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Comparison of Amplification Systems in a Classroom[a]

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Abstract — "Listening systems" are used for hearing impaired listeners as an alternative to public address systems (PA) used for the general public. These listening systems allow individual control of sound pressure level and minimize the effects of background noise and room reverberation. Three listening systems, based on (i) an audio induction loop (AL), (ii) frequency modulation of radio frequencies (FM),and (iii) modulation of infrared light (IR) were compared among themselves and with a PA system in a medium-size classroom. Listening groups were (i) normal hearing, (ii) hearing impaired, (iii) hearing aid users, and (iv) elderly. Word identification scores were obtained with the Modified Rhyme Test at two conditions: with a babble of 12 voices at a speech-to-noise ratio (S/N) of +8 dB, and without the babble at S/N of +20 dB. Analysis of variance indicated that the main effects of systems, groups and room S/N were significant. Also significant were interactions of systems by groups, and systems by S/N. For all groups, the three listening systems provided better scores than the PA system. It can be concluded that all three of the tested listening systems are suitable for listeners with various degrees of hearing losses.

INTRODUCTION

Perception of speech in rooms is affected by several factors that were described by Knudsen in 1929 in the following way: ". . .the resulting percent articulation in any specified auditorium can be estimated by the following equation:

$$\text{Percentage Articulation} = 96\, k_\ell\, k_r\, k_n\, k_s$$

where k_ℓ is the reduction factor owing to the inadequate loudness of the speech, k_r the reduction or distortion factor owing to reverberation, k_n the reduction factor owing to noise, and k_s the reduction factor owing to the shape of the room" (1).

Communication involves the transmisstion of acoustic waves from a source, through an environment, to a receiver. Knudsen's model refers primarily to the effects of environment, with the exception of k_ℓ which refers to both the source output level and to the distance between source and receiver. To describe Knudsen's percentage articulation more fully, two factors should be added to the model: k_t describing the talker or other source of speech and k_p describing the perceptual abilities of the listener.

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It has been well documented, i.e., by Náběelek and Pickett in 1974 (2), and by Finitzo-Hieber and Tillman in 1978 (3), that for good speech perception, hearing impaired listeners require better speech-to-noise ratios (S/N) and shorter room reverberation than normal hearing young adults. In addition, hearing impaired listeners need sound pressure levels (SPL) higher than normal hearing listeners do, to compensate for their hearing loss.

Thus there are three conditions necessary to assure a good listening environment for hearing impaired listeners: (i) adequate SPL, (ii) low background noise, and (iii) short reverberation. It is expected that modern technology will be able to fulfill these three requirements. Amplification of the sound level can be accomplished at two points; at the source, or at the listener. Sound from the source can be amplified and transmitted to the room at levels higher than could be obtained using only the live voice. Electroacoustic technology has developed sufficiently so that the reproduced sound need not lose the "live voice" quality. Most modern facilities, such as auditoriums and places of worship, use amplification systems, sometimes called public address systems (PA). A PA system consists of a microphone and one or more loudspeakers. Proper microphone placement is critical for high fidelity reproduction. If more than one microphone is needed, the expertise of an audio engineer is often required. The loudspeakers deliver amplified sounds to a listening area. Frequently, loudspeakers are located on each side of a stage, podium, or altar, or the loudspeakers may be located above the stage. A well-designed PA system should deliver an even SPL over the entire listening area. The SPL is set by an audio technician to produce comfortable listening for a normal-hearing audience. This level may be too low for hearing impaired listeners. Moreover, since the loudspeakers are located at a distance from the listeners, the arriving sounds are mixed with background noise and degraded by room reverberation in varying amounts depending on a listener's location in the room. In effect, the listening conditions may not be fully satisfactory for a hearing impaired listener.

Hearing impaired listeners can use personal amplifying devices, such as hearing aids. The hearing aid amplifies sound to the level required by the individual listener and may also shape frequency response to compensate for different degrees of hearing loss at various frequencies. However, the hearing aids indiscriminately amplify both the wanted sounds and background noise, being unable to differentiate between the direct, non-reverberant and reverberant signals. Speech enhancement in noisy and reverberant listening conditions has not yet been accomplished by presently available technology for a wearable hearing aid.

At this time, the only known practical remedies are a proper room design which maintains a low background noise level and short reverberation time, or use of a listening system. A listening system delivers speech signals from the source directly to a receiver placed at the listener's ear, thereby evading the problem of background noise and room reverberation. The gain control in the receiver allows individual setting of the SPL.

The following five systems have been thus far used for delivering speech signals to hard-of-hearing listeners:

1. Hardwired;
2. Audio induction loop (AL);
3. Amplitude modulation (AM) of radio signals;
4. Frequency modulation (FM) of radio signals; and
5. Modulation of infrared (IR) waves.

Several publications have indicated that listening systems can be beneficial for listening even if less than optimal conditions exist. Hawkins, Fluck, and Van Meter in 1982 described an FM system installed in a large auditorium for the general public and for hearing-impaired listeners (4). Speech perception scores were not obtained but the authors reported that 90 percent of the patrons who responded to a questionnaire indicated satisfaction with the equipment. Vaughn in 1983 and Williams in 1984 described five listening systems used in auditoriums for hearing impaired listeners, discussing applications, advantages, disadvantages, and approximate cost (5, 6). They did not compare speech perception among the systems. Bankoski and Ross in 1984 compared speech discrimination in an auditorium for normal-hearing and hearing impaired listeners with a PA and an AM/FM system (7). When subjects were sitting in the center and rear sections of the auditorium, the FM system yielded speech perception scores which were significantly better for both groups of subjects. While the authors indicated that similar results probably would have been obtained with any other listening system, the testing was limited to the FM system.

