Speech Recognition in Noise in Children With Cochlear Implants While Listening in Bilateral, Bimodal, and FM-System Arrangements

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Purpose: Speech recognition performance in noise was examined in children with cochlear implants (CIs) when using (a) a second CI (bilateral group), (b) a hearing aid (HA) on the nonimplant ear (bimodal group), and (c) a frequency modulation (FM) system on 1 or both sides.
Method: While always maintaining use of the first CI, 2 groups participated in 6 conditions each using various listening arrangements with the second CI, HA, or FM system. Speech-in-noise thresholds were determined using simple phrases, classroom noise, and a method-of-limits approach.
Results: No group differences were detected across any conditions. In the no-FM-system conditions, no significant benefit of bilateral or bimodal input was found relative to a single CI. In the FM-system conditions, thresholds were significantly lower (up to 20 dB) relative to all other conditions when FM-system input was provided to the first-implanted side or to both sides simultaneously.
Conclusions: Children's speech-in-noise thresholds did not improve when providing input to the second side with a CI or an HA relative to a single CI. However, children with CIs had better speech recognition in noise with the use of an FM system on one or both sides relative to the conditions with no FM system. Binaural conditions with a single FM receiver on the second CI or HA yielded significantly poorer performance than any other FM condition.

Key Words: cochlear implant, frequency modulation, bimodal, bilateral

Cochlear implantation is an option for children with severe-to-profound hearing loss when hearing aids (HAs) cannot provide adequate audibility of speech. Children with cochlear implants (CIs) may develop open-set speech recognition in quiet listening situations when they are implanted at an early age (Geers, 2004; Geers, Brenner, & Davidson, 2003; Osberger, Zimmerman-Phillips, & Koch, 2002; Waltzman, Cohen, Green, & Roland, 2002). Despite this achievement, children with CIs often experience reductions in speech recognition in noise ranging from 20% to 35% relative to quiet listening conditions regardless of the type of speech and noise stimuli (Davies, Yellon, & Purdy, 2001; Eisenberg, Kirk, Martinez, Ying, & Miyamoto, 2004; Litovsky et al., 2004; Schafer & Thibodeau, 2003).

This difficulty in noise is significant because young children with CIs will encounter noise in all aspects of their lives, including school, where there is a constant level of noise in the classroom ranging from 34 to 73 dBA (Arnold & Canning, 1999; Bess, Sinclair, & Riggs, 1984; Knecht, Nelson, Whitelaw, & Feth, 2002). Many children with CIs are enrolled in preschool by the age of 3 and will be educated in classrooms that are often noisier than those of older children (Picard & Bradley, 2001). In addition, children who receive CIs often transition into larger, partially or fully mainstreamed classrooms (Daya, Ashley, Gysin, & Papsin, 2000; Picard & Bradley, 2001; Tobey, Geers, Rekart, & Buckley, 2004). Adding to all of these challenges, younger children with CIs may have more difficulty hearing than older children with CIs because on average speech recognition in noise improves with age (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000). Although federal law mandates that children with hearing loss should receive a free and appropriate education in the least restrictive environment, classrooms with excessive noise and signal-to-noise ratios (SNRs) as poor as –6 dB will not allow for a suitable listening environment (Picard &

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Bradley, 2001). Therefore, factors that may contribute to educational restrictions for children with CIs are the presence of noise in the classroom, distance from the teacher, and reverberation. Identifying possible solutions to address these limitations is imperative as children with CIs are already facing deficits including delays in speech and language development and reading ability (Blamey et al., 2001; Geers, 2004; Tomblin, Spencer, & Gantz, 2000).

Use of a second CI (bilateral input), an HA on the nonimplant ear (bimodal input), and frequency modulation (FM) system input to one or both sides improves speech recognition in noise of children with CIs (Ching, 2000; Ching et al., 2005; Ching, Psarros, Hill, Dillon, & Incerti, 2001; Davies et al., 2001; Dettman et al., 2004; Holt, Kirk, Eisenberg, Martinez, & Campbell, 2005; Kühn-Inacker, Shehata-Dieler, Muller, & Helms, 2004; Litovsky et al., 2004; Luntz, Shpak, & Weiss, 2005; Schafer & Thibodeau, 2003; Senn, Kompis, Vischer, & Haeusler, 2005). The use of a second CI or an HA on the nonimplant ear improves speech recognition in noise and may provide several binaural benefits including binaural summation, binaural squelch, reduction of the head shadow effect, and improved localization (Cox, DeChicchis, & Wark, 1981; Nabelek & Pickett, 1974a, 1974b). An FM system provides direct access to the talker's voice through a teacher-worn transmitter and a student-worn receiver plugged into the CI speech processor. Use of an FM system reduces the negative effects of distance from the speaker, noise, and reverberation in the environment because of the placement of the transmitter microphone 3 to 6 in. from the mouth of the speaker. If using bilateral or bimodal input while also using an FM system, a child may receive even greater improvements in speech recognition in noise from the combination of binaural benefits and improved SNR.

Bilateral CIs improve speech recognition in noise for children with CIs when the speech and noise are spatially separated, particularly when the noise is presented toward the second implant (Kühn-Inacker et al., 2004; Litovsky et al., 2004; Senn et al., 2005). Although the studies include various speech stimuli (bisyllabic words and sentences), competing noise (speech noise, babble), and speaker arrangements, the findings are consistent that speech recognition in noise improves for the majority of the children when using two implants relative to one. Bimodal input (CI and HA on nonimplant ear) also significantly improves speech recognition in noise for children with CIs when the speech (words, phrases) and noise (babble, speech noise) are presented from the same speaker (Ching, 2000; Ching et al., 2001; Dettman et al., 2004; Holt et al., 2005; Luntz et al., 2005) or when the speech and noise are spatially separated (Ching et al., 2005). When the gain on the HA is adjusted to allow for loudness balancing between the HA and CI, children show even larger gains in speech recognition in the bimodal condition relative to the CI alone (Ching et al., 2001). In summary, children's speech recognition significantly improves with binaural input (bilateral or bimodal) relative to a CI alone regardless of stimuli, type of noise, and speaker azimuths.

For children using a single CI, speech recognition in noise significantly improves when using an FM system and listening to spatially separated speech and noise (Davies et al., 2001; Schafer & Thibodeau, 2003). Currently, research addressing speech recognition performance in adults with bilateral HAs also shows significantly better performance with FM-system input to two ears relative to one (Lewis, Crandell, Valente, & Horn, 2004). Therefore, similar benefits from FM-system input to both sides are expected for children using bilateral and bimodal listening arrangements.

