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Speech Perception in Noise: Directional Microphones versus Frequency Modulation (FM) Systems

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Abstract

The major consequence of sensorineural hearing loss (SNHL) is communicative difficulty, especially with the addition of noise and/or reverberation. The purpose of this investigation was to compare two types of technologies that have been shown to improve the speech-perception performance of individuals with SNHL: directional microphones and frequency modulation (FM) systems. Forty-six adult subjects with slight to severe SNHL served as subjects. Speech perception was assessed using the Hearing in Noise Test (HINT) with correlated diffuse noise under five different listening conditions. Results revealed that speech perception was significantly better with the use of the FM system over that of any of the hearing aid conditions, even with the use of the directional microphone. Additionally, speech perception was significantly better with the use of two hearing aids used in conjunction with two FM receivers rather than with just one FM receiver. Directional microphone performance was significantly better than omnidirectional microphone performance. All aided listening conditions were significantly better than the unaided listening condition.

Key Words: Directional microphones, frequency modulation (FM) systems, HINT sentences, speech perception

Abbreviations: BTE = behind-the-ear; DAI = direct audio input; EM = environmental microphone; FM = frequency modulation; HINT = Hearing in Noise Test; MIL = Most Intelligible Level; PTA = average of the pure-tone air-conduction thresholds at 500, 1000, and 2000 Hz; RTS = reception threshold for sentences; SAV = select-a-vent; SD= standard deviation; SNHL = sensorineural hearing loss; SNR = signal-to-noise ratio; WRS = word-recognition score

Sumario

La consecuencia mayor de una hipoacusia sensorineural (SNHL) es la dificultad comunicativa, especialmente con la adición de ruido y/o reverberación. El propósito de esta investigación fue comparar directamente dos tipos de tecnologías que han mostrado mejorar el desempeño en la percepción del lenguaje en individuos con SNHL: los micrófonos direccionales y los sistemas de modulación de frecuencia (FM). Cuarenta y seis adultos con una SNHL leve a severa fueron los sujetos del estudio. La percepción del lenguaje fue evaluada utilizando la Prueba de Audición en Ruido (HINT), usando un ruido difuso, en cinco condiciones auditivas diferentes. Los resultados revelaron que la percepción del lenguaje fue significativamente mejor con el uso del sistema FM que con cualquiera de las condiciones con un auxiliar auditivo, aún con el uso del micrófono direccional. Además, la percepción del lenguaje fue significativamente mejor con el uso de dos auxiliares auditivos, utilizados en conjunto con dos receptores FM, más que con sólo un receptor FM. El desempeño del micrófono direccional fue significativamente mejor que el

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desempeño del micrófono omni-direccional. Todas las condiciones de escucha con amplificación fueron significativamente mejores que aquellas sin amplificación.

Palabras Clave: Micrófonos direccionales, sistemas de modulación de la frecuencia (FM), frases HINT, percepción del lenguaje

Abreviaturas: BTE = retroauricular; DAI = ingreso directo de audio: EM = micrófono ambiental; FM = modulación de frecuencia; HINT = prueba de audición en ruido; MIL = nivel de mayor inteligibilidad; PTA = promedio de umbrales tonales puros por conducción aérea a 500, 1000 y 2000 Hz; RTS = umbral de recepción para frases; SAV = seleccione una apertura; SD = desviación estándar; SNR = tasa señal/ruido; WRS = puntaje de reconocimiento de palabras

Recent estimates suggest that over 29 million individuals in the United States exhibit some degree of hearing impairment (National Institutes of Deafness and Communication Disorders ([NIDCD], 2001). A major consequence of sensorineural hearing loss (SNHL) is communicative difficulty, especially with the addition of noise and/or reverberation (Dubno et al, 1984; Hawkins and Yacullo, 1984; Suter, 1985; Helfer and Wilber, 1990; Crandell, 1991; Helfer and Huntley, 1991; Needleman and Crandell, 1995, Killion, 1997a; Moore, 1997). Unfortunately, conventional amplification technologies may provide little or no improvement to the signal-to-noise ratio (SNR) in adverse listening environments (Duquesnoy and Plomp, 1983; Plomp, 1986; Crandell and Smaldino, 2000, 2001). In fact, a lack of perceptual improvement in noisy listening environments is one of the major reasons why individuals with SNHL report dissatisfaction with and reject amplification (Kochkin, 1993). At present, there are various technologies that have been shown to improve speech perception in poor listening environments. These technologies include directional microphones and personal frequency modulation (FM) systems (Hawkins, 1984; Hawkins and Yacullo, 1984; Fabry, 1994; Valente et al, 1995; Gravel et al, 1999; Kuk et al, 1999; Pittman et al, 1999; Preves et al, 1999; Ricketts and Dhar, 1999; Pumford et al, 2000; Ricketts, 2000a, 2000b; Valente et al, 2000; Ricketts et al, 2001).

Directional microphones are typically designed to provide less amplification to signals originating from the rear and the sides relative to signals arriving from the front, which is where the speaker will ideally be located. Numerous investigations have demonstrated that directional microphone technology can significantly improve the speech-perception ability of individuals with SNHL, particularly in noisy listening environments relative to unaided or aided listening with the use of an omnidirectional microphone (Valente et al, 1995; Gravel et al, 1999; Kuk et al, 1999; Preves et al, 1999; Ricketts and Dhar, 1999; Pumford et al, 2000; Ricketts, 2000b; Valente et al, 2000; Ricketts et al, 2001). Past investigations have demonstrated that the use of directional microphone technology can improve speech perception in noise by as much as 3 to 8 dB over omnidirectional microphone technology in the same hearing instrument depending on microphone location, type of noise, test materials, and so on (Hawkins and Yacullo, 1984; Valente et al, 1995; Gravel et al, 1999; Ricketts and Dhar, 1999; Pumford et al, 2000; Valente et al, 2000).