The goal of this study was to compare speech perception with PA, AL, FM, and IR systems. (The hardwired and AM systems were not tested because they are becoming obsolete; they are, however, described here to provide thorough comparison of all the systems which have been in use and may be encountered in public places.) The systems were

Journal of Rehabilitation Research and Development Vol. 23 No. 1 1986

tested without microphones; the test speech was delivered from a tape recorder. All testing was performed in a medium-size classroom using listeners with various degrees of hearing loss. One group of listeners wore hearing aids.

Listening Systems

Hardwired — The hardwired listening systems employ a direct wire connection between a microphone positioned at the signal source location and an earphone or hearing aid located at the listener's ear. These installations usually provide a very good quality signal, and are not susceptable to electromagnetic interference. They are easily designed for small rooms but can become complicated and expensive in large auditoriums. They are prohibitively cumbersome and of limited value for public places where full mobility must be obtained. Cable breakage is the main maintenance problem.

Audio induction loop — Induction loop systems have been used as permanent installations or portable facilities for both group and individual listeners. The essential system component is a multiturn loop of wire encircling a room and connected to the output of an audio power amplifier. The signal fed into the amplifier can come from a microphone, tape recorder, or similar source. The electric current passing through the loop creates a room magnetic field that varies in strength and frequency according to the speech signal. The signal carried by the alternating magnetic field has to be converted back into an electric signal which is used to produce an acoustic signal that is delivered to the listener's ear. The magnetic-to-electric conversion can be achieved in a small pickup loop (also called a teleloop) connected to the input of a receiver, or in a pickup coil of a hearing aid switched to the "T" (telephone) position.

The layout and dimensions of the transmitting loop depend on the shape and size of the room. In order to obtain a strong and uniform magnetic field in a whole room, the loop must be individually designed. Loops for use in small areas are simple and commercially available; the loop for a large hall can be complicated, especially when some constructional restraints exist.

The main interferences are caused by audio and electrical equipment used in the same or adjacent rooms. The most frequent sources of interferences are devices such as light dimmers, metal detectors, fluorescent lights, and other current-carrying, magnetic-field-generating magnetic loops including AC power cables and the coils of electric motors. High levels of existing or projected interferences in a building can preclude the use of AL systems.

AM and FM systems—In both AM and FM systems, the audio signal is transmitted by radiofrequency carrier. In AM transmission, the amplitude of the carrier is changed proportionally to the changing amplitude of an audio signal. In FM transmission the amplitude of the carrier remains constant, and its radio frequency is made to change proportionally to the changing amplitude of an audio signal.

A radiofrequency listening system, regardless of its mode of modulation, consists of a microphone and transmitter unit with an antenna, and a receiver connected to an earphone or a hearing aid. The microphone and transmitter unit imposes the speech or other audio signal onto the electromagnetic waves of radio frequency which are radiated by an antenna into the environment. The receiver converts radiofrequency waves back into an audiofrequency electrical signal which is used to produce an acoustic signal that is delivered to the listener's ear. The maximum distance of transmission depends on the radio transmitter power, the type of transmission, and the receiver's sensitivity.

For an AM listening system, as a result of FCC regulations limiting the radiated field strength, an antenna has to be specially designed. In many AM systems, the antenna is a one-turn loop of wire encircling the room. Its installation may be as difficult as the installation of a multiturn loop for an audio induction system. The typical radio carrier frequency is in the ordinary AM radio band of 525–1610 kHz or below. The receiver can be a commercially available AM pocket radio or a special fixed-frequency receiver. The range of transmission, limited to a maximum of 15 meters, is usually adequate for covering areas of small theaters and churches and does not create problems with unintended "broadcasting" outside the building. However, the nature of AM transmission can create problems when the goal is to achieve a homogeneous field in a large hall. Additionally, AM systems are very susceptible to high frequency electrical interferences generated within the same building (e.g. by electric motors) and by strong external sources.

Generally, AM listening systems do not perform well in buildings with substantial amounts of structural steel.

FM systems usually operate at higher radio frequencies than do AM systems. FM's shorter radio waves are less susceptible to the absorption phenomenon caused by structural steel in the building. Furthermore, these frequencies are easily radiated into a room by short antennas. The transmitting strength of an FM system allows for good reception within very large rooms. However, the system can radiate outside the enclosure, which can produce both interferences and "eavesdropping" problems. The main advantage of FM systems over AM systems is that FM transmission is less affected by interfering sources, such as radio signals, sparks, lightning, electric motors, etc.

Until 1982, FCC regulations restricted the use of FM listening systems to educational institutions. As a result, the AM systems were promoted in the 1970's as an inexpensive listening aid for hard-of-hearing people in public places, but since 1982 they have been losing their appeal in comparison with the FM systems. The FM systems, comparable in price to AM systems, can be used in auditoriums, do not require installation of an antenna, and provide better sound quality. It seems that AM systems will probably disappear from the market in the near future.

Infrared light—The infrared-light listening systems transmit audio signals by using an infrared light beam. The signal from a microphone is fed into a high-frequency transmitter which drives the infrared emitters. The transmitter and light emitter are built as one unit for small portable systems or as independent units for multi-emitter systems in large halls. These systems differ from audio- or radio-frequency systems mainly in the frequency band used for transmission. Infrared light transmission takes place in the frequency bands immediately below the frequencies corresponding to visible light, i.e., somewhere around 3×10^{14} Hz.

The infrared systems available on the market are based on the design of Sennheiser Electronic Company of Germany. The device used to produce the infrared light in the Sennheiser system is the gallium arsenide (GaAs) light-emitting diode (LED) which emits light beams with a wavelength of 930 nm. One GaAs diode is sufficient to cover an area of 3-to-5 m^2, according to Nebozenko writing in 1982 (8). For good transmission quality in large auditoriums, multiple-diode arrays have to be assembled.

