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Evaluation of Speech Recognition in Noise with Cochlear Implants and Dynamic FM

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Abstract

Background: Use of personal frequency-modulated (FM) systems significantly improves speech recognition in noise for users of cochlear implants (CIs). Previous studies have shown that the most appropriate gain setting on the FM receiver may vary based on the listening situation and the manufacturer of the CI system. Unlike traditional FM systems with fixed-gain settings, Dynamic FM automatically varies the gain of the FM receiver with changes in the ambient noise level. There are no published reports describing the benefits of Dynamic FM use for CI recipients or how Dynamic FM performance varies as a function of CI manufacturer.

Purpose: To evaluate speech recognition of Advanced Bionics Corporation or Cochlear Corporation CI recipients using Dynamic FM vs. a traditional FM system and to examine the effects of Autosensitivity on the FM performance of Cochlear Corporation recipients.

Research Design: A two-group repeated-measures design. Participants were assigned to a group according to their type of CI.

Study Sample: Twenty-five subjects, ranging in age from 8 to 82 years, met the inclusion criteria for one or more of the experiments. Thirteen subjects used Advanced Bionics Corporation, and 12 used Cochlear Corporation implants.

Intervention: Speech recognition was assessed while subjects used traditional, fixed-gain FM systems and Dynamic FM systems.

Data Collection and Analysis: In Experiments 1 and 2, speech recognition was evaluated with a traditional, fixed-gain FM system and a Dynamic FM system using the Hearing in Noise Test sentences in quiet and in classroom noise. A repeated-measures analysis of variance (ANOVA) was used to evaluate effects of CI manufacturer (Advanced Bionics and Cochlear Corporation), type of FM system (traditional and dynamic), noise level, and use of Autosensitivity for users of Cochlear Corporation implants. Experiment 3 determined the effects of Autosensitivity on speech recognition of Cochlear Corporation implant recipients when listening through the speech processor microphone with the FM system muted. A repeated-measures ANOVA was used to examine the effects of signal-to-noise ratio and Autosensitivity.

Results: In Experiment 1, use of Dynamic FM resulted in better speech recognition in noise for Advanced Bionics recipients relative to traditional FM at noise levels of 65, 70, and 75 dB SPL. Advanced Bionics recipients obtained better speech recognition in noise with FM use when compared to Cochlear Corporation recipients. When Autosensitivity was enabled in Experiment 2, the performance of Cochlear Corporation recipients was equivalent to that of Advanced Bionics recipients, and Dynamic FM was significantly better than traditional FM. Results of Experiment 3 indicate that use of

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Autosensitivity improves speech recognition in noise of signals directed to the speech processor relative to no Autosensitivity.

Conclusions: Dynamic FM should be considered for use with persons with CIs to improve speech recognition in noise. At default CI settings, FM performance is better for Advanced Bionics recipients when compared to Cochlear Corporation recipients, but use of Autosensitivity by Cochlear Corporation users results in equivalent group performance.

Abbreviations: ADRO = Adaptive Dynamic Range Optimization; ASC = Automatic Sensitivity Control or Autosensitivity; BTE = behind the ear; CIs = cochlear implants; FM = frequency modulated; HINT = Hearing in Noise Test; IDR = input dynamic range

Communication in noise is often difficult for people with cochlear implants (CIs). In fact, speech-recognition scores in noise may be as much as 50 percentage points poorer than speech recognition in quiet (Schafer and Thibodeau, 2004; Wolfe and Schafer, 2008b). Additionally, people with CIs cite speech recognition in noise as one of their most significant challenges (Schafer and Thibodeau, 2004; Noble et al, 2008). Reasons for the difficulties users of CIs experience in noise are thought to include degraded spectral resolution (Nelson et al, 2003; Stickney et al, 2004) and poor preservation of fine temporal structure (Qin and Oxenham, 2003; Nie et al, 2006).

Numerous studies conclusively demonstrate substantial improvements in speech recognition in noise when using personal frequency-modulated (FM) systems (Schafer and Thibodeau, 2004; Anderson et al, 2005; Wolfe and Schafer, 2008b). Specifically, personal FM receivers improve speech-recognition performance of people with CIs by up to 50 percentage points when compared to the no–FM system condition (Wolfe and Schafer, 2008b). For many people, this improvement results in similar performance to what was achieved in quiet. Furthermore, adults report a preference for the personal FM system when compared to their CI alone (Schafer and Thibodeau, 2004) and cite better clarity of speech with the use of an FM system (Wolfe and Schafer, 2008b).

PARAMETERS AFFECTING THE CI–FM INTERFACE

A number of adjustable parameters may significantly impact speech-recognition performance when using a personal FM system coupled to a CI. In the FM system, the FM receiver gain may influence speech recognition. Within the speech processor, the input dynamic range (IDR), microphone sensitivity, and audio-mixing ratio may affect performance. The first adjustable parameter, the FM receiver gain, has the potential to improve speech recognition for signals directed to the FM transmitter. For example, speech recognition in noise of people using Advanced Bionics CIs systematically improves with increases in FM receiver gain (Schafer and Wolfe, 2008; Wolfe and Schafer, 2008a; Schafer et al, 2009). The signal-to-noise ratio necessary for adults to recognize sentences in noise at a 50 percent correct level improved by approximately 6 dB when increasing the FM receiver gain from the +6 to the +20 setting (Schafer and Wolfe, 2008). Similarly, children with Advanced Bionics CIs experienced significant average improvements in speech recognition of 18 percentage points with the +16 relative to the +10 receiver gain setting (Wolfe and Schafer, 2008a). However, some of the adult subjects reported distortion, uncomfortable loudness, and occasional static when listening at higher FM receiver gain settings (i.e., +20) in quiet environments (Schafer and Wolfe, 2008). In contrast to the findings with Advanced Bionics recipients, Schafer et al (2009) found that average speech-recognition performance does not significantly improve with increases in FM receiver gain for subjects using Cochlear Corporation processors.[1] These authors also found that the FM performance of participants using Cochlear Corporation ESPrit 3G processors was significantly poorer than that of Advanced Bionics Auria users.

Performance discrepancies between users of the Advanced Bionics and Cochlear Corporation devices may relate to the second adjustable parameter impacting performance with FM systems, the speech processor IDR. Schafer et al (2009) relate the manufacturer differences to the upper end of the IDR of the CI speech processor. The IDR is the range of sound-input levels coded by the speech processor into the recipient's electrical dynamic range (i.e., range between the threshold and the most comfortable stimulation levels for an electrical signal). Acoustic inputs below the IDR are not mapped into the electrical dynamic range and are presumably inaudible, while inputs that exceed the IDR are subjected to high-level compression. The lower end of the IDR (i.e., lower-level inputs) may be adjusted by the audiologist in the CI programming software, but the upper end of the dynamic range is fixed.

