IE341: Human Factors Engineering

Lecture 6 – Auditory Displays

Lesson Overview

- **Hearing**
  - – Nature and Measurement of Sounds
    - Frequency of Sound Waves
    - Intensity of Sound
    - Complex Sounds
  - – Masking
  - – Noise
- **Auditory Displays**
  - – Detection of Signals
  - – Relative Discrimination of Auditory Signals
  - – Absolute Identification of Auditory Signals
  - – Sound Localization

Hearing

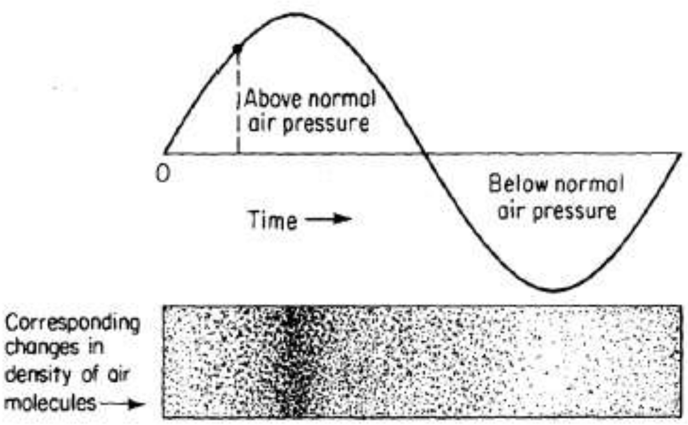
- Direct vs. Indirect hearing:
  - Direct hearing: e.g. baby's natural cry
  - Indirect hearing: e.g. doorbell ⇒ someone at door
  - Indirect stimulus can be more effective than direct
    - e.g. fire alarm (100% detectable) vs. heat/smoke (75%)
- Nature and Measurement of Sounds
  - **Sound** is created by vibrations from a source and is transmitted through a medium (such as atmosphere) to the ear
  - Two primary attributes of sound:
    - **Frequency**
    - **Intensity** (or **amplitude**)

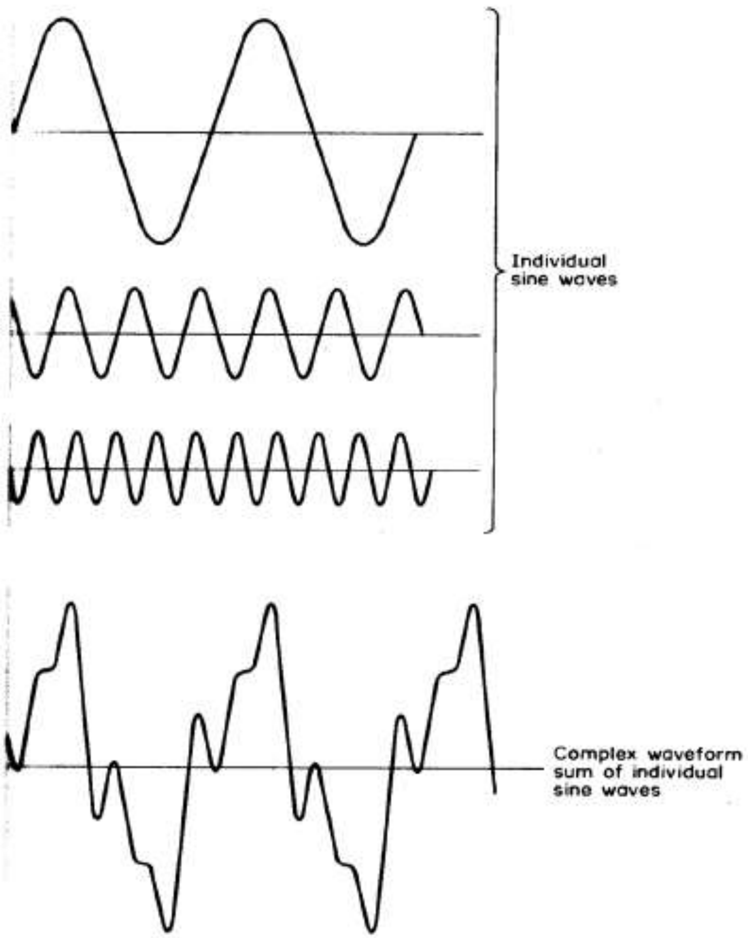
Cont. Hearing

- **Frequency of Sound Waves :**
  - When sound is generated,
    - vibration ⇒ air molecules to move back and forth
    - this alternation ⇒ ↑ and ↓ in air pressure
  - Vibration forms sinusoidal (sine) waves
    - height of wave above and below the midline represents the amount of above-normal and below-normal air pressure respectively
    - The waveform above the midline is the image of the waveform below the midline in a sine wave.
    - The waveform repeats itself again and again in a sine wave
    - **frequency** of sound:
      - "number of cycles per second"
      - expressed in: hertz (Hz) ; 1 Hz ≡ 1cycle / 1 second

Sound

- Sound – changes in air pressure, stimulus for ear
- Complex sinusoid format
  - Frequency: 20-20,000 Hz
  - Amplitude