Personal FM systems also been shown to have the capability to improve the speech-perception ability of individuals with SNHL (Hawkins, 1984; Fabry, 1994). Past investigations have demonstrated that FM technology can improve speech perception in noise by as much as 10 to 20 dB over the unaided listening condition (Crandell and Smaldino, 2000, 2001). With a personal FM system, the speaker's voice is picked up via an FM wireless microphone located near the speaker's mouth, where the effects of reverberation, distance, and noise are minimal. The FM system converts the acoustic signal to an electrical waveform at the microphone, and the signal is transmitted via FM signal, from the transmitter to the receiver. Both the transmitter and the receiver are tuned to the same transmitting and receiving frequency. At the receiver's end, the electrical signal is amplified, converted back to an acoustical waveform, and conveyed to the listener. A recent, and increasingly popular, method for coupling FM systems to listeners with hearing impairment is via an "audio boot" coupled to a behind-the-ear (BTE) hearing aid. This type of technology, such as the Phonak Microlink, allows the user to convert his/her personal hearing aid into an FM system simply by attaching the audio boot and using an FM transmitter. Typically, such systems enable the user to have three settings: (1) FM only, for the purpose of focusing primarily on the talker; (2) environmental microphone (EM) only, for the purpose of listening to all individuals in the immediate listening environment as well as monitoring his/her own voice; and (3) FM plus EM for listening to both the speaker as well as other individuals in that listening environment.

Despite the documented enhancement in speech perception with directional microphone and FM technologies, to date, only one investigation has attempted to compare these technologies. Hawkins (1984) evaluated the effect of various hearing aid and FM system configurations on speech perception in noise. Nine children with bilateral mild to moderate SNHL served as study participants. These subjects used a Phonic Ear 805 CD BTE hearing instrument that had the capability to switch between omnidirectional and directional microphone modes. The Phonic Ear 441T microphone transmitter and the Phonic Ear 445R FM receiver served as the FM system. Speech perception was assessed using spondees and Phonetically Balanced Kindergarten (PB-K) words presented in a classroom with a reverberation time of 0.6 sec. Speech was delivered from a loudspeaker located 2 m from the child at 0° azimuth. Speech noise was presented from a loudspeaker located 4 m from the child at 180° azimuth. Speech perception was assessed in the following conditions: (1) monaural hearing aid in the omnidirectional microphone mode; (2) monaural hearing aid in the directional microphone mode; (3) binaural hearing aids in the omnidirectional microphone mode; (4) binaural hearing aids in the directional microphone mode; (5) FM only connected via a neck loop to a monaural hearing aid with a directional microphone on the FM transmitter; (6) FM only connected via a silhouette inductor to a monaural hearing aid with a directional microphone on the FM transmitter; (7) FM only connected via direct audio input (DAI) to a monaural hearing aid with a directional microphone on the FM transmitter; (8) FM only connected via DAI to a monaural hearing aid with an omnidirectional microphone on the FM transmitter; (9) FM plus EM with no attenuation connected via DAI to a monaural hearing aid in the omnidirectional microphone mode; (10) FM plus EM with no attenuation connected via DAI to binaural hearing aids in the omnidirectional microphone mode; and (11) FM plus EM with no attenuation connected via DAI to binaural hearing aids in the directional microphone mode. Results of this study suggested that FM technology does significantly improve speech perception in noise when compared to any of the hearing aid alone arrangements (11.8 dB to 18.4 dB improvement). Additionally, FM-only strategies were significantly better than any of the FM plus EM arrangements (7.9 to 16.9 dB). Finally, for most listening conditions, the FM plus EM arrangements were not significantly better than any of the hearing aid alone conditions.

Unfortunately, while an important and seminal investigation, several experimental limitations existed in that study that preclude the generalization of these data to current fitting options for patients with mild to moderate SNHL. First, Hawkins (1984) utilized only a single noise source located at 180° from the subject. It is well recognized that a single noise source is not typical of everyday listening environments that contain multiple noise sources (Valente et al, 2000; Ricketts, 2000b). Thus, any reported FM advantages may not be similar in "real world" listening environments. Second, the study contained relatively few subjects as Hawkins (1984) only evaluated the speech perception of nine children with SNHL. Additionally, the hearing aids in this study utilized earlier directional microphone technology. In recent years, directional microphone technology has improved significantly with the advent of improved directional microphone components, dual-microphone technology, the D-mic™, analog to digital converters, real-time calibration of dual microphones, wider and smoother frequency responses, adaptive microphones, and so forth (Valente, 2000). Thus, it is not known whether the difference reported by Hawkins (1984) between directional microphones and FM systems would remain with advanced directional microphone technology and the introduction of digital signal processing. Finally, due to the time of the investigation, relatively obsolete FM technology was used. As previously mentioned, Phonak Corporation developed a new personal FM system receiver, the Phonak Microlink, which does not utilize wires or a body-worn box like its predecessors. This lack of accessories is more cosmetically appealing and as such is growing in popularity in the FM market. Although one would assume that this type of product would also enhance speech-perception performance in noise, at this point in time, no data is available to demonstrate this. With these considerations in mind, the purpose of this study was to examine the speech-perception ability in noise of adults with mild to severe SNHL utilizing current directional microphone and FM technology. Since there is limited empirical data comparing directional microphones and FM technologies, this investigation examined numerous configurations of both technologies. Specifically, speech perception was assessed, using the Hearing in Noise Test (HINT) (Nilsson et al, 1994) with diffuse noise, in the following listening conditions:

(1) unaided;

(2) binaural digital Phonak Claro 311 dAZ BTE hearing aids alone in the omnidirectional microphone mode;

(3) binaural digital Phonak Claro 311 dAZ BTE hearing aids alone in the directional (adaptive) microphone mode;

(4) monaural digital Phonak Claro 311 dAZ BTE HA utilized with one Phonak Microlink FM receiver with the EM attenuated (FM-only mode) and one Phonak Claro 311 dAZ BTE HA in the omnidirectional microphone mode worn on the opposite ear; and

(5) binaural digital Phonak Claro 311 dAZ BTE hearing aids utilized with binaural Phonak Microlink FM receivers with the EM attenuated (FM-only mode).

