INTRODUCTION

The ear, seemingly by magic, converts incoming sound energy into eardrum oscillations, then into middle ear bone motions, standing waves on the basilar membrane and ultimately into nerve impulses that are relayed to the brain. The brain processes this information, psychologically interprets it and determines the meaning and value of that sound. The frequency range of human hearing is generally considered as 20 – 20,000 Hz. The upper range varies greatly among individuals and decreases with age and noise exposure.   The amplitude of our sensation ranges from the threshold of hearing (~0 dB) to thresholds of discomfort and pain (above 140 dB).

Objectives of this lesson:
This lesson introduces the concepts of loudness, annoyance, frequency sensitivity, hearing threshold, masking, binaural hearing and non-auditory effects of noise. After completion, the reader should have a fundamental knowledge of the psychological response of humans to noise.

References:

1. *Effects of Noise on Man*, K. Kryter, Academic Press, 1980.
2. *Handbook of Acoustical Measurements and Noise Control*, C. Harris ed., Third edition, McGraw-Hill, 1991.
3. *Noise Control for Engineers*, H. Lord, W. Gatley and H. Evensen, Robert Krieger Publishing Co., Malabar, FL, 1987
4. *Engineering Noise Control,* D. Bies and C. Hansen, Unwin Hyman, London, 1988.
5. *Music, Physics and Engineering,* H. Olson, Dover, 1967.

3.2 LOUDNESS

Loudness is a subjective response to the amplitude of sound. It is a judgement of the intensity of a sound by a human being.   It is *not* linearly related to either sound pressure (Pa), sound pressure level (dB) or sound power level. Doubling of sound power raises pressure level by 3 dB but only produces a barely noticeable increase in loudness (not a doubling). A 10 dB increase in SPL approximately results in twice the subjective loudness (equivalent to 10 identical sources instead of one).

Increase in Source Power (watts)	Change in SPL (dB)	Change in apparent loudness
2 (doubled)	3	Just Perceptible
3	5	Clearly Noticeable
10	10	Twice as Loud
100	20	Much Louder

The implications for these trends are important to the noise control engineer. If the intent is to achieve a noticeable decrease in loudness, you must add sufficient noise control measures to obtain 5 dB or more of improvement. An improvement of one or two decibels may not even be noticed. Achieving a 10 dB improvement can be a serious challenge, since it means that you must decrease the sound energy by 90%.

The sensation of loudness of pure tones has been thoroughly studied. Equal loudness contours for single pure tones have been determined by subjective listening tests and are shown in Figure 1.   These were empirically measured, first by Fletcher and Munson in 1933, and later by Robinson and Dadson in 1956. They have been established as an international standard (ISO/R 226-1961). The contours were determined by asking listeners to adjust the volume of single pure tones of various frequencies so that they sound just as loud as a 1000 Hz tone of a prescribed sound pressure level.
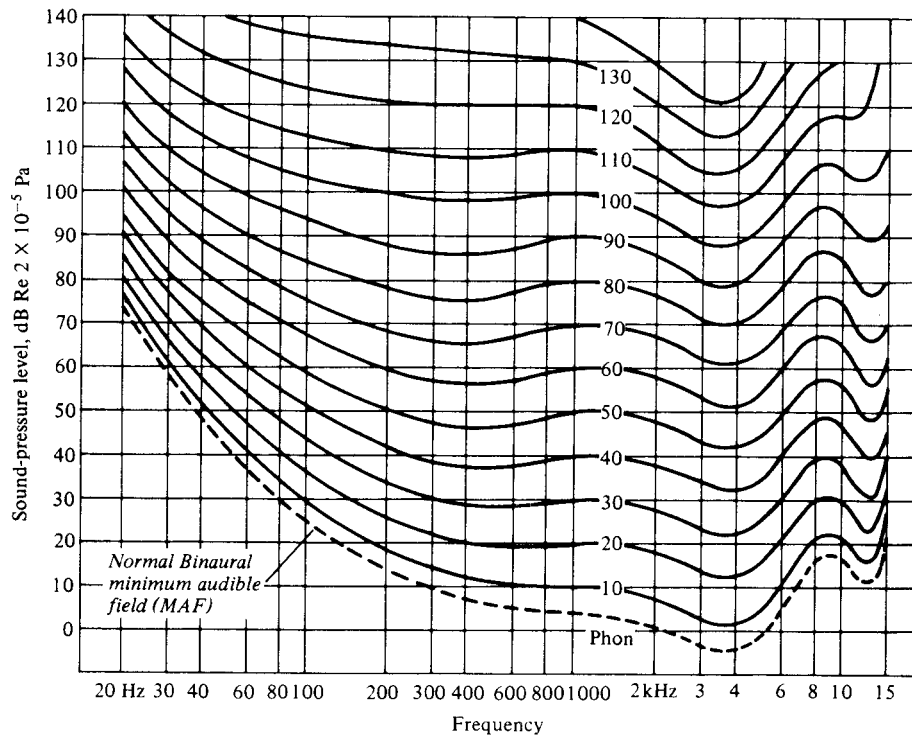
Figure 1.   Free field equal-loudness contours for pure tones as determined by
Robinson and Dadson 1956 (ISO/R226-1961)