A system that uses direct amplitude-modulation of the diode current is susceptible to a variety of interferences from other light sources. To limit interferences, the audio signal is first used to modulate the frequency of a low-frequency "sub-carrier" electric signal. The resulting "FM" signal is then used to modulate the amplitude of the diode current. Because changes in frequency carry the information, other light sources in the room are less able, or unable, to distort the signal.

The infrared receiver has a photodetector diode mounted behind a hemispherical lens which increases the amount of light intercepted and presented to the sensitive area of the diode. The possibility of interferences from ambient light is reduced by an optical filter which is transparent only to infrared light.

The receivers are available either as a stethoscope-type device placed under the chin of the listener or as a chest-type receiver. The first type is designed for listeners who do not wear hearing aids. The second type is designed to work in combination with hearing aids or with separate earphones. The induction neck loop is used for coupling with a personal hearing aid switched to "T" position.

Infrared light has properties similar to those of visible light. Like visible light, infrared rays are completely absorbed by a black velvet curtain, and they are reflected directionally by shiny metal surfaces. Except for escape through windows and other openings, infrared light will remain confined to the room of its source. (That feature has special significance in the professional theater where prevention of illegal recording might be important.)

Infrared transmission is highly directional. In large auditoriums, light reflections should provide omnidirectional reception. Useful reflections are obtained from room surfaces with light reflection coefficients greater than 0.5 (where more than half of the light energy is reflected).

Bright sunlight and other light sources which contain infrared energy interfere with infrared transmission. Incandescent (tungsten) light produces the most detrimental form of interference; this light contains a great deal of infrared energy, especially when it is dimmed (8). Infrared systems are primarily designed for indoor use. The intensity of infrared radiation of sunlight is less indoors than outdoors. On a bright day, the intensity of outdoor infrared radiation can reach such high levels that infrared transmission becomes impossible. Although fluorescent light includes only small amounts of infrared energy, it too may produce interference if its source is close to the IR receiver. Thus the performance of an infrared system in a large auditorium is very dependent on architectural and interior design conditions such as reflections from boundary surfaces and amount of ambient light. Infrared systems, except for the small-room units, are permanently installed by specialists.

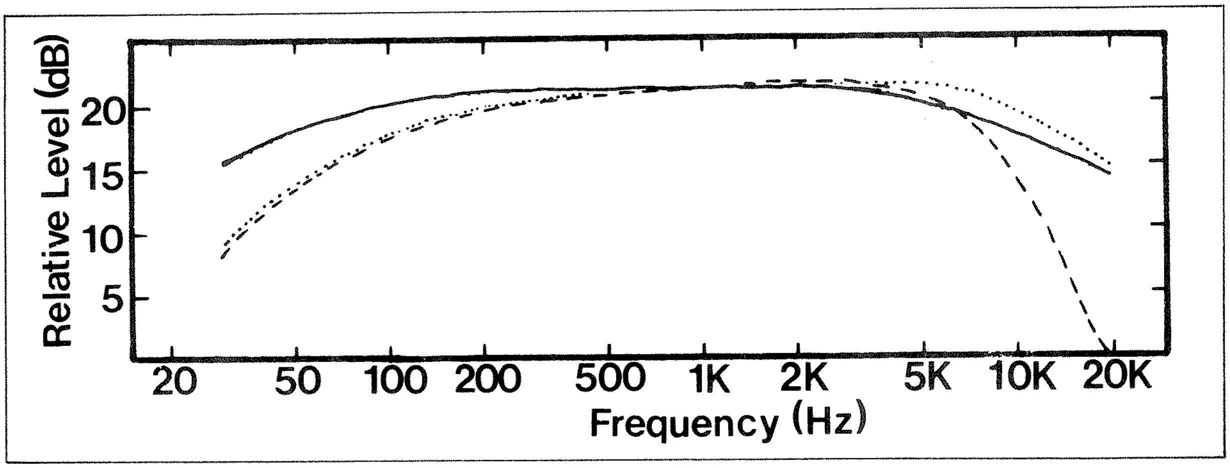

FIGURE 1
Electrical frequency responses of the three listening systems: AL (full line), FM (dashed line), and IR (dotted line).

METHOD

Classroom

The experiment was performed in a classroom with a volume of 91.2 m^3 (7.6 $\times$ 5.0 $\times$ 2.4 m). The classroom had a floor carpet and acoustic tiles on the ceiling. Two large windows had single glass panes and no drapes. The major source of background noise in the classroom came from highway traffic. The average SPL of noise during day hours was 46 dB (A). The average reverberation time (T) of the room for the 500, 1000, and 2000 Hz octave bands of noise was 0.35 s, measured with a pink noise. The critical distance was calculated as equal to 1.1 meters.

Amplification Systems

Three listening systems, AL, FM, and IR, were compared among themselves and with a PA system.

The PA system consisted of two identical loudspeakers (Bang and Olufson Beovox S45) located 0.5 meters apart on the short wall of the classroom.

The transmitting AL system was specially designed for the classroom: see Letowski, Donahue, and Nábělek, 1985 (9). The system contained a power amplifier and equalizer used for smoothing frequencies response.

The FM system was a commercially available Phonic Ear PE 551A and PE 551T unit designed for auditorium use.

The IR transmitter was a commercially available Siemens S1 406 unit advertised for home use. All three transmitters were suitable for use in a medium-size classroom.

The following receivers were used for testing without hearing aids:

1. The receiver for AL was composed of a Phonic Ear AT 119 neck loop, connected to a Radio Shack Archer miniamplifer with volume control and a stethoscope;
2. The FM receiver was a Phonic Ear PE 555R with a stethoscope, and
3. The IR receiver was a Sennheiser HDI 407-S with a stethoscope. The same Phonic Ear AT 360 stethoscope, composed of a button-type transducer and tubes, was used on all three receivers.

