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Speech Recognition Abilities of Adults Using Cochlear Implants with FM Systems

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Abstract

Speech recognition was evaluated for ten adults with normal hearing and eight adults with Nucleus cochlear implants (CIs) at several different signal-to-noise ratios (SNRs) and with three frequency modulated (FM) system arrangements: desktop, body worn, and miniature direct connect. Participants were asked to repeat Hearing in Noise Test (HINT) sentences presented with speech noise in a classroom setting and percent correct word repetition was determined. Performance was evaluated for both normal-hearing and CI participants with the desktop soundfield system. In addition, speech recognition for the CI participants was evaluated using two FM systems electrically coupled to their speech processors. When comparing the desktop sound field and the No-FM condition, only the listeners with normal hearing made significant improvements in speech recognition in noise. When comparing the performance across the three FM conditions for the CI listeners, the two electrically coupled FM systems resulted in significantly greater improvements in speech recognition in noise relative to the desktop soundfield system.

Key Words: Cochlear implants, FM systems, speech recognition

Abbreviations: CI = cochlear implant; ENV = environmental; FM = frequency modulated; HINT = Hearing in Noise Test; SNR = signal-to-noise ratio

Sumario

Se evaluó el reconocimiento del lenguaje en diez adultos con audición normal y en ocho adultos con implantes cocleares (IC) Nucleus, a diferentes tasas de relación señal/ruido (SNR) y con tres tipos de sistemas FM: de escritorio, de uso corporal y de conexión directa en miniatura. Se le pidió a los participantes que repitieran frases del HINT presentadas con ruido de lenguaje en un ambiente de clase, y se determinó el porcentaje correcto de repetición de palabras. Se evaluó el desempeño tanto de los participantes normo-oyentes como de aquellos con CI, usando el sistema de campo sonoro de escritorio. Además, el reconocimiento del lenguaje para los participantes con CI fue evaluado usando dos sistemas FM acoplados eléctricamente a sus procesadores de lenguaje. Cuando se comparó el campo sonoro de escritorio con las condiciones No-FM, sólo aquellos con audición normal lograron mejorías significativas en el reconocimiento del lenguaje en medio de ruido. Cuando se comparó el desempeño en las tres condiciones FM para los sujetos con CI, los dos sistemas FM acoplados eléctricamente aportaron una mejoría significativamente mayor en el reconocimiento del lenguaje en ruido, con relación al sistema de campo sonoro de escritorio.

Palabras Clave: Implantes cocleares, sistema FM, reconocimiento del lenguaje

Abreviaturas: CI = implante coclear; ENV = ambiental; FM = frecuencia modulada; HINT = Prueba de audición en ruido; SNR = tasa señal/ruido

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Increased distance from a speaker, reverberation, and the presence of noise in a listening environment can negatively affect the speech recognition abilities of adults and children with hearing loss (Dubno et al, 1984; Erber, 1971; Finitzo-Hieber and Tillman, 1978; Ross and Giolas, 1971). Although cochlear implantation results in significantly improved speech recognition for adults and children with profound hearing loss (Geier et al, 1999; Svirsky and Meyer, 1999; Waltzman and Cohen, 1999), persons with cochlear implants (CIs) continue to have significant difficulty understanding speech in noisy environments (Battmer et al, 1997; Dorman et al, 1998; Hamzavi et al, 2001; Fetterman and Dominco, 2002).

The Hearing in Noise Test (HINT), created by Nilsson et al (1994), has often been used to determine speech recognition in noise performance of persons with cochlear implants for clinical trials or research purposes (Dorman et al, 1998; Waltzman et al, 1999; Parkinson et al, 2002). Although the original HINT was designed for the presentation of the sentences in an adaptive manner with noise at a fixed intensity, when used to evaluate persons with CIs, the HINT stimuli have been presented at fixed signal-to-noise ratios (SNRs) and were scored by the number of words repeated correctly. The modified HINT procedures were likely used because the original adaptive procedures were too difficult for the adults with CIs. The adaptive HINT requires the listener to repeat the entire sentence, and performance is maintained near a 50% correct level. In contrast, the modified HINT allows the listener to receive credit for any words heard within each sentence, and performance may be greater than 50% depending on the listening condition.

Dorman et al (1998) used the HINT sentences to measure speech recognition in noise for normal-hearing participants listening to speech through a CI simulator and for CI participants at several SNRs (+15, +10, and +5). As expected, average performance worsened progressively from the +15 to the +5 SNR conditions for both groups of listeners, and the CI participants had poorer average scores, by 10% to 20%, than the normal-hearing participants for every condition. One disadvantage to using percent correct speech recognition at fixed presentation levels is the possibility for ceiling effects, which may have occurred in this study for several of the participants.

One solution to reduce the negative effects of noise and reverberation is to use a frequency-modulated system (FM System). As explained in detail by Flexer (1997) and Lewis (1995), the primary benefit of an FM system is that the transmitter microphone is placed three to six inches from the speaker's mouth, which results in an improved SNR. FM systems are commonly used to improve the SNR for children with hearing impairment in the classroom setting. The FM receiver options for people with cochlear implants can be categorized as sound field or electrical coupling. Soundfield FM systems involve the use of a speaker that is wall mounted, ceiling mounted, or placed on a desktop. Electrical coupling options involve connecting the FM receiver to the cochlear implant speech processor with a patch cord or a device that is plugged in directly.

Electrical coupling can be complicated because there are numerous types of processors and FM systems. To facilitate the discussion of these electrical arrangements, CI speech processors can be categorized as body worn or ear level. Additionally, electrically coupled FM systems can be separated into body-worn and miniature direct-connect or cord-connect devices. These options are shown in Figure 1 for Nucleus speech processors (SPrint and ESPrit) and three FM receivers from three different manufacturers (Phonic Ear Easy Listener, AVR Sonovation Logicom CI, and Phonak MicroLink CI).