Findings in these pediatric studies suggest that use of a second CI, an HA on the nonimplant ear, and an FM system allow for improvements in speech recognition in noise ranging from 10% to 30% or 0.3 to 3.0 dB relative to a single CI alone. Similar improvements are reported for adults with CIs (Armstrong, Pegg, James, & Blamey, 1997; Ching, Incerti, & Hill, 2004; Hamzavi, Pok, Gstoettner, & Baumgartner, 2004; Litovsky et al., 2004; Muller, Schon, & Helms, 2002; Schafer & Thibodeau, 2004; Schon, Muller, & Helms, 2002; Tyler et al., 2002; van Hoesel & Tyler, 2003). It is important to evaluate the relative effectiveness of each of these approaches in order to facilitate the audiologists' or parents' selection of a listening arrangement for a child that will allow for the most consistent access to the speech signal in noisy environments, such as the classroom. Therefore, the purpose of our study was to evaluate the enhancement in speech recognition in noise provided by these three approaches for children with CIs. The research questions included the following:

1. Are there differences between groups (bilateral vs. bimodal)?
2. Are there differences between monaural and binaural arrangements (CI alone vs. bilateral/bimodal)?
3. Are there differences among the FM-system arrangements?

The methodology used in this study assessed children's speech recognition in a simulated classroom environment and did not address other auditory skills associated with binaural listening, such as localization abilities, binaural squelch, binaural localization, or reduction of the head shadow effect.

Method

Participants

Twenty-two children with CIs who ranged in age from 3;0 (years;months) to 12;0 participated in the study. One group of 12 children had sequential CIs (bilateral group), and one group of 10 children had a CI and an HA on the nonimplant ear (bimodal group) as shown in Tables 1 and 2, respectively. All children had severe-to-profound hearing loss prior to implantation and were prelingually deafened before 1 year of age. The children learned English as a first language and used an Advanced Bionics, MED-EL, or Cochlear Corporation internal implant with the associated ear-level or body-worn speech processor (see Tables 1 and 2). Children were using Cochlear Corporation Nucleus 22 or 24 internal implants with the exception of 2 children in the bilateral group and 3 children in the bimodal group. All children received their first implant at or before 5 years of age and used oral language as their primary means of communication. Children used their first CI for at least 6 months and their second CI (bilateral group) or HA (bimodal group) for at least 4 consecutive months. All children received updated speech processor

Table 1. Implant and participant information for the bilateral group.

Participant information		First-implanted side					Second-implanted side				
Participant	Age at testing	Implanted side	Age at 1st implant	Internal implant	Processor	Processing strategy	Implanted side	Age at 2nd implant	Internal implant	Processor	Processing strategy
1	4;1	R	1;7	Nucleus 24	SPrint	ACE	L	3;1	Nucleus 24	SPrint	ACE
2	3;1	L	1;0	COMBI 40+	TEMPO+	CIS+	R	2;0	COMBI 40+	TEMPO+	CIS+
3	7;8	L	5;9	COMBI 40+	TEMPO+	CIS+	R	6;4	COMBI 40+	TEMPO+	CIS+
4	3;6	R	2;3	Nucleus 24	3G	ACE	L	3;0	Nucleus 24	3G	ACE
5	3;8	R	1;5	Nucleus 24	3G	ACE	L	3;1	Nucleus 24	3G	ACE
6	5;1	R	1;0	Nucleus 24	3G	ACE	L	4;7	Nucleus 24	3G	ACE
7	6;1	R	3;5	Nucleus 24	3G	ACE	L	4;7	Nucleus 24	3G	ACE
8	8;1	R	2;8	Nucleus 24	3G	ACE	L	6;4	Nucleus 24	3G	ACE
9	9;9	R	4;6	Nucleus 24	3G	ACE	L	8;3	Nucleus 24	3G	ACE
10	10;4	R	2;1	Nucleus 22	3G	SPEAK	L	10;0	Nucleus 24	3G	ACE
11	10;7	R	2;7	Nucleus 22	3G	SPEAK	L	9;8	Nucleus 24	3G	SPEAK
12	11;5	L	2;1	Nucleus 22	3G	SPEAK	R	10;1	Nucleus 24	3G	ACE
Average	7;0		2;6					6;0			

Note. Ages are given in years;months. 3G = ESPrit 3G; ACE = Advanced Combination Encoder; SPEAK = Spectral Peak; L = left; R = right.

Table 2. Implant and participant information for the bimodal group.

Participant information		Implant information					Hearing aid (HA) information			
Participant	Age at testing	Implanted side	Age at 1st implant	Internal implant	Processor	Processing strategy	HA side	Age at 1st HA	HA make	HA model
1	5;0	R	4;3	HIRes 90K	Auria	HIRes-P	L	0;3	Unitron	Unison
2	7;0	R	3;7	HiFocus/CII	Auria	SAS	L	1;6	Phonak	PicoForte PPCP2
3	7;7	L	3;3	HiFocus/CII	Platinum BTE	SAS	R	0;2	Phonak	PicoForte PPCLP2
4	5;3	R	1;7	Nucleus 24	SPrint	ACE	L	0;3	Phonak	PicoForte PPCP2
5	4;4	R	1;9	Nucleus 24	SPrint	ACE	L	0;2	Oticon	Personic 425
6	11;9	L	5;9	Nucleus 24	SPrint	ACE	R	0;9	Phonak	Maxx 311
7	4;1	R	1;8	Nucleus 24	3G	ACE	L	1;0	Phonak	Maxx 311
8	5;7	R	2;2	Nucleus 24	3G	ACE	L	3;0	Phonak	PicoForte PPCP2
9	8;0	R	2;7	Nucleus 24	3G	ACE	L	2;5	Phonak	Maxx 311
10	8;0	L	3;4	Nucleus 24	3G	ACE	R	3;0	Widex	Senso P38
Average	6;7		3;1					1;3		

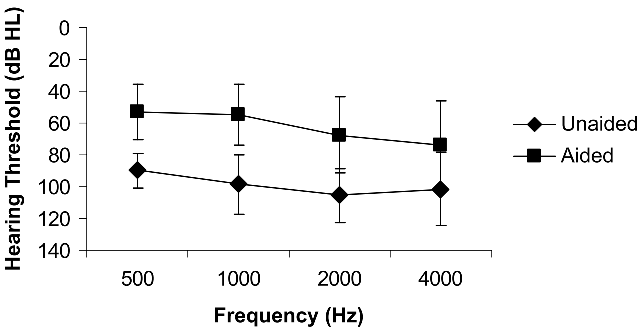
Note. Ages are given in years;months. Hi-Res-P = High Resolution; SAS = Simultaneous Analog Strategy.

programming within 1 year prior to testing. Information about the children's ages and devices is provided in Tables 1 and 2 for the bilateral and bimodal groups, respectively. The majority of the children in the study were female, with the exception of 3 males in the bilateral group and 2 males in the bimodal group. The children's etiology of hearing loss was unknown or resulted from cytomegalovirus, with the exception of 2 children in the bimodal group where the connexin 26 mutation was identified and a hereditary hearing loss was reported by the parent. All or all but two electrodes were active in all of the children's internal implants.