The hearing aid wearers used their own monaural hearing aids with a microphone input when tested using the PA system, and they used a telecoil input (the aid input switch in the "T" position) when tested using the three listening systems. The hearing aid was the only receiver these subjects needed for the AL system. For the FM and IR systems, the respective receivers with a Phonic Ear AT 119 neck loop were coupled to the hearing aid.

The electrical frequency responses of three listening systems are shown in Figure 1. These were obtained in the test room between the input to which the signal-source tape recorder would be connected and the output to which the stethoscope would be connected. All three systems had flat wideband frequency response.

For all electroacoustic measurements, the volume control of the listening system receivers was set to the middle position of the gain control. Due to the transmission levels, all subjects used receiver volume control settings of no greater than medium gain. This level setting was deemed more representative of the output received by our subjects than

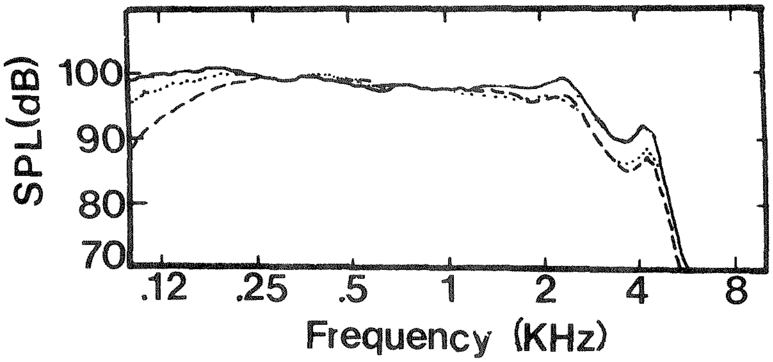

FIGURE 2
Electroacoustic frequency responses of the three systems at the output of the Phonic Ear AT 360 button-type transducer (as in Figure 1).

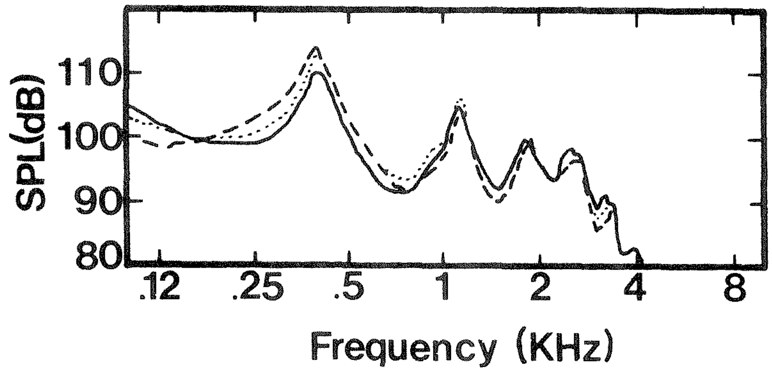

FIGURE 3
Electroacoustic frequency responses of the three systems at the output of the Phonic Ear AT 360 stethoscope tube (as in Figure 1).

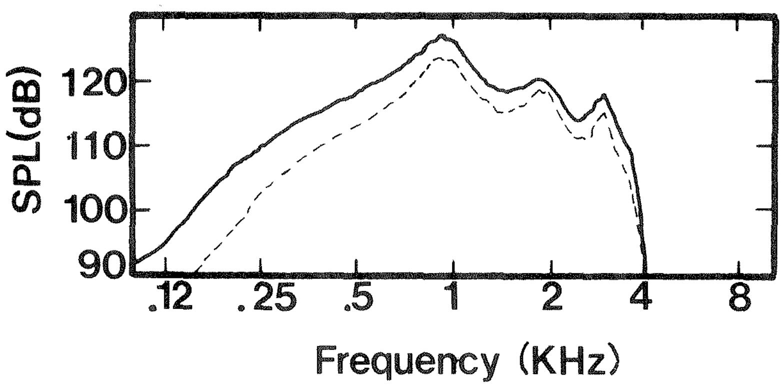

FIGURE 4
Electroacoustic frequency responses of the FM system, Phonic Ear PE 551A amplifier, PE 551T transmitter, and PE 555R receiver at the output of the Phonic Ear 841 LA hearing aid; hearing aid telecoil input coupled through a Phonic Ear AT 119 neck loop to the FM receiver. With perpendicular positioning of the loop and telecoil (full line); with parallel positioning (dashed line).

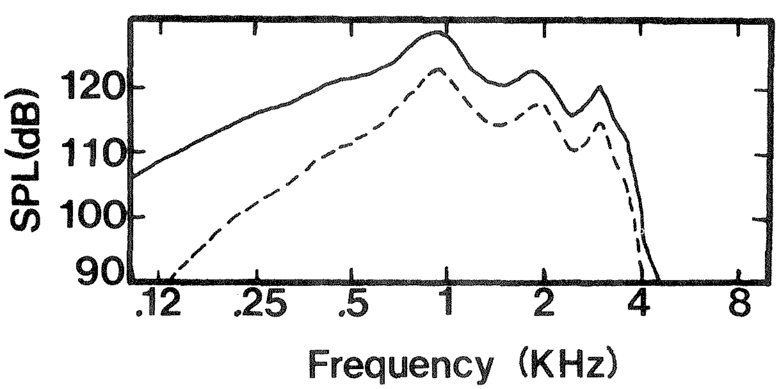

FIGURE 5
Electroacoustic frequency responses of the IR system, Siemens SI 406 transmitter and Sennheiser HDI 407-S receiver, with the hearing aid as in Figure 5.

having the volume control set to full-on gain for the electroacoustic measurements.