Use of personal and soundfield FM systems can result in improved speech recognition scores for adults and children with and without hearing loss. Boothroyd and Iglehart (1998) evaluated speech recognition in noise for 13 teenagers with severe-to-profound hearing losses using FM systems and hearing aids. Speech recognition in noise scores (+15 SNR) improved up to 25% for the teenagers who had speech recognition scores of 40% to 60% correct with their hearing aids alone. Hawkins (1984) evaluated word recognition abilities for nine children with hearing loss in +6 and +15 SNRs. Use of the FM systems in the FM + hearing aid condition resulted in an average improvement of 12% and 8% for the +6 and +15 SNR conditions, respectively. Pittman et al (1999) measured speech recognition performance with FM systems for eight children with normal hearing and eleven children with severe hearing losses. The authors reported an average improvement of 23% for the hearing-impaired group and 7% for the normal-hearing

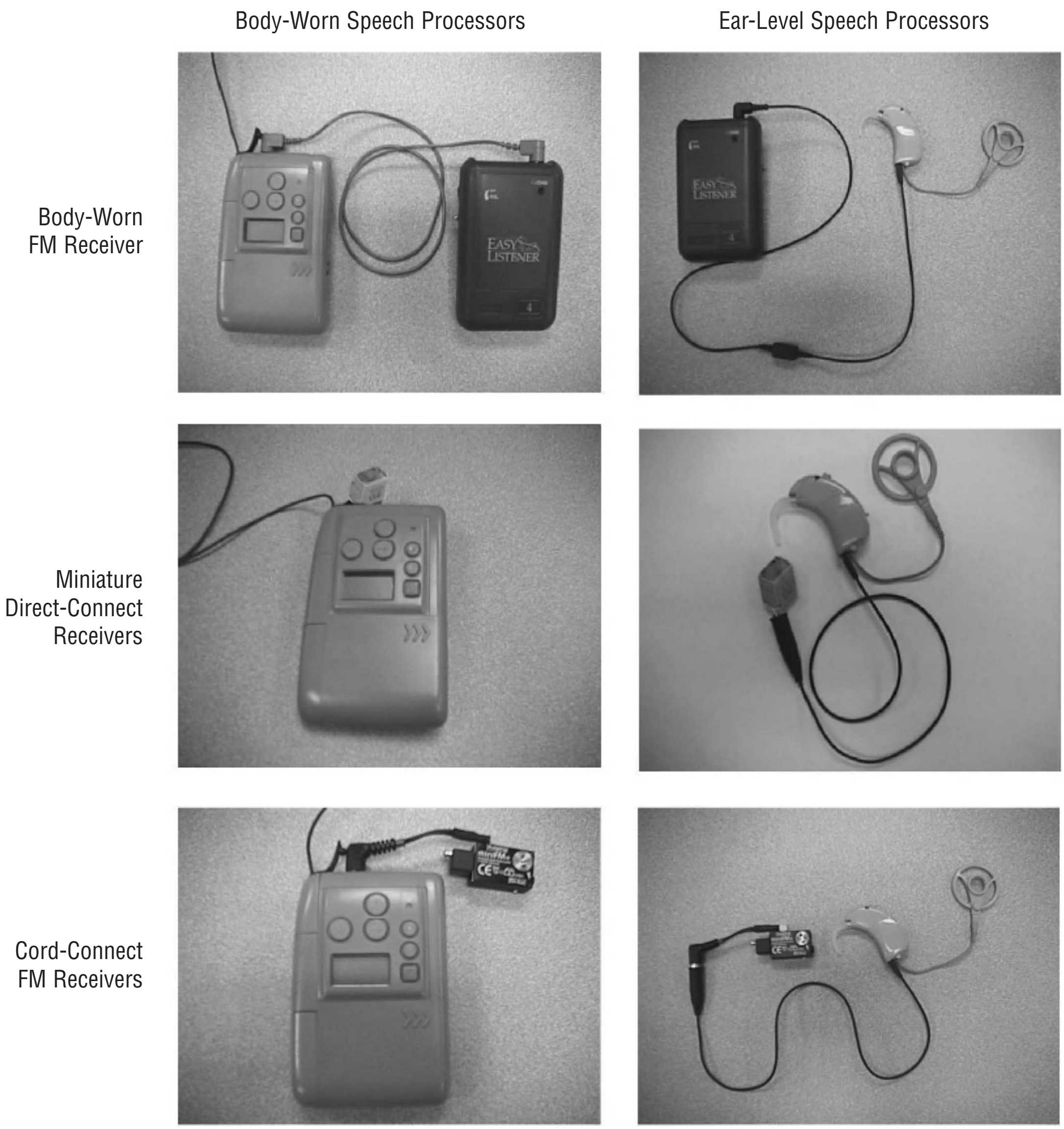

Figure 1. Electrical coupling options for FM receivers and CI speech processors. The left column shows options connected to body-worn CI processors, and the right column shows options for ear-level CI processors. The Phonic Ear Easy Listener is illustrated in the top row; the AVR Sonovation Logicom CI is shown in the middle row; and the MicroLink-CI is shown in the bottom row.

group when using a binaural FM system. In these studies, use of the FM systems often resulted in significant increases in speech audibility and understanding by the participants with hearing losses.

There have been relatively few objective evaluations of adults' and children's performance using FM systems interfaced with CIs. Crandell et al (1998) evaluated speech recognition in noise (+6 SNR) for eight children, ages 7 to 16, and ten adults, ages 20 to 80, with CIs while listening to speech through a wall-mounted soundfield FM system. The four speakers for the soundfield system were mounted in the four corners of the classroom (27' x 15' x 10'), and the participant was seated in the middle of the classroom approximately six feet from the front of the room where the stimuli was presented. There were no significant improvements in speech recognition for either age group while using the soundfield system. They related these negative findings to the mild gain and frequency response of the wall-mounted soundfield system and/or the settings on the cochlear implant speech processors.