The Advanced Bionics Corporation utilizes a compression circuit with dual compression time constants coupled with the default IDR of 60 dB in an attempt to provide access to low-level sounds and also reduce unwanted noise in environments with moderate to high levels of speech and noise. Therefore, for Advanced Bionics Harmony and Auria speech processors, inputs ranging from approximately 25 to 85 dB SPL are mapped into the electrical dynamic range. In contrast, the Cochlear Corporation Nucleus Esprit 3G uses a fast-acting compression circuit coupled with a 30 dB IDR in an attempt to code the ongoing fluctuations of average conversational-level speech into the electrical dynamic range. As a result, for the Esprit 3G, inputs ranging from 35 to 65 dB SPL are mapped into the electrical dynamic range. The Cochlear Corporation Nucleus Freedom uses a similar approach, but the IDR is 40 dB, with the lower end of the range set at 25 dB SPL when at default settings.

Previous studies examining the effect of IDR on the speech recognition of CI users (without personal FM use) have produced mixed results. Spahr, Dorman, and Loiselle (2007) report better speech recognition for Advanced Bionics and MED EL users with a wider IDR (i.e., 55–60 dB SPL) than Cochlear Corporation users with a narrow IDR (i.e., 30 dB IDR). Similarly, Holden and colleagues (2007) show that users of Cochlear Corporation CIs had significantly better speech recognition in quiet and noise with a 40 dB vs. a 30 dB IDR. In contrast, Dawson et al (2007) show no differences in speech recognition in noise for a narrow vs. a wide IDR for Cochlear Corporation recipients. Advantages and disadvantages of wide and narrow IDRs will be further examined in the “Discussion” section. The more pertinent question for the present study is related to how IDR influences performance with FM systems.

The IDR of the speech processor is highly relevant to performance with FM systems because it may compress the FM signal. If the estimated 75 dB SPL signal from the FM system to the CI processor exceeds the upper end of the IDR, the FM signal will be infinitely compressed. We could predict, therefore, that the upper IDR setting of 65 dB SPL for Cochlear Corporation processors would result in similar compression for each FM gain setting. As a result, there would be no performance differences across gain settings. In contrast, the wider IDR (and more important for FM use, the upper cutoff of 85 dB SPL of the IDR) of the Advanced Bionics processors allows increases in receiver gain to be effectively coded, resulting in improved performance across FM gain conditions. It should be noted that when connected to an FM receiver, the lower end of the Nucleus Freedom IDR increases from 25 to 35 dB SPL. However, the upper end of the IDR is more relevant to FM performance and the effects of FM gain.

For both the Advanced Bionics and the Cochlear Corporation devices, the IDR is also influenced by the third adjustable parameter, microphone sensitivity. Microphone sensitivity controls the gain applied to inputs from the speech-processor microphone. Increasing the microphone sensitivity from the default setting results in mapping of lower-level sounds into the electrical dynamic range and reduces the input level subjected to compression. This may result in degraded performance in noise, as the additional compression may cause the peaks of speech to be embedded in the competing noise. In contrast, decreasing the microphone sensitivity from the default setting results in mapping of low- to moderate-level sounds below the IDR and increases the input level required to trigger compression at the upper end. This hinders audibility for soft inputs but may improve speech recognition in noise. When an FM receiver is connected to the processor, evidence suggests that lower-sensitivity settings may improve speech-recognition performance in noise because more input is provided from the FM receiver relative to the processor microphone (Aaron et al, 2003).

Cochlear Corporation speech processors also possess an input-preprocessing feature known as Autosensitivity (ASC), which automatically adjusts the microphone sensitivity depending on noise level and signal-to-noise ratio at the speech-processor microphone. Modulation rates and depths are used to classify a signal as speech or noise. When modulation rates are consistent with typical speech (i.e., 2–20 Hz), an estimate of the level of the speech signal is determined. During the pauses of speech, an estimate of the noise level is determined. When ASC is enabled and the level of ambient background noise is below 57 dB SPL, the sensitivity of the speech-processor microphone is fixed at the manufacturer-default setting of 12. Once the ambient noise level reaches or exceeds 57 dB SPL, the sensitivity of the speech-processor microphone is reduced according to the level of the background noise so that the peaks of speech exceed the long-term spectrum of the noise by at least 15 dB. The automatic reduction in microphone sensitivity provided by ASC diminishes the likelihood that the signal from the FM system will receive considerable compression in noisy environments. As a result, FM performance should improve, and the user should benefit from increases in FM receiver gain. However, there are no published studies that have systematically examined the effect of microphone sensitivity settings or ASC on speech recognition with personal FM systems. Furthermore, the use of ASC is not currently recommended by Cochlear Corporation for users of personal FM systems.

The fourth and final adjustable parameter on the speech processor that may impact performance with FM systems is the audio-mixing ratio, which determines the relationship between signals from the speech-processor microphone and FM system. In the Advanced Bionics CI system, a 50/50 mixing ratio results in equal emphasis of the signals from the speech-processor microphone and FM system, while a 30/70 mixing ratio provides 10 dB of attenuation to the signal from the speech-processor microphone. Similarly, in the Cochlear Corporation Freedom CI system, a 1:1 mixing ratio results in equal emphasis of the signals from the speech-processor microphone and FM system, while a 3:1 mixing ratio provides approximately 10 dB of attenuation to the signal from the speech-processor microphone. As shown by Wolfe and Schafer (2008b), audio-mixing ratios that result in attenuation of the signal from the speech processor (i.e., 30/70 or 3:1) may improve speech recognition in noise. However, the audibility of low-level sounds arriving at the speech-processor microphone may be compromised in quiet environments. For this reason the investigators recommend use of the 50/50 or 1:1 mixing ratios for people with CIs to prevent a loss of audibility for incidental sounds. However, the ideal audio-mixing ratio may vary across different listening situations.

The aforementioned discussion of factors influencing performance with FM systems highlights the need for new technology and signal processing for the FM system–CI interface. The ideal FM system and CI parameters would (1) adjust the FM receiver gain according to the noise level in the environment; (2) optimize the IDR, compression, and sensitivity settings on the CI processor for FM use; and (3) automatically change to a fixed audio-mixing ratio when using an FM system to avoid attenuation of the speech-processor microphone (i.e., 1:1 or 50/50). The first of these desirable parameters, adaptive FM receiver gain, is addressed with new technology from Phonak.

