Speech-Recognition Performance of Children Using Cochlear Implants and FM systems

Erin C. Schafer
Linda M. Thibodeau
Advanced Hearing Research Center
Callier Center for Communication Disorders
University of Texas at Dallas

Sentence recognition was evaluated for ten children with cochlear implants (CIs) in quiet, noise, and in four FM system arrangements: desktop soundfield, body-worn, miniature direct-connect, and miniature cord-connect. The CI speech processors remained at user settings during testing, and the children adjusted the volume controls on the FM receivers to comfortable levels while listening to running speech. No significant differences were found in thresholds for speech-weighted noise obtained across the four FM system arrangements, which suggested that the children were able to adjust the volume settings on the FM system receivers to relatively equal perceptual levels. When listening with their implant alone, the children's sentence recognition was significantly affected by the presence of the background noise. The use of all four FM system arrangements resulted in significantly improved performance in noise relative to the implant-alone condition. There were no significant differences in average speech recognition scores across the FM systems.

Introduction

Persons with hearing loss and hearing aids experience speech-recognition difficulties in the presence of noise and reverberation (Dubno, Dirks, & Morgan, 1984; Erber, 1971; Finitzo-Hieber & Tillman, 1978; Ross & Giolas, 1971). Adults with cochlear implants (CIs) also experience reductions in speech recognition in noise and may experience up to a 60% reduction in adverse listening conditions as compared to performance in quiet (Battmer, Reid, & Lenarz, 1997; Hamzavi, Franz, Baumgartner, & Gstoettner,, 2000; Fetterman & Domico, 2002). Classrooms are difficult learning and listening environments for children with hearing loss because of the presence of noise, reverberation, and distance from the teacher. One recommendation for reducing these negative effects is use of an FM system in the classroom. FM systems improve the signal-to-noise ratio (SNR) to a child because of the relative distance of the transmitter microphone from the speaker's mouth at three to six inches. This close proximity results in an increase in the signal level arriving at the FM microphone compared to a hearing aid or CI microphone at a typical distance of three feet (Flexer, 1997; Lewis, 1995).

These FM systems provide significant benefit for children with CIs in educational settings, but there are significant challenges in both the physical connections to the various CI devices and verification measures. Connecting FM systems to CI speech processors may be difficult because processors have different impedances, and therefore require different cords for interfacing FM systems. In general, FM system options for persons with CIs may involve soundfield or electrical coupling. Soundfield coupling may include wall-mounted, ceiling-mounted, or desktop systems, while electrical coupling includes body-worn and miniature direct-connect or cord-connect devices. Body-worn devices are the size of a typical pager (3"x4") and connect to CI speech processors with cords and adaptors. Miniature direct-connect and cord-connect devices are smaller receivers (1"x1") and are plugged directly into body-worn speech processors or are connected with a cord to ear-level speech processors.

Several researchers have evaluated speech-recognition performance of persons with CIs with different FM systems arrangements, but results have been variable in determining benefit (Aaron, Sonneveldt, Arcaroli, & Holstad, 2003; Crandell, Holmes, Flexer, & Payne, 1998; Davies, Yellon, & Purdy, 2001; Hanin & Adams, 1996; Ludena & Thibodeau, 1993; Schafer & Thibodeau, in press). Two studies involved evaluation of speech recognition by persons with cochlear implants when listening via wall-mounted soundfield FM systems (Crandell et al., 1998, Hanin & Adams, 1996). Hanin and Adams (1996) evaluated percent correct speech-recognition performance in noise (+6 SNR) in a simulated classroom for six children with CIs, ages six to ten years. The children's speech recognition was tested with and without the use of a wall-mounted soundfield FM system. Average speech-recognition performance improved by 12% while using the soundfield FM system in noise as compared to the implant-alone condition. Hanin and Adams recommend using soundfield systems for persons with CIs because of reported electrical interference experienced when using an electrically-coupled FM system. Crandell et al. (1998) measured speech recognition in quiet and noise (+6 SNR) for eight school-aged children and ten adults with CIs while using a wall-mounted classroom soundfield system. The authors hypothesize that the reverberation in the classroom, frequency response of the FM system, and/or participant speech processor settings may have contributed to the lack of significant improvements in speech recognition in the quiet or the noise condition while using the soundfield FM system.

Evaluation of speech recognition for persons with CIs while using electrically-coupled FM systems was addressed in four studies (Aaron et al., 2003; Davies et al., 2001; Ludena and Thibodeau, 1993; Schafer and Thibodeau, in press). Ludena and Thibodeau (1993) evaluated percent correct sentence recognition in noise (+10 SNR) for two young adults with CIs while using four body-worn FM systems (Telex, Comtek®, and two types of Phonic Ear®). Use of all of the systems resulted in improvements in speech recognition ranging from 34% to 52% as compared to performance with their CI alone.

Davies et al. (2001) used the Hearing in Noise Test (HINT) sentences (Nilsson, Soli, & Sullivan, 1994) to measure sentence recognition in noise (0 and –3 SNR) for 14 children using a Nucleus® cochlear implant and a body-worn FM system (Phonic Ear Solaris) in a typical classroom setting (area 53.28m^2, RT=.20 sec.). Speech recognition in noise declined from the quiet condition by 20% and 28% for the 0 and –3 SNRs, respectively. Percent correct performance significantly improved by up to 15% in both SNRs while using the FM system, and the children with previous FM experience received even more benefit on average (4%). The latter finding suggests that the children with previous experience might have selected higher FM volume levels or were more accustomed to functioning in a better SNR.