The shape of the average hearing frequency response is determined by the
mechanical characteristics of the ear. We are least sensitive to low frequencies.
We are most sensitive in the 3-4 kHz region, corresponding with the first
resonance of the ear canal.   As seen in Section 2, the bones of the middle ear
provide amplification around 1000 Hz. Not surprisingly, most of our speech
occurs in the region of maximum hearing sensitivity. AT&T determined that
most of the information content of our speech is in the range of 300 – 3000 Hz
and designs their equipment accordingly.

Our hearing is bounded at low levels by the ***threshold of hearing***. The Minimum Audible Field (MAF) is the threshold of hearing for young adults with normal hearing. MAF is the minimum sound pressure level at which a sound is audible with both ears to a listener in a free field, facing the source. The threshold of hearing shows a pronounced variation of amplitude with frequency, almost 80 dB difference from 20 to 4000 Hz. At higher exposure levels, this variation with frequency diminishes, i.e. the equal loudness contours become flatter. For example, the 90 phon line varies only 40 dB. Above approximately 120 dB, the average listener will begin to experience physical discomfort. At around 130 dB, the large motions of the ear drum and bone chain will cause a sensation of feeling or tickling. Over 140 dB, the sensation is painful, hence the name ***threshold of pain***.

Units of Loudness
The unit used for loudness in Figure 1 is the ***phon***. At 1000 Hz, phons = dB from the equal loudness contours. As previously stated, the subjective judgement of loudness does not directly correspond to SPL or even with loudness (phons). Because most people cannot deal with anything more complicated than a linear relationship, a new unit is thus defined to linearize loudness, - called the ***sone.***
1 sone is defined as equal to the subjective loudness of a 40 phon sound. N sones means N times as loud as a 40 phon sound. There is a simple relation between sones and phons at 1000 Hz:

$$SONES = 2^{(PHONS-40)/10}$$

At other frequencies, data tables, (such as Table 2.1 Lord, Gatley and Evensen) or the graph below (Figure 2) can be used to determine the loudness. We will learn how to calculate the overall loudness in Section 4.
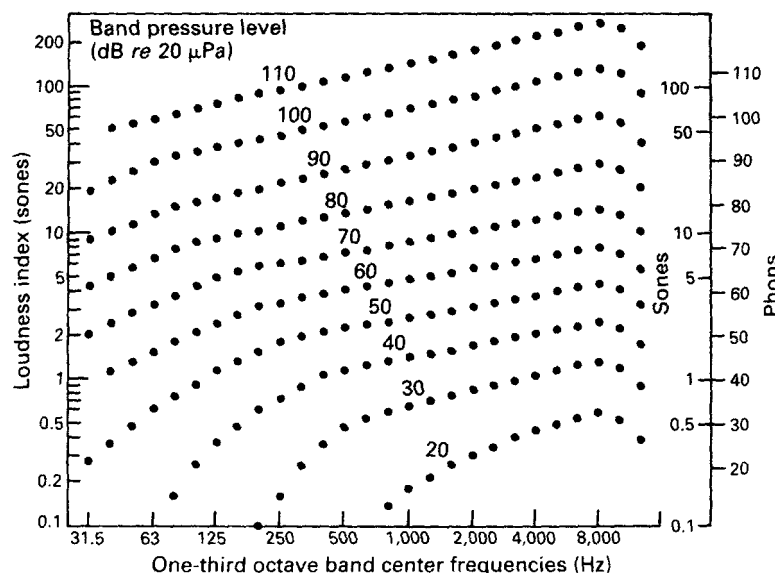
Figure 2. Band level loudness indices, for determining loudness in sones or phons
(fig 2.6, Bies and Hansen)

3.3 NOISINESS, ANNOYANCE

"Noisiness" and "annoyance" are subjective terms that involve value judgements of the sound in question. Your Harley motorcycle sounds great to you, but to your neighbor, it can be very annoying, especially at 2 am. Annoyance is a reaction to sound based on its physical nature and its emotional effect. Noisiness and annoyance are hard to quantify. The physical aspects of sound which contribute most to perceived noisiness are:

1) spectrum content and level
2) spectrum complexity and existence of pure tones
3) time duration
4) amplitude and frequency of level fluctuations
5) rise time of impulsive sounds

Experimental studies have resulted in equal-noisiness contours (similar to equal loudness contours). The unit of noisiness is the *noy*.

1 noy is defined as the noisiness of a 1000 Hz tone at a SPL of 40 dB,
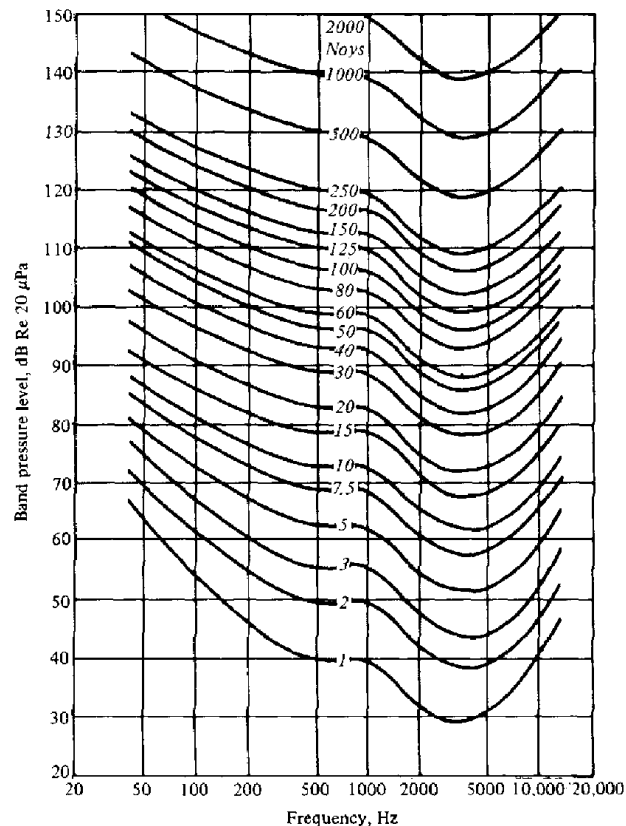
2 noys are twice as noisy as 1

Figure 3. Contours of equal perceived noisiness of octave band noise (Fig 2.12,
           source Lord, Gatley and Evensen)