In the bilateral group, duration between the first and second implant ranged from 6 months to 9 years. All of the bilateral children used their second CI for at least 6 months prior to testing, with the exception of Participant 9, who used the second CI for 4 months. The children with bilateral implants consistently used their two CIs. The children's average aided threshold (0° azimuth) across 500, 1000, 2000, and 4000 Hz was 34.9 dB HL (*SD* = 5.7 dB) with the first implant alone, 34.2 dB HL (*SD* = 6.6 dB) with the second implant alone, and 32.2 dB HL (*SD* = 6.9 dB) with the bilateral implants. All but 3 children were educated in fully mainstreamed classrooms for the entire school day, and all but 1 child was receiving auditory-verbal (AV) therapy by a certified AV therapist.

In the bimodal group, the children were consistently using a digital or a nonprogrammable analog HA on the nonimplant ear, as shown in Table 2. Seven of the 10 children used bilateral HAs prior to receiving the CI and continued to use an HA on the nonimplant ear after receiving the CI. Participants 5, 6, and 10 used their HA and CI simultaneously for a duration of 10 months, 9 months, and 55 months, respectively. The children's average aided threshold (0° azimuth) across 500, 1000, 2000, and 4000 Hz was 28.1 dB HL (*SD* = 6.0 dB) with the CI alone, 63.5 dB HL (*SD* = 22.2 dB) with the HA alone, and 29.4 dB HL (*SD* = 3.2 dB) for the CI and HA combined. The average unaided and aided (HA alone) hearing thresholds for the children's nonimplant ear are shown in Figure 1. Seven of the 10 children in the bimodal group were partially or fully mainstreamed, while the remaining 3 children were in oral deaf education classrooms. All of the children were in AV therapy.

Figure 1. Unaided and aided hearing thresholds for nonimplant ear of children in the bimodal group.



Equipment Setup

Speech recognition in noise testing was conducted in a double-walled, sound-treated booth. The children were seated at a child-sized table in the middle of the sound booth. The signal speaker was located at 0° azimuth, and the noise speakers were at 135° and 225° azimuth, relative to the listener. The speaker arrangement was selected to simulate classroom listening for a child seated preferentially at the front of the classroom with classmates seated behind on either side. Each of the speakers was placed 1 m from the listener. To facilitate participant recruitment, testing was conducted at three centers. All of the equipment was identical with the exception of the noise speakers and the noise presentation equipment. Frequency-response measurements made with a Fonix FP40 hearing aid analyzer and the stimuli-calibration noise at 60 dBA (speech-shaped noise) revealed that the output of the three sets of noise speakers was similar (±2 dB) across octave frequencies from 250 to 4000 Hz.

The equipment included a signal speaker (8-Ω RCA 20-W Full-Range Mini Speaker), CD player (Sony SDP-390), and amplifier (Crown D60). The noise was presented from a CD player (Sony CDP-CE275) routed through a Grason-Stadler 61 Clinical Audiometer or a Crown amplifier and delivered through two speakers (Grason-Stadler High Performance or Basic Speakers and RCA 20-Watt Full-Range Mini Speakers). The stimuli were calibrated using a Quest Diagnostics Type 1 sound level meter (Model 1800) placed at the location of the child's head.

The children's CI and HA batteries were replaced before testing if necessary. The children's HAs were tested electroacoustically using a Fonix FP40 hearing aid analyzer and the ANSI S3.22-1996 standard (American National Standards Institute, 1996) to determine appropriate function. Simulated real-ear testing using average real-ear-to-coupler differences and the age of the child was used to determine the recommended amount of gain by the National Acoustics Laboratories–Revised (NAL-R) prescriptive HA fitting method (Byrne & Dillon, 1986). The majority of the children's HAs provided more gain than recommended by the NAL-R method for at least one or more frequencies. When gain was less than the NAL-R target, it was within 5 dB.

For the FM-system conditions, a Phonak Campus S transmitter, two Phonak MicroLink CI-S, and two Phonak MLx-S receivers set to the default +10 FM advantage were used. The adaptors, cords, and cables used to connect the MLx-S receivers to the children's HAs and CIs and equipment settings are shown in Table 3 for the bilateral group and Table 4 for the bimodal group. The speech processor settings shown in these tables were maintained throughout all testing conditions. Functioning of the children's CIs, HAs, and FM systems was verified prior to testing by having the child repeat simple words with input into the respective microphones without visual cues. When a volume control was accessible on the FM receiver (MicroLink CI-S), it was gradually increased until the child indicated a comfortable level on a loudness chart while listening to running speech presented via live voice at average conversational level (approximately 60 dBA). During the FM-system conditions,

Table 3. Processor and FM settings for bilateral group.

Participant	Processor	Program	Sensitivity	Volume	FM receiver	FM cable	Receiver volume
First CI							
1	SPrint	P2	9	12	MicroLink CI-S	Orange	2
2	TEMPO+	1	3:00	X	MicroLink CI-S	Red	2
3	TEMPO+	1	3:00	X	MicroLink CI-S	Red	2
4	3G	P1	Dis	Dis	Adapt/MLx-S	NA	NA
5	3G	P2	Dis	Dis	Adapt/MLx-S	NA	NA
6	3G	P1	NA	3	Adapt/MLx-S	NA	NA
7	3G	P1	NA	5	Adapt/MLx-S	NA	NA
8	3G	P1	NA	3	Adapt/MLx-S	NA	NA
9	3G	P2	3	NA	Adapt/MLx-S	NA	NA
10	3G	P1	3	NA	Adapt/MLx-S	NA	NA
11	3G	P1	Dis	Dis	Adapt/MLx-S	NA	NA
12	3G	P1	1½	NA	Adapt/MLx-S	NA	NA
Second CI							
1	SPrint	P3	9	12	MicroLink CI-S	Orange	2
2	TEMPO+	1	3:00	X	MicroLink CI-S	Red	2
3	TEMPO+	1	3:00	X	MicroLink CI-S	Red	2
4	3G	P1	Dis	Dis	Adapt/MLx-S	NA	NA
5	3G	P2	Dis	Dis	Adapt/MLx-S	NA	NA
6	3G	P1	3	NA	Adapt/MLx-S	NA	NA
7	3G	P1	NA	5	Adapt/MLx-S	NA	NA
8	3G	P1	NA	3	Adapt/MLx-S	NA	NA
9	3G	P2	3	NA	Adapt/MLx-S	NA	NA
10	3G	P1	4	NA	Adapt/MLx-S	NA	NA
11	3G	P1	Dis	Dis	Adapt/MLx-S	NA	NA
12	3G	P2	2	NA	Adapt/MLx-S	NA	NA