Davies et al (2001) used the modified HINT procedure to evaluate open-set speech recognition for 14 children with cochlear implants in a noisy classroom (0 and -3 SNR) while using an electrically coupled FM system. The children's percent correct speech recognition significantly improved while using the FM system in both SNRs, and there was a significant interaction between speech recognition and previous FM system use. The latter finding suggested that children with previous FM system experience received more benefit. This finding may be related to a higher FM receiver volume level selected by the children who were accustomed to the sound from an FM system.

Schafer and Thibodeau (2003) reported results for ten children with CIs using a desktop soundfield system and three electrically coupled systems. Speech recognition in noise was significantly better using the FM systems as compared to using their CI alone. No significant differences were found in performance among the desktop soundfield and electrically coupled systems.

Many students with CIs are currently using FM systems in the classroom despite the inconclusive research to date and the lack of standardized procedures for selection and evaluation of CIs and FM systems. Therefore, it is possible that children may not be using the optimal FM systems coupled to their CIs. Furthermore, FM systems are not widely utilized and recommended as an option for adults with CIs, which may be related to limited and inconclusive research for this population. An audiologist may choose a soundfield FM system rather than an electrically coupled FM system for easy confirmation of the FM signal. The desktop soundfield systems resemble small lunch boxes, which are usually placed about one foot in front of the listener. This arrangement could be cumbersome for young children who may move around to various learning centers in a classroom or adults who may want to use the FM system in several different environments. Additionally, a soundfield system may not provide an optimal SNR for persons with CIs (Crandell et al, 1998) because of the distance of the soundfield speaker to the listener's ear. Although audiologists are not able to objectively measure the output of FM systems electrically coupled to CIs, these FM systems are likely to provide a greater improvement in SNR than soundfield systems because the speech signal is delivered directly to the speech processor.

The purpose of this study was to determine the effects of noise and the benefits of different FM systems for adult users of CIs in a simulated noisy classroom. The following research questions were addressed:

1. At what SNR does average percent correct speech recognition of HINT sentences fall below 50% for adults with normal hearing and CIs?

2. Does the use of a desktop FM system significantly improve percent correct speech recognition in noise scores for the adults with normal hearing and adults with CIs?

3. Is there a significant difference in percent correct speech recognition scores for the adults with CIs when using two types of FM systems, soundfield and electrically coupled?

4. How do the adults with CIs rate the quality of the soundfield and two electrically coupled FM systems compared to the quality of their implants alone?

METHOD

Subjects

Participants included ten adults with normal hearing, ages 23 to 55, and eight adults with CIs, ages 20 to 58. The normal-hearing adults had hearing thresholds below 20 dB HL at octave frequencies from 250 to 4000 Hz. Demographic data for the CI participants are provided in Table 1. All of the CI participants were postlingually deafened with one exception. Five of the participants with CIs used Nucleus (Cochlear, Ltd) body-worn processors, Spectra or Sprint, while three used Nucleus ear-level processors, ESPrit 22 or ESPrit 24. Criteria for participation in the CI group included being implanted for at least six months, speaking English, and demonstrating average speech recognition scores (in quiet) of 50% correct or higher on two lists of the Hearing in Noise Test (Nilsson et al, 1994). The 50% correct criterion was determined for each participant in the first listening condition of the study. One adult with a CI did not meet the 50% criteria and was therefore excluded from the study. Two of the participants with body-worn Spectra speech processors (CI7 and CI8) could not receive the environmental signal from their processors when using the electrically coupled FM systems. Their speech processor microphones were deactivated when an external audio source was plugged into the processor. Results for these two subjects will be reported separately following comparisons across FM systems for the adults with CIs.

Table 1. Demographic Information for Participants with Cochlear Implants

Subject	Gender	Age	Etiology of Hearing Loss	Type of Implant/ Processor	Years of Hearing Loss	Years of Hearing Aid Use	Years of Implant Use	Coding Strategy	% Correct Quiet
1	F	58	Unknown	N 22 / E 22	23	15	6	SPEAK	91%
2	F	40	Mumps	N 24 / E 24	38	30	3	SPEAK	84%
3	F	40	Hereditary	N 24 / E 24	33	19	3	SPEAK	85%
4	F	24	Meningitis	N 24 / Sprint	21	11	1	SPEAK	91%
5	F	53	Unknown	N 24/ Sprint	18	Not consistent	1	ACE	76%
6	M	20	Traumatic brain injury	N 22 / Spectra	4	Not consistent	4	SPEAK	84%
7*	F	40	Meniere's	N 22 / Spectra	8	2	6	SPEAK	98%
8*	F	37	Maternal measles	N 22 / Spectra	37	27	7	SPEAK	57%
Mean	†	39	†	†	23	†	4	†	83%

Note: **N = Nucleus, E = ESPrit**
***Participants who could not receive the environmental signal through their processor when interfaced with an FM system**
† Did not calculate mean

Equipment

The separate channels of HINT sentences and noise were played through Technics Compact Disc Changer (SL-PD887) and routed to a Crown D60 amplifier. The sentences were presented through an Optimus speaker (XTS 36), and the noise was presented through two AIWA speakers. A Quest Technologies Type 1 sound level meter (Model 1800) was used for calibration and measures of speaker frequency response. The frequency response of the three speakers was flat (±4 dB) as measured at octave frequencies. Reverberation times in the classroom were measured with a Communications Company Reverberation Timer (RT-60B).

Stimuli

The stimuli on the HINT CD included 25 equivalent ten-sentence lists on one channel and gated speech noise on the other channel. The sentence lists had a ±4 phoneme deviation from exact phonetic balance and were equated for difficulty and audibility (Nilsson et al, 1994). The speech noise was spectrally matched to the average long-term spectrum of the HINT sentences. The speech-noise track included on the HINT CD was used to calibrate the signal and noise speakers.