The electroacoustic frequency response of each system is modified by an electroacoustic transducer and the manner in which acoustic energy is delivered to the ear. Frequency responses of some arrangements were measured using a FONIX 5500Z Hearing Aid Test Set. The output of the FONIX Test Set was fed into the power amplifier of the room loop or to the line inputs of the FM and IR transmitters. The stethoscope of the system receiver was placed in the sound chamber of the FONIX Test Set. The tubing of the stethoscope was coupled to the 2cc coupler and sealed with putty. Figure 2 shows electroacoustic frequency responses of the three systems at the output of the Phonic Ear AT 360 button-type transducer. It can be seen that the responses remained reasonably flat, with some high-frequency attenuation. Subsequent modification of the frequency responses was caused by the stethoscope tubes (Fig. 3); the long tubes introduced large irregularities and an even further limitation of high-frequency energy. Average harmonic distortions for various configuration of the systems for 500, 800 and 1600 Hz, respectively, were as follows: 0, 1, and 1 percent for AL; 4, 1, and 1 percent for FM; and 2, 1, and 1 percent for IR.

The hearing aid users had their hearing aid telecoil inputs coupled with the receivers by means of a neck loop. Since the subjects used various hearing aids, there was no common frequency response for that listening mode. As an example, frequency responses of the FM and IR systems with the respective receivers coupled through the Phonic Ear neck loop AT 119 to a Phonic Ear hearing aid 841 LA telecoil are shown in Figures 4 and 5, respectively. Because there was no uniform setting of hearing aid volume control among the subjects, the hearing aid volume control having number indicators of zero to 4 was set at 2.5. For both receivers, the responses depended on the relative position of the neck loop and the telecoil. When the loop and telecoil were perpendicular, maximum SPL at 900 Hz was greater than with the parallel arrangement by 3.5 dB and 6.0 dB for the FM and IR receivers, respectively.

Subjects

Four groups of subjects were tested:

1. Young adults, mean age 23.5, range 20 to 25 years, with audiometrically normal hearing (hearing threshold level no greater than 10 dB at any of the audiometric frequencies between 250 Hz and 8000 Hz).
2. Hearing impaired with mild-to-moderate hearing loss not using hearing aids, mean age 62.8, range 44 to 72 years.
3. Hearing aid users with moderate hearing loss, mean age 54.2, range 22 to 74 years.
4. Elderly, mean age 71.7, range 66 to 77 years, with hearing losses typically expected for their age.

There were 10 subjects in each group except for the last group which consisted of 9 subjects. The average air conduction thresholds using criteria described by ANSI, 1976 (10) for the last three groups are shown in Figure 6.

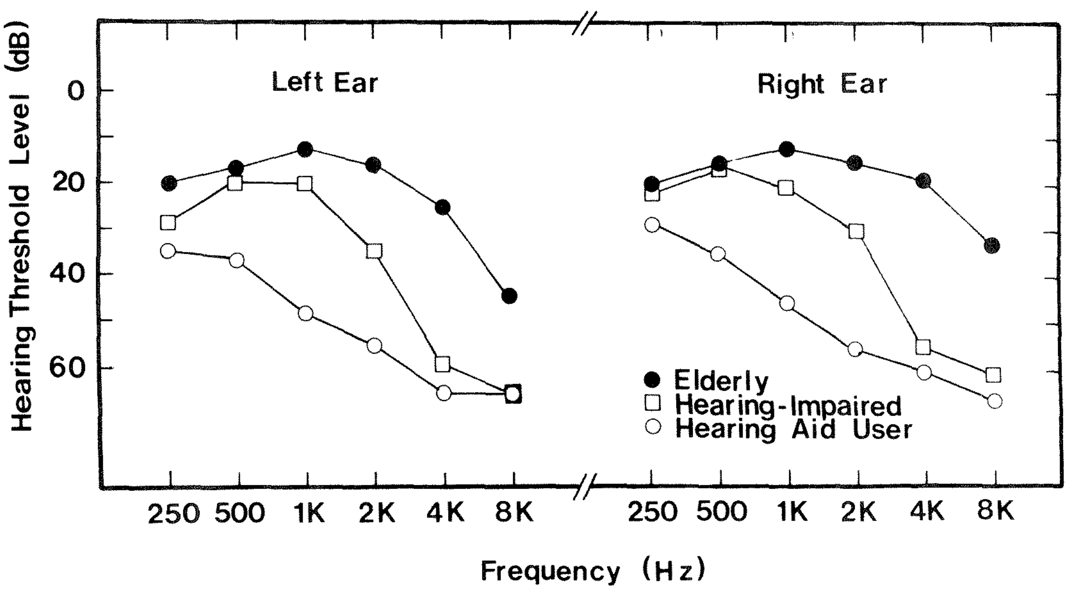

FIGURE 6
Hearing threshold levels in decibels for three groups of subjects.

Procedures

The Modified Rhyme Test published by Kreul et al. in 1968 (11) was played from a tape recorder. The same recordings were previously used by Náběiek and Robinson, 1982 (12). The output of the tape recorder was connected to the inputs of the PA system and all three listening systems. In the cases of the PA and AL systems, the tape recorder was connected to the respective amplifiers. For the FM and IR systems, the line input was utilized. These inputs are designed for use with tape recorders. The microphone input was not tested in this study because the main goal was to compare the systems. The systems had different input impedances and were designed to be used with different microphones; if different microphones had been used, comparisons between systems would have been difficult.

The PA system was constantly activated during all testing. The other systems were activated only while they themselves were being tested. This arrangement simulated the typical situation in an auditorium where a listening system is used as an auxiliary amplification for selected listeners at the same time that the PA system is used by the general audience.