METHODS

Subjects

Subjects were recruited from the audiology clinics at two sites. Site I was the University of Florida in Gainesville, Florida, and Site II was Washington University School of Medicine in St. Louis, Missouri. At Site I, 22 subjects were evaluated, of which 15 (68%)

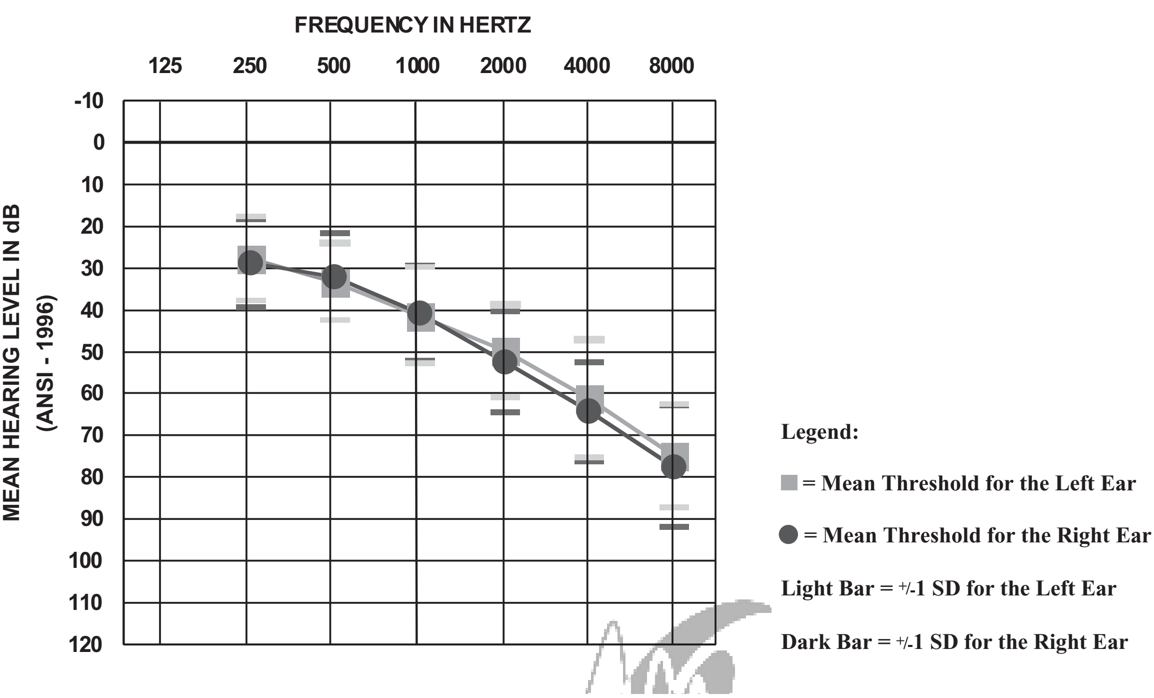

Figure 1. Mean pure-tone air-conduction thresholds for the right and left ears (± 1 SD) at Site I.

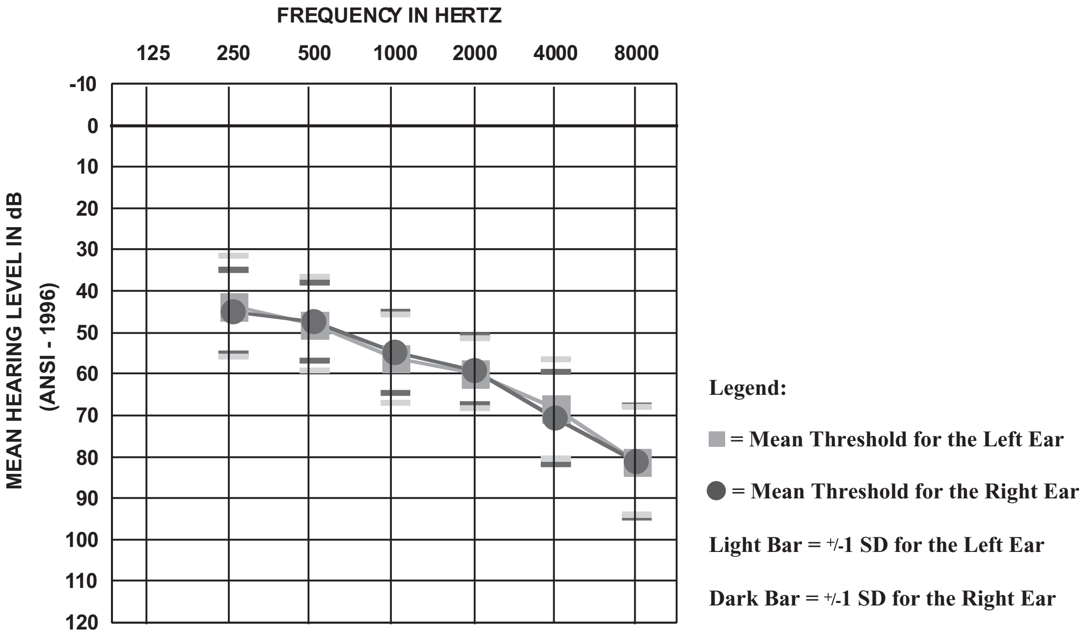

Figure 2. Mean pure-tone air-conduction thresholds for the right and left ears (± 1 SD) at Site II.

were male and 7 (32%) were female. These subjects ranged in age from 24 to 84 years, with a median age of 73 years. At Site II, 23 subjects were evaluated, of which 13 (57%) were male and 10 (43%) were female. These subjects ranged in age from 34 to 81 years, with a median age of 73 years. An independent samples t-test revealed that there was no statistically significant difference between the two sites in terms of age (p = 0.646).