Note. CI = cochlear implant; Adapt = Cochlear Corporation 3G MicroLink adaptor; FM = frequency modulated; Dis = disabled; CNE = could not evaluate; NA = not applicable.

the FM transmitter microphone was placed 6 in. from the signal speaker on a stand. Repeated measurements with the sound-level meter showed that the one-coned speakers used in the study provided a consistent response within ±2 dBA when the transmitter was placed near the 6-in. location (±1 in.).

Stimuli

Given the limited number of speech recognition in noise tests designed for young children with hearing loss, new materials were created that were appropriate for the age range in the study. The goal of these materials was to reduce effects of receptive-vocabulary level and to allow for the detection of small differences between conditions by using adaptive speech levels in the presence of continuous background noise. The test is similar to a recently developed test known as the Bamford-Kowal-Bench Speech-in-Noise Test, which is designed to test speech recognition in noise but includes sentence material for children age 6 to 14 years (Etymotic Research, 2004). Other speech recognition in noise tests available for children are problematic because of vocabulary level required for the task, floor (0%) and ceiling effects (100%), and performance variability that may occur with fixed-intensity levels (Jerger & Jerger, 1982; Jerger, Lewis, Hawkins, & Jerger, 1980; Nilsson, Soli, & Gelnett, 1996).

Table 4. Processor and FM settings for bimodal group.

	Processor information							Hearing aid information		
Participant	Processor	Program	Sensitivity	Volume	FM receiver	FM cable	FM volume	HA model	HA volume	FM receiver
1	Auria	1	Dis	Dis	MicroLink CI-S	Blue-red	2	Unison	2	MLx-S
2	Auria	2	NA	1:00	MicroLink CI-S	Blue-red	2	PicoForte PPCP2	4	MLx-S
3	Platinum	1	NA	3:00	MicroLink CI-S	Blue-red	2	PicoForte PPCLP2	3.5	MLx-S
4	SPrint	P1	12	9a	MicroLink CI-S	Orange	3	PicoForte PPCP2	4	MLx-S
5	SPrint	P1	12	9a	MicroLink CI-S	Orange	3	Personic 425	4	MLx-S
6	SPrint	P2	10	8	MicroLink CI-S	Orange	3	Maxx 311	NA	MLx-S
7	3G	P2	5	NA	Adapt/MLx-S	NA	NA	Maxx 311	NA	MLx-S
8	3G	P1	2.5	NA	Adapt/MLx-S	NA	NA	PicoForte PPCP2	4	MLx-S
9	3G	P2	2	NA	Adapt/MLx-S	NA	NA	Maxx 311	NA	MLx-S
10	3G	P1	4	NA	Adapt/MLx-S	NA	NA	Senso P38	NA	MLx-S

Table 5. Phrases and objects for identifying phrases.

Phrase	Object to use with the doll
Blow his nose	Kleenex, napkin
Stomp his feet	–
Touch his tongue	–
Comb his hair	Comb
Brush his teeth	Toothbrush
Wipe his mouth	Napkin, Kleenex
Scratch his chin	–
Pull his toes	–
Bend his leg	–
Hide his face	Child's hand, Kleenex, napkin

In the present study, speech recognition was tested using fixed-intensity, concatenated multiclassroom noise, and 10 simple phrases about body parts that systematically varied in intensity. The children were asked to act out the phrases with a doll and several objects listed in Table 5. Given the simplicity and predictability of the phrases, it was likely that the child only needed to hear one word to get the sentence correct. Therefore, equating the phrases for intelligibility was extremely important and required several steps. The intensity (presentation level) of each phrase was adjusted for equal intelligibility in the multiclassroom noise based on results from 40 adults with normal hearing. They were tested in four sessions over which intensity for each phrase was sequentially adjusted based on average performance in the preceding session. This intensity-adjustment procedure to equate intelligibility was similar to that used by Nilsson, Soli, and Sullivan (1994) to create the Hearing in Noise Test.

Following the intensity-adjustment procedure, seven lists of 28 phrases were created in which the intensity of each phrase was decreased by 3 dB for 13 consecutive steps and then increased by 3 dB for 13 consecutive steps. The decision was made to adapt the speech levels as was done in the binaural FM-system study by Lewis et al. (2004). The adapted speech levels used in the present study prevented uncomfortable noise levels for the children with CIs while still allowing a range of SNRs sufficient to measure a threshold for speech with and without an FM system. In this arrangement, only the first 3 phrases, which were rarely missed, exceeded the compression threshold of the FM transmitter (72 dB SPL) when it was in use. Therefore, the speech-in-noise thresholds in the FM-system conditions were not affected by compression in the transmitter and allowed for comparison across various FM-system arrangements.

The multiclassroom noise was recorded from a first-, second-, third-, and fourth-grade school classroom during independent work time. The noise from the four classrooms was digitally overlapped and edited to reduce the root-mean-square (RMS) difference across the 37-min sample. The final edited version of the noise had a difference of 2.95 dB between the minimum and maximum RMS values (50-ms time window), and was matched to the long-term average RMS intensity and spectrum of the phrases. In the final version, the multiclassroom noise was digitally filtered to match the long-term average spectrum of the phrases using Cool Edit Pro software (Syntrillium Software, 2003).

The speech and noise stimuli were recorded on separate CDs. The speech-stimuli CD included a calibration track, a practice track at a fixed +15 SNR, and seven prerecorded lists of test stimuli. The calibration track was a 3-min segment of white noise filtered to match the long-term average spectrum of the phrases. The practice track included the 10 phrases with an 8-s interstimulus interval. Each test list consisted of 28 randomly selected phrases, making the probability of the children guessing a phrase approximately 10%. The noise CD included a calibration track with the same filtered noise as the speech-stimuli CD and 37 min of the filtered, four-classroom noise on two separate channels. The noise was out of phase on each channel to allow for the presentation of uncorrelated noise through the two speakers. Based on a pilot study with 40 adults and 10 children with normal hearing, no significant differences were detected among the lists or across three consecutive trials of the current procedure according to repeated measures analysis of variance (ANOVA). Therefore, the lists of randomized phrases were considered equivalent, and no learning effects were expected for the children with CIs.