The speech level from the PA system was set at 66 dB (A). This level was measured at 3 meters in front of the loudspeakers with a Rion Sound Level Meter NA-21. As a calibration signal, a segment of pink noise recorded at the beginning of each speech test (at a level corresponding to average peak levels in test words) was used. This level was kept constant throughout the experiment.

There were two modes of presenting the MRT: with and without a 12-voice babble. Babble level was set at 58 dB (A) as measured at the same point as the speech level measurement. The babble was reproduced by a third loudspeaker placed midway between the two loudspeakers producing the MRT. The subjects were seated 3 meters in front of the loudspeakers. The room S/N at this distance was +20 and +8 dB, without and with masking noise, respectively. The first (+20) S/N represents listening conditions which are adequate for all subjects while the second (+8) S/N represents listening conditions which tend to cause perceptual problems for hearing impaired and elderly listeners. Lower S/N's would be even more difficult but they are atypical of classroom conditions. The reverberation time of 0.35 s, typical for acoustically treated classrooms, tends to be a source of perceptual errors for hearing impaired listeners: see Náběiek and Pickett, 1974 (2), and for elderly listeners: see Náběiek and Robinson, 1982 (12).

Listening modes depended on whether or not the subject used a hearing aid, and on the system being tested. Listeners without hearing aids were tested in the following ways:

1. PA system with unaided ears, therefore there was no control of the listening level;
2. AL system with a neck loop, amplifier with volume control, and a stethoscope, with the opportunity to adjust the loudness to a comfortable level; and
3. FM system with an FM receiver, a stethoscope, and the opportunity to adjust the loudness with a receiver volume control; and
4. IR system with an IR receiver with a stethoscope, and opportunity to adjust the loudness with a receiver volume control. The stethoscope was delivering acoustic signals to both ears.

The hearing aid users had binaural hearing losses but were using only one hearing aid. These subjects were tested using their own hearing aids. The hearing aids, of different makes, all had telecoil (T) switches. The hearing aid users were allowed to adjust the hearing aid gain control only two times during each session: first, for the microphone input while listening to the MRT without babble through the PA system, and later (for the telecoil input) while listening to the MRT through the AL system. During that condition, the PA was also activated and there was no babble masking. This telecoil gain setting was then left unchanged for listening to the FM and IR systems. (If desired, the subjects could use the volume control of the respective receivers, but not of their aids, to additionally adjust the loudness level.)

Each condition was tested with two MRT lists equalling a total of 100 words. All eight conditions (four systems, each tested with and without babble noise) were tested using different randomizations of the MRT word lists.

The conditions were tested in the following order: PA without babble, PA with babble and AL without babble. The remaining conditions, FM and IR with and without babble in the room, and AL with babble, were tested in random order. The AL without babble was tested before FM and IR systems so that the hearing aid users could adjust their gain controls for the telecoil input.

RESULTS

The word-identification scores in percentage correct were transformed to the proportions p, which in turn were converted to arcsins $\sqrt{p}$, using the

TABLE 1
Mean word-identification scores and standard deviations (sd) in percentage correct, transformed from mean Φ scores for two room speech-to-noise ratios, four systems, and four groups of subjects.

Group	SYSTEM							
	PA		AL		FM		IR	
	mean	sd	mean	sd	mean	sd	mean	sd
				(S/N = +20 dB)				
Normal	99.1	0.5	99.9	0.4	99.9	0.2	99.8	0.4
Elderly	96.5	0.2	96.9	0.4	98.4	0.4	98.2	0.4
Hearing impaired	89.0	1.5	95.2	1.2	95.8	1.3	93.0	2.1
Hearing aid users	86.9	1.2	92.2	1.6	92.0	2.5	89.6	2.3
				(S/N = +8 dB)				
Normal	93.6	0.7	99.9	0.3	99.9	0.3	99.9	0.4
Elderly	94.3	0.4	97.9	1.0	98.5	0.7	98.0	0.5
Hearing impaired	79.9	1.2	96.2	2.0	97.0	1.5	93.7	1.5
Hearing aid users	83.1	1.1	90.1	2.8	91.1	1.6	87.3	1.5

method of Walker and Lev, 1953 (13) to stabilize the error variance. The following equation was used:

$$\Phi = 2 \arcsin \sqrt{p}$$

The Φ values served as the criterion measure.

Analysis of variance was performed using a repeated measure model. A three-factor design was used to analyze the effect of group (G), system (S), and room signal-to-noise ratio (S/N). All main effects and two two-way interactions were statistically significant at $p < 0.001$:

$$G \; [F(3,35) = 385.47],$$
$$S \; [F(3,105) = 105.76],$$
$$S/N \; [F(1,35) = 15.12],$$
$$G \times S \; [F(9,105) = 6.37], \text{ and}$$
$$S \times S/N \; [F(3,105) = 16.84].$$

The interactions G × S/N and G × S × S/N were not statistically significant. The mean word identification scores obtained from mean Φ scores by reversed transformation are in Table 1 and in Figure 7. Consequently, all reported means were obtained by the transformation from Φ scores.

The effect of groups reflected different degrees of hearing loss. The mean scores were as follows: 99.6, 97.5, 93.1, and 89.2 percent for normal-hearing, elderly, hearing impaired and hearing aid groups, respectively. Duncan's multiple-range test indicated that all four means were different.

The means for the four systems were as follows: 97.5, 97.0, 96.2 and 91.3 percent for FM, AL, IR and PA systems, respectively. Duncan's multiple-range test indicated that the two first means (for the FM and AL systems) were not different, while the other contrasts were significantly different.

The effect of room S/N was significant but the difference between the means was small (96.3 percent and 95.3 percent for +20 dB and +8 dB, respectively).

