Improvements in Speech Recognition Using Cochlear Implants and Three Types of FM Systems: A Meta-Analytic Approach

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A meta-analytic approach was used to compare improvements in speech recognition of children and adults with cochlear implants (CIs) when using traditional soundfield, desktop soundfield, and direct-audio input (DAI) frequency-modulated systems. There was no significant benefit from traditional soundfield systems when compared to the CIs alone. No significant difference was detected between traditional and desktop soundfield receivers. The DAI receivers provided significantly greater gains in speech recognition when compared to the desktop receivers. According to the results of this analysis, audiologists working with CIs should recommend receivers that directly connect to the CI speech processor (i.e., DAI).

Introduction

Cochlear implantation is often recommended for children who have severe-to-profound sensorineural hearing impairments and limited speech-recognition abilities when using traditional amplification. The internal portion of a cochlear implant (CI) consists of a surgically implanted receiver-stimulator and electrode array, which stimulates the auditory nerve fibers. The external components include a microphone and a speech processor, which codes acoustic information according to a processing strategy. Electrical stimulation of children's auditory nerve fibers at an early age with the use of a CI often facilitates the development of open-set speech understanding in quiet listening situations (Geers, 2004; Geers, Brenner, & Davidson, 2003; Osberger, Zimmerman-Phillips, & Koch, 2002; Waltzman, Cohen, Green, & Roland, 2002). However, children's speech-recognition performance significantly declines by up to 35% in the presence of any type of background noise (Davies, Yellon, & Purdy, 2001; Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Litovsky et al., 2004).

Background noise is pervasive in most listening environments including the home, workplace, and the classroom. Typical acoustics in the schools rarely meet published guidelines of 35 dBA noise levels in unoccupied classrooms and +15 signal-to-noise ratios (SNR) in occupied classrooms (American Speech-Language-Hearing Association, 2005). Therefore, these classrooms cannot ensure children are learning in the least restrictive environment as required by federal law and recommended by speech and hearing organizations (American Speech-Language-Hearing Association, 2005; Individuals with Disabilities Education Improvement Act, 2004). For example, one study reports unoccupied noise levels of 32 elementary school classrooms ranging from 34 to 66 dBA with only one classroom meeting the ASHA criterion (Knecht, Nelson, Whitelaw, & Feth, 2002). Given the typical unoccupied noise levels of classrooms, it is difficult to achieve the recommended +15 SNR without amplifying the teacher's voice. Furthermore, children with hearing loss and cochlear implants require even higher SNRs than +15 SNR (Anderson, Goldstein, Colodzin, & Iglehart, 2005; Schafer & Thibodeau, 2003). Therefore, frequency-modulated (FM) systems are often recommended for children who have CIs (American Speech-Language-Hearing Association, 1991, 2005; Arnold & Canning, 1999; Bess, Sinclair, & Riggs, 1984; Knecht et al., 2002). Use of an FM system combats the deleterious effects of noise and reverberation in the classroom by improving the SNR at the child's ear. The SNR improvements are achieved when the teacher uses an FM transmitter, which sends the signal to an FM receiver. Once the FM receiver detects the speech signal from the transmitter, the information may be sent through (1) traditional soundfield speakers mounted to the ceiling or wall, (2) a desktop soundfield speaker, or (3) a receiver electrically coupled to the child's CI speech processor.

Traditional soundfield systems consist of a transmitter, receiver, and speakers placed around a room. These systems are often considered advantageous because the improved SNR is provided to all of the children in the classroom, the children do not have to wear any extra equipment, and the systems are easy to troubleshoot. However, the mounted speakers are not portable and provide variable improvements in SNR, which are dependent on the location of the listener relative to a loudspeaker and the amount of noise and reverberation present in the classroom.

Studies examining the benefits of traditional soundfield systems provide varied findings. Results of two studies, with 6 to 10 participants each, suggest no significant benefit for children and adults with CIs when using traditional soundfield FM systems as compared to performance with the CI alone in noise (Anderson et al., 2005; Crandell, Holmes, Flexer, & Payne, 1998). However, one author does report significantly improved performance of approximately 11% for 14 children with CIs while using a traditional soundfield system in both acoustically poor and ideal rooms (Iglehart, 2004). Given the limited research on the benefits of traditional soundfield FM systems, small sample sizes, and variable findings in the aforementioned studies, further research is necessary to determine the effectiveness of this type of system for people using CIs. The recent position statement from the Acoustical Society of America (n.d.) also supports the need for further research. This position statement suggests that soundfield amplification should not be routinely used in typical small mainstream classrooms because they are not effective in reverberant rooms and increase overall sound levels in the classroom. Furthermore, the position states that other types of FM systems are more effective for students who have hearing loss.

Desktop soundfield systems consist of a transmitter and a receiver that is electrically connected to a small speaker. The portable speaker is often placed in front of the listener on a desk or tabletop and is fairly easy to transport throughout the school day. Similar to classroom soundfield systems, the desktop system does not require the child to wear any additional equipment and is easy to troubleshoot. The amount of noise and reverberation in a classroom directly affects the amount of benefit a child receives from a desktop system, but this type of receiver often provides more gain to the child than a classroom soundfield system. Desktop systems may not be feasible for some children who independently move to different parts of a building throughout the school day, receive direct instruction while sitting on the floor, or move around to various activity centers during class.

Authors of two studies report significant improvements in speech recognition in noise when using a desktop soundfield system relative to performance with a CI alone (Anderson et al., 2005; Schafer & Thibodeau, 2003). When subtracting the no-FM-system performance from the scores with the desktop system, average improvements of the six to ten participants ranged from 9.8 to 25.2% (Anderson et al., 2005; Schafer & Thibodeau, 2003). However, in another study, Schafer and Thibodeau (2004) did not report significant improvements for eight adults with CIs when using a desktop soundfield system compared to the CI alone. One study provides a comparison of performance with traditional and desktop soundfield systems. Iglehart (2004) reports significantly better speech-recognition performance of 14 participants with the desktop relative to scores with the traditional soundfield FM system in an acoustically poor and ideal environment. Similar to traditional soundfield systems, the limited research on desktop soundfield systems for use with CIs, small sample sizes, and lack of consensus among the available studies warrants further research.