DYNAMIC FM

Recently, Phonak introduced Dynamic FM, which features a proprietary component referred to as the Dynamic Speech Extractor. The Dynamic Speech Extractor adaptively varies the gain of the FM receiver depending on the level of noise at the microphone of the FM transmitter. In quiet and in noisy environments, when speech is not present at the input of the FM microphone of the Phonak inspiro Dynamic FM transmitter, the receiver is muted in an attempt to optimize sound quality. This feature may reduce the audibility of unwanted noise, which may be present in the form of "static noise" or a "rushing noise" that accompanies the primary FM signal. When speech is presented to the FM microphone and ambient noise is less than 57 dB SPL, the default gain of the Dynamic FM receiver is set to +10. When ambient noise levels exceed 57 dB SPL, the gain of the FM receiver is increased by an amount that is proportional to the noise level. The maximum gain of the FM receiver is +24 at a noise-input level of approximately 75 dB SPL.

Thibodeau (unpublished data, cited in Henry, 2008) reports that use of Dynamic FM results in substantial improvements in speech recognition in noise over traditional fixed-gain FM systems for persons using hearing aids and FM systems. There are, however, no published reports describing CI recipients' performance with Dynamic FM. The benefits and limitations of Dynamic FM use with CIs would likely differ from what is found for hearing aid users. The input-processing parameters of a CI speech processor, such as the mixing ratio, IDR, and microphone sensitivity setting, may normalize changes in output level (i.e., gain) of the FM receiver. Consequently, speech recognition in noise may not improve with Dynamic FM relative to traditional fixed-gain FM receivers. Alternatively, Dynamic FM may address the need for increased FM gain settings in noisy vs. quiet listening situations. Furthermore, it is unknown whether the muted FM setting, low-gain settings in relatively low-level noise environments, and high-gain settings for high-level noise environments will result in acceptable sound quality for CI users.

Therefore, the primary goal of this study was to examine the effects of Dynamic FM on speech-recognition performance of people with CIs. The study was conducted in three experiments. Experiment 1 examined benefits of Dynamic FM vs. traditional FM for users of Advanced Bionics and Cochlear Corporation implants. Completion of Experiment 1 highlighted the need for additional research for users of Cochlear Corporation implants. For that reason, Experiment 2 assessed the benefits of ASC on performance with Dynamic FM vs. traditional FM for users of Cochlear Corporation implants. Finally, Experiment 3 determined the effects of ASC on speech perception of environmental signals when the FM system was active but not receiving input.

MATERIALS AND METHOD

Participants and CIs

In order to participate, subjects had to achieve open-set speech recognition in quiet of at least 80 percent correct on Hearing in Noise Test (HINT [Nilsson et al, 1994]) sentences or 30 percent correct on monosyllabic words. These criteria were chosen because participants with poorer speech recognition are likely to have substantial difficulty with speech recognition in noise testing. In addition, similar criteria proved successful in previous FM research (Wolfe and Schafer, 2008b).

Demographic information about the 25 subjects who met the criteria for participation in one or more

Table 1. Demographic Characteristics of Participants

Cochlear Implant (CI)	Participant	Experiment	Age	CI Duration (years;months)	Duration Deaf (at 1st CI; years)	Internal CI	Implant Ear	Processing Strategy	Active Electrodes
Advanced	1	1, 2	15	7;1	8	CII/90K	L/R	HiResP 120	16/14
Bionics	2	1, 2	42	5;5	9	C1	R	HiResS	14
Corporation	3	1, 2	69	4;3	9	90K	L	HiResS	15
	4	1, 2	61	4;3	6	90K	R	HiResS 120	16
	5	1, 2	62	4;2	1	90K	R	HiResP 120	14
	6	1, 2	73	4;10	2	CII	R	HiResP 120	13
	7	1, 2	51	4;4	6	90K	R	HiResS 120	13
	8	1, 2	18	7;5	10	C1	L	MPS	8
	9	1, 2	56	4;8	1	90K	L/R	HiResS 120	14/14
	10	1, 2	59	4;10	2	CII/90K	L/R	HiResS	14/14
	11	1, 2	8	7;0	1	90K/C1	L/R	HiResS/MPS	16/8
	12	1, 2	12	9;0	3	90K/C1	L/R	HiResS/MPS	16/8
	13	1, 2	12	9;9	2	C1/90K	L/R	MPS/HiResP 120	8/16
Cochlear	14	1, 2, 3	62	2;9	3	CI24RE	R	ACE	19
Corporation	15	1, 2, 3	61	4;6	2	CI24R/CI24RE	L/R	SPEAK	20/20
	16	1, 2, 3	58	1;8	2	CI24RE	L	ACE	21
	17	1	20	3;0	2	CI24R	R	ACE	19
	18	1, 2, 3	82	1;10	4	CI24RE	L	ACE	21
	19	2, 3	51	2;8	1	CI24RE	R	ACE	20
	20	1, 2, 3	37	2;6	23	CI24RE	R	ACE	22
	21	1, 2, 3	62	2;9	2	CI24RE	L	ACE	20
	22	1, 2, 3	62	2;7	2	CI24RE/CI24RE	L/R	ACE	22/20
	23	1, 2, 3	19	4;0	3	CI24R	R	ACE	20
	24	1, 2, 3	41	0;6	3	CI24RE	L	ACE	22
	25	1, 2	67	5;0	4	CI24R	R	ACE	20
Average			44.4	4.4	4.5				
SD			23.2	2.3	4.8				

experiments is shown in Table 1. The average ages of the Advanced Bionics and Cochlear Corporation groups were 41 years (SD = 24) and 52 years (SD = 19), respectively. The Advanced Bionics group had a longer average duration of implant use (M = 5 years, 9 months, SD = 2) than the Cochlear Corporation group (M = 2 years, 9 months, SD = 2). Two-sample *t*-tests were used to examine any group differences in age, duration of CI use, and duration of deafness prior to CI for the users of Advanced Bionics and Cochlear Corporation implants. These analyses revealed no significant group differences for age ($t[23] = -1.18$, $p = .25$) or duration of deafness ($t[23] = 0.18$, $p = .085$). However, a significant group difference was found for the duration of CI use ($t[23] = 4.77$, $p < .01$). The first analysis in Experiment 1 showed no significant differences in performance between the two groups when listening to sentences in a quiet environment; therefore, the group differences for duration of CI use do not appear to influence speech performance.

Twenty-four subjects, ranging from 8 to 82 years of age, participated in Experiment 1 of the study. Thirteen participants used the Advanced Bionics Corporation CII or HiRes 90K internal cochlear stimulator and one of the following external speech processors: (1) Platinum body-worn processor, (2) CII behind-the-ear (BTE) speech processor, (3) Auria BTE speech processor, or (4) Harmony BTE speech processor. Five of these subjects had bilateral CIs. The effect the bilateral participants had on the analysis will be examined in the results of Experiment 1. Eleven participants used the Cochlear Corporation Nucleus 24 or Nucleus Freedom internal cochlear stimulator with a Freedom BTE speech processor. Two of these subjects had bilateral CIs.