The two- way interaction G × S indicated that the system performance depended upon the group. Post hoc least-squares means analysis was performed to determine the relationship between the systems and groups. For all four groups, the PA system was significantly different from the remaining three systems ($p < 0.005$). Furthermore, there was no significant difference among the AL, FM, and IR systems for normal hearing and elderly subjects. For the hearing impaired subjects and hearing aid users there was a significant difference between the AL, FM, and IR systems. For the first group, the IR was different from both the AL and FM but the AL and FM were not different. For the hearing aid group, the AL was not significantly different from the FM and IR but the FM was different from IR.

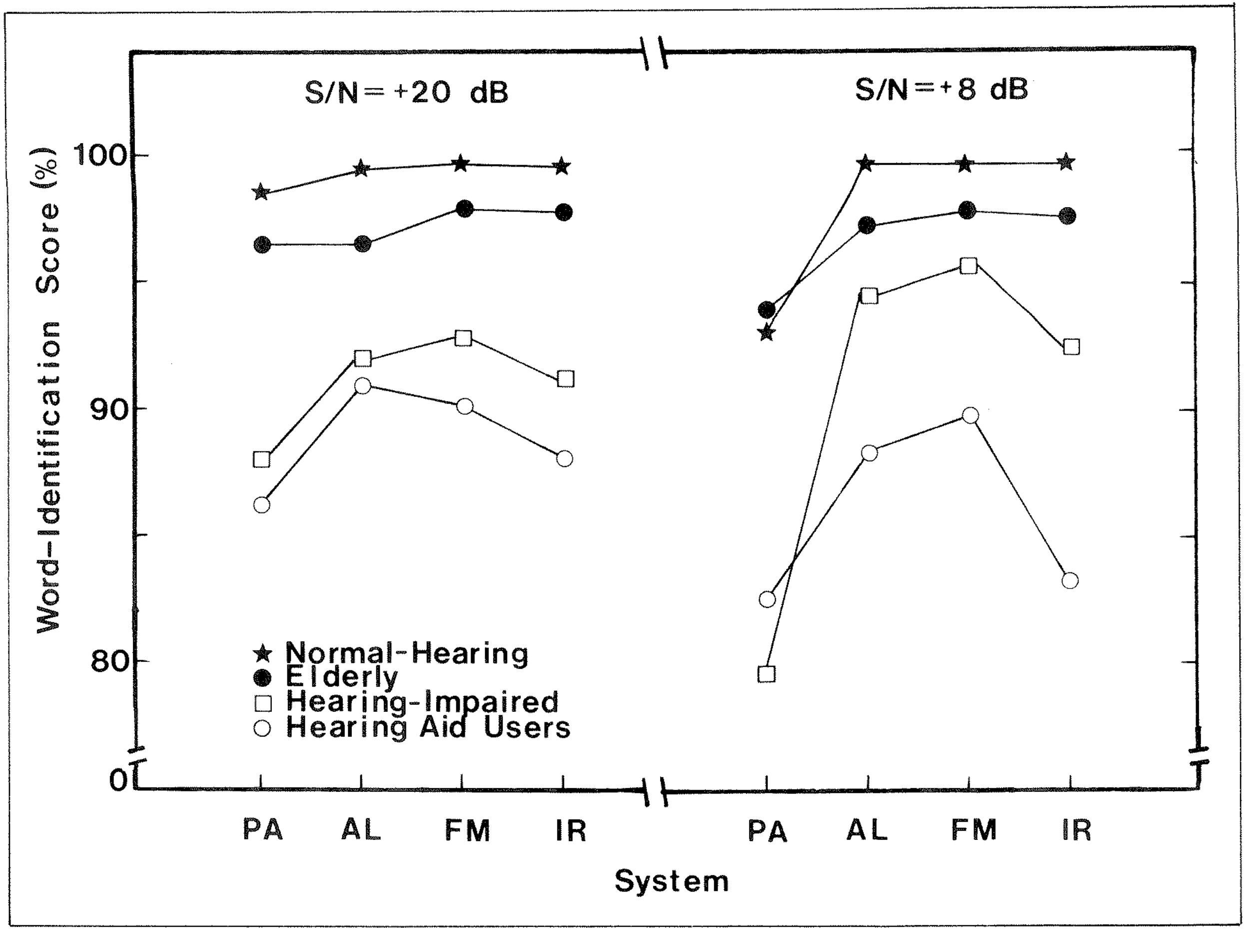

FIGURE 7
Word identification scores for four amplification systems, two speech-to-noise ratios and four groups of subjects.

The two-way interaction S × S/N indicated that the system performance depended on the S/N. The differences between the two S/N's for the AL, FM, and IR systems were less than 1 percent while the difference for the PA system was 6 percent. To illustrate more clearly that the performance of only the PA system depends on the S/N, an additional group of 10 normal hearing subjects was tested at a S/N of 0 dB with all four systems, and with the PA at S/N of +20 dB. The performance of this second group at S/N of +20 dB was comparable to the performance of the first group (98.7 percent and 99.1 percent respectively). The results of the first group at S/N of +20 and +8 dB, and the second group at S/N of 0 dB, are shown in Figure 8.

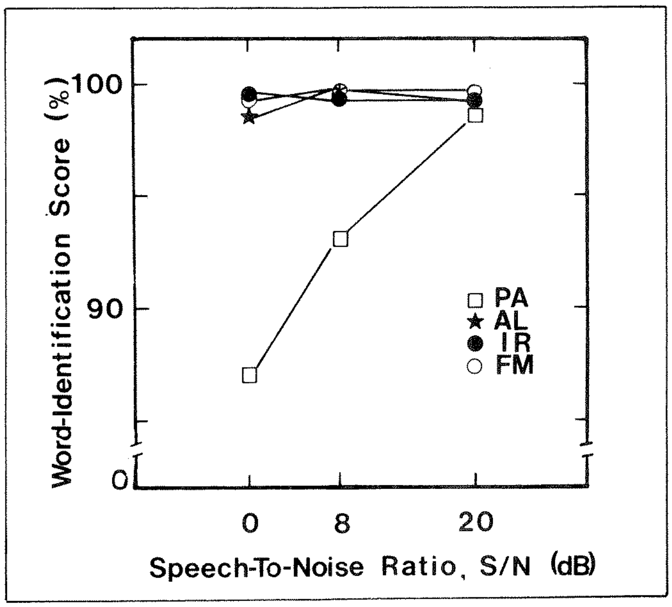

FIGURE 8
Word identification scores as functions of speech-to-noise ratio for four amplification systems with normal hearing subjects.