Personal FM systems for CIs consist of a transmitter and a receiver that is electrically connected to the speech processor via adaptors, cords, or special earhooks. These body-worn or ear-level receivers provide direct-audio input (DAI) into the child's speech processor. These devices are generally easy to transport to different classrooms throughout the school day and will likely provide the most consistent SNR at the child's ear. According to comparisons across different DAI receiver models, there are no significant performance differences when using body-worn and ear-level FM receivers from various manufacturers (Schafer & Thibodeau, 2003, 2004).

DAI receivers significantly improve speech-recognition performance of children and adults with CIs (Aaron, Sonneveldt, Arcaroli, & Holstad, 2003; Anderson et al., 2005; Catlett & Brown, 2003; Schafer & Thibodeau 2003, 2004; Wolfe & Schafer, in press, 2008). In these studies, the average improvements with the DAI receivers ranged from 9 to 56% relative to the no-FM-system conditions. Three studies of 6 to 10 participants each compare the benefits of desktop soundfield systems and DAI receivers (Anderson et al., 2005; Schafer & Thibodeau, 2003, 2004); however, the results among the experiments are variable and inconclusive. In two of the three studies, authors report no performance differences between the desktop and DAI receivers (Anderson et al., 2005; Schafer & Thibodeau, 2003), while the remaining study does report significant differences in speech recognition with the two types of systems (Schafer & Thibodeau, 2004). While it is clear from existing studies that DAI receivers significantly improve listening in noise, it is unknown whether these systems provide the same or greater benefits than traditional and desktop soundfield systems.

Despite the mounting research evidence that FM systems significantly improve speech-recognition performance in noise, they are not always recommended for children who use CIs. According to a survey conducted by Phonak in 2003, only 46% of children with CIs who are seen by audiologists (N=209) are using FM systems, despite reports that 99% of audiologists (N=239) see these children as candidates for FM-system technology (*Participant surveys*, 2003). When asked what factors are preventing the audiologists (N=246) from implementing the use of FM systems for children with CIs, they report one of four primary reasons: concern about the variability between systems and among individuals (26%), lack of understanding about the benefits of FM systems (25%), intimidation (24%), and limitations relating to cost (22%). Some of the audiologists' concern and confusion may be related to reports of variable FM-system benefits in research studies and the lack of consensus regarding which type of FM system is most optimal for children with CIs.

Given the disparity of findings in current FM-system research, it is challenging to make sound treatment decisions regarding the optimal device for children and adults with CIs. The limited number of studies, small sample sizes in current research, and lack of strong evidence across all types of FM receivers warrants further investigation. One way to explore treatment efficacy in audiology is to conduct a meta-analysis on scientifically rigorous studies. A meta-analysis synthesizes data from a set of similar studies and yields cumulative results aimed at addressing one or more research questions. The American Speech-Language-Hearing Association (ASHA) strongly encourages audiologists to use the principals of evidence-based practice, including meta-analyses, in order to promote high-quality patient care (ASHA, 2004). In fact, ASHA declares that a well-designed meta-analysis is the highest-ranking and most credible form of evidence for treatment efficacy. When conducting meta-analyses, ASHA recommends use of rigorous criteria, as published in the Cochrane Collaboration Handbook (Higgins & Green, 2006), for determining which studies to include in the analysis. The stringent criteria outlined in the Cochrane Handbook include a thorough search of all possible studies, use of specific criteria for study inclusion, and use of appropriate statistical analyses to summarize results. Given the power of the analysis and cumulative nature of the results, meta-analyses are commonly published in medical literature and are becoming increasingly popular in the field of communication disorders.

Further research is vital in the area of FM systems and CIs to foster evidence-based clinical decisions for children and adults. A meta-analysis is warranted because, to date, no large-scale study compares the benefits of all three types of FM receivers. The sole study that compares performance with all three types of FM receivers has only six participants (Anderson et al., 2005). Furthermore, in the additional three small-scale studies that compare performance with two types of receivers, the findings are variable, without agreement on the better system (Iglehart, 2004; Schafer & Thibodeau, 2003, 2004). Therefore, the purpose of the present study is to use a meta-analytic approach to compare the relative improvements in speech recognition in noise of children and adults with CIs when using traditional soundfield, desktop soundfield, or DAI FM receivers. The following research questions will be addressed:

1. Do traditional soundfield, desktop soundfield, and DAI FM receivers provide significantly better speech recognition in noise than performance with a CI alone?
2. What type or types of FM receivers provide the greatest improvements in speech recognition relative to a CI alone?

Methods

Selection of Studies and Study Characteristics

As shown in Tables 1 and 2, nine studies were identified for inclusion in the analysis. Using recommendations from the Cochrane Handbook (Higgins & Green, 2006), all studies in the meta-analysis met the following stringent inclusion criteria: use of (1) within-subjects designs (repeated measures), (2) randomized-listening conditions, (3) multiple randomized stimuli lists, and (4) more than one participant. Within-subject designs are beneficial because the variance across subjects is removed, thereby increasing the power of the study. This design controls for the varied individual subject characteristics, such as age of participant, gender, etiology of hearing loss, duration of deafness, type of implant, and receptive-language level. In all studies, practice or carry-over effects were minimized by the randomized order of conditions and stimuli lists. The repeated measures in each study included a no-FM and one or more FM-system conditions. Three additional inclusion criteria were chosen to minimize variability related to methodological differences across studies. These included: (1) the evaluation of speech recognition in noise, (2) the use of a fixed SNR ranging from +5 to +20 dB, and (3) children and adults using monaural CIs.

Data from children ($<$ 18 years) and adults ($\geq$ 18 years) are included in the meta-analysis because the benefits achieved from FM-system use are similar for the two age groups. This is evidenced by a comparison of FM benefit for children and adults using desktop soundfield systems in the Anderson et al. (2005) and Schafer and Thibodeau (2004) studies. When subtracting the FM score from the no-FM score, children and adults received average improvements of 9% and 10%, respectively, for the same stimuli. Analogous results are found for comparisons of other studies. The similarity of FM benefits between children and adults with CIs were further evidenced in the *post-hoc* results section of this paper, where we specifically compare data from these two age groups across several types of stimuli.