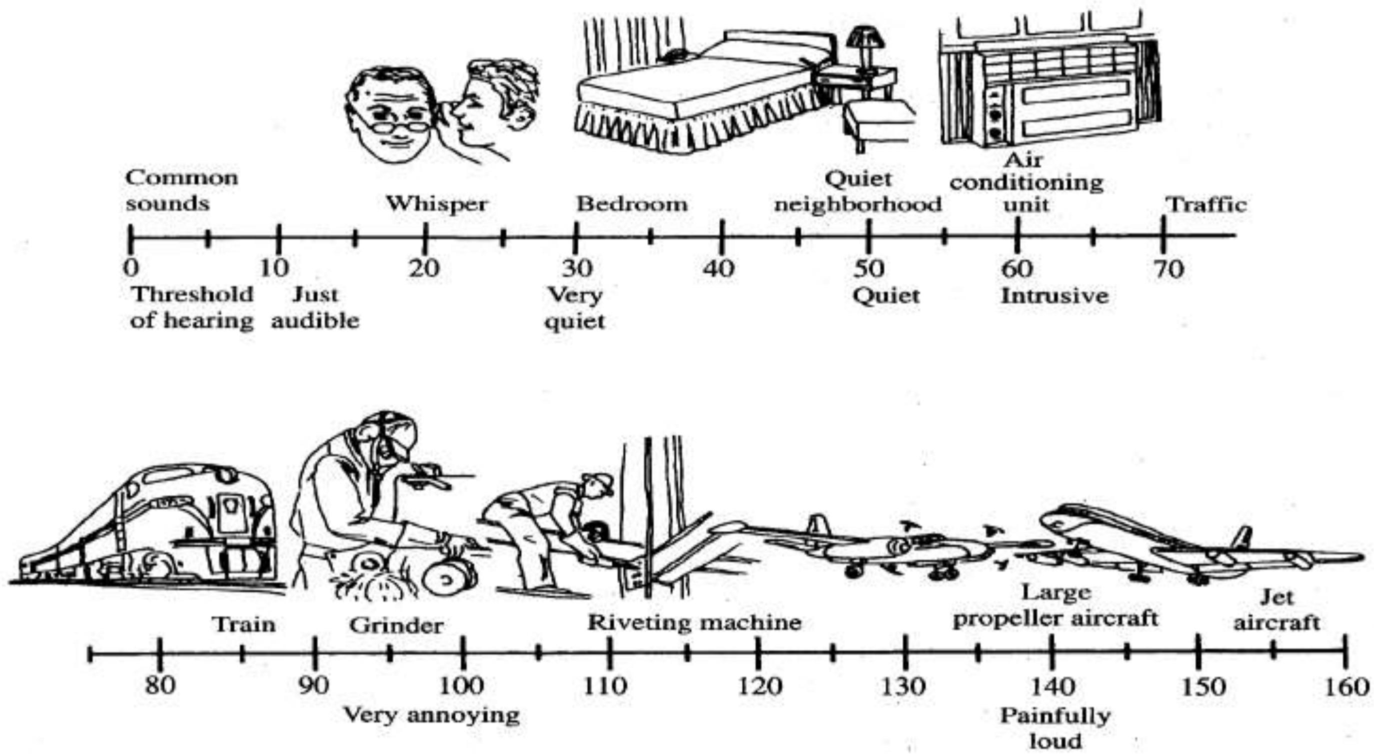
Cont. Hearing

- **Cont. Frequency of Sound Waves :**
  - The human ear is sensitive to frequencies
    - 20 to 20,000 Hz
    - highest sensitivity: between 1,000 to 3,000 Hz
  - Ear is not equally sensitive to all frequencies
  - People differ in their relative sensitivities to various frequencies

- **Intensity of Sound (amplitude/loudness):**
  - defined in terms of power per unit area
  - The Bel (B) [after *Alexander Graham Bell*] is the basic unit for measuring sound (log scale)
  - The most convenient measure is:
    - decibel (dB)

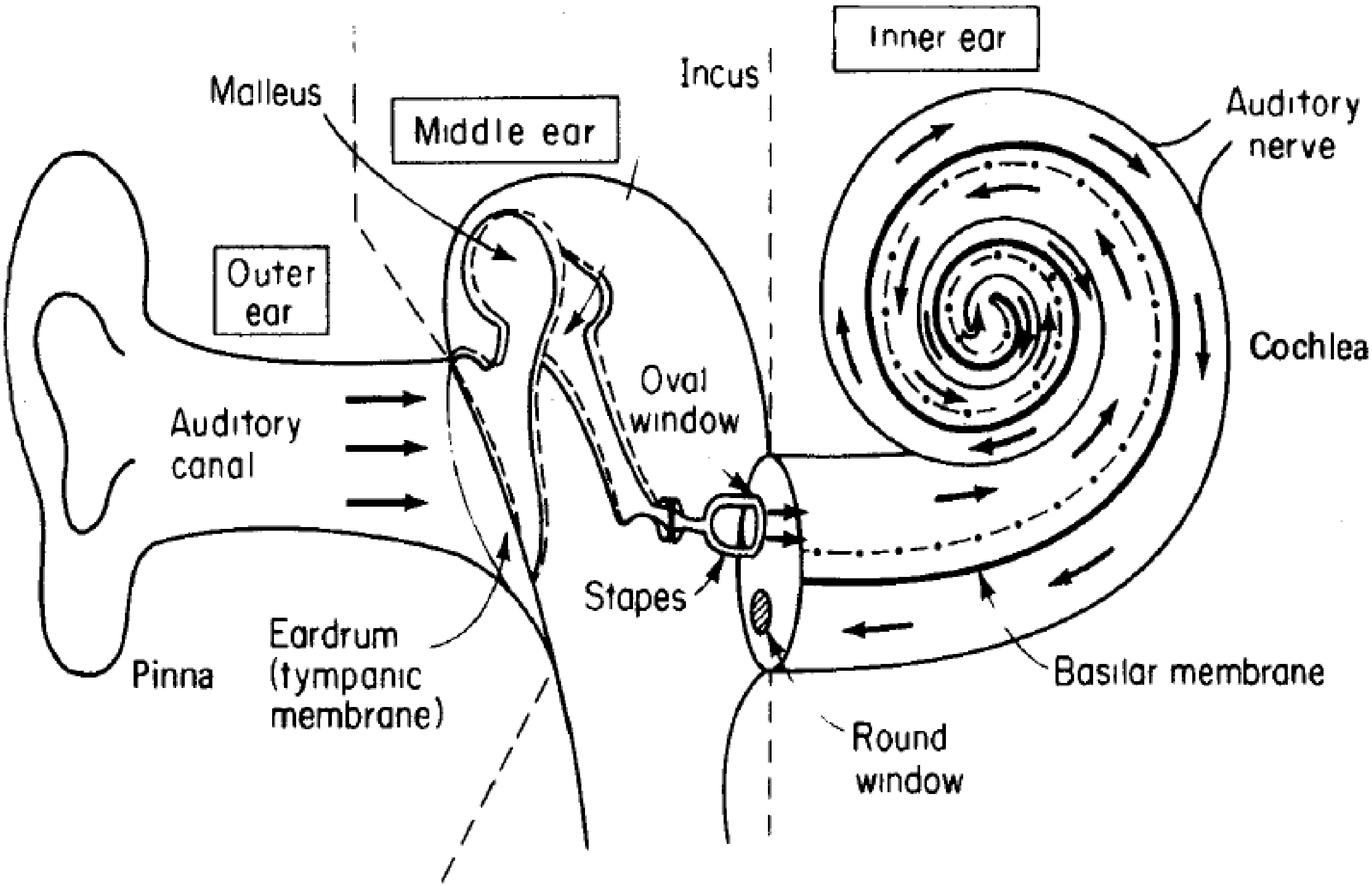
Amplitude = intensity

- Measured in dB = $20 \log_{10} P_1/P_0$
  - P_0=threshold of hearing, Range = 0-150 dB



Anatomy of the ear

- Complex process
  - Pneumatic pressure waves
  - Mechanical vibrations
  - Hydraulic waves
  - Mechanical vibrations
  - Electrical impulses


Inner ear
Incus
Malleus
Middle ear
Auditory
nerve
Outer
ear
Cochlea
Oval
window
Auditory
canal
Stapes
Eardrum
(tympanic
membrane)
Pinna
Basilar membrane
Round
window

Noise = unwanted sound

- Startle response, annoyance
- Interference with speech, sounds (masking)
- Decreases complex task performance
  - (May improve simple task performance!)