Aaron et al. (2003) evaluated percent correct sentence recognition with the Hearing in Noise Test for Children (HINT-C) (Nilsson, Soli, & Gelnett, 1996) and multi-talker babble for 12 children with Nucleus 24 CIs and SPrint processors. Children were tested in quiet and noise with their implant alone and in noise with a Phonak MicroLink CI. The noise significantly degraded speech recognition and the FM system significantly improved performance for 11 of the 12 participants when their speech processors remained at user settings.

Schafer and Thibodeau (in press) determined speech recognition in noise (+5 SNR) for eight adults with Nucleus CIs using three FM system arrangements: desktop soundfield (Phonic Ear Toteable), body-worn (Phonic Ear Easy Listener), and direct-connect (AVR Logicom CI). Although use of the desktop soundfield condition resulted in an average speech-recognition increase of 6% from the no-FM noise condition, this improvement was not significant compared to the 22% and 28% increase in speech recognition obtained with the Easy Listener and Logicom, respectively.

In summary, persons with CIs can benefit from using FM systems when listening in noise. Four studies showed benefit with electrically-coupled receivers, but there are some concerns regarding electrical interference and a child's ability to provide reliable subjective feedback (Hanin & Adams, 1996). In addition, technological developments have allowed for the miniaturization of FM receivers for persons with CIs (miniature cord-connect and direct-connect), but there is little evidence regarding the benefit of these receivers for children. Furthermore, when working with children with CIs and FM systems, it is difficult to verify the relationship between the level of the FM signal and the environmental signal, often referred to as "audio mixing". The purpose of this study was to determine the effects of noise and the potential benefits of the use of four FM system arrangements on the speech-recognition abilities of children with CIs. Ten children were asked to participate in four consecutive phases of the study in which the following research questions were addressed:

1. Audibility Matching: Can children with CIs select equivalent volume settings across FM receivers?
2. Volume Verification: Can equivalency of volume settings be verified by measuring a threshold for speech-weighted noise in a sound booth?
3. Speech Recognition with the CI Alone: Do sentence recognition scores significantly decline in the presence of background noise when children listen with their CI alone?
4. Speech Recognition with the CI and FM Systems: Do sentence recognition scores significantly differ for children with CIs across four FM system arrangements: desktop soundfield, body-worn, miniature direct-connect, and miniature cord-connect? Which of the four FM arrangements did the children with CIs prefer?

General Methods

Participants

Participation was limited to children who were English speaking, had receptive vocabulary levels equivalent to six years of age, and had implant use for at least six months. In addition, the children with implants had to achieve a speech-recognition score 50% or higher with their implant alone on one list from the Hearing in Noise Test for Children (HINT-C) in quiet (Nilsson et al., 1996). Although a total of 16 children were screened for participation, six were excluded because of inadequate vocabulary or device failure.

Demographic data are provided in Table 1 for the ten children, ages 6 to 12 years, with profound hearing impairment and CIs. All of the children had congenital hearing loss and were therefore prelingually deafened before the age of one. Six of the ten children had Nucleus 22, and three of the children had Nucleus 24 cochlear implants. Six used ESPrit 22 ear-level speech processors and three children used Nucleus ESPrit 3G ear-level speech processors. The remaining child had a MED EL C40+ implant with Tempo ear-level speech processor. The speech processor coding strategies and volume and sensitivity levels are also provided in Table 1.

The children's speech processors remained at user settings for all the speech-recognition tasks. All of the Nucleus behind-the-ear speech processors allow for programming of either volume or sensitivity. When set for sensitivity, the volume setting defaults to a fixed level, which is 100% of the electrical dynamic range. When set for volume, the sensitivity setting defaults to a fixed level, which varies across processors depending on the CI programming. The user can control both the sensitivity and volume settings on the Tempo speech processor. All of the speech processors allowed for audio mixing, i.e., the processor microphone remained active when the FM system was connected.

The children's duration of deafness ranged from 2;0 to 6;0 years with an average duration of 3;6 years. The age at speech processor hook-up ranged from 2;0 to 6;0 years with an average age of 3;5 years. Duration of implant use at the time of the study ranged from 3;0 to 8;8 years with an average use of 5;4 years. Seven of the children were receiving speech-language therapy, and all but one of the children had previously used an FM system at school.

The HINT-C has a vocabulary level equivalent to that of an average six-year-old child. In order to determine that each child had adequate vocabulary levels for use of the HINT-C, the children's receptive vocabulary levels were screened using the Peabody Picture Vocabulary Test- III

Table 1. Demographic Information and Receptive Vocabulary Scores for Children with Cochlear Implants.