Journal of Rehabilitation Research and Development Vol. 23 No. 1 1986

DISCUSSION

The results indicate that speech perception with any of the three listening systems was better than with the PA system.

For normal-hearing and elderly subjects, there was no significant difference in performance of the AL, FM, and IR systems.

For the hearing-impaired listeners, the performance of the IR system (93.4%) was worse than that of the AL (95.7%) or of the FM (96.4%) system. While the differences were statistically significant, they were small and should not be considered important.

For hearing aid users, the performance with the AL (91.2%) was not significantly different from the performance with the FM (91.6%) or the IR (88.5%) systems, but the performance with the FM was better than performance with the IR system. Here again, while the difference was statistically significant, it was small.

It can be concluded that all three listening systems were equally effective in overcoming acoustic degradations. The improvement, in comparison with performance when relying on the PA system, was modest, but for those tests the listening conditions in the room were relatively good; an additional experiment with normal hearing subjects indicated that when room noise was increased, the relative improvement was greater.

The good performance of the AL system was probably achieved by its proper design and use of the equalizer. The equalizer was responsible for the similarity of the AL frequency response to the frequency responses of the FM and IR systems. Without the equalizer, the frequency response of the AL system was irregular and narrower, as reported by Letowski, Donahue, and Nábělek in 1985 (9). However, even when tested without the equalizer, the frequency response of this audio loop was much better than that reported in 1976 by Sung, Sung, Hodgson, and Angelelli, who found a very irregular and narrow frequency response in a study of a classroom audio induction loop. Also, the special design of the loop for this study assured high homogeneity of field strength. The results of the speech perception testing indicate that a well-designed audio loop can be equally as effective as an FM or IR system.

Effects Introduced by Transducers

The frequency responses of all three listening systems were greatly modified by electroacoustic transducers. The frequency responses became irregular and high-frequency energy was attenuated. For subjects listening without hearing aids, large irregularities were introduced by the stethoscope tubes. Similar irregularities were reported by Hawkins, Fluck, and Van Meter in 1982 (4) for the 442P Phonic Ear FM receiver with a stethoscope, measured through a KEMAR anthropometric acoustic manikin with Zwislocki ear simulator.

For subjects listening with hearing aids, the frequency response was dependent on the coupling between the neck loop and the telecoil in the hearing aid. We had found (in a pilot study) that the frequency responses of neck loops vary; therefore, one neck loop was used throughout the study. We had no control over the telecoils because various hearing aids were used by the subjects. On a selected hearing aid it was shown that the transmission of low frequencies, and overall gain, depended on the relative position of the loops and the coil. The highest gain was achieved with the two perpendicular to each other, while the lowest gain was achieved with them parallel to each other. The same dependance on position was found by Hawkins and Van Tasell, who reported in 1982 that output differences were 1 to 10 dB for several hearing aids coupled via the neck loop to an FM receiver (15). Consequently, when hearing aids are coupled via the neck loop to a system receiver, the overall gain and frequency response can vary with head and body movements. This could have influenced the performance of the hearing aid users with the FM and IR systems.

A possible explanation for the relatively lower scores with the IR system is that one of the two IR receivers that were used produced occasional internal noise. This was not discovered until the end of the project. Another possible influence is suggested by the fact that all tests were performed during daylight hours. However, any interference caused by excessive light, if it occurred, failed to affect the scores of either the normal hearing or the elderly subjects.

The hearing-impaired subjects without hearing aids performed better than hearing aid users in all conditions — except with PA at S/N of +8 dB. The otherwise superior performance of the group was related to its relatively better hearing threshold levels. However, with the PA, the subjects without hearing aids had no control over the listening level, which might have been too low, and obtained scores about 3 percent lower than the hearing aid users. Such a situation is quite typical in real life, where the listening levels are set for normal hearing listeners. The amplification systems for hearing impaired listeners allow individual control of listening level.

The sound can be delivered to the ears in arrangements other than those tested. The tested arrangements were probably the worst for distortion of the frequency response. This becomes apparent from comparison of Figures 2 and 3. Bankoski and Ross in 1984 (7), reported on tests of two FM receivers, one with the transducer placed in headphones and another with the transducer placed at the entrance of the stethoscope tubes. The difference for the two arrangements was not significant; however, there was a trend in scores in favor of the headphones arrangement. For the hearing aid users, a coupling superior to the neck-loop-and-telecoil would be a direct connection between the FM output and the hearing aid input (15). Hawkins and Van Tasell reported in 1982 that, with such direct connection, the frequency response of the receiver with the hearing aid becomes very similar to the frequency response of the hearing aid with a microphone input (15). Therefore the use of headphones or insert earphones and direct connections to the hearing aids should be preferable.

The systems in this study were compared in a medium-size room because installation of an AL and IR system in a large auditorium would be much more expensive. However, the results obtained in this study can be applied to space of any size, providing that the system will secure adequately strong and homogeneous transmission.

All three tested listening systems seem to be suitable for listeners with various degrees of hearing losses. They can be used by listeners with and without hearing aids. The decision about selection of one system should be based on considerations other than speech perception, such as cost, installation requirements, maintenance, interferences, and mobility ■

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