Noise measurement

- Sound level meter
  - A-scale (~ human ear)
  - C-scale (~ flat)
  - Slow (1-sec average)
  - Fast (impulse noise)

- Adding noise levels

$$L_{tot} = 10 \log_{10}(10^{L1/10} + 10^{L2/10} + ..)$$

OSHA limits on noise

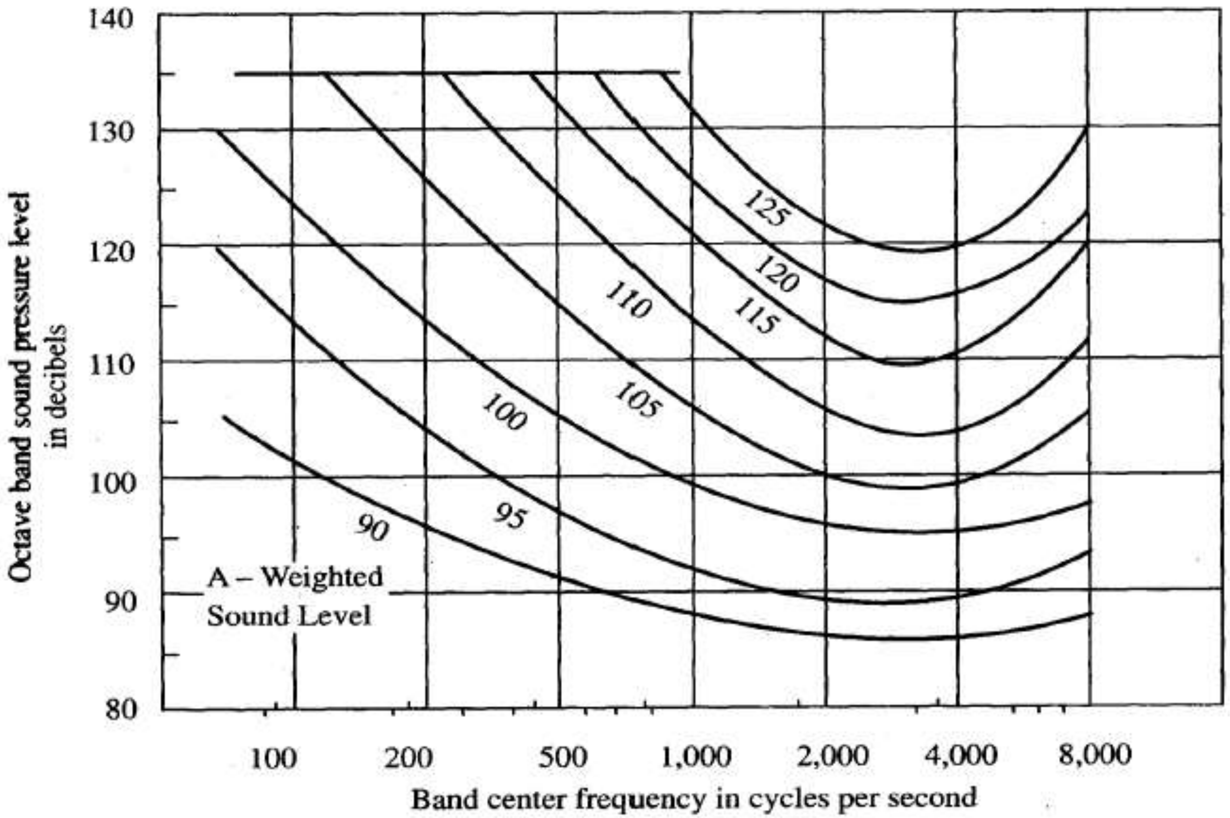
- Noise dose (D) $= C_1/T_1 + C_2/T_2 + .. \leq 1$

Hours	dBA
16	85
8	90
6	92
4	95
3	97
2	100
1	105
0.5	110

Time weighted average

- TWA = 16.61*log D + 90

Equal loudness contours (A scale)



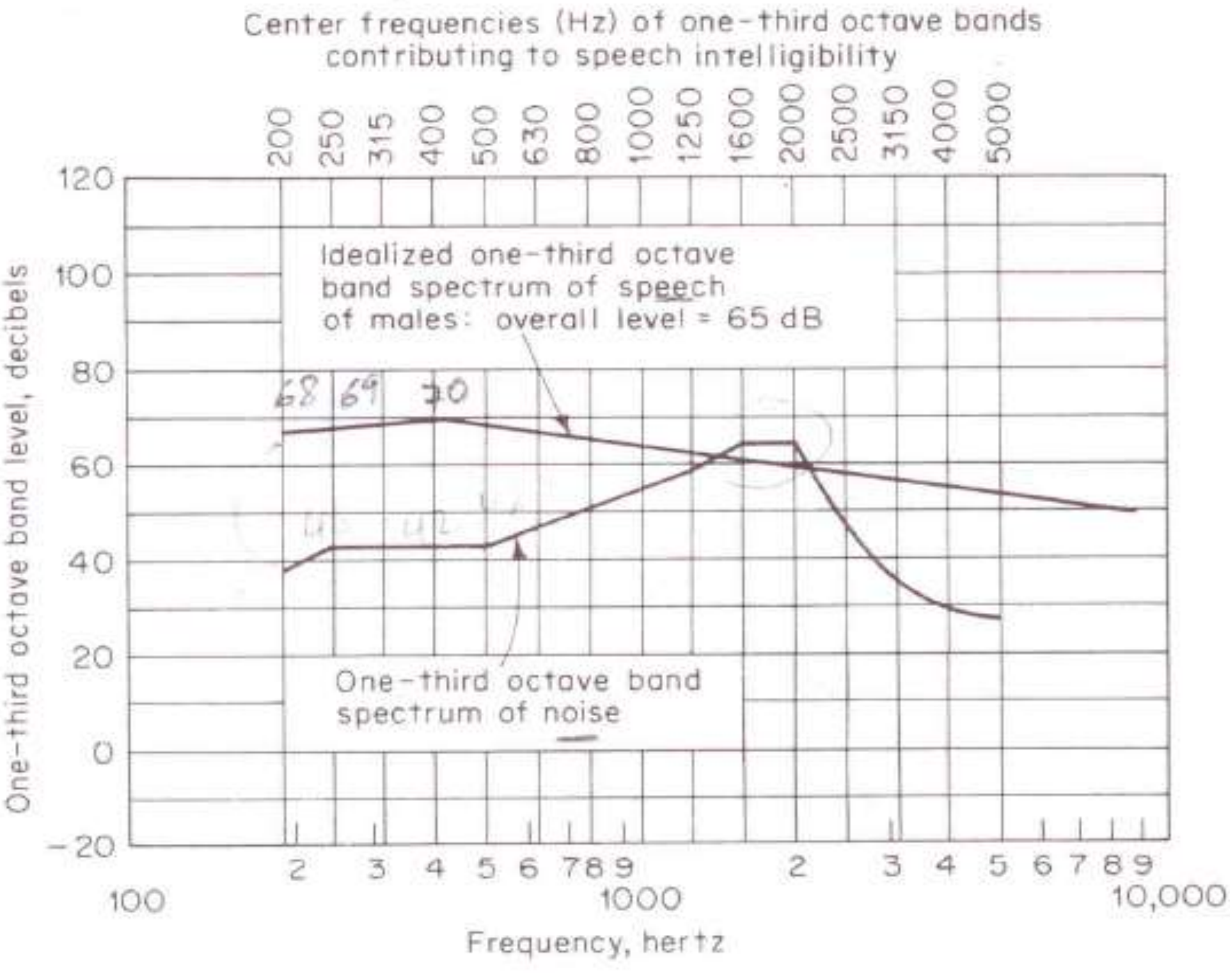
Cont. Hearing

- Masking (defined):
  - Condition when one component of the sound environment reduces the sensitivity of the ear to another component
  - It is amount that the “**threshold of audibility**” of a sound (the masked sound) is raised by the presence of another (masking) sound
  - **Q**: Can you a give an example of “masked” and “masking” sounds from our everyday lives?
  - **Q**: difference between masked and complex sounds?