ID	Age	DOD	Implant/Cod.	Proc.	Age CI	Yrs. CI	Sen.	Vol.	SLT	Etiology	FM	PPVT
1	8;0	2;0	N22/ SPeak	ESPrit 22	2;0	6;0	Default	2.5	Dis.	Unknown	+	6;3
2	9;3	2;3	N22/ SPeak	ESPrit 22	2;3	7;0	Default	Default	y	CMV	+	6;5
3	11;8	3;0	N22/ SPeak	ESPrit 22	3;0	8;8	4	Default	Dis.	Genetic	+	13;4
4	7;8	3;2	N22/ SPeak	ESPrit 22	3;2	4;6	Default	3	y	Unknown	+	6;7
5	12;0	4;0	N22/ SPeak	ESPrit 22	4;0	8;0	Default	3	y	Unknown	+	8;9
6	8;5	2;0	N22/ SPeak	ESPrit 22	2;7	5;7	Default	Default	n	Meningitis	+	7;2
7	9;7	6;0	N24/ Ace	3G	6;0	3;7	Default	6	y	Unknown	-	10;3
8	6;8	2;0	N24/ SPeak	3G	2;0	4;1	Default	6	y	Unknown	+	7;7
9	7;8	4;7	N24/ Ace	3G	4;7	3;2	Default	Default	y	Unknown	+	6;0
10	8;0	5;0	C40+/ CIS+	Tempo	5;0	3;0	5:00	Y	y	CMV	+	6;3

Note. ID=participant number; DOD=duration of deafness; Cod.=Coding Strategy; Proc.=processor; Age CI=age received cochlear implant; Yrs. CI=Years of cochlear implant use; Sen.=processor sensitivity; Vol.=processor volume; PPVT=*Peabody Picture Vocabulary Test*; SLT=currently speech-language therapy; FM=previous FM use; Default=setting internally programmed in participant's map; CMV=cytomegalovirus; Dis.=dismissed; y=yes; n=no; +=previous FM use; - = no previous FM use.

(PPVT) (Dunn & Dunn, 1997). As shown in Table 1, the children's receptive vocabulary levels ranged from 6;0 to 13;4 years. The average receptive vocabulary age was 7;9 years with a standard deviation of 2;3 years. As determined by PPVT normative data, seven of the ten children showed deficits in receptive vocabulary that were greater than one standard deviation away from the mean for a child their chronological age. The deficits in receptive vocabulary for these seven children ranged from 1;1 to 3;1 years with an average deficit of 2;0 years. The remaining three children (#3, #7, and #8) had vocabulary age levels ranging from 7;7 to 13;4 years and scored an average of nine months above their chronological age.

Equipment

A Technics Compact Disk (CD) Changer (SL-PD887) and a Crown D60 amplifier were used to play the HINT-C stimuli from a CD. An Optimus speaker (XTS 36) was used to present the sentences, and two AIWA speakers were used to present the noise during speech-recognition testing. All speakers had a single cone and had a flat frequency response with ±4 dB deviation. A Quest Technologies Type 1 sound level meter (Model 1800) was used for calibration and noise measurements, and a Communications Company Reverberation Timer (RT-60B) was used to measure reverberation. For verification of volume levels and measurement of behavioral thresholds with the FM system, a Grason Stadler Clinical Audiometer and Grason Stadler 8-ohm speakers were used.

Stimuli

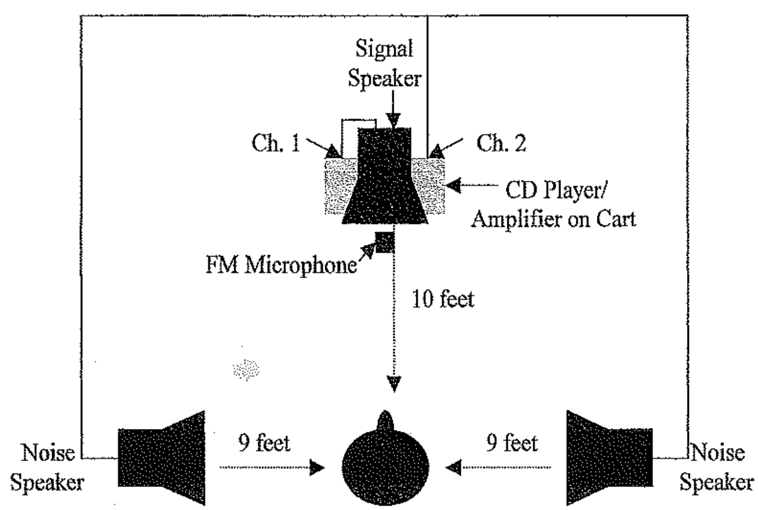
Speech recognition was evaluated using the HINT-C, which includes 13 lists of 10 sentences each (Nilsson et al., 1996). Each list of 10 sentences had approximately 50 words. The HINT-C sentences were phonetically balanced, and the lists of sentences were equated for intelligibility and difficulty. The speech noise from the HINT CD was spectrally matched to the long-term spectrum of the HINT sentences and was gated with each sentence presentation. Calibration for the HINT-C sentences and noise was performed using the speech-weighted noise provided on the CD. The sentences were presented at a constant level of 65 dBA as measured at the participant's head and at approximately 80 dBA at the location of the transmitter microphone. During sentence recognition testing, the speech noise was fixed at either 60 or 65 dBA depending on performance.

For matching audibility across FM systems, the Davy Crockett Story from the VA Medical Center CD was presented at 65 dBA (Wilson, 1989, tracks 27-35). The speech-weighted noise from the audiometer was used during the volume verification phase for measurement of thresholds.