The published studies were found using multiple electronic reference databases (e.g., PubMed, ERIC) and a manual search of journals and references in published literature (Anderson et al., 2005; Crandell et al., 1998; Iglehart, 2004; Schafer & Thibodeau, 2003, 2004). Search criteria were limited to publications and presentations from January 1998 to August 2007 that included English-speaking subjects and were written in English. In addition to published studies, two unpublished, non-peer-reviewed studies (Aaron et al., 2003; Catlett & Brown, 2003) were included because they met the stringent inclusion criteria for the meta-analysis. The inclusion of unpublished data in a meta-analysis is recommended by the Cochrane Collaboration to ensure use of all available data and to avoid publication bias (Higgins & Green, 2006). These studies may have non-significant findings or null hypotheses that many peer-reviewed journals neglect to publish because of a wealth of submitted papers indicating statistical significance (Rosenthal, 1979). Utilizing unpublished studies in meta-analyses is a common practice in communication disorders (Amlani, 2001; Cheng, Grant, & Niparko, 1999) and medical fields (Afilalo et al, 2008; Anzarut, Olson, Singh, Rowe, & Tredget, 2009).

Data from the two unpublished studies were acquired by obtaining copies of oral and poster presentations from national conferences and contacting authors for further details. These data met the strict inclusion criteria, and they did not differ from results of published studies, which will be discussed in greater detail in the results section of the main analysis. Finally, four published or unpublished studies were identified, but not included, in the analysis for failure to meet the inclusion criteria (Davies et al., 2001; Schafer & Thibodeau, 2006; Thibodeau et al, 2005; Wood, Flynn, & Greenham, 2005).

The participant characteristics and the equipment used in the studies are provided in Table 1. One study included both adult and child participants, and data for the two age groups were analyzed separately (Crandall et al., 1998). The speech processors used by the participants included all current manufacturers: Advanced Bionics™, Cochlear™ Corporation, and MED-EL. The manufacturer and model of the FM systems and location of the transmitter microphone during the FM-system conditions are also given in Table 1. The distance of the transmitter microphone relative to the loudspeaker or talker ranged from 3 to 12 inches, which was often dependent on the type of transmitter microphone in use (e.g., 3-4 inches for boom, 6-12 inches for lapel). Iglehart (2004) used an arrangement where, rather than placing the microphone in front of a loudspeaker, the transmitter was coupled directly to a computer which delivered the speech signal via patch cords. In addition to the input to the transmitter microphone in the FM-system condition, the speech stimuli were delivered through a signal speaker at 0-degrees azimuth and multi-talker babble was presented through four loudspeakers placed around the room. Thus, the FM-system signal was directly transmitted from the computer signal and was not processed through an external microphone. Interestingly, Iglehart (2004) was the only study reporting significant traditional soundfield benefit. These results may have been attributed to reduced feedback between the classroom speakers and the transmitter, as well as the possibility of the transmitter not detecting ambient noise present in the room.

The speech stimuli, noise stimuli, SNR, type of presentation (e.g., live voice), and loudspeaker arrangement are provided in Table 2. All researchers used word or sentence stimuli in the presence of speech-weighted noise, multi-talker babble, or cafeteria noise. Most authors used a +5 or +6 SNR, while two authors used either a +10 (Anderson et al., 2005) or a +18 SNR (Iglehart, 2004) in some conditions. The varied SNRs used in the studies did not appear to influence the results of the meta-analysis, which are discussed further in results section.

Identifying Study Statistics

Each no-FM-system condition and FM-system condition in a study was paired and treated as an independent experiment to increase the overall sample size. Each independent experiment was then grouped according to the type of FM receiver: traditional soundfield, desktop soundfield, or DAI. Ten experiments were identified for the traditional soundfield FM system group (N=98), five experiments were in the desktop soundfield group (N=52), and 20 experiments were included in the DAI group (N=228). The data extracted for each independent experiment included the sample size, mean, and standard deviation for the no-FM-system and FM-system conditions. The majority of this data was found in tables, figures, or within text. If the data was not clearly provided in the publication or poster presentation, it was obtained through direct communication with the authors.

Table 1
Description of Participant Characteristics and Equipment Used in Studies

Author (year)	N	Age Range (years)	CI Company	CI Processor	Manufacturer/ FM Receiver	Transmitter Mic Location
Aaron (2003)	24	4 - 12	CC	SPrint	Phonak/ MicroLink	4 inches
Anderson (2005)	6	7 - 13	CC	3G, SPrint, ESPrit	PE/ 900R Vocalight, LS/ LES 390 Desktop, Phonak/ MicroLink CI+	3.5 inches
Catlett (2003)	18	17 - 18	ABC	Clarion 1.2, CII	Phonak/ MicroLink CI S	12 inches
Crandell (1998)	18	18 - 80	CC	Spectra	Audio Enhancement Omni Deluxe	3 inches
Iglehart (2004)	14	6 - 16	ABC, CC	S-Series, SPrint, Spectra, ESPrit 22, Clarion 1.2	PE/ Toteable, PE/ 210 Soundfield System	DAI from computer to loudspeaker
Schafer (2003)	10	7 - 12	CC, M	ESPrit 22, 3G, Tempo	PE/ Toteable, PE/ Easy Listener, AVR/ Logicom CI, Phonak/ Microlink CI+	6 inches
Schafer (2004)	8	20 - 58	CC	Spectra, SPrint, ESPrit 22/24	PE/ Toteable, PE/ Easy Listener, AVR/ Logicom CI	3 inches
Wolfe (in press)	5	6-17	ABC	Auria®	Phonak/ MLxS	6 inches
Wolfe (2008)	12	40-71	ABC	Auria®	Phonak/ MLxS	6 inches

Note. Studies are listed by first author. N=number of participants; CI=cochlear implant; MIC=microphone CC=Cochlear Corporation, ABC=Advanced Bionics Corporation; M=MED; EL Corporation; PE=Phonic Ear.