Classroom Environment

The testing was performed in a 23 x 19 foot classroom as shown in Figure 2. The noise speakers were 90 degrees azimuth to the participant's head at a distance of 9 feet. The signal speaker was directly in front of the participant at a distance of 16 feet. The CD player and amplifier were located at the front of the room on a cart. When the FM transmitter was used, the boom microphone was placed three inches in front of the signal speaker and was supported by a cart.

The participant was seated near the middle of the classroom. The classroom had two dry erase boards on the front and right walls and 35 desks in rows. The ceiling had acoustic tiles and the floor was carpeted. Unoccupied sound level measurements of the room were 45 dBA. Reverberation times measured at octave frequencies using an impulse sound were 0.98, 0.85, 0.68, 0.86, and 1.02 seconds at 250, 500, 1000, 2000, and 4000 Hz, respectively.

FM Systems

One soundfield and two electrically coupled FM systems were evaluated. The soundfield system, the Phonic Ear Toteable, consisted of a Phonic Ear Easy Listener (PE 300R receiver and PE 300T transmitter) and a 6.5 x 5.0 x 3.0 inch speaker bag (ATO723-First Version). As

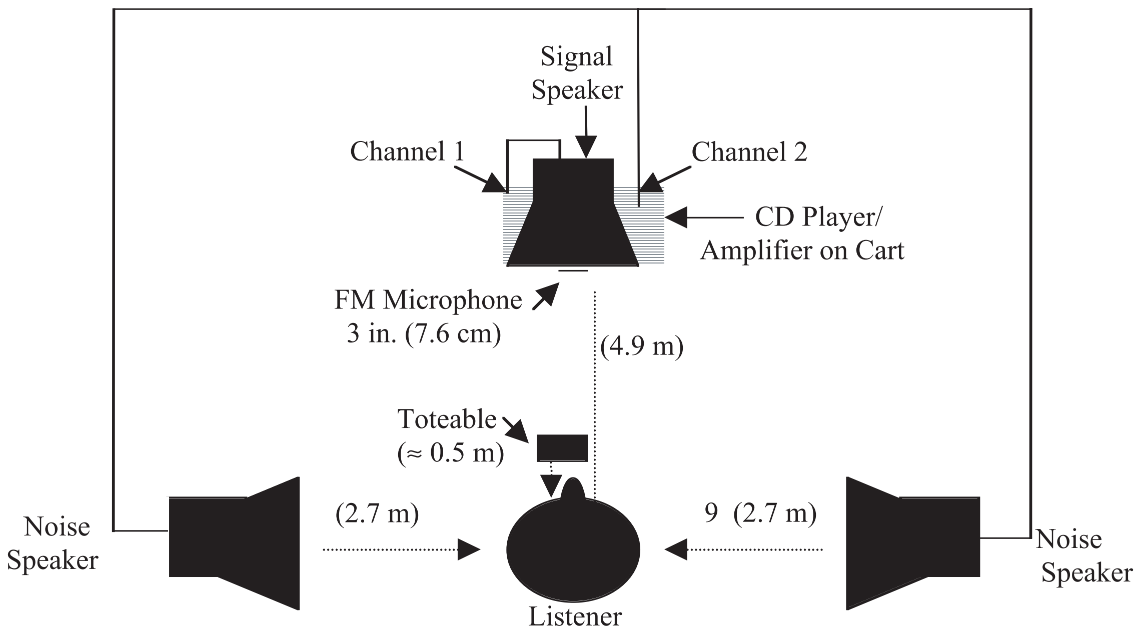

Figure 2. Classroom set-up for testing.

shown in Figure 2, the speaker/receiver bag was placed directly in front of the participant or on the side closest to the participant's speech processor microphone at a distance of approximately 0.5 meters (20 inches) from the processor microphone.

The two electrically coupled FM systems were the Phonic Ear Easy Listener and the AVR Sonovation Logicom CI. The Easy Listener, a 2.5 x 3.5 inch body-worn FM system, consisted of the same PE 300R receiver and PE 300T used in the Toteable. It was connected to the body-worn processors using a Cochlear Cable (FM2) and to ear-level processors using an ESPrit FM Listening Cable (FM 02-E) as shown in the top portion of Figure 1.

The Logicom, a miniature direct-connect system, consisted of a Logicom-CI receiver and a Logicom TX 20 transmitter. The .5 x .75 x .75 inch Logicom was connected to the body-worn processors by plugging it directly into the audio jack. The Cochlear ESPrit Accessory Adaptor Cable (Z77081) and the Audio Cover for the ESPrit (Z77015) were used to connect the Logicom to the ear-level speech processors as shown in the middle portion of Figure 1.

The same Phonic Ear Directional Boom Microphone (AT 0814 M) was attached to each of the transmitters to maintain consistency of microphone style across manufacturers and because AVR Sonovation did not have a boom microphone for the TX20. Listening checks for all the FM systems were performed prior to testing by speaking into the respective transmitter microphone when the receivers were coupled to speakers. The output for the Easy Listener and the Toteable was verified by using the speaker of the Toteable. A listening check of the Logicom was determined by plugging it into a Radio Shack Mini Amplifier-Speaker (Cat. No. 277-1008C).

Procedure

The participants with normal hearing were tested in four randomized listening conditions: (1) No-FM, +5 SNR; (2) No-FM, 0 SNR; (3) No-FM, -5 SNR; and (4) Toteable, -5 SNR. The No-FM conditions were included to determine how adults with normal hearing performed on this modification of the HINT using a fixed presentation level and percent correct scoring rather than the traditional adaptive approach. It was determined through pilot data that a -5 SNR would likely cause speech recognition to fall below 50% correct. This SNR could then be used to determine benefit with the Toteable while avoiding possible ceiling effects.