Procedure

Children's speech-in-noise thresholds were determined in six randomized testing conditions. Each condition included one test list of 28 randomized phrases. The CI (first CI for the bilateral group) was in use during every condition. The conditions for both groups were similar but differed for input to the second side where the bilateral group used their second CI and the bimodal group used the HA. As shown in Figure 2, we identified each of the conditions with an acronym. A "+2nd" within the acronym symbolizes that the child was using his or her second CI (bilateral group) or HA on the

Figure 2. Visual representations of the listening conditions. CI = cochlear implant; +2nd = input to second side; $_{FM}$ = frequency-modulated input to preceding device; HA = hearing aid.

Condition	Acronym	Bilateral Group	Bimodal Group
1	CI	CI	CI
2	CI+2nd	CI CI	CI HA
3	CI_{FM}	CI_{FM}	CI_{FM}
4	CI_{FM}+2nd	CI_{FM} CI	CI_{FM} HA
5	CI+2nd$_{FM}$	CI CI_{FM}	CI HA_{FM}
6	CI_{FM}+2nd$_{FM}$	CI_{FM} CI_{FM}	CI_{FM} HA_{FM}

nonimplant ear (bimodal group). If there is no "+2nd" sign in the acronym, the child was using his or her CI alone (first CI for the bilateral group). When an FM receiver was in use for a condition, the CI or HA will be followed by the subscript letters "FM" (e.g., CI_{FM}). The definitions and the acronyms for each of the conditions are as follows:

1. CI alone (CI)
2. CI plus the second CI or HA (CI+2nd)
3. CI with an FM receiver (CI_{FM})
4. CI with an FM receiver plus the second CI or HA (CI_{FM}+2nd)
5. CI plus the second CI or HA with an FM receiver (CI+$2nd_{FM}$)
6. CI with an FM receiver plus the second CI or HA with an FM receiver (CI_{FM}+$2nd_{FM}$)

A clinical method-of-limits procedure was used to determine the speech-in-noise threshold. The phrases ascended and descended in intensity according to predetermined SNRs as shown in Table 6. The testing procedure was modeled after the QuickSIN, a speech recognition in noise test for adults with prerecorded SNRs (Etymotic Research, 2001). While noise was presented continuously at 60 dBA, the phrases started at an advantageous SNR of +18 dB and descended in 3-dB steps until a –18-dB SNR was achieved. After that, two stimuli were given at an advantageous SNR to refocus the child's attention to the task. Then, phrases ascended in 3-dB steps from a –18- to a +18-dB SNR. Testing was suspended when a child received three correct responses in a row on the ascending portion of the form, as it was expected that the child would get the remainder of responses correct as intensity increased. During the stimuli creation process, none of the 10 children with normal hearing who were tested missed two consecutive phrases following three consecutive correct phrases on the ascending portion of a list.

Table 6. Sample scoring sheet for the testing procedure.

Trial	SNR	Response
1	+18	+
2	+15	+
3	+12	−
4	+9	+
5	**+6**	+
6	+3	−
7	0	−
8	−3	−
9	−6	−
10	−9	−
11	−12	−
12	−15	−
13	−18	−
14	+18	+
15	+18	+
16	−18	−
17	−15	−
18	−12	−
19	−9	−
20	−6	−
21	−3	−
22	**0**	+
23	+3	−
24	+6	+
25	+9	+
26	+12	+
27	+15	+
28	+18	+

Note. Boldface values are signal-to-noise ratio (SNR) prior to 2 incorrect responses for the descending trials and SNR subsequent to 2 incorrect responses for the ascending trials. The 2 boldface SNRs averaged to predict 50% speech-in-noise threshold level: (+6 +0)/2 = +3; + = correct; − = incorrect.

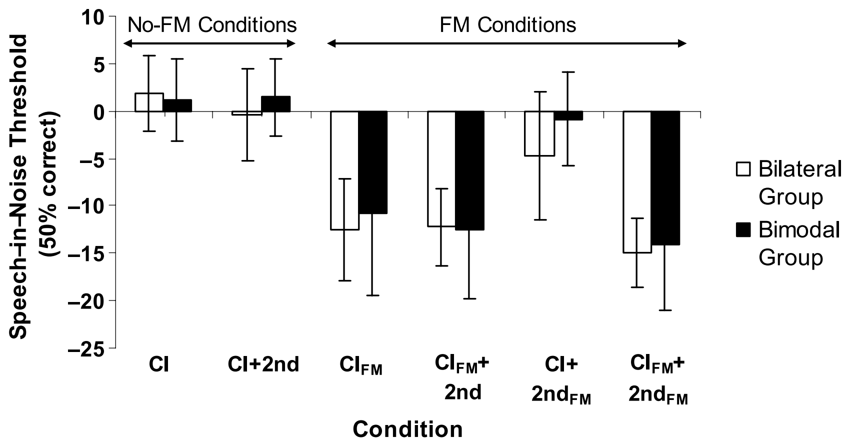
The child was required to act out the entire phrase with the doll to get a correct response. A speech-in-noise threshold was determined for each condition using one of the seven randomly selected lists. Testing for each condition took approximately 3 min. The speech-in-noise threshold was defined by taking an average of two SNRs: one for the phrases that descended in intensity and one for the phrases that ascended in intensity. The SNR where there was a correct response prior to the first two incorrect responses was noted for the descending phrases, and the SNR where there was a correct response subsequent to the first two incorrect responses was noted for the ascending phrases. These two SNRs were averaged to predict the 50% speech-in-noise threshold for the condition. In the hypothetical condition in Table 6, the child had a speech-in-noise threshold of +3 dB. The speech-in-noise threshold was validated as a measure of 50% performance level because thresholds obtained in the pilot study were not significantly different than scores obtained using the Hearing in Noise Test adaptive-test procedure, which was shown to measure 50% speech-in-noise thresholds (Nilsson et al., 1994; Schafer, 2005). For training, the examiner presented the phrases to the child using live-voice presentation and acted them out with the doll and objects. As the examiner repeated the phrases a second time, the child was asked to act them out with the doll. Once the child mastered acting out the phrases with the doll, the examiner and the child entered the sound booth for testing. The examiner was seated beside the child to keep the child focused on the speech-recognition task, score the responses, and control the CD player.