Data Analysis

Data were analyzed using statistical software (Hintze, 2007). Percent-correct difference scores (FM – no FM score) and corresponding 95% confidence intervals were calculated for each individual experiment. These relative differences allowed for comparisons of the FM-system benefits obtained in individual experiments. In addition, data from the individual experiments were combined to calculate weighted-average difference scores and 95% confidence intervals for each FM-receiver group (traditional soundfield, desktop soundfield, and DAI). The individual experiments within each receiver group were weighted, or given a value rating by predetermined formulas within the statistical software program (Hintze, 2007). A larger weight was given to studies with larger sample sizes and smaller standard deviations, which gave these studies more influence on the final results. The combined-group-weighted averages and 95% confidence intervals allowed for comparisons across the three types of receivers.

The data were analyzed using a random effects model (Berlin, Laird, Sacks, & Chalmers, 1988), which accounts for variation between and within studies. A chi-square value was computed to test the null hypothesis that there was no benefit from use of an FM system. A forest plot was used to display the difference scores from the individual experiments and from each of the FM-receiver groups (i.e., traditional soundfield, desktop, DAI). The individual-experiment and combined-group symbols on the forest plot represent average performance, and the corresponding lines indicate the 95% confidence intervals, or the range of difference scores that would be expected from a similar population of listeners. Within each receiver group, the individual experiments with greater numbers of participants are represented by larger symbols. On the forest plot, significant improvements in speech recognition with the use of the FM receiver were identified by comparing the upper and lower limits of the 95% confidence intervals to the 0% difference, no-FM-system-benefit line. Individual experiments and receiver groups resulting in significant FM-system benefits did not overlap with the 0% difference line. In order to determine if the performance in individual experiments or receiver groups were significantly different, the confidence intervals were compared. Confidence intervals that did not overlap were considered significantly different. Therefore, the non-overlapping 95% confidence intervals between individual experiments and among receiver groups resulted in the acceptance of the alternate hypothesis of significant difference ($p \leq 0.05$).

Table 2
Description of Stimuli, Speaker Arrangements, and Conditions in Studies

Author (year)	Stimulus/ Noise	SNR/ Presentation Type	Loudspeaker Arrangement (Signal/ Noise)	Conditions
Aaron (2003)	Sentences/ Multi-talker babble	+5 dB/ Recorded	0°/90° at CI	DAI
Anderson (2005)	Sentences/ Hospital cafeteria	+10 dB/ Recorded	0°/180°	T, D, DAI
Catlett (2003)	Sentences/ Speech	+5 dB/ Recorded	0°/90° at CI	DAI
Crandell (1998)	Patterns, Words/ Multi-talker babble	+6 dB/ Live voice	0°/90° at CI	T
Iglehart (2004)	Words/ Multi-talker babble	+5, +18 dB/ Recorded	0°/45°, 135°, 225°, & 315°	T, D
Schafer (2003)	Sentences/ Speech	+5 dB*/ Recorded	0°/90 & 270°	D, DAI
Schafer (2004)	Sentences/ Speech	+5 dB/ Recorded	0°/90 & 270°	D, DAI
Wolfe (in press)	Words, Sentences/ Multi-talker babble	+5 dB/ Recorded	0°/180°	DAI
Wolfe (2008)	Words, Sentences/ Multi-talker babble	+5 dB/ Recorded	0°/180°	DAI

Note. Studies are listed by first author. Loudspeaker arrangement is in degrees azimuth relative to the listener's head in the no-FM system conditions. SNR=signal-to-noise ratio; CI=cochlear implant; DAI=direct-audio input; T=traditional soundfield; D=desktop soundfield; *2 of 10 children in the study had a 0 dB SNR.

Results

The data for 35 individual experiments and corresponding 95% confidence intervals are illustrated in the forest plot in Figure 1 and summarized in Table 3. Weighted-average difference scores and 95% confidence intervals are shown for each receiver group and for all receiver groups combined. In the following paragraphs, the results are discussed for (1) all FM systems combined, (2) each receiver type separately, and (3) the comparisons among FM-receiver groups. Findings from the primary analysis are followed by results from several *post-hoc* analyses.

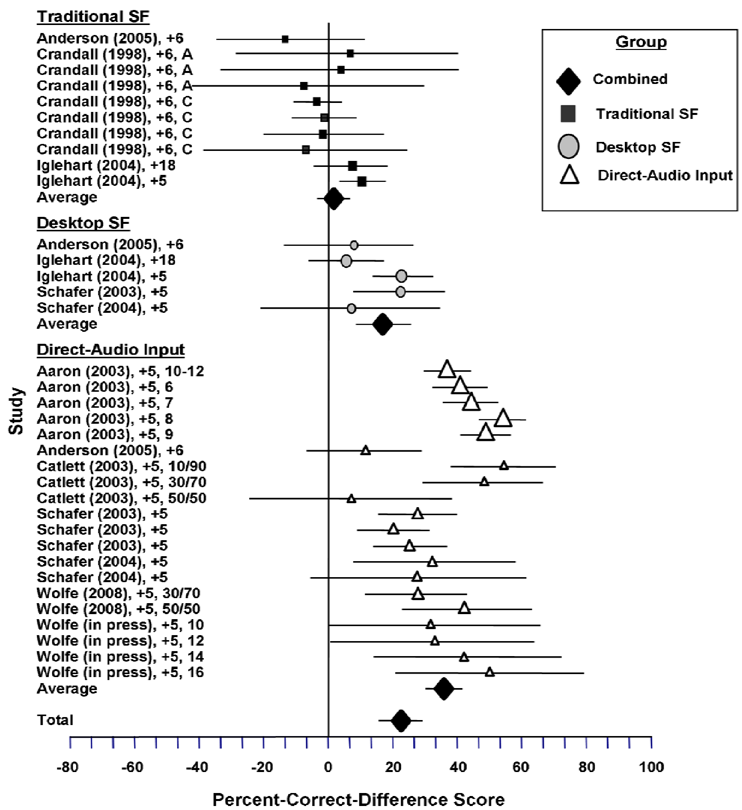
Combined Results

According to the results in Figure 1, the weighted-average improvement in speech recognition in noise with an FM system across all receiver types was 24.5% (±6.9) and was significant relative to performance with a CI alone (X^2 [35, 378] = 1056.8, $p < .0001$). This finding suggests use of an FM system should improve a listener's speech-recognition performance by 18 to 31% when compared to performance with a monaural CI. Despite the significance of the overall findings, an examination of the 95% confidence intervals across all of the individual experiments suggests only 57% (20/35) showed significant improvements in speech recognition.