3.4 PITCH

Pitch is a subjective response to frequency. The presence of a discernible pitch in
a complex noise is indicative of one or more pure tone components.
Qualitatively, high frequencies correspond to high pitch. However, at low sound
pressure levels, pitch is not linearly related to frequency (see Figure 5, Bies and
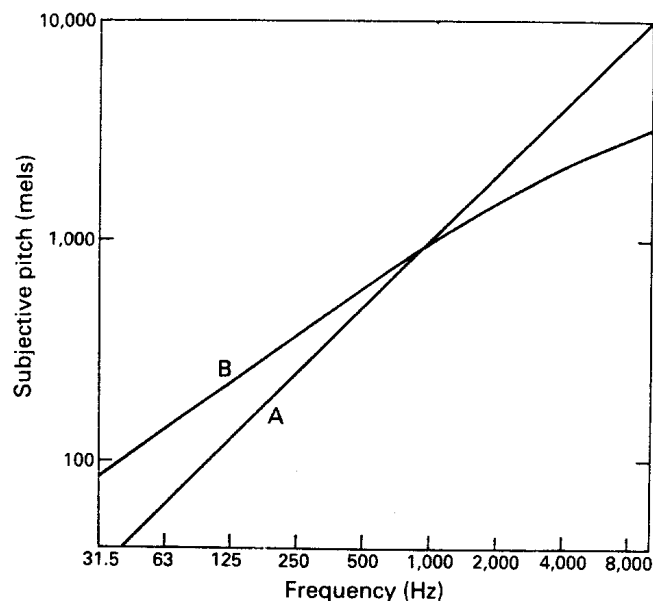Hansen)

Figure 4. The relationship between pitch and frequency: curve A represents a linear
          relationship, while curve B represents the observed relationship at low
          sound pressure levels. At high sound levels, the observed relationship
          tends to approach linear. (ref. Figure 2.7 Bies and Hansen)

The pitch of a combination of pure tones (with harmonics at integer multiples of
the fundamental tone) is determined by both the fundamental frequency and the
difference between adjacent frequencies.

3.5 MASKING

Masking occurs when one sound interferes with the perception of another. It is
caused when two excited areas overlap on the basilar membrane (due to two or
more sounds). As shown in Figure 5, two tones are only distinguishable as

separate tones if there is a sufficient difference in their frequencies. This "sufficient difference" is called the critical bandwidth and is a function of frequency.
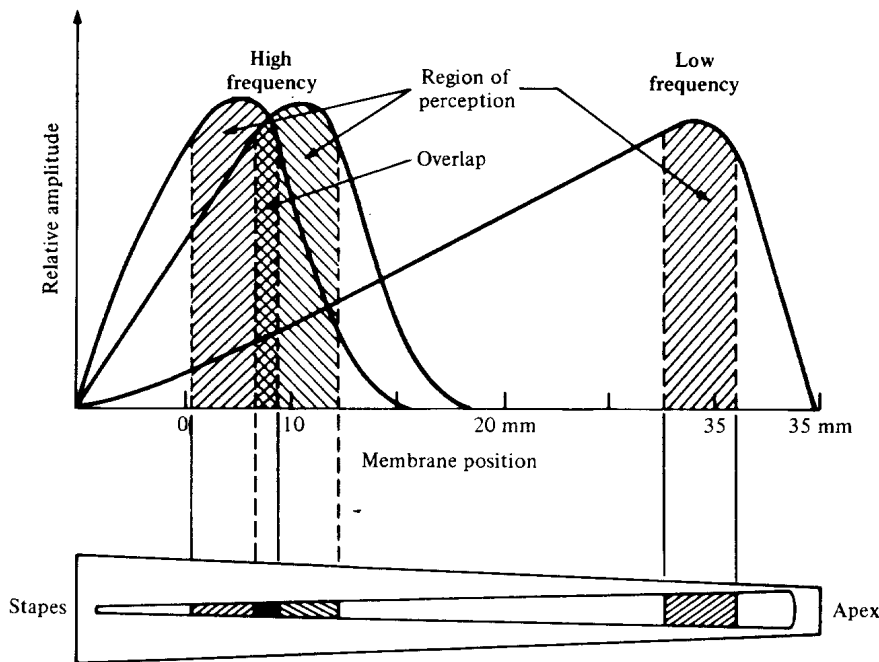

Figure 2.9 Activity in the basilar membrane for narrow-band noise signals at constant intensity. Note the competition for hair-cell activity in the overlap region.