During the practice and the testing conditions in the sound booth, children were asked to act out the phrases with the doll instead of repeating them to avoid any scoring errors related to lack of intelligibility. To ensure that the child was facing the signal speaker during the presentation of the phrases, a colorful light was placed on top of the signal speaker and was turned on and off with a foot pedal approximately 1 s prior to each phrase. All of the children were given stickers, verbal praise, and breaks as needed.

The child was given the recorded practice list of 10 phrases at a +15 SNR with the continuous classroom noise at 60 dBA. If the child could not complete the practice list with 100% correct accuracy, the examiner practiced the phrases with the child again in noise using live voice presentation. Then, the recorded practice list was repeated. Failure to complete the practice list the second time with 100% correct accuracy resulted in exclusion from the study.

A second scorer, seated outside the booth, was used during testing of 6 children to check accuracy of scoring. Of the

Figure 3. Average speech-in-noise thresholds for the bilateral and bimodal groups.



896 phrases that the second scorer observed, disagreement only occurred on 10 phrases. The scoring differences did not occur in successive phrases and did not affect the final speech-in-noise threshold for a given condition.

Results

All but 3 of the 22 children were able to complete the six testing conditions. The average speech-in-noise thresholds and standard deviations are shown in Figure 3. Lower (more negative) scores reflect better speech-in-noise thresholds. Average scores and standard deviations in the no FM-system conditions (CI, CI+2nd) were similar for the two conditions and the two groups. A two-way, partially repeated ANOVA of the no FM-system conditions revealed no significant effect of group (bilateral or bimodal), $F(1, 20) = 0.12$, $p = .74$, or condition (monaural or binaural), $F(1, 20) = 1.96$, $p = .18$, and no significant interaction between group and condition, $F(1, 20) = 3.28$, $p = .09$. Therefore, no significant differences were detected in speech-in-noise thresholds for children using monaural relative to binaural input or for a group of children using bilateral input (two CIs), relative to a group of children using bimodal input (one CI and one HA).

Speech recognition in the FM-system conditions was remarkably better than the no-FM-system conditions by up to 20 dB. Improvements of up to 20 dB are surprisingly large for threshold-based assessments of speech recognition and suggest a substantial benefit of FM system use for the children with CIs. Performance was the poorest in the CI+2nd$_{FM}$ condition, suggesting that this arrangement should not be considered for children with bilateral or bimodal input when only one FM receiver is available. Scores were similar between the bilateral and bimodal groups across the four conditions. A two-way, partially repeated measures ANOVA showed no significant effect of group, $F(1, 9) = 0.19$, $p = .67$, a significant effect of condition, $F(3, 27) = 43.9$, $p < .0001$, and no significant interaction between group and condition, $F(3, 27) = 0.66$, $p = .58$. Therefore, no significant differences in speech recognition in noise were detected between the bilateral group and the bimodal group when using FM systems. However, a significant difference was found across the four FM-system conditions when the two groups were combined.

Results from the Duncan Multiple Range Test are shown in Table 7. A significant difference (≤.05 probability) was detected for the conditions that have different letters in the Duncan grouping column. No significant difference was detected for the children's performance between the CI$_{FM}$+2nd$_{FM}$ and CI$_{FM}$+2nd conditions or between the CI$_{FM}$+2nd and CI$_{FM}$ conditions. A significant difference was detected between the CI$_{FM}$+2nd$_{FM}$ and the CI$_{FM}$ condition suggesting that performance was superior with FM-system input to both ears relative to FM-system input to the CI alone with no input to the second side. Performance in the CI+2nd$_{FM}$ condition was significantly poorer than any of the other FM-system conditions. Overall, these comparisons show the best performance with an FM receiver on the first CI side alone or on both sides simultaneously.

Discussion

According to group analyses, the children's speech-in-noise thresholds did not significantly improve while using bilateral or bimodal input relative to a CI alone. However, the use of an FM system allowed for improvements in speech-in-noise thresholds of up to 20 dB relative to the no-FM conditions. Conditions with FM input to the first CI or to both sides were significantly better than the condition with FM-system input

Table 7. Analysis of the FM-system conditions using the Duncan Multiple Range Test.

Condition	*M* (dB)	*N*	Duncan grouping
CI$_{FM}$+2nd$_{FM}$	−14.6	22	A
CI$_{FM}$+2nd	−12.3	22	A B
CI$_{FM}$	−11.7	22	B
CI+2nd$_{FM}$	−3.0	22	C

Note. CI = first cochlear implant; +2nd = input to second side; FM = frequency-modulated input to preceding device.

Table 8. **Confidence intervals at the 95% level for each condition.**

Condition	Confidence interval (dB)
CI	1.8
CI+2nd	2.1
CI_{FM}	3.2
CI_{FM}+2nd	2.6
CI+$2nd_{FM}$	2.8
CI_{FM}+$2nd_{FM}$	2.4

only to the second side. The following discussion will focus on the three research questions in the study: (a) monaural versus binaural input, (b) bilateral versus bimodal input, and (c) different FM-system arrangements. In addition, possible trends will be discussed based on 95% confidence intervals for the children's speech-in-noise thresholds in each condition. The confidence intervals shown in Table 8 will be used to address questions regarding individual differences for listening arrangements of interest as shown in Table 9. A visual summary of the improvement in speech-in-noise thresholds from the CI-alone condition relative to all other listening arrangements is illustrated in Figure 4.

Should a Child With a CI Use Binaural Input?

The lack of binaural benefit from input to the second ear as shown in the far left of Figure 4 is not surprising in the present study because of several differences between this study and previous studies of children with bilateral or bimodal arrangements (Ching et al., 2001; Kühn-Inacker et al., 2004). In the largest study on children with bilateral implants, Kühn-Inacker and colleagues (2004) evaluated 18 German-speaking children with simultaneous or sequential bilateral implants using German speech-recognition materials at a fixed SNR. In the present study, English speech recognition materials were used and were presented using a different type of noise and presentation method (method-of-limits). Children in the present study used any type of CI and speech-processing strategy, while all of the children in the Kühn-Inacker et al. study used MED-EL Combi 40 or 40+ implants and likely used a similar speech-processing strategy. Three factors that likely contributed to the differences between the studies were the greater number of participants, the fewer conditions, and the different speaker arrangement used in the Kühn-Inacker et al. study. Kühn-Inacker et al. presented the speech signal from two speakers at 135° and 115° azimuth and the noise signal from two speakers at 45° and 225° azimuth. In summary, the similarity of processors combined with a larger number of participants and fewer conditions likely contributed to greater power in their statistical model.