Pure-tone air-conduction and bone-conduction thresholds were obtained bilaterally. Test results revealed mean pure-tone thresholds consistent with a mild sloping to severe SNHL bilaterally and a moderate sloping to severe SNHL bilaterally at Sites I and II respectively (see Figures 1 and 2). Word-recognition scores (WRS) were also obtained at the Most Intelligible Level (MIL) on each ear, using recorded NU-6 word lists, for all study participants. Test results revealed mean word-recognition scores (± 1 SD) of 80.2% (± 13%) and 79.4% (± 11%) for the right and left ears respectively at Site I and 73.4% (± 11%) and 77.0% (± 7%) at Site II. These were no significant differences between the two ears in terms of pure-tone average (PTA) at Site I (p = 0.789) and at Site II (p = 0.730) and WRS at Site I (p = 0.971) and Site II (p = 0.157). However, an independent samples t-test revealed that there were statistically significant differences between the two sites in terms of PTA for both ears (p = 0.000). There were no statistically significant differences between the two sites in terms of WRS for the right (p = 0.101) and the left (p = 0.460) ears. All subjects met the following inclusion/exclusion criteria:

1. Ear inspection via otoscopy within normal limits.
2. Normal middle ear function bilaterally (+/- 100 dekapascals [daPa]) as indicated by tympanometry.
3. No evidence of conductive or retrocochlear pathology as indicated by pure-tone testing and immittance measurements.
4. No air-bone gap greater than 10 dB at any test frequency as indicated by pure-tone test results.
5. Slight (20 to 40 dB HL)-to-severe (65 to 85 dB HL) high-frequency or flat SNHL as indicated by pure-tone test results (250 Hz to 8000 Hz, including 3000 and 6000 Hz).
6. Symmetrical hearing loss that does not differ by more than 15 dB at more than one audiometric test frequency as indicated by pure-tone test results.

7. Word-recognition scores of 50% or better in quiet as assessed by recorded versions of NU-6 monosyllables at the subject's MIL.
8. Motivated to try amplification as reported by the participant.
9. Native speaker of English as reported by the participant.
10. Intact mental status as measured by the Short-Portable Mental Status Questionnaire (SPMSQ; Erkinjutti et al, 1987).
11. No history of chronic or terminal illness, psychiatric disturbance, or senile dementia as reported by the participant.
12. No history of being bedfast/chairfast as reported by the participant.
13. Not home or nursing bound.
14. No history of stroke or cerebral vascular disorder with a paresis or aphasia as reported by the participant.
15. Willing and able to give written informed consent to participate in this investigation, as noted by their signature on the "Informed Consent to Participate in Research" document.

Amplification Systems

All subjects were fit with digital Phonak Claro 311 dAZ BTE hearing aids bilaterally. All earmolds had select-a-vent (SAV) venting and #13 or 3 mm horn tubing. In addition to the hearing aids, subjects were fit with Phonak Microlink ML8 FM receivers bilaterally. These FM receivers attach to the bottom of a BTE hearing aid and may be utilized in either the "FM only" mode, which attenuates the hearing aid microphone by 20 dB, or in the FM plus hearing aid mode, which allows for FM input and input of environmental sounds via the hearing aid microphones simultaneously at the same output level. The Phonak TX3 HandyMic FM transmitter served as the FM transmitter. This transmitter has three microphone options: (1) Wide Angle, which picks up sounds arriving from all directions around the transmitter microphone equally; (2) Zoom, which provides reduced amplification to signals arriving from the rear (cardioid); and (3) SuperZoom, which provides reduced amplification to signals originating from the rear and the sides (hypercardioid). The hearing aids were fit as recommended via the Desired Sensation Level (DSL) (Seewald, 2000) prescriptive fitting formula on the Phonak Fitting Guideline (PFG) Version 7.3 software. All fittings were compared to prescriptive targets using probe-microphone measures. Additionally, all subjects used their amplification systems for at least 30 days prior to assessing speech perception in noise.

Speech Stimuli

Speech perception was assessed using the Hearing In Noise Test (HINT) sentences (Nilsson et al, 1994). The HINT consists of 25 lists of ten sentences each. Each sentence is six to seven syllables in length and is at a first-grade reading level (Nilsson et al, 1996). All sentence lists are equivalent in length, phonemic content, and difficulty level in both quiet and noise (Nilsson et al, 1994). These sentences have also been shown to exhibit high test-retest reliability (Nilsson et al, 1994). The HINT sentences were presented via a commercially available compact disc recording that uses a male speaker with a normal American dialect.

Noise Competition

Correlated (i.e., the same noise source was presented from 45°, 135°, 225°, and 315° azimuth) speech spectrum shaped noise served as the competing stimulus. This noise has been filtered to match the long-term average speech spectrum of the HINT sentences (Nilsson et al, 1996). This type of noise is typical of the acoustic spectra of everyday listening situations (Plomp, 1986; Crandell, 1991). Additionally, speech spectrum shaped noise has the most deleterious effect on speech perception for both young and old individuals with normal hearing and hearing impairment relative to other types of noise sources (Prosser et al, 1990; Nilsson et al, 1994). The competing stimulus was presented through the second channel of the HINT compact disc recording.

Procedures

At both sites, reception threshold for sentences (RTS) in noise testing was conducted in a double-walled sound-treated booth [1.9 m (height) x 2.5 m (width) x 2.7 m (length)] using a clinical audiometer (GSI-61).