Receiver Group Results

For traditional soundfield systems, the average-weighted difference between the no-FM system and FM-system conditions was 3.5% (±5.1). As shown in Figure 1, the 95% confidence

Figure 1. Forest plot of FM-system benefits with three types of receivers.



Note. Studies are listed by first author, and horizontal lines represent the 95% confidence intervals. A=adult; C=child. Ratios (e.g., 50/50) represent amount of input from the FM system relative to input from the speech processor microphone. Numbers are FM-advantage settings programmed into the receiver (e.g., 10-12).

interval for this receiver group overlaps with the 0% difference line, suggesting no significant benefit from use of the traditional soundfield systems relative to a CI alone (X^2 [10, 98] = 16.3, $p = 0.0927$). Examination of the 95% confidence intervals for the individual experiments shows only 10% (1/10) of the individual experiments demonstrated significant benefits from use of this type of FM receiver when compared to performance with a CI alone. The 95% confidence intervals for all individual experiments overlapped, suggesting similar results across the experiments.

According to group results with the desktop soundfield FM receiver, the average improvement was 17.1% (±8.8) relative to the no-FM system conditions. The confidence intervals for the weighted-average score do not overlap with the 0% line, which supports a significant increase in speech-recognition scores with the use of the desktop system (X^2 [5, 52] = 49.0, $p < .0001$). According to the results of the individual experiments, 40% (2/5) of the paired conditions yielded significantly better performance in the desktop condition relative to the no-FM condition. The overlapping confidence intervals suggest performance in these experiments is similar regardless of methodology, which addresses possible issues related to the limited number of individual experiments in this receiver group. Therefore, the results likely provide a representative sample of typical performance with a desktop soundfield system.

Use of the DAI system provided an average-weighted improvement of 38.0% (±5.7) relative to the no-FM-system condition. According to the analysis, the DAI receiver significantly improved speech-recognition performance when compared to a CI alone (X^2 [20, 228] = 991.6, $p < .0001$). Eighty-five percent (17/20) of the individual experiments in the DAI receiver group illustrated significant improvements when using the FM system relative to a CI alone. Seventy-five percent of the 95% confidence intervals for the individual experiments overlapped, suggesting most DAI arrangements provided similar benefits. Potential causes of the minimal variability among some experiments will be explored in the discussion section.

Comparisons Among Receiver Groups

To examine the magnitude of improvement obtained from use of the various types of FM receivers, the average-weighted improvements and corresponding confidence intervals were compared for the three receiver groups. The 95% confidence intervals that did not overlap between receiver groups were considered significantly different ($p < .05$). As shown in Figure 1 and Table 3, the 95% confidence interval for the traditional soundfield group (3.5% ±5.1) overlaps with the confidence interval for the desktop soundfield group (17.1% ±8.8), suggesting no difference in the amount of FM-system benefit achieved between these groups. Therefore, the desktop receiver provided significant improvements in speech recognition relative to a monaural CI, but the difference scores were no greater than what would be expected when using a traditional soundfield system. However, it is important to note that the overlap of the 95% confidence intervals for these two receiver groups was slight. If a larger number of individual experiments were available for the desktop soundfield group, the power of the model would increase and the 95% confidence interval would likely decrease, assuming the results were similar to other experiments. This increased sample size may result in significantly different weighted-average performance when compared to the traditional soundfield group. The confidence intervals for the DAI (38.0% ±5.7) receivers did not overlap with the intervals for either the traditional or the desktop soundfield receivers. Overall, the desktop soundfield and DAI receivers both provided significant improvements in speech recognition relative to a CI alone, but the DAI receiver provides significantly greater improvements when compared to the other receiver types.

Table 3
Results from Meta-Analysis

Group	DF	N	Average Improvement (± CI_{95})	Chi-Square Value	Probability Level
Traditional SF	10	98	3.5% (± 5.1)	16.3	0.0927
Desktop SF	5	52	17.1% (± 8.8)	49.0	< 0.0001
Direct-Audio Input	20	228	38.0% (± 5.7)	991.6	< 0.0001
Combined	35	378	24.5% (± 6.9)	1056.8	< 0.0001

Note: Average improvement is relative to the no-FM system condition. DF=degrees of freedom and number of experiments; N=total number of subjects; CI_{95}= 95% confidence Intervals; SF=soundfield.

Post-Hoc Analyses

Several *post-hoc* analyses were conducted to examine whether additional factors may have contributed to greater FM-system benefit in one receiver group relative to another. Data for these analyses were categorized according to type of FM receiver and were examined for effects related to the (1) age of participant, (2) type of internal implant, (3) type of speech processor, and (4) type of noise. Some studies did not provide the information necessary for inclusion in the *post-hoc* analyses; therefore, not every individual experiment was included in the following results. Analyses were conducted with a minimum of two individual experiments and 10 participants per group. (See Table 4)

Age of participants. Sufficient data were available to examine benefits from use of traditional soundfield and DAI receivers when separated into child (< 18 years) and adult (> 18 years) age groups. No significant differences in the amount of FM-system benefit were detected between children and adults when using traditional soundfield ($p > 0.05$) or the DAI FM receivers ($p > 0.05$). Similar to the findings in the main analysis, the traditional soundfield system did not provide significant improvements ($p > 0.05$) in speech recognition for adults relative to performance with their CI alone. Conversely, children received significant improvements in speech recognition when using the traditional soundfield system relative to their CI alone ($p = 0.03$). While this finding was statistically significant, a 3.3% (±6.2) improvement in speech recognition is not clinically significant or likely to improve overall listening abilities. Use of the DAI receiver significantly improved performance of both children and adults relative to the no-FM condition ($p < 0.01$). This analysis is also representative of results for pre- and post-lingually deafened individuals because the majority of the children lost their hearing before the age of one year, and most adults lost their hearing later in life. Overall, there were no age effects, which suggests that children and adults with CIs receive similar benefit from FM-system use.

Type of internal implant. This analysis included results for people using a Nucleus® 22 or a Nucleus® 24 internal implant from Cochlear™ Corporation or a Clarion CII or HiRes™ 90K internal implant from Advanced Bionics™. Data were provided for Nucleus® 22 and 24 implants with the desktop soundfield receiver and all four aforementioned implants with the DAI receiver. According to the analysis, there were no significant differences ($p > 0.05$) in the amount of FM-system benefit received by users of Nucleus® 22 and 24 implants with desktop soundfield receivers, and both types of implant allowed for significant gains in speech recognition in noise ($p < 0.001$).