The participants with CIs were tested in five randomized listening conditions following the first condition: (1) No-FM, quiet; (2) No-FM, +5 SNR; (3) Toteable, +5 SNR; (4) Easy Listener, +5 SNR; and (5) Logicom, +5 SNR.

The No-FM, quiet condition was included to ensure that the participant would meet the 50% criteria for participation in the study and for a comparison to the No-FM, +5 SNR condition to quantify the effect of noise on speech recognition. According to pilot data, difficulty with speech recognition was expected in the No-FM, +5 condition making this an ideal SNR for examining speech recognition with the FM systems while avoiding ceiling effects. Following the listening conditions, the CI group was asked to complete an informal questionnaire regarding sound quality FM system preference. The CI group was paid ten dollars an hour, and testing generally lasted one hour.

The CI speech processors were set at user settings during all the listening conditions. The user setting allowed for audio mixing of the environmental and FM signal when the electrically coupled FM systems were used. It was not possible to control the volume and/or sensitivity settings across individuals because these controls were set during the CI mapping session.

For the No-FM and electrically coupled FM conditions, the HINT sentences were presented at a constant level of 65 dBA as measured at the participant's head. The level of the sentences at the location of the transmitter microphone was approximately 88 dBA. The HINT noise was fixed at 60, 65, or 70 dBA as measured at the participant's head. Because the noise from the two speakers was correlated, performance may have been better than expected in a "real-life" listening situation.

For the Toteable condition, a nominal volume control setting of 7 on the FM receiver was chosen because it was the highest level that could be attained without the occurrence of feedback. This resulted in a sentence presentation level of 72 dBA at the location of the participant's head. Note that different SNRs were used with the normal-hearing (-5 SNR) and CI participants (+5 SNR) for the Toteable condition in order to compare with the respective performance in the No-FM condition. Each participant with a CI determined the comfortable volume settings for the electrically coupled FM receivers while listening to running speech from the examiner, which was presented with the respective transmitter at the front of the room. The FM system settings selected by each participant are shown in Table 2.

Data Analysis

Listeners were asked to repeat each sentence, and an examiner, who was seated in the same room, recorded the responses. Two ten-sentence lists were randomly selected for each condition. Percent correct speech recognition scores were determined by dividing the number of words repeated correctly for the two lists of HINT sentences by the total number of words in the lists. Alternates for linking verbs and articles were accepted as indicated in the HINT manual (e.g., a/the, is/was). An arcsine transformation (Studebaker, 1985) was performed for the speech recognition scores before statistical analysis to account for unequal variances that occur with percent correct scores.

Table 2. Individual Volume or Gain Settings for FM Systems

Subject	Phonic Ear Toteable (Range 1–9)	Phonic Ear Easy Listener (Range 1–9)	AVR Sonovation Logicom CI (Range Red, Blue, Yellow, Green)
1	7	7	Red/Blue
2	7	7	Red/Blue
3	7	7	Red/Blue
4	7	7	Red/Blue
5	7	7	Yellow/Green
6	7	8	Yellow
7	7	9	Yellow/Green
8	7	8	Yellow/Green

Note: Colors for Logicom-CI represent gain settings that provide an increase in gain as the color is changed in the order presented.

RESULTS

Results are presented first for the normal-hearing and CI participants for the quiet, noise, and Toteable conditions followed by comparisons of the FM conditions for the CI participants. All figures represent percent correct scores prior to arcsine transformation.

Speech Recognition in Noise without FM Systems by Participants with CIs and Normal Hearing

The average performance of ten participants with normal hearing and eight participants with CIs in the No-FM conditions is shown in Table 3. For the listeners with normal hearing, a one-way, repeated-measures ANOVA revealed a significant main effect of SNR, $F(2, 18) = 97.56$, $p < .0001$. Post-hoc tests showed a significant difference between the +5 and 0 SNR conditions ([98 vs. 91%], $t[9] = 2.78$, $p = 0.01$ [one-tailed]) and, as expected, between the 0 and -5 SNR conditions ([91 vs. 49%], $t[9] = 13.03$, $p < 0.001$ [one-tailed]). These results suggest that in order to measure improvement in speech recognition in noise, testing should be conducted in a -5 SNR condition.

As shown in Table 3, the average speech recognition score of the CI group when using their implant alone in quiet was 83% correct. The individual scores in quiet, shown in the last column of Table 1, ranged from 57 to 98%. With the addition of noise at a +5 SNR, the average speech recognition score was significantly reduced to 36% correct, $t(7) = 4.13$, $p = 0.002$ (one-tailed). It is noteworthy that the average CI speech recognition score was 36% correct at a positive SNR (+5), while the average normal-hearing speech recognition score was 49% correct with a 10 dB poorer SNR (-5).

Speech Recognition in Noise by Participants with Normal Hearing and CIs When Listening with a Desktop FM System

As shown in Figure 3, speech recognition for the participants with normal hearing improved from 49% in the No-FM condition to 92% correct in the Toteable condition. The CI group did not receive as much benefit from the Toteable and only improved from 36% in the No-FM condition to 45% correct in the Toteable condition. A two-way partially repeated-measures ANOVA revealed a significant main effect of hearing status ($F[1,16] = 14.11$, $p = 0.002$); significant main effect of FM system use ($F[1, 16] = 49.07$, $p < 0.001$); and a significant interaction between hearing status and FM use ($F[1,16] = 18.68$, $p = 0 .001$). Post-hoc comparisons using the Sidak correction (1967) to account for multiple comparisons revealed that the improvement in speech recognition with the Toteable was significant for the normal-hearing group ($t[9] = -8.85$, $p < 0.001$ [one-tailed]) but not for the participants with CIs ($t[7] = 1.32$, $p = 0.114$ [one-tailed]).