Speech Communication Measures

1- Articulation Index (AI)

Requires 1/3-octave bandwidth readings

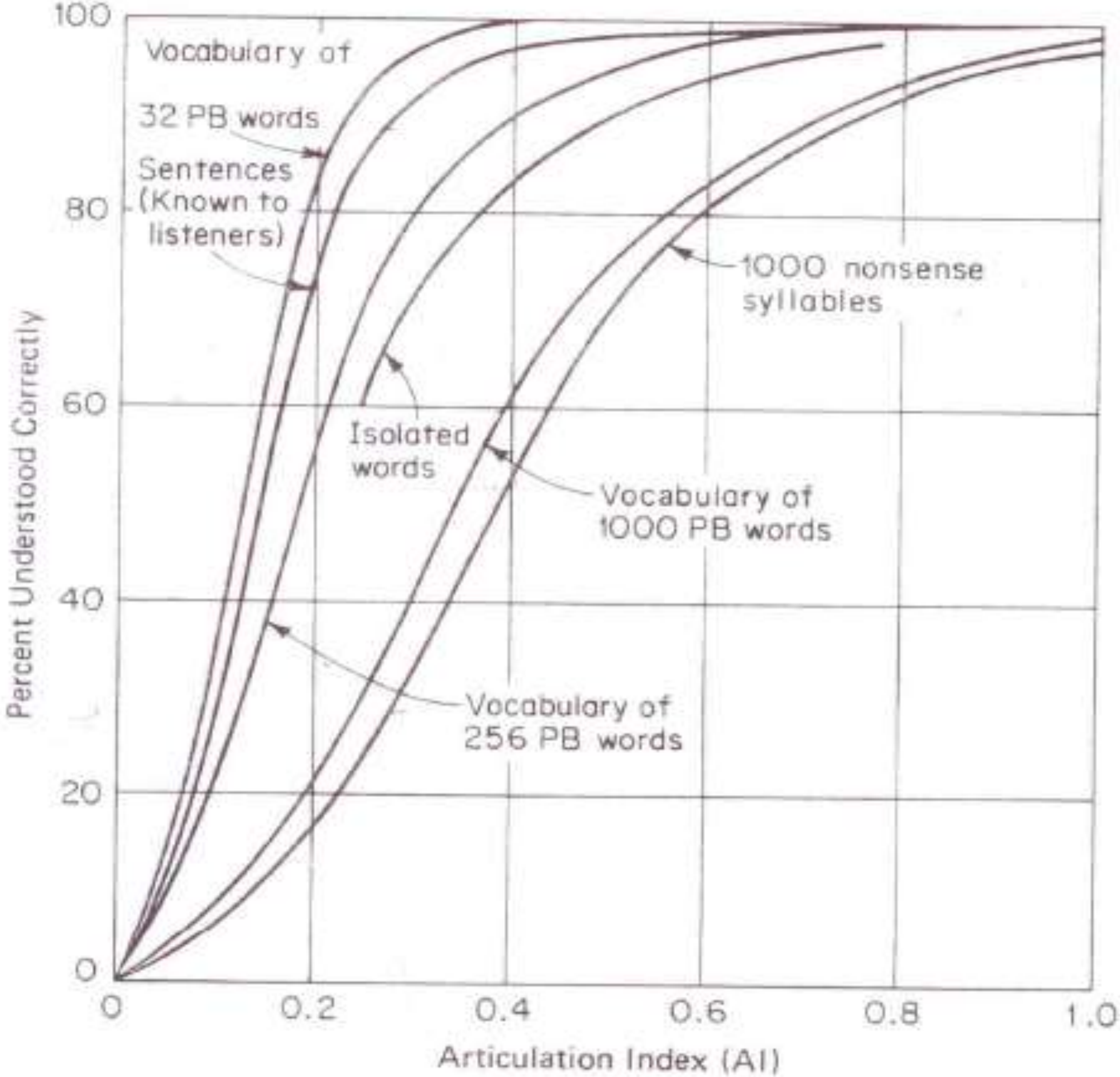


1. Band	2. Speech peaks minus noise, dB	3. Weight	4. Column 2 x 3
200	30	0.0004	0.0120
250	26	0.0010	0.0260
315	27	0.0010	0.0270
400	28	0.0014	0.0392
500	26	0.0014	0.0364
630	22	0.0020	0.0440
800	16	0.0020	0.0320
1000	8	0.0024	0.0192
1250	3	0.0030	0.0090
1600	0	0.0037	0.0000
2000	0	0.0038	0.0000
2500	12	0.0034	0.0408
3150	22	0.0034	0.0758
4000	26	0.0024	0.0624
5000	25	0.0020	0.0500
		AI =	0.4738

RELATIONSHIP BETWEEN ARTICULATION INDEX AND EXPECTED USER SATISFACTION WITH A COMMUNICATION SYSTEM

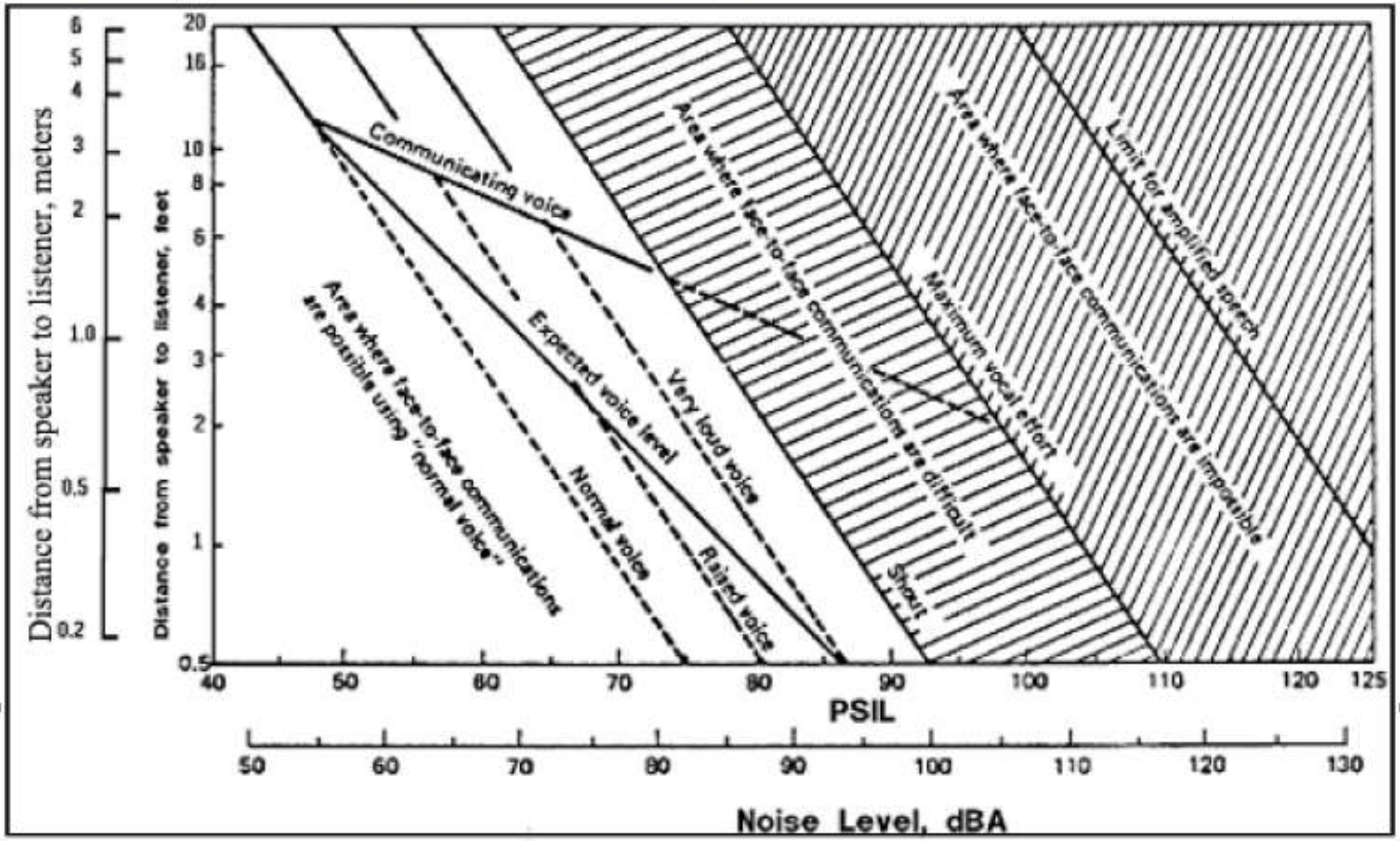
AI	Rating of satisfaction
<0.3	Unsatisfactory to marginal
0.3–0.499	Acceptable
0.5–0.7	Good
>0.7	Very good to excellent