Testing environments

All but one phase of the study was performed in a 23 x 19 foot classroom as described by Schafer and Thibodeau (in press) and shown in Figure 1. The classroom had two dry-erase boards mounted on the front and right walls, 35 desks in rows, carpeted flooring, and acoustic-tiled ceiling. Reverberation times in the classroom, measured with 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. The sound level in the unoccupied classroom was 45 dBA. The volume verification phase of the study was performed in a double-walled sound booth and the quiet space adjacent to the booth with an unoccupied noise level of 39.2 dBA as measured at the location of the participant's head. During the volume verification phase, the focus of the study is relative comparisons across FM systems. Therefore, the actual noise levels in the environment are not significant factors because they remained constant across the conditions to be compared.

Figure 1. Equipment set-up for the classroom



Note. Classroom was the same set up as Schafer and Thibodeau (in press) and diagram was adapted from a figure in this manuscript, Ch.= channel.

FM systems

Four types of FM system arrangements were evaluated: desktop soundfield, body-worn, miniature direct-connect, and a miniature cord-connect. The desktop soundfield was a Phonic Ear Toteable, which consisted of a PE 300R receiver, PE 300T transmitter, and a speaker in a 6.5 x 5 x 3 inch bag (ATO723- version released in 2002). Cords, accessories, and adaptors for connecting the electrically-coupled FM systems to the children's speech processors are provided in Table 2. The body-worn system was the Phonic Ear Easy Listener, which included the same 2.5 x 3.5 inch PE 300R and PE 300T as the Toteable. The miniature direct-connect device was the AVR Sonovation Logicom-CI receiver, a 0.5 x 0.75 x 0.75 inch cube. The Phonak Campus S transmitter was used with the Logicom receiver. The cord-connect device was a Phonak MicroLink CI+, a 1.5 x 0.5 x 0.5 inch rectangular device, which was used with the Phonak Campus S transmitter. Phonak recommends specific MicroLink cords for each type of speech processor (Table 2) to account for impedance differences. Omnidirectional lapel microphones from each respective manufacturer were used with the FM transmitters.

Listening checks were performed on all FM systems prior to testing. The listening checks for the Toteable and Easy Listener were performed by speaking into the transmitter microphone when the receiver was coupled to Toteable speaker. The listening checks for the Logicom and MicroLink were performed by plugging them into the input jack of a Radio Shack Mini Amplifier Speaker (Cat. No. 277-1008C) and speaking through the transmitter microphone.

Table 2. Cords and Adaptors for Connecting Electrically-Coupled FM Systems to Ear Level Speech Processors

Speech Processor	FM System 1: Easy Listener -- Phonic Ear 300T; Phonic Ear 300R	FM System 2: Logicom -- Phonak Campus S; AVR Sonovation Logicom CI	FM System 3: MicroLink -- Phonak Campus S; Phonak MicroLink CI
ESPrit 22	Cochlear FM2-E FM Cable (Z77089)	Cochlear Accessory Adaptor Cable (Z77081), Audio Cover (Z77015)	Cochlear Accessory Adaptor Cable (Z77081); Audio Cover (Z77015); Phonak MicroLink Cord – Blue (MLCI-0010)
ESPrit 3G	Cochlear FM2-E FM Cable (Z77089); 3G Accessory Adaptor (Z60121)	Cochlear Accessory Adaptor Cable (Z77081); 3G Accessory Adaptor (Z60121)	Cochlear Accessory Adaptor Cable (Z77081); 3G Accessory Adaptor (Z60121); Phonak MicroLink Cord – Blue (MLCI-0010)
Tempo	Custom Cable: Plug Configuration of Tempo Adaptor Plug to 3.5 mm Mono Plug	Custom Cable: Plug Configuration of Tempo Adaptor Plug to 3.5 mm Input Socket	Phonak MicroLink Cord –Red (MLCI-0014)

Note. Custom cables were ordered from Bob Mendoza of Rohnert Park, CA.

Phase 1: Audibility Matching

Rationale. The purpose of the audibility-matching phase was to determine the children's ability to adjust FM receiver volume controls to comfortable loudness levels while listening to running speech.

Method. Audibility matching was done in the classroom with the participant seated near the front of the room (Figure 1). The Davy Crockett Story on CD was presented through the signal speaker at a 0-degree azimuth at a distance of ten feet. The CD player and amplifier were placed on a cart in the front of the room and were attached to the signal speaker. The FM systems were connected to the child's speech processor (electrically coupled) or placed on the student's desk (Toteable). Speech processors remained at user settings and all processors allowed for audio mixing of the input from the processor and FM system microphones. The FM transmitters were placed approximately six inches from the signal speaker at the front of the room, which resulted in a signal level at the transmitter microphone of approximately 80 dBA.

Comfortable volume levels of the FM receivers were determined by using a loudness chart from Cochlear Corporation. This chart has faces, numbers, words, and colored dots to represent levels of loudness ranging from a whisper to a very loud sound. The child was asked to point to the region of the chart related to their level of comfort while the Davy Crockett story was presented to the transmitter microphone. The receiver volume was adjusted up from zero, or the lowest setting, in an ascending procedure to find the level on the chart representing "just right." The ascending procedure was repeated twice for each child and the average of the two measurements was recorded. The order of the FM systems was randomized for each child.