In Experiment 2, 11 subjects ranging in age from 19 to 82 with Cochlear Corporation Nucleus 24 or Nucleus Freedom internal cochlear stimulators and Nucleus Freedom speech processors participated. Most of these subjects also participated in Experiment 1 and used Freedom speech processors. Experiment 3 included 10 subjects with Cochlear Corporation implants who ranged in age from 19 to 69 years. All but one of these subjects participated in Experiment 1 or 2 of the study.

All the subjects outlined in Table 1 had used their CIs for at least six months and were satisfied with their CI performance according to anecdotal reports. Adults in the study were postlingually deafened, while children under the age of 18 were prelingually deafened and received their cochlear implant prior to three years of age. All of the pediatric patients had age-appropriate receptive vocabulary levels according to their speech-language pathologist. Previous experience with FM systems was not a prerequisite for study inclusion, but most subjects did have some FM experience from previous studies.

For all experiments, the audio-mixing ratio of the CI speech processors was set so that equal emphasis was placed on the signals from the FM system and speech-processor microphone (i.e., 50/50 for Advanced Bionics Corporation and 1:1 for Cochlear Corporation). Per recommendations from Cochlear Corporation, ASC, Whisper, and Beam preprocessing were disabled in the speech processors of all recipients in Experiment 1 of the study. However, Adaptive Dynamic Range Optimization (ADRO) was enabled for Cochlear Corporation subjects who used it in their primary daily listening program (Subjects 16, 20, 22, 25), as the manufacturer encourages use of the ADRO preprocessing strategy with personal FM systems. The purpose of ADRO is to ensure comfort and audibility for sounds in each channel of the cochlear implant. In all experiments of the study, IDR was set to the default values of 40 dB for Cochlear Corporation recipients and either 60 or 65 dB for Advanced Bionics Corporation recipients. It should be noted that the default IDR of 40 dB for the Cochlear Corporation Freedom device is automatically reduced to 30 dB when a personal FM receiver is activated with the processor. Specifically, the lower end of the IDR is increased by 10 dB.

FM Systems

Each subject was fit with a personal FM receiver and adaptor designed for his or her speech processor. The two different FM receivers used for study were the Phonak MicroMLxS (i.e., "traditional FM") and the Phonak MLxi receiver (i.e., "Dynamic FM"). Traditional FM is a receiver with a fixed gain setting (+10 in this study) that is predetermined by the clinician, while Dynamic FM is adaptive and automatically increases the gain setting with increases in input noise level. Input impedance values of various CI speech processors vary widely across manufacturers and across speech processors within a manufacturer. Therefore, preprogramming of the output level of Dynamic FM receivers was necessary to achieve the desired starting FM gain setting of +10 for all CI recipients. The Dynamic FM receivers were preprogrammed to provide +10 dB of gain when speech was present at the FM microphone for input levels up to 57 dB SPL. For input levels exceeding 57 dB SPL, the gain setting of the Dynamic FM increased as input noise level increased. The maximum gain setting of +24 dB was achieved when the input noise level reached approximately 75 dB SPL.

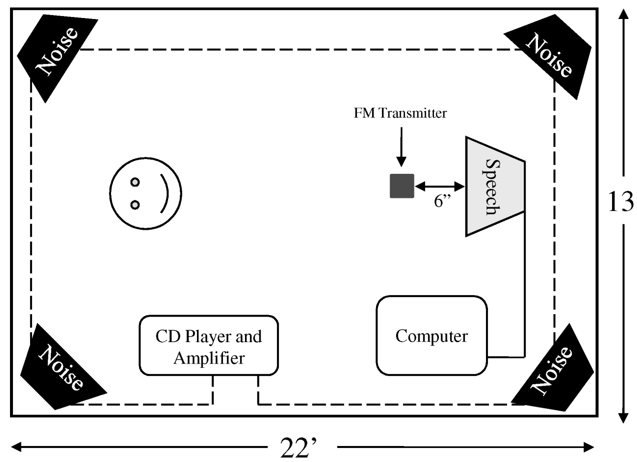

Figure 1. Classroom and equipment arrangement.

The Phonak MLCI adaptor was used to connect the FM receivers to the Platinum body-worn speech processor, while the Advanced Bionics iConnect earhook was used to couple FM receivers to the Auria and Harmony speech processors. For the Freedom CI users, the Freedom body-worn FM cable and controller were used to couple FM receivers to the Freedom speech processor. The participants with bilateral CIs used two FM receivers. In Experiment 3, the FM system was active, but the microphone coupled to the FM transmitter was disabled.

The Phonak inspiro transmitter was used for transmission of the signal of interest to both types of FM receivers under study. A lapel microphone with a hypercardioid directional pattern was coupled to the inspiro transmitter.

Equipment and Stimuli

In all experiments, open-set speech recognition in noise was assessed in a 13 ×22 × 8′ classroom (Figure 1) using two lists of HINT sentences scored for number of words repeated correctly. The ambient noise level in the room was 46 dBA as determined with a Type 1 sound-level meter. The transmitter microphone of the FM system was suspended 6 inches in front of the single cone of the loudspeaker used to present the speech stimuli. The HINT sentences were presented from a Dell Latitude D-520 laptop computer with a SigmaTel High Definition Audio CODEC sound card and a Creative Labs SBS270 loudspeaker with a built-in amplifier. The sentences were presented at 85 dBA at the location of the FM transmitter microphone and 60 dBA at the location of the CI speech-processor microphone. The competing noise signal was generated by a Panasonic DVD-S1S CD player, amplified by a Radio Shack 250 Watt PA amplifier, and presented from four KLH B-Pro6 Titan Series loudspeakers positioned in the four corners of the room. Classroom noise (Schafer and Thibodeau, 2006), which has a difference of 2.95 dB between the minimum and maximum root mean square values, served as the competing noise signal.

In Experiments 1 and 2, the loudspeaker used to present the sentences was located 19 ft from the subject at 0 degrees azimuth, and the four noise loudspeakers were placed in the corners of the room. The rationale for this speaker location was selected to ensure optimal FM benefit and to simulate listening in a noisy environment at a distance from the talker of interest. In Experiment 3, the speech loudspeaker was positioned approximately 1 m from the subject, and the noise loudspeakers remained in the corners of the room.