Table 4
Post-Hoc Testing Results

Effect	Group	DF	Average Improvement (± CI_{95})	Chi-Square Value	Probability Level
Age	Adult: Trad SF	3	1.0% (± 19.2)	0.3	0.9570
	Child: Trad SF	7	3.3% (± 6.2)	15.9	0.0257
	Adult: DAI	4	34.0% (± 9.9)	47.1	< 0.0001
	Child: DAI	16	38.5% (± 6.4)	944.5	< 0.0001
Internal Implant	N22: Desktop	3	24.1% (± 10.5)	20.5	0.0001
	N24: Desktop	4	22.5% (± 14.8)	38.2	< 0.0001
	CII: DAI	2	31.3% (± 23.2)	7.2	0.0278
	90K: DAI	2	37.1% (± 18.1)	32.9	< 0.0001
	N22: DAI	5	33.1% (± 3.0)	456.1	< 0.0001
	N24: DAI	11	39.9% (± 6.4)	773.7	< 0.0001
Processor	Sprint	8	35.1% (± 13.2)	721.9	< 0.0001
	ESPrit 22	3	33.2% (± 3.9)	445.9	< 0.0001
	ESPrit 3G	4	30.4% (± 10.8)	33.4	< 0.0001
	Auria®	6	37.7% (± 8.7)	76.2	< 0.0001
Type of Noise	Speech: Desktop	2	21.2% (± 13.7)	15.9	0.0004
	Babble: Desktop	3	15.1% (± 12.7)	33.1	< 0.0001
	Speech: DAI	8	33.5% (± 10.5)	192.7	< 0.0001
	Babble: DAI	12	41.0% (± 6.2)	798.9	< 0.0001

Note. Trad SF=traditional soundfield FM system; DAI=direct-audio input FM receiver; DF=degrees of freedom and number of experiments; N22/24=Nucleus 22/24; CI_{95}=95% confidence interval.

In addition, there were no differences among the four types of internal implants with the DAI receivers ($p > 0.05$), as the 95% confidence intervals overlapped. All four internal implants provided significantly better speech-recognition performance than the implant alone ($p < 0.05$). Based on these findings, FM-system benefit does not appear to be contingent upon the type of internal implant.

Type of processor. A third *post-hoc* analysis was conducted to determine the benefit of DAI receivers with four types of speech processors, Cochlear™ Corporation ESPrit™ 3G, ESPrit™ 22, and SPrint™ and Advanced Bionics™ Auria®. Comparisons between 95% confidence intervals suggested no significant differences in performance among the speech processors ($p > 0.05$). All four speech processors provided significant gains in speech recognition in noise when compared to the no-FM-system condition ($p < 0.001$). These findings show that the type of processor likely does not impact gains in speech recognition with an FM system.

Type of noise. A final *post-hoc* analysis was conducted to determine differences in the amount of FM-system benefit from a desktop or DAI receiver when using continuous speech-weighted noise versus multitalker-babble noise. The multitalker-babble group also included cafeteria noise (Anderson et al., 2005). No significant differences were detected between the experiments using speech noise relative to those using multitalker-babble noise for the desktop or the DAI receivers ($p > 0.05$). Significant improvements in speech recognition were obtained with both types of receivers relative to performance with no FM system ($p < 0.001$). These findings suggest use of either type of noise is sufficient for measuring the benefits of FM systems for users of CIs.

Discussion

According to the main analysis, combined results across all types of FM receivers suggested significantly improved speech recognition in noise for children and adults relative to performance with no FM system (FM score – no-FM score). Traditional soundfield receivers did not improve speech recognition in noise; however, desktop and DAI did significantly improve performance relative to a CI alone.

Comparisons among receiver groups show no difference between traditional and desktop soundfield receivers. The DAI receivers provided significantly greater improvements in speech recognition than the traditional or the desktop soundfield receivers. Although some previous studies were unable to differentiate participant scores for desktop soundfield and DAI receivers (Anderson et al., 2005; Schafer & Thibodeau, 2003), the meta-analysis provided strong evidence that electrically-connected receivers provide optimal speech recognition in noise. The primary difference between the present and past studies is the greater power and larger number of participants achieved for the current study. The meta-analysis of the data from nine studies allowed for large groups of participants in the traditional soundfield (N=98), desktop soundfield (N=52), and DAI (N=228) receiver groups. In summary, the weighted-average difference scores between the no-FM and FM-system conditions show DAI receivers provided the greatest improvements in speech recognition in noise.

When examining individual experiments in Figure 1, the 95% confidence intervals overlap across all studies in the traditional and desktop soundfield groups. In addition, 75% of confidence intervals overlapped in the DAI group. The differing 95% confidence intervals may be related to factors including the type of DAI receiver, sensitivity or audio-mixing settings of the speech processors, programmability of the FM advantage on the receivers, and the number of participants in the experiment. Certainly, the various DAI receivers from a variety of manufacturers could have been related to the differing confidence intervals. The type of receiver and the way it is coupled is highly dependent on what speech processor is in use. Older ear-level and body-worn processors often require patch cords to connect to a DAI receiver, while some newer processors may only require specialized adaptors, earhooks, or receivers (e.g., Auria®, ESPrit™ 3G, Freedom™).

Another source of variability among the individual experiments in the DAI group may be related to the programming or settings on the speech processor. On some speech processors, the amount of FM-system input a listener may receive relative to the input from the processor microphone is controlled with audio-mixing settings or ratios that are accessible on the speech processor or programmed into the MAP (e.g., ESPrit™ 3G, Auria®). Three studies included in the meta-analysis examined the effects of audio-mixing ratios or sensitivity settings on participant's speech recognition in noise (Aaron et al., 2003; Catlett & Brown, 2003; Wolfe & Schafer, in press, 2008). Within each study, the overlapping 95% confidence intervals for the various mixing ratios and sensitivity settings suggest these variables should not affect the amount of speech-recognition improvement for the majority of the population.