Results. All of the children seemed to understand how to use the loudness-scaling chart, and many of the children reported that they had used similar charts in CI programming sessions. The range of volume levels available on the FM receivers as well as children's selected volume levels for the receivers are shown in Table 3. The nominal volume control on the Toteable and the Easy Listener ranged from 1 to 9 while gain settings on the Logicom were represented with colored dots on a trim pot with the lowest to highest gain settings progressing from red, to blue, to yellow, and to green. The range of the volume control on the MicroLink was 1 to 4. The children's selected volume levels for the Toteable and the Easy Listener were similar and ranged from 4 to 7. The average setting on the Toteable was 5.6 (SD=0.9), and the average setting on the Easy Listener was 5.4 (SD=1.2). Gain settings on the Logicom ranged from red to green with an average of half way between blue and yellow (SD=0.9). Volume settings on the MicroLink ranged from 1.5 to 2.0 with an average of 1.8 (SD=0.3). Although demographic information suggests that all but one child had used an FM system before, the type of FM system used was not specified.

Table 3. Selected Volume/Gain Settings on the FM receivers

ID	Device	Toteable (1-9)	Easy Listener (1-9)	Logicom (R/B/Y/G)	MicroLink (1-4)
1	Esprit 22	4	5	Red	2
2	Esprit 22	7	6	Yellow/Green	2
3	Esprit 22	5	5.5	Blue	1.5
4	Esprit 22	5.5	5	Blue	1.5
5	Esprit 22	5	4	Red/Blue	2
6	Esprit 22	6	4	Blue/Yellow	2
7	3G	6	7	Blue/Yellow	2
8	3G	5	6	Red/Blue	1.5
9	3G	5.5	4	Blue/Yellow	1.5
10	Tempo	7	7	Yellow/Green	2

Note. ID=participant number; R= red; B= blue; Y=yellow; G= green.

Phase 2: Volume Verification

Rationale. The purpose of the volume verification phase was to determine that the child was receiving input from the FM microphone and speech processor microphone simultaneously when the FM systems were in use. In addition, this procedure was done to verify that the children could reliably set the volume controls on the FM receivers to similar perceptual levels. Therefore, speech-recognition testing would not be affected by differences in FM receiver settings. The child's ability to select similar perceptual volume levels on the FM receivers was evaluated by comparing thresholds for speech-weighted noise across the FM systems for input to the FM microphone and input to the processor microphone separately.

Method. This procedure was done in the sound booth and the space adjacent to the sound booth. Two thresholds were obtained for each of the four FM systems. Thresholds were measured for each participant for (1) the input to the FM microphone first (FM thresholds) and then for (2) the input to the environmental microphone of the speech processor (processor thresholds). The order of the FM systems (Toteable, Easy Listener, Logicom, and MicroLink) was randomized for each microphone condition.

The first set of thresholds with input to the FM transmitter microphone was obtained by seating the participant in the space outside the sound booth facing the opposite direction of the examiner who was seated at the audiometer. For these thresholds, the electrically-coupled FM receivers were connected to the child's speech processor, and the Toteable was placed in front of the participant on a desk. The volume/gain controls on the FM receivers were set by the examiner to the levels selected in the audibility-matching phase. The transmitter microphone was attached to a stand placed in the calibrated location in the sound booth (3 feet from the speaker). A threshold for speech-weighted noise was obtained using the audiometer and an up-down bracketing procedure in two-dB steps. The participant was asked to either raise his or her hand or say "yes" when hearing the speech noise to determine the thresholds in response to input to the transmitter microphone.

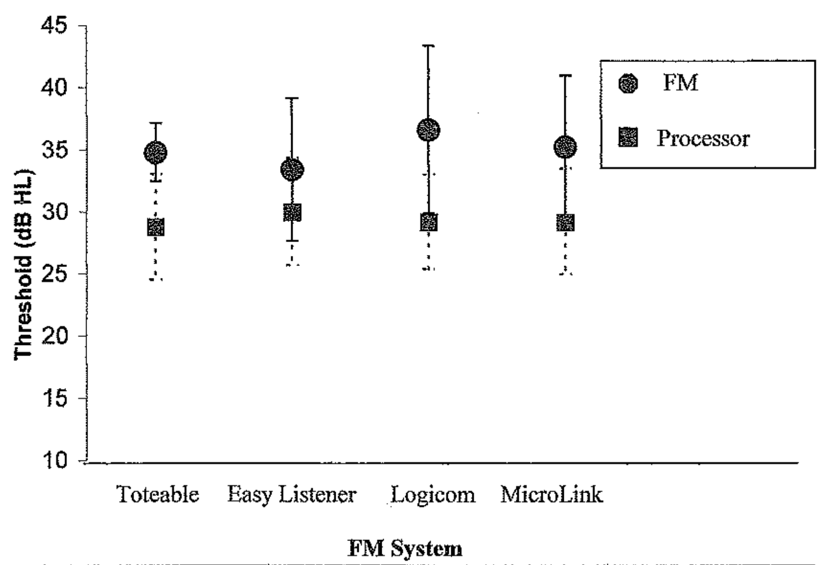
The second set of thresholds was obtained in response to input to the environmental microphone on the speech processor while the FM receivers were still connected and active. Because the Toteable did not require a direct electrical connection, the processor threshold for this condition was measured with the CI alone. During this procedure, participants were seated in the sound booth at the calibrated location (three feet from the speaker). The transmitter microphone was receiving no input and was placed outside the booth in a quiet chamber. The same procedure was used to obtain the thresholds in response to speech-weighted noise input to the environmental microphone of the speech processor.