As shown in Table 9, 8 of the 12 children in the bilateral group had significant improvements with the bilateral implants relative to the first CI alone according to the 95% confidence intervals. Although the group analysis did not suggest a trend, it is important to consider the significant gains made by these individual children. In addition, the speaker arrangement used in the present study did not allow for examination of additional binaural benefits including localization and reduction of the head shadow effect, which could contribute to even greater success with the bilateral implants.

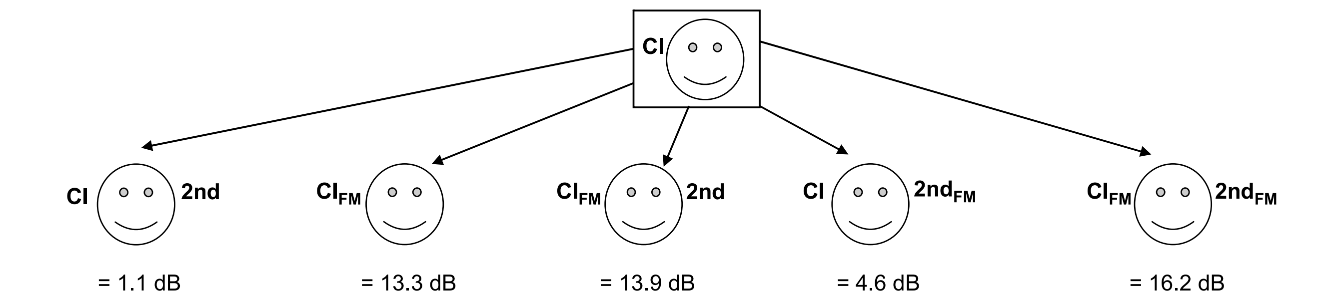
Differences are also present for studies examining the benefit of bimodal input (Ching, 2000; Ching et al., 2001, 2005; Dettman et al., 2004; Holt et al., 2005; Luntz et al., 2005). In the largest study of children using bimodal input, Ching and colleagues (2005) evaluated sentence recognition in the presence of babble by 18 children using Nucleus 22 or 24 internal implants, the Advanced Combination Encoders or Spectral Peak speech-processing strategy, and the same HA on the nonimplant ear. In the present study, the children were using all types of implants, speech-processing strategies, and HAs with different prescriptive fitting methods, which likely contributed to some of the variability in this group. Furthermore, Ching et al. (2005) used a different speaker arrangement than the current study when they presented speech from a speaker at 0° azimuth and noise at 60° azimuth on the side of the HA. Similar to the present study, Ching and colleagues (2001) reported no significant improvements with bimodal input relative to the CI alone condition when the HA was left at user settings. However, these authors reported significantly better speech recognition with bimodal input relative to the CI alone when the HA was loudness balanced with the CI. In the present study, the children were tested with the HAs at user settings determined by their respective audiologist who may not have balanced the two devices as suggested by Ching and colleagues (2001). Therefore, children in the present study may have shown greater bimodal benefit if the HA was balanced for loudness with the CI and they were using similar CIs and HAs.

Table 9. Questions addressing significant individual differences for participants according to the 95% confidence intervals between conditions.

		Participant number											
Question	Group	1	2	3	4	5	6	7	8	9	10	11	12
When not using FM, does adding a CI or HA to the second side help?	BIL	+	+	−	+	−	+	+	+			+	+
	BIM			+			+	−				*	*
When using FM on the first CI, does adding a CI or HA on the second side help?	BIL				+	−		+		−	−		
	BIM		−	−		+	+	+		+	+	*	*
When using FM on the first CI, does adding FM to the second side help?	BIL	+			−	+	+	+	+		+		
	BIM	+	+	−	+	−						*	*

Note. BIL = bilateral group; BIM = bimodal group; + = significant improvement; − = significant decrease; * = not applicable for this group.

Figure 4. Average differences for both groups combined between speech-in-noise thresholds in the CI alone condition relative to all other conditions.



As shown in Table 9, 2 of the 10 children in the bimodal group did show significant improvements with the bimodal arrangement relative to the CI alone. It is also important to note that 7 of the 10 children did not experience significant decreases in speech recognition when adding the HA on the nonimplant ear. It is possible that with an increased duration of bimodal usage, the children would show even greater speech recognition improvements with input to the two ears relative to one. In fact, Holt and colleagues (2005) reported a substantial increase in children's word and sentence recognition scores in noise (28%) after 2 years of bimodal use relative to 1 year of bimodal use.

The results of the present and previous studies suggest that binaural input should be considered for children with CIs with the use of a second implant or an HA on the nonimplant ear. Loudness balancing between the two sides may allow for improved speech recognition performance in noisy conditions. In addition, initial testing of the bilateral or bimodal arrangement may not predict the child's full potential with the binaural input. Speech perception may improve gradually over at least a 2-year period (Holt et al., 2005). Children may also benefit from other binaural benefits in "real-life" listening situations including localization, binaural squelch, binaural summation, and reduction of the head shadow effect. This experiment was limited to speech perception; therefore, future studies should include performance of other auditory skills of children with bilateral and bimodal input.

Is Bilateral or Bimodal Input Better?

Although no statistical differences were detected between the two groups, a trend was found in the individual analysis suggesting that a greater number of children in the bilateral group ($N = 8$) relative to the bimodal group ($N = 2$) received significant binaural benefit from binaural relative to monaural input as shown in the first row of Table 9. All but 2 of these children using bilateral implants were mainstreamed into a general education classroom for at least part of the day, and all of these children received their first implant before the age of 3;5. In addition, 6 of the 8 children in the bilateral group with significant binaural benefit used their second implant approximately 1 year prior to testing. Although no correlation was noted for the 12 children using bilateral implants in this study, the duration of the bilateral implant use may have an effect on the child's speech recognition abilities in noise. It is also important to consider that a greater number of children may have shown bimodal benefit with controlled loudness balancing between the implant and HA, a greater degree of residual hearing, or a longer duration of combined HA and CI use.