Speech Recognition in Noise by Participants with CIs across FM System Conditions

Average speech recognition performance and standard deviations in the three FM conditions are shown in Table 4. Relative to the No-FM, quiet condition, five of the six participants with CIs benefited from using either the Logicom or Easy Listener FM systems with speech recognition scores ranging from 47% to 100%. Only half of the participants

Table 3. Performance in No-FM Conditions

	Condition	Quiet	+5 SNR	0 SNR	-5 SNR
Normal	Mean	DNT	98%	91%	49%
(N = 10)	SD	DNT	3.0	10.0	19.0
	Range	DNT	91%–100%	67%–100%	26%–81%
Implanted	Mean	83%	36%	DNT	DNT
(N = 8)	SD	13.0	27.0	DNT	DNT
	Range	57%–98%	3%–76%	DNT	DNT

Note: Participants with normal hearing were not tested in quiet, and participants with cochlear implants were not tested at 0 and -5 SNRs. DNT = did not test.

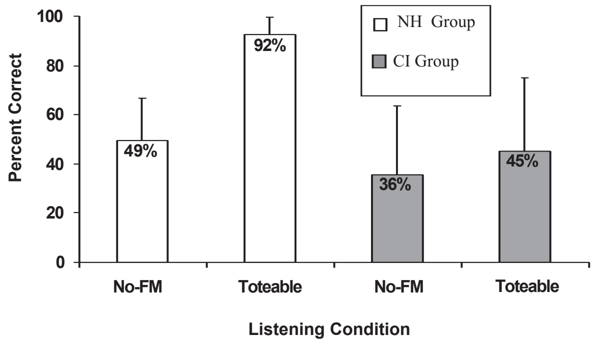

Figure 3. Average percent correct speech recognition in noise and Toteable condition for normal-hearing adults (NH = 10) and adults with cochlear implants (CI = 8). Error bars represent one standard devia-

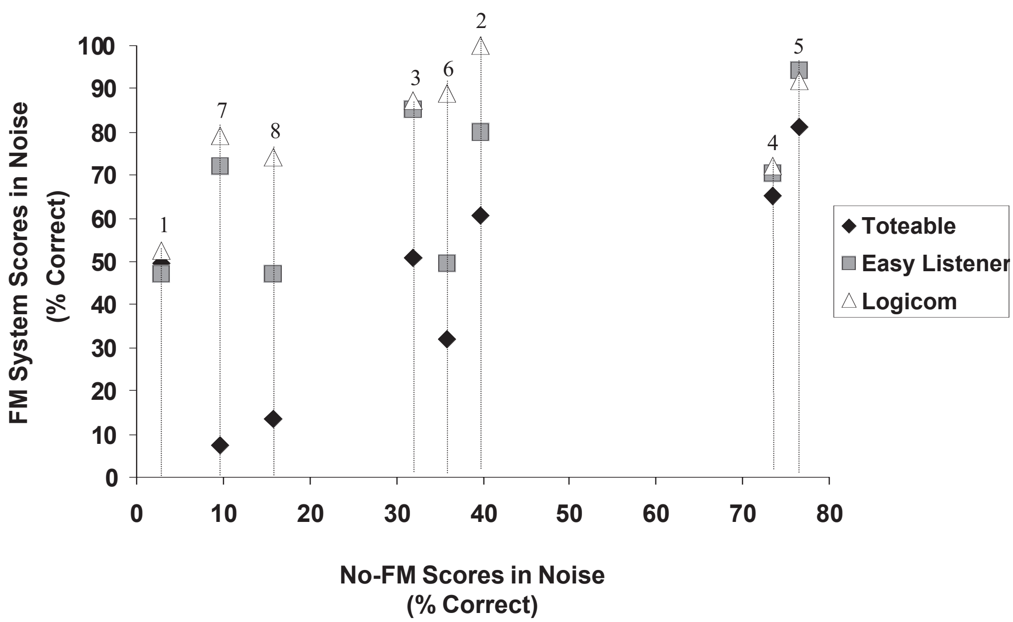

Figure 4. Individual percent correct speech recognition in noise for adults with cochlear implants (N = 8) in each FM system condition as a function of percent correct speech recognition in the No-FM, +5 SNR condition. Participant numbers are indicated above the column of data for that participant, and vertical lines are provided to facilitate comparisons.

showed improvement with the Toteable FM system with scores ranging from 7% to 81%. As shown in Figure 4, the individual speech recognition scores for the FM conditions as a function of their No-FM, noise score revealed a positive relationship. Therefore, a one-way repeated measures analysis of covariance (ANCOVA) was performed on the FM system conditions with the No-FM, noise condition as the covariate. Significant differences were found across the FM system conditions when controlling for performance in the noise condition, $F(2, 17) = 4.50$, $p = 0.03$.

Post-hoc comparisons revealed that the average percent correct scores of 71% with the Easy Listener and 66% with the Logicom were significantly higher than the 45% correct score obtained with the Toteable, $t(5) = -2.95$, $p = 0.016$ and $t(5) = -2.91$, $p = 0.017$ (one-tailed), respectively. However, the performance with the Logicom was not significantly different than that with the Easy Listener, $t(5) = -1.72$, $p = 0.07$ (one-tailed). It is noteworthy that all of the participants with audio mixing (N = 6) received a higher speech recognition score using the Logicom or Easy Listener than with their implant alone in the No-FM, quiet condition or in the Toteable condition. These findings support the use of electrically coupled FM arrangements for persons with CIs.