Results. Eight thresholds for speech-weighted noise were collected from each participant. Average threshold responses with standard deviations are shown in Figure 2. The measurement of separate thresholds for the input to the transmitter microphone and the processor microphone allowed for the verification of volume levels for all of the participants.

Average FM thresholds while using the Toteable, Easy Listener, Logicom, and MicroLink were 35, 33, 37, and 35 dB HL, respectively. Average thresholds for input to the processor while the Toteable, Easy Listener, Logicom, and MicroLink receivers were still active, were 29, 30, 29, and 29 dB HL, respectively. The differences in FM and Processor thresholds are expected based on the differences in microphone sensitivity as well as placement in the soundfield. In the audibility-matching procedure the children adjusted the FM systems to have relatively equal perceptual levels when the FM microphone was placed six inches from the speaker receiving an input of approximately 80 dBA. Meanwhile, speech processors were at approximately one meter from the speaker receiving an input of approximately 65 dBA. In the volume verification procedure, the FM microphone was placed at the same distance as the child's speech processor microphone. Therefore, the FM microphone was not given the typical advantage of a close proximity to the speaker. The FM thresholds measured in this way are expected to be higher (poorer) than the processor thresholds.

Two repeated measures ANOVAs were performed on the FM thresholds and the processor thresholds across the FM systems to determine if the children had selected perceptually similar volume levels on the FM receivers in the audibility-matching phase. Analyses revealed no significant differences across FM thresholds, $F(3, 27)=1.72$, $p=0.19$ and no significant differences across processor thresholds, $F(3, 27)=1.74$, $p= 0.18$. The lack of threshold differences for input to the FM transmitter microphone or input to the speech processor microphone supports the conclusion that the children selected volume levels on the FM receivers that resulted in relatively equivalent perceptual levels in the audibility-matching phase.

Figure 2. Children's thresholds for separate inputs to the FM transmitter and processor microphones



Note. Dotted and solid lines represent FM and processor standard deviations; FM= FM microphone; Processor=processor microphone.

Phase 3: Speech recognition with the CI alone

Rationale. The purpose of the speech recognition with CI alone phase was to quantify the effect of noise on speech recognition for these children and to obtain a baseline for comparison to their performance with FM systems in noise.

Methods. Speech-recognition testing using HINT-C sentences was done in the classroom with the participant seated near the front of the room as shown in Figure 1. The signal speaker was placed at a 0-degree azimuth to the participant's head at a distance of ten feet, and the noise speakers were placed at a 90-degree azimuth to the participant's head at a distance of nine feet. A CD player and amplifier were used to present the stimuli and were located at the front of the room on a cart.

Sentence recognition for this phase was evaluated using a randomly selected HINT-C sentence list (ten sentences) in a consecutive quiet and noise condition. The participants were given two practice sentences in quiet and noise before each respective condition began. The sentences were presented at 65 dB SPL at the listener's ear and the speech noise was presented 60 or 65 dB SPL depending on their performance as described below.

In the first condition, the participant was asked to repeat sentences presented in quiet with their implant alone. The participant had to achieve at least 50% of words correct in the quiet condition to continue with the speech-recognition testing. In the second condition, speech noise from the HINT-C CD was added at 60 dB SPL, resulting in a +5 SNR. The intensity of the noise was increased to 65 dB SPL (0 SNR) for two children in order to cause at least a 25% decrease in performance relative to the quiet condition (participants 7 and 10).

The participants were asked to repeat every word that they heard. The responses were recorded graphically and via audiotape, and responses were scored based on the number of words the child repeated correctly. The percent correct score for a condition was calculated by dividing the number of words that the participant repeated correctly by the total number of words. As indicated in the HINT manual, certain words have multiple correct responses (e.g. a/the).

Results Individual and average performance based on the raw scores are shown in Table 4 and Figure 3, respectively. The mean percent correct score in quiet was 80% with a standard deviation of 13.44%. The average speech-recognition score at the +5 SNR was 45% with a standard deviation of 12.98%. The two children, participants 7 and 10, who were tested at 0 SNR scored 34% and 38%, respectively.

In order to account for the unequal variances that occur with percent correct scores, scores were arcsine transformed before statistical analysis (Studebaker, 1985). On average, there was a significant effect of the noise on speech recognition for the children with their CIs alone as shown by a paired t-test, $t(9) = 2.26$, $p < 0.001$.

Phase 4: Speech recognition with FM systems

Rationale. The purpose of this phase was to evaluate whether FM systems are beneficial to children with CIs when listening in noise as compared to performance with their implant alone. In addition, comparisons of speech-recognition scores were done to determine if there were differences across four types of FM arrangements: desktop soundfield, body-worn, miniature direct-connect, and miniature cord-connect.

Method. Speech recognition with the FM systems was evaluated in the classroom with the same arrangement described in the speech recognition with CI-alone phase. The same signal and noise intensities were also used for the HINT-C stimuli as discussed in the previous phase. The presentation level for the noise was the level that resulted in at least a 25% decrease in speech recognition relative to the quiet condition. When the FM transmitters were used, the omnidirectional lapel microphones were placed six inches in front of the signal speaker supported by tripod. The input to the transmitter microphone was approximately 80 dBA.