Variability may also be related to the programmability of the FM receiver. Many newer DAI receivers may be programmed or set to provide different levels of FM-system input to the processor (i.e., FM advantage or gain). The effects of these settings were examined with children in several conditions of the Wolfe & Schafer (in press) study, and the overlapping confidence intervals in these experiments are evidence that most children with CIs will not exhibit significantly different performance with various gain settings on the FM receiver.

According to the *post-hoc* analyses, there were no effects of the age of the participant, the internal implant the participant was using, the type of speech processor, nor the type of noise used during testing. The *post-hoc* analysis on effects of age confirms that the benefit from FM systems is similar for children and adults. Therefore, the inclusion of adults and children in the same analysis is appropriate, and the results apply to recommendations for both populations of listeners. No differences were found across several types of internal implants and speech processors showing that FM benefit is similar across internal and external CI devices. Finally, results were similar regardless of the whether continuous speech noise or babble was used.

Clinical Implications

According to a survey of audiologists (*Participant Surveys*, 2003), many professionals are concerned about the variability between systems and among individuals and are intimidated by FM-system technology for users of CIs. The surveyed audiologists believe people who use CIs are candidates for FM-system technology, yet only 50% of their patients are using FM systems. The results of this meta-analysis provide evidence regarding the effectiveness of FM systems for improving speech recognition in noise for a large population of pediatric and adults listeners using CIs. The results obtained through the meta-analysis support that the majority of listeners with CIs would gain significant improvements in speech recognition when using FM systems with desktop soundfield or DAI receivers. Specifically, the systems that are electrically connected to speech processors (DAI) provide the greatest improvements in speech recognition in noise. Similar benefits are reported for use of two DAI receivers for children using bilateral CIs or bimodal stimulation with a CI and a hearing aid on the non-implant ear (Schafer & Thibodeau, 2006). With the recent evidence supporting binaural-listening arrangements for users of CIs, audiologists may consider use of two receivers for children who use bilateral CIs or bimodal stimulation.

The audiologists' concerns about performance variability (*Participant surveys*, 2003) may be eased by the significant FM-system benefits obtained by the large number of listeners with CIs in this meta-analysis. While these findings do not alleviate the intimidation many audiologists feel when trying to determine how to couple FM systems to speech processors, the results do support that DAI coupling is worth the effort of determining the necessary patch cords or adaptors. Manufacturers of FM systems recognize the challenge of connecting systems to processors and have responded by creating specialized websites that outline necessary equipment according to the type of processor. In addition, they provide step-by-step directions for coupling devices (*eSchoolDesk,* n.d.). Continued research on the benefits of FM systems for children and adults with CIs will increase audiologists' knowledge on FM system fitting practices and lend further support for FM system fittings as a standard practice.

While statistical analysis provides empirical evidence supporting the use of DAI receiver with CIs, user preferences are also an important aspect of the type of receiver selected for an individual. Subjective comments and questionnaires were collected in several of the experiments included in the meta-analysis, which provide ecological validity to the findings in the present study. In the Anderson et al. (2005) study, children with hearing aids and CIs were asked their preferences for use of a traditional soundfield, desktop soundfield, and a DAI system. Over half of the children chose the DAI receiver as the overall easiest system to listen to (18/28) and the most preferred system (21/28). In addition, the DAI receiver was rated as the system their teacher would prefer to use (15/28). Furthermore, the majority of the children rated the traditional soundfield system as the least preferred device (15/28). In Schafer and Thibodeau (2003), 8 of 10 children with CIs preferred using DAI receivers over a desktop soundfield receiver for speech-recognition-in-noise tasks. In another study, Schafer and Thibodeau (2004) administered a questionnaire to eight adults with CIs following a study including desktop soundfield and DAI receivers. The adults rated the DAI receiver as the device that was most preferred, provided the best sound quality, and allowed for the best speech understanding in noise. In addition, the participants rated the desktop soundfield as the least preferable receiver, and none of the participants reported understanding most sentences with the desktop soundfield. Therefore, subjective comments and ratings from children and adults who use CIs clearly convey preferences for the DAI receiver when compared to traditional and desktop soundfield receivers.

Findings of the meta-analysis may be used to support audiologists' recommendations for DAI FM-system receivers to parents, school district administrators, and insurance companies. There is a strong movement toward evidence-based practices in the field of audiology. The results of this study provide clinical and educational audiologists unequivocal evidence to support the use of a specific type of FM system for children and adults using CIs. Based on the findings in the present study, traditional soundfield FM systems are not effective for improving speech perception in noise of adults and children with CIs. While desktop soundfield FM systems significantly improve performance, DAI receivers that are electrically connected to CI speech processors provide the greatest improvements in speech recognition in noise relative to a CI alone.

References

Aaron, R., Sonneveldt, V., Arcaroli, J., & Holstad, B. (2003, November). *Optimizing microphone sensitivity settings of pediatric Nucleus 24 cochlear implant patients using Phonak MicroLink CI+ FM system*. Poster presented at ACCESS: Achieving Clear Communication Employing Sound Solutions - Proceedings of the First International Conference, Chicago, IL.

Acoustical Society of America, (n.d.). *Position on the Use of Sound Amplification in the Classroom*. Retrieved October 12, 2006 from http://asa.aip.org

Afilalo, J., Duque, G., Steele, R., Jukema, J. W., de Craen, A. J., & Eisenberg, M. J. (2008). Statins for secondary prevention in elderly patients: a hierarchical bayesian meta-analysis. *Journal of the American College of Cardiology, 51*(1), 37-45.

American Speech-Language-Hearing Association. (1991). The use of FM amplification instruments for infants and preschool children with hearing impairment. Asha, *33* (Suppl. 5), 1-2.

American Speech-Language-Hearing Association. (2004). *Evidence-based practice in communication disorders: an introduction* [technical report]. Available at: http://www.asha.org/members/deskref-journals/deskref/default

American Speech-Language-Hearing Association. (2005). *Position statement and guidelines for acoustics in educational settings*.

Amlani, A. M. (2001). Efficacy of directional microphone hearing aids: a meta-analytic perspective. *Journal of the American Academy of Audiology, 12*(4), 202-214.