Source: Beranek (1947).


100
80
60
40
20
0
Percent Understood Correctly
0
0.2
0.4
0.6
0.8
1.0
Articulation Index (AI)
Vocabulary of
32 PB words
Sentences
(Known to
listeners)
Isolated
words
1000 nonsense
syllables
Vocabulary of
1000 PB words
Vocabulary of
256 PB words

Preferred speech interference level (PSIL)

- Average of dB at 500, 1000, and 2000 Hz



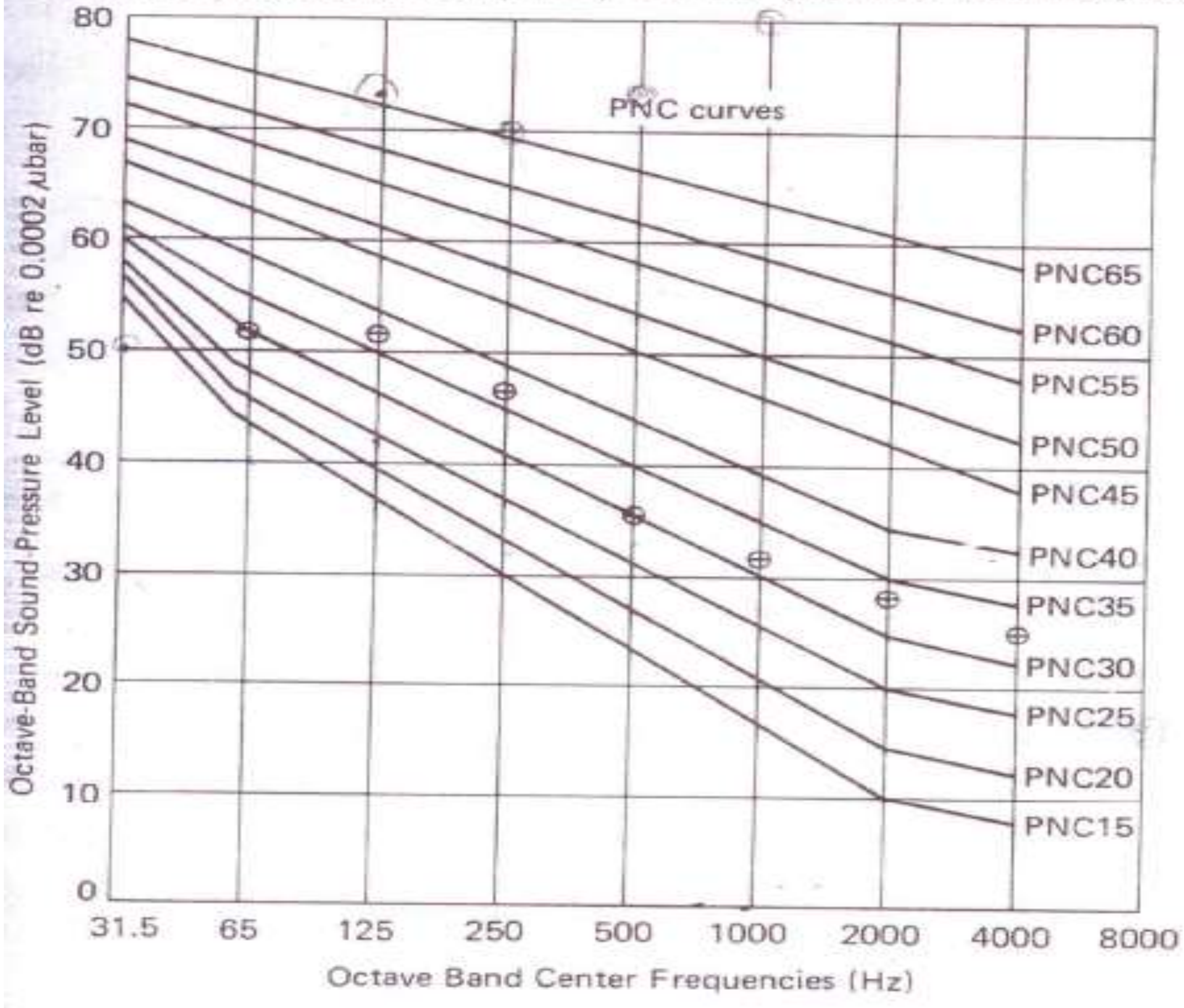
MAXIMUM PERMISSIBLE PSIL FOR CERTAIN TYPES OF ROOMS AND SPACES

Type of room	Maximum permissible PSIL (measured when room is not in use)
Secretarial offices, typing	60
Coliseum for sports only (amplification)	55
Small private office	45
Conference room for 20	35
Movie theater	35
Conference room for 50	30
Theaters for drama, 500 seats (no amplification)	30
Homes, sleeping areas	30
Assembly halls (no amplification)	30
Schoolrooms	30
Concert halls (no amplification)	25

Source: Peterson and Gross, 1978, Table 3-5, p. 39.

3- Preferred Noise Criterion (PNC)

Preferred noise criterion (PNC) curves. (*Source: Beranek, Blazier, and Figwer, 1971.*)



RECOMMENDED PNC LEVELS FROM STEADY BACKGROUND NOISE ACCORDING TO TYPE OF SPACE FOR INDOOR ACTIVITIES INVOLVING SPEECH COMMUNICATIONS

Type of space	Recommended PNC level
Concert halls, opera houses	10–20
Large auditoriums, theaters, churches	Not to exceed 20
Small auditoriums, theaters, churches	Not to exceed 35
Bedrooms	25–40
Private or semiprivate offices, classrooms	30–40
Large offices, retail stores, restaurants	35–45
Shops, garages, power plant control rooms	50–60

Source: Beranek, Blazier, and Figwer, 1971.