Figure 5   (source fig 2.9, Lord Gatley and Evensen)

Low frequencies tend to mask higher frequencies. As mentioned in section 2, the ear is a highly sensitive frequency analyzer. Different regions of the basilar membrane are sensitive to different frequencies. High frequency sounds excite only the basal end (closest to the middle ear and stapes). A low frequency tone asymmetrically excites a larger portion of the basilar membrane, from the basal end outward.   This motion of the basal end can interfere with the perception of high frequency sound. High frequencies on the other hand, cause motions only in the basal end, and do not interfere with the perception of low frequency sound. This is the so-called "upward spread of masking" effect – where low frequencies can effectively mask higher frequencies, but not vice versa. This effect is shown qualitatively in Figure 5 and quantitatively in Figure 6 a) and b).

This asymmetry is most pronounced for high masking sound levels. Figure 6c) shows that narrowband noise (band-limited white noise) causes greater masking around its center frequency than a pure tone of that same frequency, since it excites more area of the basilar membrane.
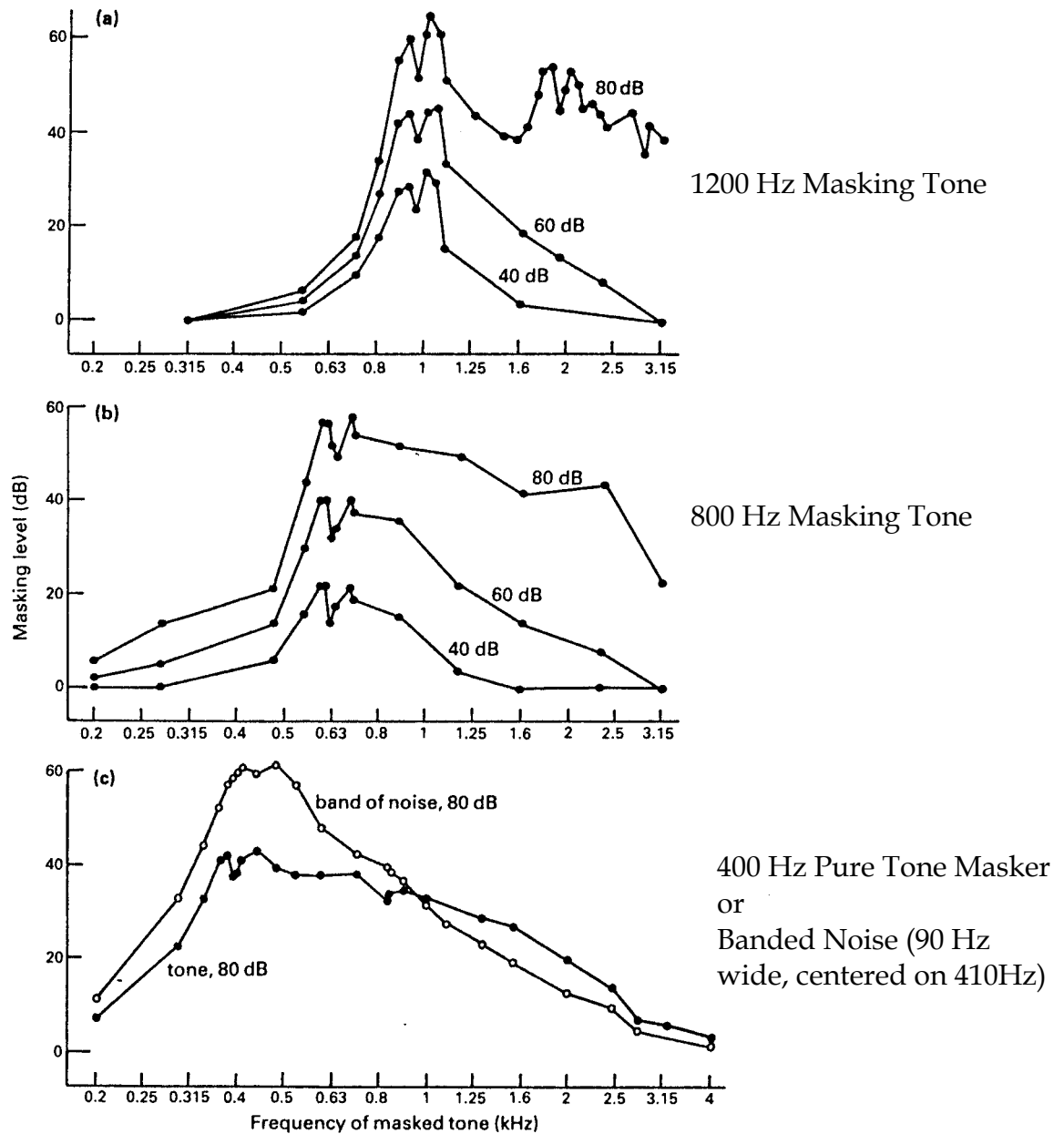
Figure 2.9 Curves illustrating masking. The amount by which the threshold level for detection of a masked tone is shifted upward in the presence of an interfering sound is plotted in the figures. The level of the interfering sound is indicated parametrically. The frequency of the masking tone is (a) 1,200 Hz, and (b) 800 Hz. In (c) the masking frequency is 400 Hz, and the masking band is 90 Hz wide, centered on 410 Hz.