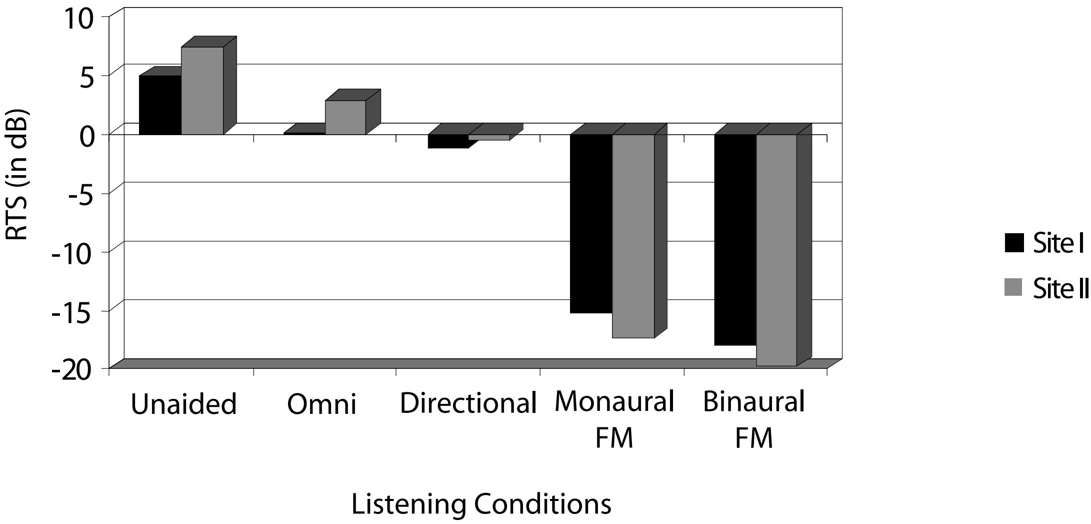

Figure 3. Mean RTS for each listening condition at Site I and Site II.

The HINT sentences were presented from a loudspeaker positioned at 0° azimuth located one meter from the study participant. At Site I, this loudspeaker was a Tannoy model 600 loudspeaker while at Site II it was an RCA Pro-X44AV loudspeaker. The Phonak TX3 HandyMic FM transmitter was placed on a microphone stand located 7.5 cm from this loudspeaker at a height of 0.5 meters to simulate an ideal user position (as might be utilized with a boom microphone) (Crandell et al, 1995). Testing was conducted with the FM transmitter in the SuperZoom position, which is the Phonak recommended setting for maximum speech perception in noise. Correlated speech spectrum shaped noise was presented from four loudspeakers positioned at 45°, 135°, 225°, and 315° azimuth. All loudspeakers were located one meter from the study participant, which is within the critical distance. These loudspeakers were Definitive Technology BP 2X loudspeakers at Site I and RCA Pro-X44AV loudspeakers at Site II. All loudspeakers were single element loudspeakers. To ensure consistency in the signals, daily calibration of the speech stimuli and noise competition were conducted at the center of the subject's head with the subject absent via a Quest 1500 sound level meter at Site I and via a Quest 1900 Precision sound level meter at Site II.

An adaptive procedure was utilized to assess the RTS in noise. This procedure has been shown to have a higher reliability and validity than percent correct perception procedures (Crandell and Boney, Submitted for Publication). Additionally, ceiling or floor effects are not a limitation in this procedure as they are in percent-correct procedures (Nilsson et al, 1994). In the adaptive procedure, the noise level was held constant at 65 dBA, and the intensity level of the sentences was varied to determine a 50% accuracy level. A noise level of 65 dBA is typical of noise levels present in many everyday listening environments (Sanders, 1965; Ross and Giolas, 1971; Blair, 1977). For each listening condition, the subject was presented with 20 sentences, consisting of two HINT sentence lists. The first sentence of the list was repeated until an intensity level was chosen in which the subject could repeat the sentence with 100% accuracy. At that point, the intensity level was varied in 4 dB increments for the first five sentences, depending on the participant's response, and then in 2 dB increments for the last 15 sentences. To calculate the RTS in noise, the intensity level that would be utilized for the 21st sentence, if there were to be one, was predicted based on the participant's response on the 20th sentence. The RTS in noise was determined by calculating the average of the intensity levels of sentences 5 through 21.

Reception thresholds for sentences in noise were determined for subjects under five different listening conditions. These listening conditions were: (1) unaided; (2) binaural Phonak Claro 311 dAZ BTE hearing aids alone in omnidirectional mode; (3) binaural Phonak Claro 311 dAZ BTE hearing aids alone in directional mode; (4) binaural but fit with one Phonak Claro 311 dAZ BTE hearing aid utilized with one Phonak Microlink FM receiver in the FM only mode and one Phonak Claro 311 dAZ BTE hearing aid in the omnidirectional microphone mode in the opposite ear (half of the subjects utilized the FM on the right ear and half on the left ear); and (5) binaural Phonak Claro 311 dAZ BTE hearing aids utilized with two Phonak Microlink FM receivers in the FM only mode. All conditions and sentence lists were randomized to avoid order effects. In addition, no list was repeated to reduce potential learning effects.

RESULTS

Mean RTS for each listening condition at each site are presented in Figure 3. A repeated-measures analysis of variance (ANOVA) was conducted to determine if there was any overall statistical significance between the mean RTS across the five listening conditions at the two sites. The ANOVA revealed a statistically significant difference between listening conditions at Site I ($F_{4,84}$ = 299.01, $p < 0.001$) and at Site II ($F_{4,88}$ = 293.13, $p < 0.001$). Since there proved to be a statistical significance between the listening conditions, Least Significant Difference multiple comparison procedures (at an alpha level of $p = 0.05$) were performed to determine where significant differences existed. These post-hoc procedures revealed that:

(1) Subjects at both sites obtained the poorest speech-perception scores in the unaided listening condition ($p < 0.001$). The mean RTS (±1 SD) for this condition was 4.9 dB (± 4 dB) for Site I and 7.4 dB (± 5.9 dB) for Site II.