Solved Problems

1- The PSIL, AI, and PNC curves are quantitative measures of speech communication. Circle **all** appropriate answers below:

a. Which measure(s) require(s) 1/3-octave bandwidth noise measurements?

PSIL AI PNC

b. Which measure(s) require(s) the noise source to be approximately equally distributed across its measured noise spectrum?

PSIL AI PNC

c. Which measure(s) can account for differences between female and male speakers?

PSIL AI PNC

a. The **AI** is the only one that requires 1/3-octave bandwidths.

b. The **PSIL** requires an approx. equally distributed, broad band noise, as its the only measure that is based upon only 3 octave readings. The other measures consider higher and lower frequency noise components as well.

c. The **AI** is the only measure that includes the male (or female) speech spectrum; the other measures do not.

2- One-third octave bandwidth sound level readings for a noise are shown in the following table.

Freq. (Hz)	400	500	630	800	1000	1250	1600	2000	2500
dBA	77	76	80	84	81	79	76	75	71

a. Compute the Preferred Octave Speech Interference Level (PSIL), and determine how far apart two individuals can communicate without shouting.

b. What additional information is required to compute an Articulation Index (AI) for this example?

a. Note that the PSIL requires whole octave readings for noise!! You must convert the 3, 1/3 octave readings to whole octave by taking dBtot for each octave.

The three one-octave readings are 82.8, 86.6, and 79.2 dB.

The average of these is the PSIL, or 82.87 dB.

At this level of noise, two people must be within 1.6 feet to talk without shouting, according to the figure on page 14.

b. The Articulation index additionally requires:
1/3 octave readings across a larger frequency range
a male or female typical speech spectrum and a table of weight to correct speech-noise differences.

3- Time-Weighting	dBA	dBC
Slow	82	91
Peak	87	97

The table above contains sound level meter readings at a company. These readings were taken at the same time, in the same area, by flipping switches on the meter.

a. Describe the frequency and temporal characteristics of the noise source at the company.

b. What specific noise control method would you use to attenuate this noise, considering your answer to part (a)?

a. We know that dBC>dBA, so low frequency.
Also, Peak>Slow, so Impulsive noise with frequent peaks.

b. Isolate the low frequency source on separate flooring; there might be a resonance created by a rotary shaft which could be damped.

4- Foundry operators were exposed to the noise from a blast furnace according to the following table:

Time

8 am - 10 am	80dBA
10 am -noon	90
noon - 2 pm	92
2 pm - 4 pm	85
4 pm - 6 pm	80

a. Determine whether the company is in compliance with OSHA over the 8 am - 4 pm time period.

b. What maximum noise could be presented from noon – 2 pm, so that the company just falls under the OSHA action limit during the 8 am - 4 pm time period?

c. If the company did exceed the OSHA action limit, what steps would it be required to take?

d. Determine the Equivalent Noise Level during the 8 am - 6 pm time period, then state the meaning of this result.

a. D = 2/32 + 2/8 + 2/6 + 2/16 = .77,

which is less than 1.

The company is in compliance.

b. **80 dBA.** At the action limit,

D=.5, so:

.5 = 2/32 + 2/8 + 2/x + 2/16

2/x = .0625,

So x=32 hrs.

80 dBA is permitted for 32 hours.

c. The following should be done:

i) employee monitoring and audiometric testing

ii) hearing conservation program

iii) noise monitoring

iv) employee training

v) hearing protection record keeping.

d. $L_{eq} = 10\log[1(2)(10^{8}+10^{9}+10^{9.2}+10^{8.5}+10^{8})]$

$= 10^{8.79} =$ **87.9 dBA**

This is the constant noise that emits the same acoustical energy as the 10 hr. time-varying noise

5- A company exposes its workers to the following noises over an 8-hour shift: 100 dBA for 30 minutes, 95 dBA for 30 minutes, and 85 dBA for the remainder of the shift.

The employer knows that the overall noise exposure is OSHA-legal. Show your work for each of the following:

a. Given this information, determine the workers' noise dosage. State any actions the employer needs to take based upon the dosage.
b. Determine the maximum **additional** hours of 95 dBA noise may be presented, while keeping the total noise exposure legal.

a. Dosage = .5/2 + .5/4 + 7/16 = .25 + .125 + .4375 = **.8125**; the noise is **regulated** since dosage > .5, so the employer must do noise monitoring, record keeping, audiometric testing, and provide hearing protection (required if noise>90 dBA).

b. Dosage = 1 = .5/2 + (7-x)/16 + (.5+x)/4 ; 3x=3, so **x=1 hour** additional. Note that the question was for an 8-hour shift. If interpreted to be noise added beyond the 8-hour shift, then the correct answer is: Dosage = 1 = .8125 + x/4; in this case, **x = 0.75 hour** additional, which is certainly close to the preceding answer.

6- The Equivalent Noise Level and the OSHA Time-Weighted Average (TWA) differ in that:

a. The TWA cannot measure noise that varies over time.

b. The Leq can only measure the effects of impulse noise.

c. The TWA is only for use over 8-hour time periods.

d. The Leq is only for simultaneous noises.

C - The OSHA TWA was developed only for 8-hour time periods.

7- A punch press was causing 96 dB noise, primarily in the 100-300 Hz noise bandwidth. Describe and order four **different noise control procedures** that should be used in this instance.

The presented noise is quite loud in the lower frequencies. Here, as in any noise, you would like to control it in the source - path - receiver - administrative order:

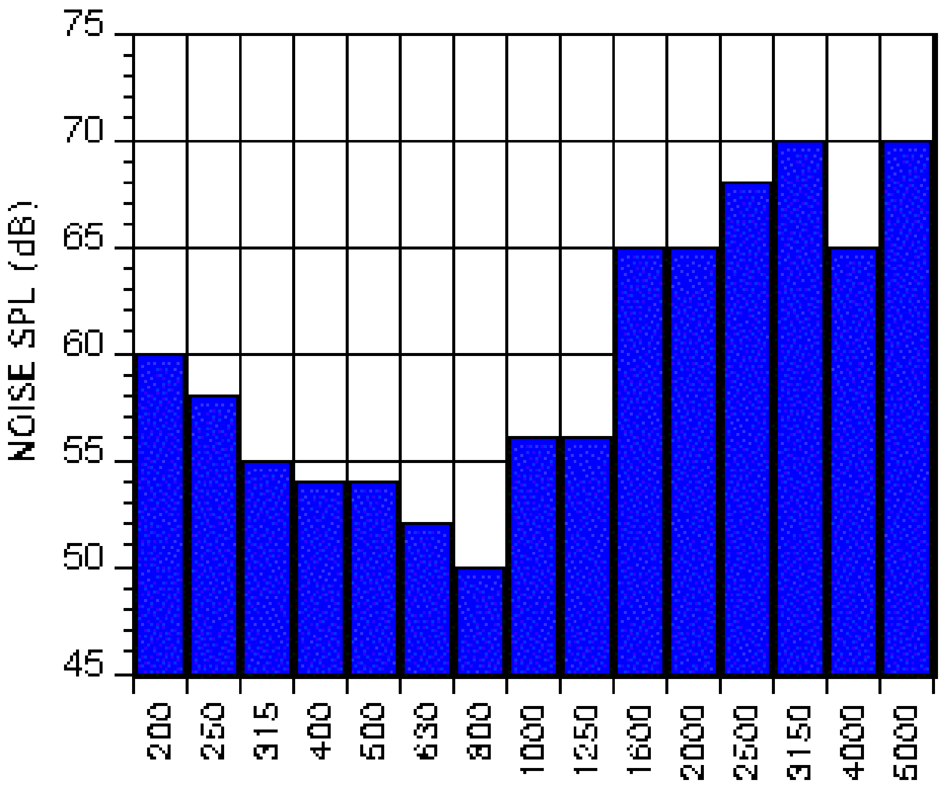
source: Try to eliminate noise by changing the shape of the press.