Speech recognition was evaluated with the FM systems using four lists of HINT-C sentences. The sentence lists and the FM system were randomly selected for each condition. The participants received three practice sentences with each FM system before the testing began. The volume or gain settings on the FM receivers were set according to loudness preferences chosen by the participants in the audibility-matching phase. The cochlear implant speech processors remained at user settings. After the testing, the participant was asked which FM system he or she preferred. Approximately ten percent of the audio-recorded participant responses (ten lists) were randomly selected and analyzed by a second scorer after testing was completed to determine scoring reliability.

Results. Individual and average raw speech-recognition scores are shown in Table 4 and Figure 3. Mean percent correct speech-recognition scores for the participants while using the Toteable, Easy Listener, Logicom, and MicroLink were 70%, 75%, 67%, and 72%, respectively. For scoring reliability, approximately 10% (ten lists) of the audio recordings were randomly selected and analyzed by a second person. The comparisons between scorers show that eight of the ten lists were scored within ± 6% correct.

As before, speech-recognition scores were arcsine transformed before statistical analysis. Paired t tests were used to compare scores obtained with CI alone in noise and with the different FM systems to determine if each FM system allowed for a significant increase in speech recognition. The multiple comparisons were accounted for by using the Bonferroni correction. On average, children received significant improvements in speech recognition using all the FM systems as compared to the noise condition with their CI alone, Toteable ($t(9) = 2.26$, $p = 0.001$), Easy Listener ($t(9) = 2.26$, $p < 0.001$), Logicom ($t(9) = 2.26$, $p = 0.003$), MicroLink ($t(9) = 2.26$, $p = 0.002$).

To statistically compare the benefit across the FM systems, a one-way repeated measures analysis of variance on the arcsine-transformed scores was performed. There was no significant difference across FM systems, $F(3,27) = 1.18$, $p = 0.33$. As shown in Table 3, five of the children preferred using the MicroLink, two preferred the Easy Listener, two preferred the Toteable, and one preferred the Logicom. In general, there was agreement between the children's preference and their performance when differences between scores are interpreted relative to Thornton and Raffin critical difference ranges for a 50-word list (1978). Only one child (#3) preferred an FM system (the Toteable) that resulted in a significantly lower recognition score than with the FM system (Easy Listener) that resulted in his highest speech recognition score.

Figure 3. Average percent correct speech-recognition scores in quiet, noise, and using four FM systems.

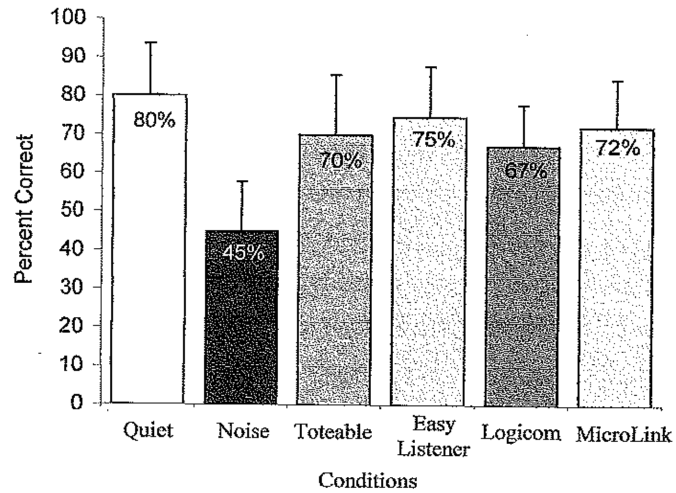


Table 4. Percent Correct Speech-Recognition Scores for the Quiet, Noise and FM Conditions and FM System Preference

ID	Processor	Quiet	+5 SNR	0 SNR	Toteable	Easy Listener	Logicom	Micro Link	Preference
1	Esprit 22	72.0	36.0	-	40.0	56.0	**73.1**	69.8	MicroLink
2	Esprit 22	66.7	38.0	-	72.2	**82.0**	70.0	79.0	MicroLink
3	Esprit 22	94.0	48.0	-	82.7	**98.3**	68.0	73.6	Toteable
4	Esprit 22	86.8	38.9	-	70.0	**82.7**	70.6	78.0	Easy Listener
5	Esprit 22	91.7	33.3	-	51.0	58.0	66.7	**74.0**	MicroLink
6	Esprit 22	96.5	47.1	-	**80.0**	**80.0**	69.8	74.0	Toteable
7	3G	80.4	62.0	34.0	**75.4**	64.8	60.8	58.0	MicroLink
8	3G	90.2	54.0	-	**93.0**	83.3	76.0	84.0	MicroLink
9	3G	62.3	26.0	-	75.4	68.0	78.0	**87.0**	Logicom
10	Tempo	62.3	66.7	38.0	62.0	**74.5**	40.0	45.1	Easy Listener

Note. SNR=Signal-to-noise ratio; ID=participant number; the highest FM scores are indicated in bold.

Discussion

The children in this study, ages 6 to 12, had Nucleus 22, Nucleus24, or MED EL C40+ cochlear implants. Years of implant use ranged from 3;0 years to 8;0 years, and the children had receptive vocabulary levels ranging from 6;0 to 13;4 years with an average receptive vocabulary level of 7;9 years. The children were able to select FM receiver volumes using a loudness chart to indicate comfortable levels when listening to running speech presented to the transmitter microphone. The children's ability to hear input from the FM and speech processor microphones simultaneously was verified by measuring thresholds for speech-weighted noise when input was directed to each of the microphones separately. Two separate repeated measures ANOVAs, comparing thresholds across FM systems for input to the FM and speech processor microphones showed no significant differences across thresholds for input to either microphone. These findings suggest that children were able to set the receiver volumes at perceptually similar levels.