Anderson, K. L., Goldstein, H., Colodzin, L., & Iglehart, F. (2005). Benefit of S/N enhancing devices to speech perception of children listening in a typical classroom with hearing aids or a cochlear implant. *Journal of Educational Audiology*, *12*, 14-28.

Anzarut, A., Olson, J., Singh, P., Rowe, B. H., & Tredget, E. E. (2009). The effectiveness of pressure garment therapy for the prevention of abnormal scarring after burn injury: a meta-analysis. *Journal of Plastic, Reconstructive, and Aesthetic Surgery, 62* (1): 77-84.

Arnold, P., & Canning, D. (1999). Does classroom amplification aid comprehension? *British Journal of Audiology, 33*(3), 171-178.

Berlin, J. A., Laird, N. M., Sacks, H. S., & Chalmers, T. C. (1988). A comparison of statistical methods for combining event rates from clinical trials. *Statistics in Medicine, 8*, 141-151.

Bess, F. H., Sinclair, J. S., & Riggs, D. E. (1984). Group amplification in schools for the hearing impaired. *Ear & Hearing, 5*(3), 138-144.

Catlett, D. & Brown, C.J. (2003, November). *Optimal audio mix settings for pediatric Clarion cochlear implant patient using a Phonak MicroLink CI-S FM system.* Poster presented at ACCESS: Achieving Clear Communication Employing Sound Solutions - Proceedings of the First International Conference, Chicago, IL.

Cheng, A. K., Grant, G. D., & Niparko, J. K. (1999). Meta-analysis of pediatric cochlear implant literature. *Annals of Otolaryngology, Rhinology, and Laryngology Supplemental, 177*, 124-128.

Crandell, C. C., Holmes, A. E., Flexer, C., & Payne, M. (1998). Effects of soundfield FM amplification on the speech recognition of listeners with cochlear implants. *Journal of Educational Audiology, 6*, 21-27.

Davies, M. G., Yellon, L., & Purdy, S. C. (2001). Speech-in-noise perception of children using cochlear implants and FM systems. *Australian and New Zealand Journal of Audiology, 23*, 52-62.

Eisenberg, L. S., Shannon, R. V., Martinez, A. S., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *Journal of the Acoustical Society of America, 107*(5 Pt 1), 2704-2710.

eSchoolDesk (n.d.). Retrieved January 13, 2007 from Phonak Hearing Systems website: http://www.phonak.com/professional/eschooldesk/

Geers, A. (2004). Speech, language, and reading skills after early cochlear implantation. *Archives of Otolaryngology Head and Neck Surgery, 130*(5), 634-638.

Geers, A., Brenner, C., & Davidson, L. (2003). Factors associated with development of speech perception skills in children implanted by age five. *Ear & Hearing, 24*(1 Suppl), 24S-35S.

Higgins, J.P.T. & Green, S. (Eds.). (2006). *Cochrane Handbook for Systematic Reviews of Interventions 4.2.6* (updated September 2006). In: The Cochrane Library, Issue 4. Chichester, UK: John Wiley & Sons, Ltd.

Hintze, J. (2007). Number Cruncher Statistical System (Version Vista) [Computer software]. Retrived on April 25, 2007, from http://www.ncss.com/

Iglehart, F. (2004). Speech perception by students with cochlear implants using sound-field systems in classrooms. *American Journal of Audiology, 13*, 62-72.

Individuals with Disabilities Education Improvement Act of 2004, Public Law 108-446 (2004).

Knecht, H. A., Nelson, P. B., Whitelaw, G. M., & Feth, L. L. (2002). Background noise levels and reverberation times in unoccupied classrooms: predictions and measurements. *American Journal of Audiology, 11*, 65-71.

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., et al. (2004). Bilateral cochlear implants in adults and children. *Archives of Otolaryngology Head and Neck Surgery, 130*, 648-655.

Osberger, M. J., Zimmerman-Phillips, S., & Koch, D. B. (2002). Cochlear implant candidacy and performance trends in children. *Annals of Otology, Rhinology, and Laryngology (Supp), 189*, 62-65.

Participant surveys. (2003). Conducted at ACCESS: Achieving Clear Communication Employing Sound Solutions - Proceedings of the First International Conference, Chicago, IL.

Rosenthal, R. (1979). The "file-drawer problem" and tolerance for null results. *Psychology Bulletin, 85,* 638-406.

Schafer, E. C., & Thibodeau, L. M. (2003). Speech recognition performance of children using cochlear implants and FM systems. *Journal of Educational Audiology, 11*, 15-26.

Schafer, E. C., & Thibodeau, L. M. (2004). Speech recognition abilities of adults using cochlear implants interfaced with FM systems. *Journal of the American Academy of Audiology, 15*(10), 678-691.

Schafer, E. C., & Thibodeau, L. M. (2006). Speech recognition in noise in children with bilateral cochlear implants while listening in bilateral, bimodal input, and FM-system arrangements. *American Journal of Audiology, 15*, 114-126.

Thibodeau, L., Schafer, E., Overson, G., Whalen, H., Sullivan, J. (2005, March). *Clinical evaluation of the benefits provided by FM systems directly connected to cochlear implants.* Poster presented at the 10th Symposium on Cochlear Implants in Children, Dallas, TX.

Waltzman, S. B., Cohen, N. L., Green, J., & Roland, J. T., Jr. (2002). Long-term effects of cochlear implants in children. *Otolaryngology Head and Neck Surgery, 126*(5), 505-511.

Wood, E.J., Flynn, S.L., & Greenham, P. (2005). *The benefit of using an FM radio aid over distance and in noise, with the Nucleus ESPrit 3G speech processor.* Poster presented at the 10th Symposium on Cochlear Implants in Children, Dallas, TX.

Wolfe, J. & Schafer, E.C. (in press). Evaluation of FM receiver gain settings for children using Auria® sound processors coupled to personal FM systems with the iConnect™ adaptor. In D. Fabry & C. Deconde Johnson (Ed.), *Proceedings of the Second International FM Conference - ACCESS: Achieving Clear Communication Employing Sound Solutions*. Chicago: Phonak AG.

Wolfe, J. & Schafer, E.C. (2008). Optimizing the benefit of Auria® sound processors coupled to personal FM systems with iConnect™ adaptors. *Journal of the American Academy of Audiology*, *19*(8), 585-594.