While greater individual gains in speech recognition in noise were found for children in the bilateral group, the addition of an FM system may be a more feasible option in classroom listening situations. Cost-utility analyses of the benefit of a CI for children with profound deafness are well documented, but no analyses have been done to examine the benefit of two implants relative to one or of adding an FM system (Cheng et al., 2000; Francis, Koch, Wyatt, & Niparko, 1999). As sequential bilateral implantation continues to gain interest in the United States, it will be important to consider the cost-benefit ratio associated with the addition of a second implant relative to a loudness-balanced HA on the nonimplant ear. It is important to note that not all children with a unilateral CI will benefit from the use of an HA on the nonimplant ear, making a second CI the child's only option for binaural listening. In addition, it will be essential to examine the benefits of simultaneous bilateral implantation, which may allow for even greater binaural benefits than what is provided from sequential bilateral implants.

Should a Child With a CI Use an FM System?

A first step that a parent or an audiologist might consider prior to the addition of a second CI or an HA on the nonimplant ear is the use of an FM system with a single CI. As shown in Figure 4, the addition of an FM receiver to a single CI allowed for an average improvement in speech-in-noise thresholds of 13.3 dB relative to the single CI alone. The large improvements are not surprising considering the ability of the FM system to reduce the deleterious effects of the noise and the distance from the talker, although improvements of up to 20 dB are very large for a modified-adaptive testing paradigm.

In order to determine whether additional equipment will provide an additive effect, similar calculations were made between the CI alone condition and the binaural conditions (bilateral or bimodal) with FM on the first side alone, second side alone, and both sides. Average improvements in speech-in-noise thresholds were 13.9 dB for FM to the first side alone, 4.6 dB for FM to the second side alone, and 16.2 dB for FM to both sides relative to a CI alone as illustrated in Figure 4. The individual differences shown in the second row of Table 9 suggest that adding the CI or HA to the second side allowed for significant improvements in speech-in-noise thresholds for 2 of the children in the bilateral group and 5 children in the bimodal group. Therefore, additional equipment does provide an additive effect, with the exception of the use of an FM receiver on the second side alone. The poorer performance in the condition with the FM receiver on the second side may be related to the children's lack of experience with the device on that side, binaural interference, CI programming differences between ears, or a longer duration of auditory deprivation for the second side. Therefore, when a child is using binaural input (sequential bilateral or bimodal) and only one FM receiver is available, it should be placed on the side of the first CI.

These results suggest that an FM system should be considered for children with CIs, which may be a more cost-effective solution for improving speech recognition in noise than an HA or a second CI. When children with CIs are using binaural input, FM input to both sides should be considered as it may allow for binaural redundancy (diotic summation) of the FM signal (Davis & Haggard, 1982; Day, Browning, & Gatehouse, 1988). As shown in the third row of Table 9, 6 children in the bilateral group and 3 children in the bimodal group received significant improvements. In addition, 10 children had no significant differences between the FM input only to the first side and FM-system input to both sides; therefore, FM input to both sides either significantly improved or resulted in no significant decrease in performance for 19 of the 22 children in the study. These findings did not appear to be related to lag time between the first and second implant (bilateral group) or the unaided hearing thresholds in the nonimplant ear (bimodal group). The benefit of FM-system input to both ears for many of the children in this study is in agreement with findings reported for adults with HAs using similar FM systems (Lewis et al., 2004).

Although the results support the use of FM systems with children with CIs, the individual variation shown in Figure 3 and Table 9 highlight the importance of determining an optimal listening arrangement on an individual basis. As shown in Table 9, Participants 6 and 7 in the bilateral group received significant improvements in speech-in-noise thresholds with the addition of a second CI and a second FM receiver, while Participant 4 in the bilateral group actually experienced a significant decrease when adding a second FM receiver. The ideal arrangement for a child may be determined by conducting speech recognition in noise testing with different CI, HA, and FM-system arrangements.

Limitations of the Study

There are numerous factors, including age at testing, age at implantation, duration of first CI, lag time between the first and second implant, and/or hearing thresholds, that likely contributed to the children's significantly better speech-in-noise threshold in one condition relative to another. These factors are difficult to examine with the small number of participants in this study. As the population of children using bilateral CIs increases in the United States, it will be imperative to reexamine factors related to success with different listening arrangements with a larger participant pool. Even with the emerging research available on children using bilateral or bimodal arrangements, group-data analysis and studies cannot replace the need for individual speech-in-noise evaluations to determine the optimal listening arrangement for each child.

Another limitation of this study was the use of one type FM receiver, transmitter, and microphone. Certainly, future studies should examine the benefit of other types of FM systems on speech-in-noise thresholds for children with CIs. Based on previous studies with several of the other manufacturers of FM systems, similar improvements in speech-in-noise thresholds would likely be found with other electrically coupled FM systems for CIs (Schafer & Thibodeau, 2003). Additional benefit may also be measured with the use of a directional microphone on the FM transmitter.

Although the design of the study was aimed at predicting children's speech-recognition performance in a classroom setting, these results cannot be directly related to actual classroom listening abilities. First, the noise in classrooms is constantly fluctuating throughout the day as the teacher moves around the classroom and as children move to different classrooms with different teachers. Second, testing in this study was performed in a sound booth with carefully controlled stimuli and intensity levels. In addition, the stimuli used in the study were closed set, simple, and predictable, which cannot reflect the linguistic demands children face in the classroom. The unpredictable nature of real classroom listening would certainly result in a greater decrement in noise than measured in the present study. Future studies may be performed in real classroom settings to increase the ecological validity of the testing procedures. In addition, it would be valuable to determine whether poorer speech-in-noise thresholds are correlated with a similar report from a child's classroom teacher.

Summary and Clinical Implications

Speech-in-noise thresholds were measured for 22 children who were divided into two groups: bilateral ($N = 12$) and bimodal ($N = 10$). Regarding the issues of monaural versus binaural input, (a) no statistically significant differences were detected for the 22 children with input to two ears relative to one, and (b) 8 children in the bilateral group and 2 children in the bimodal group had a significant improvement with binaural relative to monaural input according to 95% confidence intervals. When comparing bilateral versus bimodal input, no statistically significant differences were found between the two groups for any of the conditions in the study. A comparison of no-FM versus FM system use showed that (a) the FM system allowed for improvements in speech-in-noise thresholds up to 20 dB relative to the no-FM conditions, and (b) statistically significant differences were detected among the FM-system conditions with FM-system input to the first CI or to both sides providing superior performance.

These results suggest that for a child with a single CI, use of an FM system may provide more improvement in speech recognition in noise than the addition of an HA or a second CI. Children using input to the second ear may receive other binaural benefits including localization and the reduction of the head shadow effect, which were not addressed in this study. For a child currently using a bilateral or bimodal arrangement, FM-system input to two ears relative to one may provide significant binaural benefits.

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