It is important to consider the performance level with the FM system in noise relative to that obtained with the cochlear implant alone in quiet given previous concerns that the electrical coupling may disrupt the signal quality. Using critical difference ranges for percent correct scores by Thornton and Raffin (1978) for a 50-word list, the highest FM score each child obtained was not significantly different from their score with their implant alone in quiet with one exception. Participant #9 actually scored significantly higher with the MicroLink FM system (87.0%) than with his cochlear implant alone in quiet (62.3%). Although not statistically supported, it appears that six of the children scored higher (2.8 to 24.7 %) with the FM system in noise than with the CI alone in quiet. Additionally, it appears that seven of the participants obtained their highest score with an electrically-coupled FM system. These findings indicate that FM systems used in this study could be electrically coupled to cochlear implants without degrading the signal.

Results of the sentence recognition with CI-alone phase of the study suggest that children with CIs experience significant difficulties listening to speech in the presence of background noise with their implant alone. Performance in noise declined on average by 35% as compared to the quiet condition. In the final experimental phase, the average performance with each of the FM system arrangements was significantly improved relative to the average performance in the implant-alone noise condition. Performance with the FM systems improved on average by 26%. No significant differences in sentence recognition performance were found across the four FM system arrangements, but half of the children preferred using the MicroLink. When asked why they preferred this system, some liked the way it looked and some did not know why.

This study was performed with the children's speech processors at user settings. It is important to note that changes to the sensitivity setting or the programming in speech processors may alter the audio-mixing ratio, i.e., the relative intensity of the FM signal to the processor signal. It is possible that adjustments to the mixing ratio to allow for higher FM input could have resulted in significant differences in speech-recognition performance across the FM systems. Because FM systems are usually fit by educational audiologists in the school setting rather than the audiologist who fit the implant, they often do not have input and/or knowledge on how the processor is programmed. Audiologists who fit the cochlear implant should consider programming one map on a child's processor to allow for control of sensitivity. A collaboration between educational and implant audiologists would allow for optimal setting of the CI and FM system in the educational setting. Further research is needed to determine how changes in sensitivity will affect speech-recognition performance in noise.

It is important for audiologists to quantify the difficulties that these children may experience in the classroom through speech-recognition testing in noise. Educational recommendations, including use of an FM system, may be supported by speech-recognition testing in noise to simulate classroom listening performance. The creators of HINT-C suggest that the test is appropriate for children as young as 6;0 years. Although the HINT was originally developed to be used in an adaptive paradigm, a fixed-level presentation of the HINT, in a percent correct format, is often used (Davies et al., 2001; Schafer & Thibodeau, in press). This may be because the standard adaptive HINT is too difficult for children with CIs. Several other researchers have used the HINT in a similar percent-correct manner for evaluating speech-recognition performance of persons with CIs (Dorman, Loizou, & Fitzke, 1998; Parkinson, Aracoli, Staller, Arndt, Cosgriff & Ebinger, 2002; Waltzman, Cohen, & Roland, 1999). Several children who were screened for participation in the current study could not be included because of receptive vocabulary levels below this criterion.

According to the results in the present study, many children with CIs have significantly delayed receptive vocabulary. In fact, those with speech-recognition levels of a typical six-year-old child had the lowest performance in quiet with their CI alone as compared to children with higher receptive vocabulary levels. This highlights the need for speech-recognition materials for younger children. Alternatively, speech recognition in noise may need to be assessed with parent inventories or questionnaires. Many children with hearing impairment begin school at the age of three subjecting them to the negative effects of noise, reverberation, and distance from the teacher at an important time for speech and language development. Therefore, it is imperative that research efforts are directed toward evaluating speech recognition in young children to determine performance in classroom-like listening situations. Testing should also be incorporated to evaluate optimal strategies for improving speech recognition in noise.

Conclusions

Results of this investigation show that use of a loudness chart is an effective way to have children set FM receiver volume levels, and that the children with CIs in this study selected similar volume settings on the receivers regardless of the type of speech processor or implant they had. Audio mixing, or dual FM and processor microphone input to the CI, was verified by measuring thresholds for speech-weighted noise for inputs to the FM and processor microphone for each FM system. Comparisons of the speech-weighted noise thresholds across the systems verify that the children were able to select similar perceptual FM receiver volume levels regardless of the FM system in use. The speech-recognition performance of the children with CIs was significantly affected by the presence of background noise, but the use of all four FM system arrangements included in this study resulted in significantly improved speech recognition. Future research should focus on the creation of speech recognition in noise materials appropriate for younger children with CIs and testing with a variety of CI speech processors. Research is needed to examine how changes to audio-mixing ratios affect speech recognition particularly with new ear-level bootable FM receivers for persons with Nucleus 3G processors (Phonak MicroLink CI-S). Clinical guidelines on fitting and evaluating FM systems for persons with CIs should be established, since currently published guidelines do not address the specific needs and challenges of verifying FM systems for this population.

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