Figure 6   Effect of Masking (Fig 2.9 Bies and Hansen)

Critical Band

When the masking sound is a broadband noise and the signal is a pure tone, various parts of the noise spectrum contribute differentially to the masking effect. *The critical band* for masking refers to that portion of the noise that is effective in masking the pure-tone signal. The critical band increases with frequency as shown in Figure 7 (ref. Harris). A related quantity, *the critical ratio*, is the bandwidth of the masking noise which contains sound power equal to that of a pure tone centered in that band when the tone is just audible.
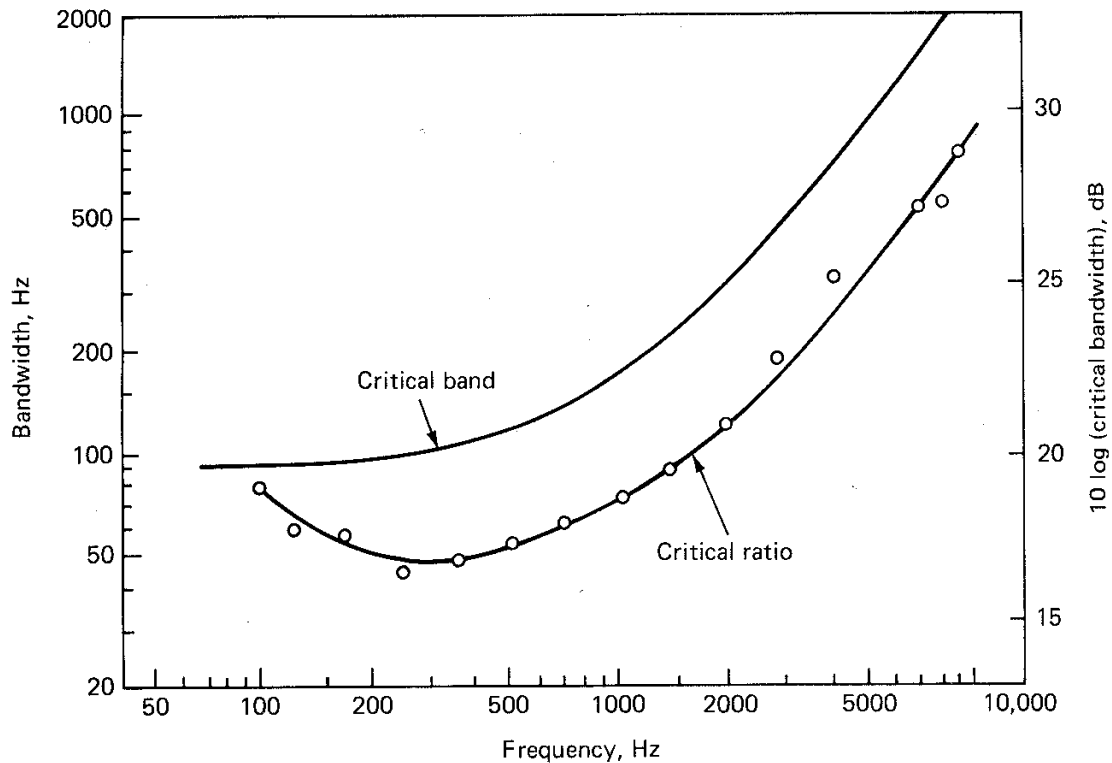