(2) These mean RTS when utilizing the hearing aids in the omnidirectional microphone mode (x_1 = 0.07 dB [±3.5 dB], x_2 = 2.9 dB [± 2.3 dB]) were significantly better than the unaided listening condition ($p < 0.001$). In other words, the mean RTS improved by approximately 5 dB with the use of binaural hearing aids in the omnidirectional microphone mode over the unaided listening condition.

(3) The directional microphone mode on the hearing aid (x_1 = -1.1 dB [± 3.5 dB], x_2 = -0.5 dB [± 1.8 dB]) yielded significantly better performance than the condition with the hearing aids in the omnidirectional microphone mode ($p_1 = 0.011$, $p_2 < 0.001$) and the unaided listening condition ($p < 0.001$). Stated otherwise, the utilization of hearing aids in the directional microphone mode improved speech perception in noise by 1.2 dB at Site I and by 3.4 dB at Site II over the omnidirectional microphone condition.

(4) The condition with the binaural hearing aids used with one FM receiver in the FM-only mode (x_1 = -15.3 dB [± 6.1 dB], x_2 = -17.2 dB [± 4.9 dB]) resulted in significantly better speech-perception performance than either of the hearing aid alone conditions ($p < 0.001$). On average, subjects improved by 14.2 dB at Site I and by 16.7 dB at Site II with the use of one FM receiver over the use of two hearing aids alone in the directional microphone mode. However, it should be noted that performance in this condition was significantly poorer than the condition with two FM receivers ($p_1 < 0.001$, $p_2 < 0.001$).

(5) The best speech-perception scores were obtained when the subjects used binaural hearing aids with two FM receivers in the FM-only mode ($p < 0.\ 001$). The mean RTS for this condition was –18.0 dB (± 4.3 dB) for Site I and –19.8 dB (± 4.7 dB) for Site II. This performance was on average 2.7 dB and 2.5 dB better at Site I and II respectively than performance in the condition with one FM receiver.

Independent-sample t-tests were conducted for each condition across the two sites. Test results revealed that there were no statistically significant differences between the two sites in terms of mean RTS for all listening conditions except for the condition with the two hearing aids alone in the omnidirectional microphone mode ($p = 0.002$). For this listening condition, the subjects at Site I (x = 0.07 dB) obtained a significantly better RTS than the subjects at Site II (x = 2.9 dB), which results in a difference of 2.8 dB between the two sites.

DISCUSSION

Prior studies suggest that individuals with SNHL have significant difficulties understanding speech, especially in noisy or reverberant listening environments (Dubno et al, 1984; Hawkins and Yacullo, 1984; Suter, 1985; Helfer and Wilber, 1990; Crandell, 1991; Helfer and Huntley, 1991; Needleman and Crandell, 1995; Killion, 1997a; Moore, 1997). In general, individuals with hearing impairment require the speech signal to be 4 to 18 dB higher than extraneous background noise in order to obtain speech recognition scores similar to individuals with normal hearing (Killion, 1997a; Moore, 1997). The individuals in this study required an SNR of approximately 5 dB in the unaided listening condition at Site I and 7 dB at Site II. This finding correlates well with past investigations. Killion (1997b), for example, suggests that individuals with pure-tone averages of 40 dB HL (which is the average PTA loss of the subjects in Site I in this study) typically require an SNR of approximately 5 dB in order to obtain 50% correct on the Speech-In-Noise (SIN) test when the signal is presented at 70 dB or at a level of "loud but OK" (Killion, 1997a). For individuals with PTA consistent with Site II, an SNR between 6–7 dB would be necessary to reach the 50% criterion.

Mean speech-perception scores were significantly better at both sites in the condition with the hearing aids in the omnidirectional microphone mode than in the unaided listening condition. Few studies have reported these two conditions with current hearing aid technologies (Nabelek and Mason, 1981; Duquesnoy and Plomp, 1983; Welzl-Muller and Sattler, 1984). However, this finding is reasonable given the enhancement of the auditory signal, particularly that of the higher frequencies, provided via amplification. With the amplification of sound provided through the use of hearing aids, the primary signal was made more audible allowing for improved comprehension of the speech signal than without the use of the hearing aids. In fact, Nabelek and Mason (1981) demonstrated that some individuals do obtain improved speech perception with the use of hearing aids over the unaided listening condition in noisy environments. Overall individuals with hearing impairment required a +3 dB SNR in order to reach 50% criterion on the Modified Rhyme Test (Bell et al, 1972) in the unaided listening condition. With the use of binaural amplification, these same individuals only required a –1 dB SNR to reach the same level of performance (i.e., a 4 dB improvement). Additionally, Shanks et al (2002) recently examined speech perception in noise in the unaided listening condition and with a single-channel ITE hearing aid equipped with an omnidirectional microphone programmed as peak-clipping (PC), compression limiting (CL), and wide dynamic range compressing (WDRC). Results revealed all three hearing aid circuits provided a significant improvement in speech perception over the unaided listening condition. This improvement in speech perception over the unaided listening condition was greatest at the lowest presentation level (52 dB SPL). Recall that in the current study an adaptive procedure was utilized suggesting that speech was presented near the patient's threshold of audibility.

The mean RTS obtained at Site I was significantly different than the mean RTS obtained at Site II for the condition with binaural hearing aids in the omnidirectional microphone mode. In this listening condition, the subjects at Site I ($x = 0.074$ dB) obtained significantly better RTS than the subjects at Site II ($x = 2.9$ dB). On average, the subjects at Site I had better pure-tone averages than the subjects at Site II. Recall that this difference in PTA between the two sites was statistically significant in both ears ($p = 0.000$). Hence, this is the likely cause of the discrepancy in RTS scores between the two sites for this listening condition.