Procedures

Experiment 1. Comparison of Performance with Dynamic FM and Traditional FM

Speech recognition in quiet was evaluated for each group of listeners (Advanced Bionics and Cochlear Corporation) with Dynamic FM to ensure adequate audibility with this type of receiver. Previous research shows good performance in quiet when using traditional FM with CIs (Wolfe and Schafer, 2008b), but no data have been reported for CIs and Dynamic FM. Sentence recognition in noise was also assessed for the two groups with each FM system (Phonak MLxS traditional FM receiver and the Phonak Dynamic FM receiver) at four different noise levels—(1) 55 dBA, (2) 65 dBA, (3) 70 dBA, and (4) 75 dBA—for a total of eight conditions. The four noise levels were the same intensity at the location of the FM transmitter and speech-processor microphones. Two 10-sentence HINT lists were completed for each condition, and scores were determined based on the percentage of words repeated correctly. The subjects repeated sentences orally, and two researchers scored the responses to ensure reliability of response recording.

Experiment 2: Effects of ASC on Performance with Traditional and Dynamic FM for Users of Cochlear Corporation Implants

The procedures in Experiment 2 were identical to those described in Experiment 1 with the exception of one noise condition. Experiment 2 testing did not include an assessment of speech recognition in noise at 55 dBA. ASC was enabled in the participants' speech processors for all ASC test conditions.

Experiment 3: Effects of ASC on Perception of Environmental Signals

During Experiment 3 testing, the transmitter microphone was disabled to evaluate the effect of ASC during FM use when signals are delivered to the speech-processor microphone rather than the FM microphone. The objective was to determine whether ASC compromises audibility for speech sounds that arrive at the speech-processor microphone (i.e., environmental microphone). Each of the following four conditions was conducted with ASC enabled and disabled for a total of eight conditions:

1. in quiet with a presentation level of 60 dBA,
2. in noise with speech fixed at 65 dBA and noise fixed at 55 dBA (65/55),
3. in noise with speech fixed at 70 dBA and noise fixed at 63 dBA (70/63), and
4. in noise with speech fixed at 74 dBA and noise fixed at 70 dBA (74/70).

The rate at which the speech and noise level increased across the three conditions was based on work by Pearsons et al (1977), who showed that a talker increases the level of his or her speech by 0.6 dB for every 1 dB increase in background noise.

RESULTS

Experiment 1: Comparison of Performance with Dynamic FM and Traditional FM

Speech Recognition in Quiet

Average speech-recognition scores in quiet with the Dynamic FM were 87 percent (SD = 10.8) and 87 percent (SD = 12.2) for the Advanced Bionics Corporation and the Cochlear Corporation groups, respectively. A statistical analysis using a one-way analysis of variance (ANOVA) revealed no significant difference in speech recognition in quiet between the two groups ($F[1, 24] = .02$, $p = .89$). Therefore, speech recognition in quiet is similar for the two groups.

Speech Recognition in Noise

The average results for users of the Advanced Bionics Corporation and Cochlear Corporation implants in the two FM conditions are shown in Figure 2a–b. In addition, means and standard deviations for both groups are provided in Table 2. A three-way, mixed-model repeated-measures ANOVA was used with one between-subjects factor, CI manufacturer (Advanced Bionics and Cochlear Corporation), and two within-subjects factors, FM system (traditional and

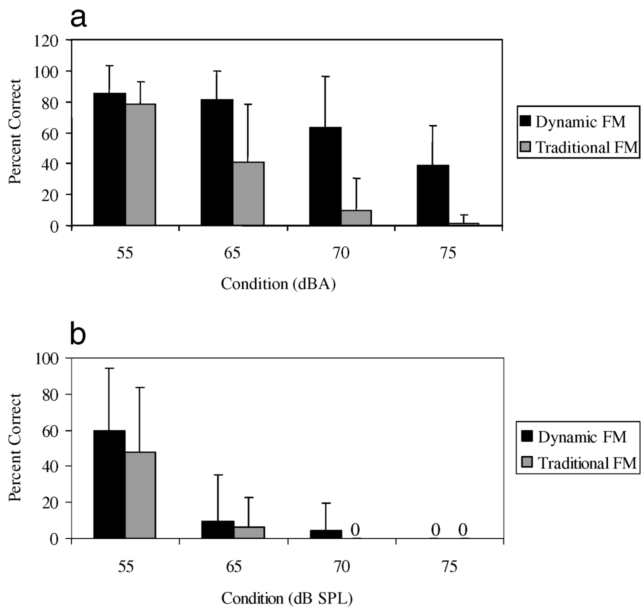

Figure 2. *a*, Speech recognition in noise for Advanced Bionics Corporation implant recipients at four different noise levels using traditional and Dynamic FM. Lines represent 1 SD. *b*, Speech recognition in noise for Cochlear Corporation implant recipients at four different noise levels using traditional and Dynamic FM. 0 = 0 percent correct.

Dynamic FM) and noise level (55, 65, 70, and 75 dBA). Statistical analysis revealed significant main effects of FM system ($F[1, 181] = 50.10$, $p < .0001$), CI manufacturer ($F[1, 181] = 26.02$, $p < .0001$), and noise level ($F[3, 181] = 80.16$, $p < .001$). There was also a statistically significant interaction between FM system and CI manufacturer ($F[1, 181] = 22.51$, $p < .0001$), FM system and noise level ($F[3, 181] = 2.95$, $p = .04$), and CI manufacturer and noise level ($F[3, 181] = 6.66$, $p < .001$). The interaction among CI manufacturer, FM system, and noise level was also significant ($F[3, 181] = 10.2$, $p < .0001$). These results suggest that Dynamic FM provided significantly better speech recognition in noise than the traditional FM and that Advanced Bionics implants had significantly better performance than Cochlear Corporation implants in noise.

To identify the conditions with significantly better performance, post hoc testing for noise level and the interaction effects was conducted using the Tukey-Kramer Multiple-Comparisons procedure. As expected, performance across the noise levels became significantly worse as the noise level increased. Specifically, the lowest noise level, 55 dBA, resulted in significantly better performance ($p < .05$) than all other noise conditions. In addition, performance in the 65 dBA condition was significantly better than performance in the 70 or 75 dB SPL ($p < .05$) conditions, with the latter two conditions resulting in similar performance ($p > .05$).

When examining the interaction effects between variables, there were several noteworthy findings. First, speech recognition in noise of the users with Advanced Bionics implants was significantly better with either type of FM (Dynamic FM or traditional) when compared to the performance of users of Cochlear Corporation implants. Also, Dynamic FM significantly improved performance over traditional FM for the users of Advanced Bionics implants but not for users of Cochlear Corporation implants. As shown in Figure 2a–b, FM benefit with the two types of receivers was significantly related to the level of noise. As expected, the best performance, when scores for the two groups were combined, was with the Dynamic FM or traditional FM receivers at the 55 dBA noise level. Once the noise level was increased to 65 dBA or greater, the Dynamic FM provided significantly better speech recognition in noise than the traditional FM.