FIG. 17.12   Comparison of estimates of critical bandwidths. The curve labeled *critical band* is based on a variety of studies including masking studies in which the signal is centered in a stopband of a noise whose spectrum is otherwise uniform.[15] Masking paradigms such as those described in the text often yield narrower estimates approximating the curve labeled *critical ratio*. *(After E. Zwicker et al.[16])*

Figure 7. Critical bandwidths (ref. Harris)

3.6 BINAURAL HEARING

The ability to localize the direction of noise arrival, i.e. to localize the direction of a source, is dependent primarily on differences in the phase and intensity of the sound received by the two ears. Above about 1500 Hz, the difference in the sound intensity received at the two ears is produced largely by the scattering of sound around the head. The head provides an acoustic shadow which reduces

the intensity at the far ear. This intensity difference increases with frequency. Below about 1500 Hz, the primary mechanism of localization is the difference in the time of arrival of the sound at the two ears. This results in a difference in the phase between the sounds at the two ears. The ears combine to form a two-element array.

The accuracy of localization is much greater in the horizontal plane than in the vertical. This is because the sound located in the vertical plane arrives at both ears at nearly the same time, with no shadowing from the head. Localization in the horizontal direction is more accurate for sources in front of the listener, for frequencies below 1500 Hz and above 2500 Hz, and for broadband than for narrowband sounds. Localization increases when the listener is free to move his or her head.

Although significantly reduced, some localization remains even with one ear. This is believed to be associated with differences in the phase shifts for different frequencies produced by the head and the pinna of the ear. We train our brains to understand how these frequency-dependent shifts are related to source location by hearing sound from sources we can see.

3.7 NON-AUDITORY EFFECTS OF NOISE

In addition to hearing loss, noise can induce several non-auditory effects, including stress, tension and adverse health effects. The surprise or "startle" generated by sudden sounds can cause physical stress and tension. Noise that interferes with activities (such as sleep, conversation, music listening, concentration, etc) can also cause stress or tension due to their psychological impact. Research indicates that $L_{DN} \sim 65$ or greater of aircraft noise in residential areas is correlated with: (ref: Kryter, Effects of Noise on Man)
1. An increase in the number of people with psychological and physiological health problems requiring the increased use of certain types of drugs and visits to physicians
2. An increase in the incidence of female infants with a reduced gestation period and body weight at the time of birth
3. An increase in the number of adults requiring admission to psychiatric hospitals

These effects are due to stress induced by annoyance and emotions arising from noise interference with normal auditory functions and sleep, and from fear by associating the noise from close-by aircraft with possible crashes. Sleep disturbance is caused by L_{EQ} levels of as little as 47 dB.