Table 4. Average Performance of Participants with Cochlear Implants in FM Conditions

	Phonic Ear Toteable (N = 8)	Phonic Ear Easy Listener (N = 6)	AVR Sonovation Logicom CI (N = 6)
Mean	45%	71%	66%
SD	25.6	19.2	34.9
Range	7%–81%	47%–94%	52%–100%

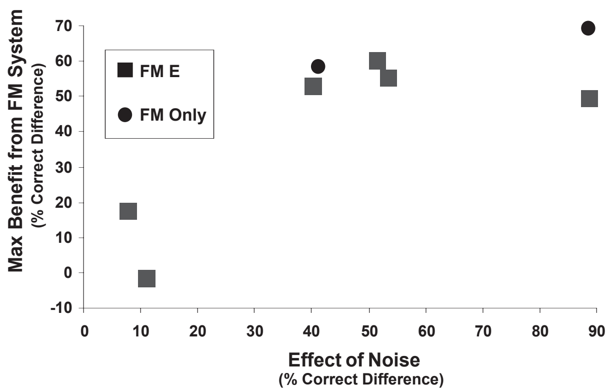

Figure 5. The maximum benefit across 3 FM systems (maximum FM score minus the No-FM, noise score) for each participant relative to the degradation caused by the noise without FM (No-FM, quiet score minus the No-FM, noise score). Black squares are the six participants who were able to receive the environmental signal when interfaced with FM systems (FM E), and the black circles were the two participants who were not able to receive the environmental signal (FM only).

Two participants using Nucleus 22 implants, who did not have the audio mixing function on their speech processors, received the signal primarily from the transmitter microphone while using the electrically coupled FM systems. Although data for these two participants were not statistically analyzed, their performance was similar to the other participants'. The addition of the Toteable did not provide an increase in speech recognition for either participant, but both of the electrically coupled FM systems (Easy Listener and Logicom) provided an increase from performance in the No-FM, +5 SNR condition (63% and 70% for CI7, and 31% and 58% for CI8, respectively). Interestingly, CI8 achieved a higher speech recognition score in the noise condition with the Logicom connected to her CI (74%) than in the quiet condition when using her CI alone (57%).

Predicting Benefit with FM Systems

It can be hypothesized that the participants who are more affected by the presence of noise will benefit most from use of an FM system. To determine the effect of noise, each participant's No-FM, +5 SNR score was subtracted from his or her No-FM, quiet score. FM benefit was determined for each participant by calculating the difference between their No-FM, noise score and the

Table 5. Sound Quality Questionnaire Results from Participants with Cochlear Implants (N = 8)

		Phonic Ear Toteable	Phonic Ear Easy Listener	AVR Sonovation Logicom CI
"Sounds as good as CI"	A	2	4	3
	N	0	1	0
	D	6	3	5
"Understood most sentences"	A	0	5	5
	N	1	1	0
	D	7	2	3
"I liked this device best"	A	1	5	4
	N	0	0	1
	D	7	3	3
"I heard interference"	A	5	1	6
	N	1	0	0
	D	2	7	2

Note: Numbers represent the total number of participants with CIs who agree or strongly agree (A), are neutral (N), or disagree or strongly disagree (D) with the statements above. All eight participants are included in the table.

maximum score received with an FM system. The maximum FM scores for all participants were obtained while using one of the electrically coupled FM systems. As shown in Figure 5, FM benefit was significantly correlated with the noise effect (Pearson's correlation, r = .71, p = 0.05). As might be expected, participants who were more affected by the presence of background noise received the most benefit from an FM system.

Sound Quality Questionnaire Results

The informal sound quality questionnaire given to the CI participants was based on a Likert scale (see Appendix). Because the responses from the participants were for information purposes, statistical analysis was not performed. On the questionnaire, the eight participants could choose "strongly agree," "agree," "neutral," "disagree," or "strongly disagree" for each statement. The first question revealed that six of the eight participants reportedly had a difficult time understanding what people were saying in noisy situations. The remainder of the questionnaire consisted of issues regarding sound quality as compared to their CI speech processor alone, interference from FM systems, ability to understand most sentences when using FM systems, and preference among the FM systems. The number of participants for each category who agreed or strongly agreed (A), were neutral (N), or who disagreed or strongly disagreed (D) with selected statements are presented in Table 5.

When asked if the FM system sounded as good as listening with their CI alone in noise, the participants favored the Easy Listener. When asked if they understood most of the sentences while using the FM systems, they favored the electrically coupled systems (Easy Listener and Logicom). None of the participants rated that they understood most of the sentences with the Toteable. This pattern was also evident in the preference ratings. The Easy Listener was most often rated as the preferred FM system followed by the Logicom and the Toteable. Most of the participants reported hearing interference while using the Toteable, but this interference was not audible to the examiner. It may be that the speech recognition difficulty encountered with the Toteable was interpreted as interference. Only one participant agreed that they heard interference with the Easy Listener in contrast to the six participants who agreed they heard interference with the Logicom.

In summary, the majority of the participants reported that they liked using the Easy Listener and that they understood most of the sentences and heard the least interference while using it. Interestingly, one participant, who was an excellent performer in noise, reported that she liked using her implant alone over the use of any FM system in noise. Further research should be conducted with other body-worn and desktop soundfield FM systems as frequency response characteristics, gain, and benefit will vary among systems from different manufacturers.

DISCUSSION

The results of the No-FM, quiet scores and No-FM, +5 noise condition for the CI participants support previous findings that adults using CIs are significantly affected by the presence of background noise. Six of the eight participants with CIs in this study experienced reductions in speech recognition of 40% or more from the No-FM, quiet to the No-FM, noise condition. Listeners with normal hearing experienced a significant degradation in speech recognition from the No-FM, +5 to the No-FM, -5 SNR condition. As shown in Figure 3, there is large variability in the respective noise conditions with the CI group showing more than the normal-hearing group. The variability in performance suggests that hearing in noise is affected by many issues such as mapping, type of implant, experience, and auditory processing skills.