Table 2. Average Speech-Recognition Performance in Noise with the Frequency-Modulated (FM) Systems in Experiments 1 and 2

Cochlear Implant and Experiment	FM System	55 dBA	65 dBA	70 dBA	75 dBA
Advanced Bionics Corporation					
Experiment 1	Traditional FM	78%	41%	10%	2%
		14.5	37.7	20.7	5.4
	Dynamic FM	85%	81%	63%	39%
		17.6	18.7	33.0	25.6
Cochlear Corporation					
Experiment 1	Traditional FM	48%	6%	0%	0%
		36.1	16.6	0	0
	Dynamic FM	60%	10%	5%	0%
		34.5	25.7	14.9	0
Experiment 2, Autosensitivity Enabled	Traditional FM	–	70%	53%	28%
			22.2	31.9	26.4
	Dynamic FM	–	85%	81%	48%
			14.6	15.3	33.4

Note: Standard deviations are shown below averages.

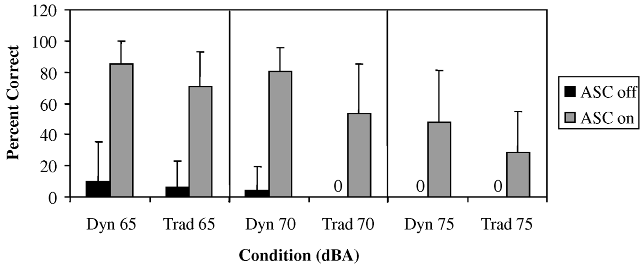

Figure 3. Results with the Dynamic FM (Dyn) and traditional FM (Trad) systems in the Automatic Sensitivity Control (ASC) enabled and disabled conditions. Lines represent 1 SD, and numbers represent noise level. 0 = average and standard deviation of 0 percent correct.

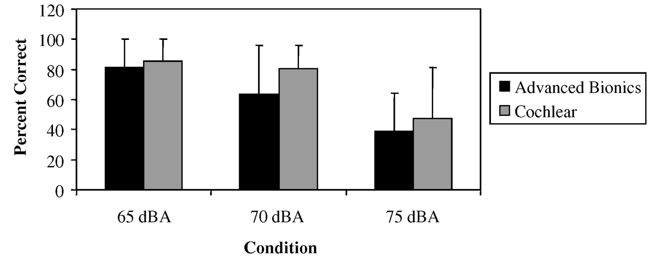

Figure 4. Speech-recognition performance with Dynamic FM: Advanced Bionics Corporation users vs. Cochlear Corporation users set to Autosensitivity. Lines represent 1 SD.

The poorest performance was with the traditional FM in the 70 and 75 dBA noise conditions.

The presence of a greater number of bilateral CI participants in the Advanced Bionics group ($N = 5$), as compared to the Cochlear Corporation group ($N = 2$), may have influenced these results. Some people with bilateral CIs receive an advantage for using two FM receivers when compared to one FM receiver (Schafer and Thibodeau, 2006). To examine this possibility, an additional ANOVA, using only the unilateral CI participants from the Advanced Bionics ($N = 8$) and Cochlear Corporation ($N = 9$) groups, was conducted. The analysis revealed the same significant main effects ($p < .05$) and interaction effects ($p < .05$) as the original analysis. Consequently, the additional benefit that may be achieved by some of the participants using bilateral implants and binaural FM did not influence the overall findings of this study.

Experiment 2: Effects of ASC on Performance with Traditional and Dynamic FM for Users of Cochlear Corporation Implants

Speech-recognition results with the Dynamic FM and traditional FM systems in the ASC enabled and ASC disabled conditions are provided in Figure 3 and Table 2. A three-way, fully repeated-measures ANOVA was used to analyze effects of noise level (65, 70, and 75 dBA), FM system (Dynamic FM and traditional), and use of ASC (ASC and no ASC). The analysis revealed significant main effects of noise level ($F[2, 131] = 25.3, p < .0001$), FM system ($F[1, 131] = 23.6, p < .0001$), and ASC condition ($F[1, 131] = 297.9, p < .0001$). In addition, a significant interaction effect was detected between noise level and ASC condition ($F[2, 131] = 8.5, p < .0001$). No significant interaction effects ($p > .05$) were found between any other factors.

A Tukey-Kramer Multiple-Comparison test was used to further examine significant differences between and among conditions. Regarding significant differences between the two types of FM systems, average performance with the Dynamic FM system was significantly better ($p < .01$) than average performance with the traditional FM system. Post hoc comparisons on the significant interaction effect between noise level and ASC condition revealed that speech recognition with ASC and noise at 65 and 70 dB(A) SPL was significantly better ($p < .05$) than in all conditions with no ASC and with ASC with noise at 75 dB(A) SPL. Also, use of ASC with noise at 75 dB(A) SPL was significantly better ($p < .05$) than all no ASC conditions. This finding suggests that (1) the use of ASC will substantially improve performance with traditional and Dynamic FM systems in the presence of moderate or higher-level noise and (2) performance at higher levels of noise will be degraded despite the use of ASC.

When comparing data from the Freedom users with ASC enabled to results of Advanced Bionics CI recipients (Experiment 1), performance was similar between the two groups when using Dynamic FM (Figure 4). A mixed-model, repeated-measures ANOVA indicated no significant effect of manufacturer ($F[1, 71] = 1.3, p > .05$), a significant effect of noise level ($F[3, 71] = 42.5, p < .0001$), and no significant interaction between manufacturer and noise level ($F[3, 71] = 0.34, p > .05$). The lack of significance between manufacturers suggests that the use of ASC with the Cochlear Corporation implants provided users with speech-recognition abilities equivalent to those of the Advanced Bionics participants. Results across the three levels of noise were similar to Experiment 1, where performance with noise at 65 dBA was significantly better than with noise at 70 and 75 dBA.

Experiment 3: Effects of ASC on Perception of Environmental Signals

Speech recognition results are provided in Figure 5. A two-way, fully repeated-measures ANOVA revealed a significant main effect of ASC condition ($F[1, 78] = 20.9, p < .0001$), significant main effect of stimulus presentation level ($F[3, 78] = 46.6, p < .0001$), and significant interaction effect between ASC condition and noise level ($F[3,78] = 3.1, p < .05$). Post hoc comparisons using the Tukey-Kramer Multiple-Comparison test

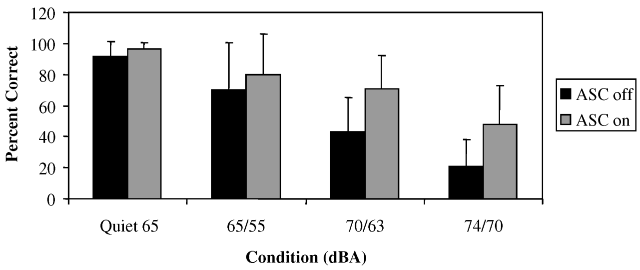

Figure 5. Speech recognition of signals presented to the processor microphone with and without the Automatic Sensitivity Control (ASC). Lines represent 1 SD, and ratios represent signal-to-noise ratio.

revealed several important findings. First, scores in the quiet conditions and 65/55 dBA conditions did not significantly differ with and without ASC. However, once the stimuli presentation levels increased, significant differences were detected between the ASC on and ASC off conditions at 70/63 and 74/70 dBA. These findings suggest that, when using Dynamic FM systems in adverse listening environments, ASC will substantially improve speech understanding through the speech processor (i.e., environmental speech).