Speech-perception performance with the use of the directional microphone was significantly better than with the omnidirectional microphone at both sites (2.8 dB at Site I and 3.4 dB at Site II). This finding is consistent with prior studies (Hawkins and Yacullo, 1984; Valente et al, 1995; Gravel et al, 1999; Ricketts and Dhar, 1999; Pumford et al, 2000; Valente et al, 2000; Amlani, 2001). Ricketts et al (2001) evaluated the speech perception in noise ability of 47 adults with mild to moderate SNHL using five different hearing aids. Speech perception was assessed via the HINT test sentences, where speech was presented from 0° azimuth, and uncorrelated cafeteria noise was presented at 65 dBA SPL loudspeakers located at 30°, 105°, 180°, 225°, and 330° azimuth. In the condition using single-channel analog BTE hearing aids, the mean RTS for the directional microphone mode of the hearing was approximately –1.2 dB. This study yielded a mean directional advantage (RTS of the omnidirectional microphone mode minus the

RTS of the directional microphone mode) of 2.2 dB. Additionally, Amlani (2001) conducted a meta-analysis of 74 studies evaluating the speech perception performance of hearing aids equipped with directional microphones. In this meta-analysis, a weighted average SNR of –2.6 dB (CI_{95} = ±1.1 dB) was obtained. This weighted average corresponds well with the mean RTS obtained in the directional microphone listening condition in this study. Amlani (2001) calculated a weighted directional advantage of 4 dB (CI_{95} = 0.8).

Although prior studies have obtained improvements with the directional microphone relative to the omnidirectional microphone in terms of speech perception in noise by as much to 6 to 8 dB, the improvement with the directional microphone in this experiment was not as great (Valente et al, 1995; Gravel et al, 1999; Kuk et al, 1999). There are a few possible reasons for this finding. As mentioned previously, the location and number of noise sources in a listening environment can significantly impact the effectiveness of a directional microphone (Ricketts, 2000b; Valente, 2000; Gnewikow, 2002). Valente (2000) directly compared the speech perception in noise utilizing ITE hearing aids in the omnidirectional microphone mode and in the directional microphone mode in two different listening conditions: (1) ideal, in which the primary speech signal is presented at 0° azimuth and the noise originates from 180° azimuth, and (2) diffuse, in which the primary speech signal is presented at 0° azimuth and the noise originates from 45°, 135°, 225°, and 315° azimuth (which is the noise source configuration used in this study). Results revealed a significant improvement in speech perception in noise with the dual-microphone directional microphone compared to the omnidirectional microphone (3.3 dB). However, this improvement was significantly greater in the ideal listening condition compared to the diffuse listening condition (0.5 dB). Additionally, Ricketts (2000a) noted a loss in directivity with hearing aids operating in the directional microphone mode with larger vent sizes. In this study, vent size was chosen based on audiometric configuration and patient comfort. Many of these subjects used relatively large vent sizes because of slight/mild hearing losses in the low frequencies. Therefore, a loss of directivity of the devices may have occurred as a result of these larger vent sizes. Certainly, this issue requires further study.

Speech perception in noise was significantly better in the FM-only condition (monaural and binaural) than any hearing aid condition (omnidirectional and dual-microphone) at both sites. That is, the mean difference between the monaural FM and the hearing aids in the omnidirectional microphone mode was 15.4 dB and 20.3 dB at Site I and Site II respectively and 14.2 dB and 16.9 dB for the directional microphone comparison. For the binaural FM setting, the mean difference between FM and the hearing aids in the omnidirectional microphone mode was 18.1 dB and 22.7 dB for Site I and Site II respectively and 16.9 dB and 19.3 dB for the directional microphone comparison. These findings agree well with the few previous studies that have examined this issue. In the Hawkins (1984) study, the FM-only conditions provided a significant improvement over all the hearing aid alone conditions (15.3 dB). The parallel between these two studies is not surprising given that proximity of the FM transmitter to the desired signal reduces the effects of noise, distance, and reverberation in such a way that hearing aids are unable to do. However, unlike the Hawkins (1984) study, a binaural advantage was demonstrated with the use of the FM system in this experiment by approximately 3 dB. This binaural advantage is most likely a result of the use of two FM receivers (true binaural). In the Hawkins (1984) study, binaural FM input was delivered through the use of one FM receiver creating a diotic signal. Additionally, this binaural advantage is consistent with prior studies regarding the benefits of binaural hearing and binaural amplification (Markides, 1977; Nabelek and Mason, 1981; Hawkins and Yacullo, 1984; Feuerstein, 1992; McCullough and Abbas, 1992). Past studies have reported a binaural advantage of 2 to 3 dB when individuals with hearing impairment listen in noise (Markides, 1977; Nabelek and Mason, 1981; Feuerstein, 1992; McCullough and Abbas, 1992). To illustrate, Nabelek and Mason (1981) evaluated the speech perception in noise ability of 21 subjects with bilateral mild sloping to moderate SNHL. Results revealed that these subjects performed 5.9 to 7.2% better in the binaural listening condition than in the monaural listening condition. Given that the PB-PI function of PB words is about 3% per dB, this finding suggests an improvement of 2 to 3 dB when an individual with hearing impairment listens with two ears versus one ear. This binaural advantage remains with the use of amplification. Hawkins and Yacullo (1984) evaluated the speech perception in noise ability of 11 subjects with bilateral symmetrical mild to moderate SNHL utilizing monaural and binaural hearing aids. In this study, subjects obtained significantly better speech perception scores when utilizing binaural amplification by 2 to 3 dB over the use of monaural amplification. Hence, it is not surprising that our subjects also performed similarly with two FM receivers versus the use of one FM receiver.