The normal-hearing group received significantly greater improvement (approximately 30%) in speech recognition when using the Toteable than the adults with CIs. The lack of benefit from the Toteable found with the CI group could be partly due to the small sample size and possibly related to the distance of the Toteable from the participant's processor microphone ($\approx$ 0.5 m). The electrically coupled FM receivers provide a more direct signal to the listener, while the signal from the Toteable may have been affected by the noise and reverberation in the classroom. It is important to consider the possibility that desktop soundfield systems from other manufacturers may provide more gain and could result in greater benefit for adults with CIs.

The electrically coupled FM systems resulted in significantly better speech recognition for users of CIs than for the Toteable.

Although output from the FM systems electrically coupled to the CI speech processors could not be measured, it is likely that they provided greater SNR than the Toteable, as evidenced by their scores. The differences between the study with children (Schafer and Thibodeau, 2003) and the present study with adults might be related to the updated desktop soundfield system used in the study with children (Phonic Ear Toteable, ATO723—version released in 2002). As shown in Figure 5, the adults who had the most difficulty listening in noise received the greatest benefit from the use of the electrically coupled FM systems.

Reports on sound quality are variable among individuals, but most of the participants reported that use of the Easy Listener sounded most like their implant alone, that they understood most of the sentences using it, and that they liked using it best. Only one of the participants agreed that they heard interference with the Easy Listener, while reports of interference on the other two systems varied. Six of the eight participants reported hearing interference with the Logicom, but decreasing the gain reduced some of the initial interference. One of the participants tried an additional TX20 transmitter and Logicom receiver to ensure that the system used for the experiment was functioning properly when interfaced with an implant, but the interference was present even when this second system was used and different transmitting frequencies were utilized. Although the performance using the Logicom was acceptable, the sound quality should be an important consideration for choosing an FM system, especially in children. Given the current results, this device would be an option for adults and children who are able to make judgments of sound quality for fine-tuning adjustments.

Options for persons with CIs that deactivate the head-worn microphone of the speech processor when using the FM system are limited at this time. It is likely that many adults would not feel comfortable with a reduced ability to hear environmental sounds, and this would not be appropriate for many children with CIs who are mainstreamed into regular classroom settings. Possible solutions for these individuals include FM systems with an environmental microphone built into the receiver or custom audio mixing adaptors and external environmental microphones. Further research is needed to determine the viability of these options for adults and children with CIs. A more plausible solution, perhaps, at least for users of Nucleus 22 SPectra speech processors, is to purchase a processor upgrade that allows for an environmental signal when using an FM system.

Although testing for this experiment was performed at user settings, it is important to note that most persons using CIs have some control over the FM and environmental signal on their speech processor. Audio mixing refers to controlling the level from the FM system microphone versus the level of the environmental signal by the sensitivity control on most CI processors. The higher sensitivity levels increase the input from the CI processor microphone above the input from the FM microphone. Sensitivity levels were not addressed in this experiment because the controls were not accessible for all participants. Some ear-level processors allow for control of either the volume or the sensitivity, but not both at the same time. The presence of the environmental signal for most of the participants during the No-FM and FM conditions likely had an affect on their performance. Changes to the sensitivity could allow for an FM-only signal where limited environmental signals are heard.

Hearing aid researchers have shown significant electroacoustic and behavioral advantages of 10 to 15 dB, for the FM-only signal over the FM plus the environmental (FM+ENV) signal (Hawkins, 1984; Fabry, 1994), but there are practical limitations to this option. Although these studies showed reduced performance in the FM+ENV condition relative to the FM-only condition, it is likely to be important to the CI user to hear other acoustic signals that may include questions from other coworkers, emergency announcements, and his or her own voice.

Audiologists working with children and adults with CIs should consider the importance of access to sensitivity settings when programming functions of speech processor controls. Access to these controls will allow the user to determine their own optimal settings when using an FM system. It can be hypothesized that persons with poorer speech recognition in noise will perform the best with FM systems when input from environmental signals are limited or eliminated. Further studies will be necessary to determine the effects of sensitivity volume on performance with different brands and models of FM systems.

CONCLUSIONS

The results of this study show the deleterious effects of noise on the speech recognition abilities of persons using CIs. Electrically coupled FM systems are an effective option for improving speech recognition in noise in persons with CIs. It can be hypothesized that children with CIs would show similar difficulties hearing speech in the presence of noise; therefore, children need to be given the same opportunity for an improved SNR as most children with hearing loss receive in classrooms. Electrically coupled FM systems were significantly more beneficial in noise than the desktop soundfield system used in this study. It is vital that future research on CIs and FM systems should include children, other types of implants, and different models and brands of FM systems. Additionally, clinical guidelines for fitting, evaluating, and monitoring FM systems on adults and children with CIs need to be established.

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APPENDIX

Sound Quality Questionnaire

For each of the following statements, please indicate the extent of your agreement by placing an X in the appropriate column.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. I have a difficult time understanding what people are saying in noisy listening situations (i.e., parties, restaurants).					
2. The sound quality of the soundfield FM system was as good as listening with my cochlear implant alone.					
3. I heard interference with the soundfield FM system. (Please circle what kind of interference you heard: hissing, crackling, buzzing, other.)					
4. The sound quality of the body-worn FM system was as good as listening with my cochlear implant alone.					
5. I heard interference with the body-worn FM system. (Please circle what kind of interference you heard: hissing, crackling, buzzing, other.)					
6. The sound quality of the Logicom FM system was as good as listening with my cochlear implant alone.					
7. I heard interference with the Logicom FM system. (Please circle what kind of interference you heard: hissing, crackling, buzzing, other.)					
8. I understood most of the sentences when using the FM plus the environmental setting.					
9. I understood most of the sentences using the soundfield FM system.					
10. I understood most of the sentences using the body-worn FM system.					
11. I understood most of the sentences using the Logicom FM system.					
12. I liked the soundfield FM system the best.					
13. I liked the body-worn FM system the best.					
14. I liked the Logicom FM system the best.					