DISCUSSION

Experiment 1. Comparison of Performance with Dynamic FM and Traditional FM

The results of Experiment 1 indicate that the participants achieved significantly better speech recognition in noise with Dynamic FM as compared to their performance with traditional FM. In other words, adjusting the FM receiver gain according to the noise level in the environment allowed the user better access to the FM signal than the fixed-gain receiver. Dynamic FM provides the user with a more favorable signal-to-noise ratio, which improves audibility and intelligibility of the signal from the FM system. Dynamic FM may also be helpful in quiet environments because the FM gain is negligible, which limits audibility of FM artifacts and reduces battery current drain.

The significant differences between traditional and Dynamic FM were only present at higher noise levels of 65, 70, and 75 dBA. Differences between the types of FM were not expected at 55 dBA because the adaptive aspect of the Dynamic FM does not activate until noise reaches a level of 57 dB SPL. Before this level, both the traditional and Dynamic FM systems provide +10 dB of gain. It is also important to note the poor average performance at the higher levels of noise (70 and 75 dBA), especially for the traditional FM. The average score for the traditional FM was 5 percent at 70 dBA and 0.83 percent at 75 dBA, while average scores were 33 percent and 19 percent for Dynamic FM in the same noise conditions. Further research is necessary to address the poor performance of CI users in high-intensity noise situations (e.g., restaurants, social events).

One of the most surprising findings in Experiment 1 was the substantially better FM performance of the Advanced Bionics Corporation users when compared to the Cochlear Corporation users. In addition, according to post hoc testing, the significantly better performance with Dynamic vs. traditional FM was limited to the group with Advanced Bionics CIs. These findings are similar to those of previous studies that have shown that manually increasing the gain in traditional FM systems significantly improves performance for Advanced Bionics CI users but not for Cochlear Corporation users (Schafer et al, 2009). Even with the fixed-gain, traditional FM receivers, users of Advanced Bionics implants had significantly better scores than Cochlear Corporation recipients when Cochlear Corporation users were evaluated with recommended map parameters. The Cochlear Corporation group had substantially lower scores with both types of FM systems because of the poor performance at the 65, 70, and 75 dBA noise levels.

Several differences exist between the CIs produced by the two manufacturers; therefore, it is important to examine these differences as possible reasons for the large disparity between the two groups. The most obvious manufacturer differences include number of active electrode contacts, signal-processing strategies, stimulation rate in electrical pulses per second (pps), and input processing. Previous research suggests that speech recognition in noise improves with increases in active electrodes (Dorman et al, 1998). The Advanced Bionics Corporation HiResolution CI system has 16 active electrode contacts, and the Cochlear Corporation implant has 22 electrode contacts. Because speech recognition in noise was better for Advanced Bionics recipients, it is improbable that a difference in number of electrode contacts is responsible for the substantial group differences.

It is also unlikely that differences in stimulation rate influenced results. To examine this hypothesis, an analysis of covariance (ANCOVA) was conducted with all FM scores from Experiment 1 as the dependent variable, the manufacturer group as the independent variable, and stimulation rate as the covariate. As expected, when controlling for the stimulation rate, the significant differences between groups remained for the Experiment 1 data ($p < .01$). This finding suggests that stimulation rate cannot explain the large disparity between groups. However, the wide range of stimulation rates used by the subjects in the Advanced Bionics group (i.e., 1020 to 3712 pps) did explain some of the variation in FM performance across this group of subjects. There was a significant ($p < .05$) trend toward better Dynamic FM performance with slower stimulation rates at the 65 ($r = -0.61$) and 70 dBA ($r = -0.66$) presentation levels.

As discussed in the introductory section, differences in input processing may be responsible for the disparity in FM performance observed between the two groups. Specifically, a relatively large difference exists between the IDRs of the two CI systems. The higher end of the IDR of the Advanced Bionics system allows for adaptive increases in FM gain from the Dynamic FM system to be relayed to the recipient, whereas the relatively lower end of the IDR of the Cochlear system does not.

For everyday use, there are advantages and limitations associated with both a relatively narrow (i.e., 30 dB) and a relatively wide IDR (i.e., 60 dB). A wide dynamic range may be more likely to facilitate a range of loudness experiences within the small dynamic range of the CI user. Indeed, Spahr, Dorman, and Loiselle (2007) and Dawson et al (2007) show wider IDR to be associated with better speech recognition for low-level signal inputs. However, a narrow dynamic range may be appealing in noisy environments because it would partially reduce the noise mapped into the electrical dynamic range. The difference between the peaks and troughs of ongoing speech typically range between 30 and 40 dB. Therefore, an IDR of 30 to 40 dB, with an upper-end level consistent with the peaks of speech, would theoretically capture all of the important components of the ongoing speech signal and optimize delivery of the speech signal into the narrow electrical dynamic range. Further research is needed to determine the optimal IDR for each implant system with and without the use of a personal FM system.

Experiment 2: Effects of ASC on Performance with Traditional and Dynamic FM for Users of Cochlear Corporation Implants

In an attempt to optimize FM performance for persons using Cochlear Corporation CIs, ASC was enabled and the test procedures were repeated. As previously suggested, the use of ASC has the potential to improve the separation of the signal from the competing noise. The results of this study suggest that clinicians should enable the preprocessing feature, ASC, when creating an FM program for recipients using Cochlear Corporation implants. Speech recognition in noise with the use of an FM was substantially better by up to 48 percentage points with ASC enabled as compared to performance when ASC was disabled, particularly at higher noise levels. Many recipients were unable to recognize any of the sentences at higher noise levels (e.g., 70 dB SPL and higher) when the ASC was disabled. At the time of the study, the manufacturer's recommended protocol for fitting personal FM to Cochlear Corporation implants indicated that the clinician should create a program with special preprocessing (i.e., ASC) disabled. Given the considerable improvement in speech recognition in noise when ASC was enabled for FM use, strong consideration should be given toward altering the FM fitting protocol for Cochlear Corporation implants.