Clinical Relevance

This study has important implications for the clinical management of patients with SNHL. As previous studies suggest, the majority of individuals with hearing impairment obtain improved speech perception in noise with the use of hearing aids with directional microphones. However, there is high individual variability in this finding (Killion et al, 1998; Ricketts and Mueller, 2000). Unfortunately, at this time, no clear predictor exists regarding which individuals will obtain this improvement in speech perception and which will not. In fact, Ricketts and Mueller (2000) examined the impact of audiometric slope, magnitude of high-frequency hearing loss, and speech-perception performance in noise using omnidirectional and directional test conditions on 80 subjects. None of these factors proved to be significant predictors of benefits with a directional microphone.

All of the study participants at the two sites obtained significantly better speech-perception performance in noise with the use of an FM system in either the monaural or binaural mode. Despite this improved performance in noise, relatively few patients are being fit with FM technology. In fact, recent estimates suggest that less than 5% of adults with hearing aids also use FM technology (Crandell and Smaldino, 2000). With these documented improvements in speech-perception ability in noise, it is imperative that clinical audiologists offer FM technology as a viable option for communication to their patients when discussing treatment options regarding hearing impairment. The audiologist should describe FM technology, its usage, and its documented benefits with their patients. This type of technology should be further reviewed and demonstrated in hearing aid orientation programs.

Additionally, this study provides documentation regarding the degree of speech-perception performance obtained under various FM technology arrangements. This information is critical for audiologists when counseling their patients regarding FM system applications in “everyday” communication situations. For instance, the vast majority of study participants realized better speech-perception performance in noise with the use of the hearing aids equipped with two Phonak Microlink FM receivers rather than with just one FM receiver. The mean difference in RTS between these two conditions in this study was 2.7 dB at Site I and 2.4 dB at Site II. Hence, just as the majority of patients benefit from the use of binaural hearing aids, audiologists can now counsel their patients that the majority of individuals with hearing impairment will perform better in background noise if the signal of interest (e.g., speech) is at the microphone of the FM transmitter and the FM receivers are fit bilaterally in the FM-only mode rather than one FM receiver on one ear and a hearing aid alone on the other ear.

Limitations of the Study

Despite the significant findings in this investigation, there are several limitations. First, the majority of study participants were older adults. Recall that the median age of this study sample was 73 years. Hence, these results cannot be generalized to other age groups, especially to children. Gravel et al (1999) evaluated the speech-perception in noise ability of children, ranging in age from 4 to 11 years, with bilateral, mild to severe SNHL using omnidirectional and dual-microphone technology. Study results revealed that the dual-microphone condition provided a significant improvement in speech perception for both words and sentences over the omnidirectional condition by 4.7 dB, which is approximately 3 dB poorer than that obtained by adults under similar conditions. Additionally, these investigators reported that older children and children with greater receptive vocabularies could tolerate more noise (4 dB) in both microphone conditions than younger children could. Hence, one should not assume that children would obtain the same speech-perception performance in noise that was obtained in this study since only adults served as subjects.

A second limitation of this study is that one cannot assume that the findings in this investigation are comparable to “real-world” performance with these devices. Although attempts were made to simulate a “real-world” environment by utilizing semidiffuse noise, the conditions utilized in this study are still not typical of “real-world” listening environments. Recall that speech-perception testing was conducted in a sound-treated environment, which results in reduced effects from reverberation. Hawkins and Yacullo (1984) evaluated the speech perception in noise ability of individuals using both omnidirectional and directional microphone technology under three different reverberation times (0.3 sec, 0.6 sec, 1.2 sec). As reverberation time increased, performance degraded. It is logical to assume that the performance obtained in this study with the hearing aids would also degrade with increased reverberation. In “real-world” listening environments, speech is not always presented at 0° azimuth nor is noise presented from a static location or from the rear/sides of the listener; therefore, various modifications of the speech and noise presentations may alter speech perception results with the experimental devices (Ricketts, 2000b). Additionally, recall that the FM transmitter was located 7.5 cm from the primary loudspeaker. This distance represents an ideal placement for the FM transmitter, thereby minimizing the effects of noise, reverberation, and distance on the speech signal. Unfortunately, this placement may not occur at all times in a “real-world” environment. At this time, we do not know what the effects of microphone distance would have on speech perception performance in noise. Also, this experiment was only conducted with the use of correlated speech spectrum shaped noise as the noise competition. Hence, no information is available regarding the effects of speech perception had the signals been presented in an uncorrelated fashion (which is probably more typical of their everyday listening environments), and there is no information regarding other types of noise that may be encountered by the individual with hearing impairment in their everyday listening environments. Additionally, FM listening conditions were only evaluated with the FM transmitter in the SuperZoom setting. The speech perception benefit obtained in the study is likely not to be similar when other FM transmitter microphone settings are utilized.

Finally, this investigation was conducted with just one particular model of hearing aid and one model FM system. Currently, a number of other companies manufacture FM system technology that is compatible with hearing aid technology, including Phonic Ear and AVR Communications Ltd. Additionally, the Phonak Microlink is compatible with hearing aids manufactured by 16 other companies. Since several studies have reported a wide degree of electroacoustic variability with the use of various FM components, it should not be assumed that all brands and models of these devices would produce the same speech perception results obtained in this study (Freeman et al, 1980; Bess et al, 1984; Thibodeau and Saucedo, 1991).

SUMMARY

Overall, results of this investigation reported that FM technology significantly improved speech intelligibility over the hearing aid conditions, both in omnidirectional and directional listening conditions. Additionally, speech perception performance is further enhanced by almost 3 dB using two FM receivers in the FM-only mode rather than one FM receiver in the FM-only mode on one ear and a hearing aid alone on the other ear. These data suggest that FM technology will offer significantly better communicative performance in adverse listening situations than any type of hearing aid microphone configuration. Stated otherwise, for maximum speech intelligibility in noise to occur for listeners with SNHL, the hearing health-care professional should consider the utilization of FM technology and counsel their patients how to maximize their use in everyday listening situations.

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