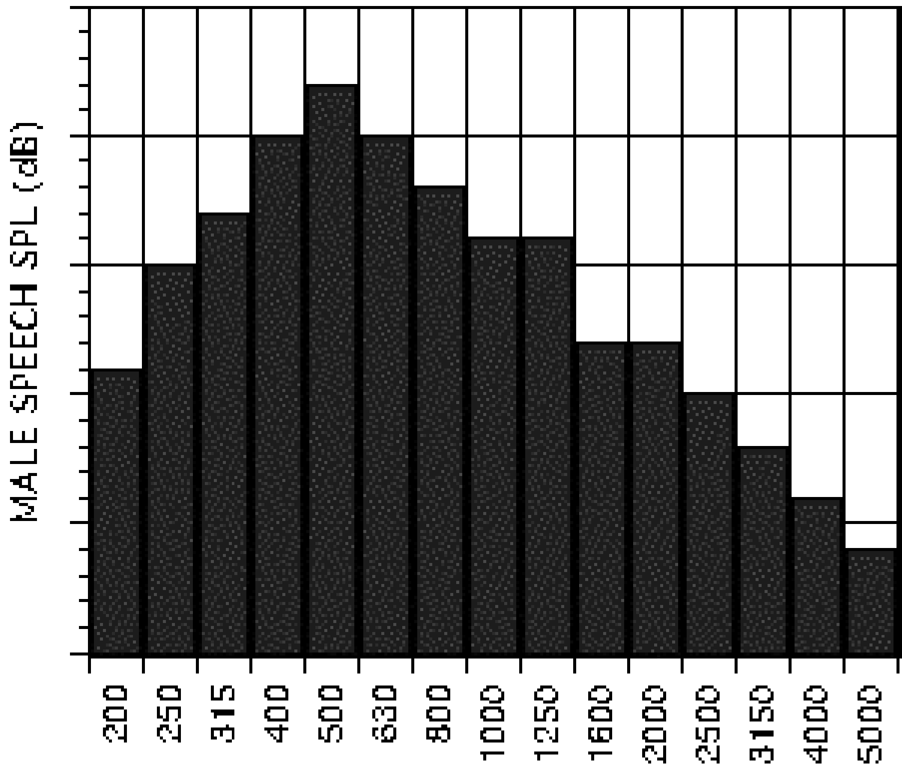
path: Enclose the machine or (more effectively in this case) mount the machine on a separately damped floor.

receiver: Require earmuffs or earplugs.

administrative: Rotate workers every hour or so to different, quiter jobs.

8- A company conducted a noise analysis in an area, producing the following 1/3-octave noise spectrum. Also, the speech spectrum for a typical male worker is shown below:





a. Compute the Articulation Index (AI) for the noise spectrum.

b. Interpret the AI computed in (a.), determining the effectiveness of speech communication. Use tables/figures from your notebook as necessary.

c. From the noise spectrum, compute the PSIL, and determine the maximum distance that two workers are expected to communicate, in a normal communicating voice.

Band	Speech	Noise	Speech - Noise*	Weight	(Speech-Noise) Weight
200	71	60	11	.0004	.0044
250	75	58	17	.0010	.017
315	77	55	22	.0010	.022
400	80	54	26	.0014	.0364
500	82	54	28	.0014	.0392
630	80	52	28	.0020	.056
800	78	50	28	.0020	.056
1000	76	56	20	.0024	.048
1250	76	56	20	.0030	.06
1600	72	65	7	.0037	.0259
2000	72	65	7	.0038	.0266
2500	70	68	2	.0034	.0068
3150	68	70	0*	.0034	0
4000	66	65	1	.0024	.0024
5000	64	70	0*	.0020	0

AI = **0.4007**

b. Using Table in slide #12, speech communication should be acceptable.

c. To compute the PSIL, we need the **one-octave** bandwidths of noise in the 500, 1000, and 2000 Hz octaves. You cannot simply pick-off a 1/3-octave level and call that a 1-octave level! To obtain the one-octave bandwidth at the 500-Hz octave, for example, dBtot = 10 log [105.4 + 105.4 + 105.2] = 58.2 dB. Similarly, the noise at the 1000 Hz octave was 59.52 dB, and was 71.0 dB at the 2000 Hz octave. The average of these three octaves is 62.9 dB. Using Figure in slide # 14, two individuals must stand within about **5.5 feet** to communicate in a normal voice.

9- An IE measured the (1/3-octave bandwidth) noise spectrum of one of the stamping machines, as shown below:

Freq., Hz	100	125	167	200	250	315	400	500
dBA	29	30	34	32	36	47	63	72
Freq., Hz	630	800	1000	1250	1600	2000	2500	
dBA	70	65	62	57	55	55	53	
Freq., Hz	3150	4000	5000					
dBA	58	60	59					

In addition, the IE measured a (1-octave bandwidth) noise spectrum of one of the collators, shown below:

Freq., Hz	125	250	500	1000	2000	4000	8000
dBA	74	70	73	80	85	84	81

a. Determine and interpret the Articulation Index for the stamping machine.
b. Determine and interpret the PSILs for both the stamping machine and the collator.

a. To compute the AI, we can use the provided table of Speech Spectrum and Weights, by frequency band. First, we take speech-noise peaks, then limit these to [0, 30]. We will only use 1/3-octave bands from 200-5000 Hz herre. Note that Two values were limited to 30, and 5 were limited to 0. Multiply the remaining values by their respective weights, then add up. **The total was .1357**. Communication will be difficult in this noise environment. About 30% of a 256 word vocabulary will be understood, and about 60% of a 32 word vocabulary will be understood (See Slide #13).

b. To compute the PSIL values, we need the **whole-octave** band noises at 500, 1000, and 2000 Hz. For the Stamping Machine, we must compute these from the provided 1/3-octave band values.

PSIL for Stamping Machine

At 500 Hz: dBA = 10log(10^6.3 + 10^7.2 + 10^7) = 74.4 dBA

At 1000 Hz: dBA = 10log(10^6.5 + 10^6.2 + 10^5.7) = 80 dBA

At 2000 Hz: dBA = 10log(10^5.5 + 10^5.5 + 10^5.3) = 59.2 dBA

Taking the average for these three, we have PSIL = **66.9**

Using a communicating voice, speaker and listener would have to be within 4 feet of each other.