The significant difference between performance with and without ASC was likely related to compression of the FM signal. When ASC was disabled and the microphone sensitivity was fixed at the default setting of 12, there was significant compression of the FM signal. In environments with moderate- to high-level noise (i.e., exceeding 65 dB SPL), both the FM signal and noise encountered significant amounts of compression. As a result, the FM signal was embedded in the ongoing noise and was likely unintelligible to the listeners. In contrast, use of ASC resulted in significantly better speech recognition in higher levels of noise because of a reduction in microphone sensitivity. The sensitivity reduction resulted in activation of the compression only at higher input levels. Therefore, the FM signal and noise were not compressed in moderate noise levels, and the FM signal, which was more intense in level than the noise because of the proximity of the FM microphone to the mouth of the talker (3–6 in), was audible to the listener.

Results of this study also indicate that use of Dynamic FM allows for significantly better speech recognition in noise as compared to use of a traditional FM system with a fixed-gain setting. These improvements are related to the automatic gain increase of the FM signal when the noise level increased. The superior performance with Dynamic FM was present with and without the use of ASC. However, there was a larger discrepancy between the types of FM systems when ASC was used. Differences between performance with the Dynamic and traditional FM ranged from zero to five percentage points when ASC was not in use and 15 to 28 percentage points when ASC was in use. Certainly, the ASC off conditions were affected by floor effects, as many participants had speech-recognition scores of 0 percent correct in all noise conditions. These effects likely influenced any possible interactions between ASC use and the type of FM system. Overall, the findings showed that use of Dynamic FM resulted in considerable improvement in speech recognition in noise when compared to a traditional, fixed-gain FM system. The improved performance was also paired with subjective preferences, as several subjects commented on the improvements in sound quality and ease of listening when using Dynamic FM in the higher noise level conditions.

These results suggest that the difference between Advanced Bionics and Cochlear Corporation observed in Experiment 1 are entirely attributable to ASC being disabled for the Cochlear Corporation users. To examine this hypothesis, Dynamic FM data from Advanced Bionics subjects in Experiment 1 were compared to data from Cochlear Corporation subjects using Dynamic FM and ASC in Experiment 2. As shown in Figure 4, the differences in speech recognition in noise between groups were no longer significant at any of the three noise levels. This finding further supports the recommendation of ASC for users of Cochlear Corporation implants when they are using Dynamic FM systems.

Experiment 3: Effects of ASC on Perception of Environmental Signals

One important aspect of FM system use is to maintain audibility of environmental and speech signals through the speech-processor microphone. While the primary goal of an FM system is to improve the signal-to-noise ratio of the primary speaker, environmental signals are important for safety reasons and for following along with group discussions. To ensure that use of ASC with FM systems did not degrade recognition of environmental signals, speech recognition was compared in ASC on and ASC off conditions for speech delivered to the speech processor. In these quiet and noise conditions, the Dynamic FM system was active, but the FM microphone was muted.

The results of this testing indicate that use of ASC did not degrade speech recognition in quiet relative to performance with ASC disabled. Furthermore, in the two highest noise conditions (70/63, 74/70), use of ASC significantly improved performance when compared to the no ASC conditions at the same noise levels. Once again, this finding is likely attributable to compression of the incoming signal. As previously discussed, when ASC is disabled and the microphone sensitivity is fixed to the default setting, all acoustic inputs exceeding 65 dB SPL are infinitely compressed. In environments with high-level noise, people have a tendency to raise their speaking level so that the level of their speech exceeds the ongoing noise level (Pearsons et al, 1977). Consequently, a positive speech-to-noise ratio exists in most situations with background noise. When substantial compression is applied to all inputs exceeding 65 dB SPL, the positive speech-to-noise ratio is diminished, and the speech signal of interest becomes embedded in the background noise.

The primary objective of ASC is to reduce the sensitivity of the microphone so that the peaks of speech exceed the background noise by 15 dB. As such, the positive speech-to-noise ratio is at least partially preserved, and speech recognition is better relative to the no ASC condition. In short, the use of ASC improves speech recognition in noise, not only for FM use but also for signals arriving at the speech-processor microphone. Additionally, no detrimental effects toward speech recognition in quiet or noise were observed with the use of ASC.

Summary and Clinical Recommendations

Dynamic FM provides significantly better speech recognition in noise for Advanced Bionics CI users than traditional FM. These improvements occur at default settings; therefore, the clinician does not need to adjust any map parameters prior to FM use. When using FM, the audio-mixing ratio in the speech processor should remain at the 50/50 setting to preserve audibility of low-level incidental sounds to the speech-processor microphone (Wolfe and Schafer, 2008b).

When using Cochlear Corporation implants programmed with the manufacturer-default map settings, users will experience substantial difficulty when using either type of FM system in moderate- to high-level noise. Differences in performance between the two manufacturers are likely attributable to differences in IDR between the two systems. To diminish these performance discrepancies, ASC should be enabled to optimize speech recognition in noise through the FM and speech processor (i.e., environmental microphone). Once ASC is enabled, users of Cochlear Corporation implants will gain significant advantages from using Dynamic FM when compared to traditional FM. Again, to allow for equal emphasis for signals from the FM system and speech-processor microphone, and to avoid reduction of low-level sounds to the speech-processor microphone, the clinician should set the mixing ratio to 1:1.

Although other types of preprocessing (i.e., ADRO, BEAM, and Whisper) in the Cochlear Corporation implant were not systematically evaluated in this study, we also recommend that clinicians enable ADRO for FM use. Previous studies have shown that ADRO improves speech recognition in quiet for low-level speech inputs and does not degrade performance in noise. As such, use of ADRO may also improve the user's ability to hear low-level sounds that arrive at the microphone of the speech processor. Further, we cannot foresee any detrimental effects of the use of ADRO with FM. Therefore, the clinician might consider the ASC + ADRO preprocessing option for users of the Cochlear Corporation implant. Additional research is needed to systematically evaluate the effect of ADRO on FM performance.

The following statements summarize the findings of this study:

1. Use of Dynamic FM personal FM systems allows for better speech recognition in noise for cochlear implant recipients when compared to performance with traditional, fixed-gain FM systems.

2. The benefits of Dynamic FM are more apparent at higher ambient noise levels (i.e., 70 dB SPL and higher).
3. No changes are necessary to default program settings for Advanced Bionics cochlear implant users to allow for desirable performance and benefits with Dynamic FM.
4. It is recommended that the preprocessing feature Autosensitivity be enabled for Cochlear Corporation cochlear implant recipients to optimize speech recognition in noise with Dynamic FM and also without FM. The benefits of Autosensitivity are more apparent at higher noise levels (i.e., 70 dB SPL and higher).

NOTE

1. Statement from Cochlear Corporation: "Cochlear appreciated the opportunity to review this important clinical research paper, 'Evaluation of Speech Recognition in Noise with Cochlear Implants and Dynamic FM.' The company is in the process of developing its FM fitting guidelines based on these important data."

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