PSIL for Collator

PSIL = Ave (73, 80, 85) = **79.3**

Using a communicating voice, speaker and listener would have to be within 2 feet of each other.

Hearing loss

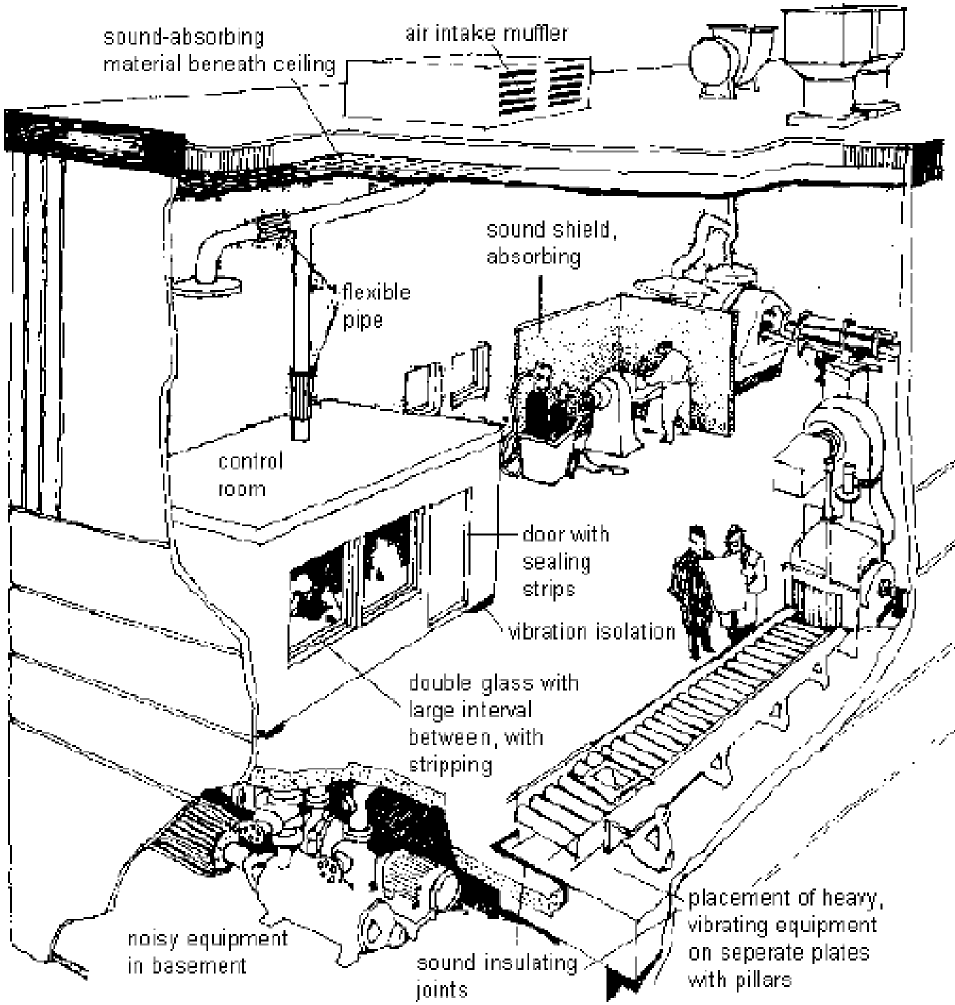
- Long term exposure → hearing loss
  - ↑ with ↑ frequencies and ↑ duration
  - Chances of damage increases as approach 2400-4800 Hz
    - First sign in 4,000-6,000 Hz range
    - Damage to hair cells (nerve damage)
- Conductive hearing loss
  - Damage to eardrum and middle ear
- Measure with audiometer
  - Bone vs. air conduction tests

Aging hearing

- 30% over 65 have significant hearing loss
- Natural damage to hair cells
  - Higher frequencies
  - 4000-6000 Hz first
  - "Mosquito" ringtone http://www.freemosquitoringtones.org/

- Aging brain
  - Cannot filter background noise
- Can cause *tinnitus*

Noise control



Auditory Displays

- Chapter 3: auditory vs. visual modality (e.g. auditory preferred: message is short, simple)

- 4 types of human functions/tasks involved in the reception of auditory signals:

1. **Detection** (i.e. whether a signal is present)
2. **Relative discrimination** (differentiating bet. ≥2 signals presented together)
3. **Absolute identification** (only 1 signal is present)
4. **Localization** (knowing the direction that the signal is coming from)

Cont. Auditory Displays

- Detection of signals
  - Signals can occur in “peaceful” surroundings or noisy surroundings
  - The signal plus noise (SN) should be distinct from the noise (N) itself
  - Otherwise, signal cannot always be detected in the presence of noise
    - i.e. signal (masked sound) + noise (masking sound) ⇒ **threshold of detectability** is elevated
    - ⇒ signal must be > threshold to detect signal
  - Using filters ⇒ noise removed ⇒ ↑ detectability, SNR ⇒ more audible sound

Cont. Auditory Displays

- Relative Discrimination of Auditory Signals
  - Relative discrimination of signals on basis of
    - intensity
    - frequency
  - A common measure of discriminability: **just-noticeable difference** (JND):
    - JND: "the smallest difference or change along a stimulus dimension (frequency, intensity) that can just be detected 50% of the time by people."
    - The smaller the JND, the easier it is for people to detect differences on the dimension being changed.
      - Small JND ⇒ subjects could detect small changes
      - Large JND ⇒ large change necessary before noticing change

Cont. Auditory Displays

- Absolute Identification
  - This is used when it is necessary to make an absolute identification of an individual stimulus (by itself)
  - e.g. identify
    - someone’s pitch/frequency
    - specific animal/bird
    - certain car siren/honk tone
    - Sound durations
  - Number of levels along a continuum (range or scale) that can identified usually is quiet small
  - It is better to use more dimensions with fewer steps or levels of each dimension, than to use fewer dimensions and more levels of each

Cont. Auditory Displays

- Localization
  - ***Stereophony:*** "the ability to localize (guess/predict) the direction from which the sound is emanating (coming from)"
  - Primary factors/cues used to determine direction
    - intensity of sound
    - phase (lag) of sound
    - e.g. if sound reaches directly one side of head first, sound reaches the nearer ear approx. 0.8 ms before other ear ⇒ localizing sounds below 1500 Hz
    - For frequencies > 3000 Hz, intensity is used to localize sound (e.g. try to gradually increase volume in one speaker and decrease volume in opposite speaker)
    - Sounds between 1500-3000 Hz: hard to localize.

Cont. Auditory Displays

- Special purpose auditory displays:
  - Warning and alarm signals
    - Each signal having preferred frequency, intensity
    - Each causing certain “attention-getting” and “noise-penetration” ability
  - Aids for the blind
    - Mobility aids (go-no-go safety signals at certain distance)
    - Environmental sensors (information about surrounding, e.g. surface characteristics, directional information, distance)

Noise

- Effects of noise
  - Hearing loss (e.g. occupational hearing loss)
  - Temporary loss, permanent loss
  - Physiological effects
  - Psychological effects