Behavioral Verification of Programmable FM Advantage Settings

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The effects of frequency-modulated (FM) receiver settings on speech perception in noise were examined in adults with and without hearing impairment. Using the Bamford-Kowal-Bamford Speech-in-Noise test, speech perception in noise of ten participants with mild-to-severe bilateral sensorineural hearing impairment and ten participants with normal hearing was evaluated while they wore Phonak iLink hearing instruments. The iLink had integrated FM receivers programmed to FM advantage settings ranging from 0 to +18 dB. Participants with normal hearing showed significantly greater benefit when listening with an FM system than did participants with hearing impairment. For both groups, there was significant improvement in performance with the addition of FM (vs. the local-microphone-only condition), and significant improvements were seen when FM advantage was increased by at least 6 dB. FM systems provide speech-perception-in-noise benefit to listeners with and without hearing impairment; however, incremental adjustments smaller than 6 dB may not result in significant improvements in performance.

Introduction

It is well-known that a reduction in audibility leads to reduced intelligibility of speech, even in the most ideal conditions (Ching, Dillon, & Byrne, 1998; Hornsby & Ricketts, 2003). Ideal conditions include optimal signal-to-noise ratio (SNR), specifically the audibility of the primary signal (e.g. speech) relative to unwanted signals (e.g. noise) in the listening environment. The SNR at a person's ear is determined both by the distance of the person from the speaker and the background noise level. Anyone can have difficulty understanding speech in poor SNR conditions, and listening to speech in the presence of background noise is one of the most common difficulties cited by people with hearing impairment (Cox & Alexander, 1995). To address the deleterious effect of poor SNR on communication, listeners with and without hearing loss may use a number of different devices to improve SNR with the goal of better understanding speech in noise (Smaldino & Crandell, 2000).

One of the most effective and widely-used technologies for enhancing SNR is the frequency modulated (FM) amplification system. This type of hearing assistance technology is composed of a microphone, a transmitter, and a receiver. The microphone is placed close to the desired signal (e.g., a person talking) and is connected to a transmitter, which sends an FM signal to the receiver that is placed on or near the listener's ear. This receiver can be a loudspeaker, a small ear-level unit, or it can be coupled with, or integrated into, a user's hearing instrument or cochlear implant. Using any of these receiver placements, the result is an improvement in SNR because the deleterious effects of distance and noise have been reduced. For people with hearing impairment, FM systems are one of the most effective ways to overcome the obstacles presented by poor SNR (e.g., Anderson & Goldstein, 2004; Arnold & Canning, 1999; Boothroyd & Iglehart, 1998; Hawkins, 1984; Lewis, Crandell, Valente, & Horn, 2004).

When fitting FM systems, the audiologist's goal is to maintain optimum intelligibility of the speech signal via the remote microphone, while allowing the user to remain connected to his surroundings either naturally or via the local microphone of a hearing instrument (American Speech-Language-Hearing Association, 2002). The SNR improvement that would be expected with the addition of an FM system is referred to as "FM advantage," or FMA. The FMA is derived by subtracting the SNR value (which would be obtained without the FM system) from the SNR obtained using the FM signal transmission (Platz, 2004). For example, if the SNR in the local-microphone-only condition was 5, but improved to 15 with the addition of an FM system, it would be considered an FM advantage of 10 dB, denoted FMA 10. The American Speech-Language-Hearing Association (ASHA) guidelines (2002) for fitting and monitoring FM systems recommend that the FM signal should be 10 dB more intense than the signal from the local microphone of the hearing instrument at the output of the user's hearing instrument; this is a starting point from which further adjustments can be made based on the needs and the comfort of the listener.

The introduction of programmable miniaturized FM receivers allowed for customized adjustment of FM gain and output to achieve a desired FMA (Platz, 2004). In light of this advancement, emerging research has focused on using electroacoustic verification procedures to evaluate whether changes to FMA settings produce the desired change in the device's acoustic output. However, there is little information available regarding the effect of manipulating the FMA settings with respect to a measurable difference in user benefit. In 2003, Lewis and Eiten conducted a survey with audiologists who listened to recordings at various SNRs. They found that listeners preferred increased SNR (as achieved by greater FMA) for audibility of the speaker's voice, but that the cost of increased FMA was decreased audibility of self and of other voices.

In addition to questions about the effect of changing FMA on subjective preferences, there have been questions raised about the electroacoustic changes that occur as FMA is changed. In 2007, Schafer, Thibodeau, Whalen and Overson examined the electroacoustic characteristics of FM receivers coupled to personal hearing instruments, and found that the output (as shown by electroacoustic verification) was affected by the type and compression characteristics of the hearing instrument and FM equipment used. For example, body-worn FM systems with neck loops provided reduced low-frequency output, and programmable receivers yielded lower average FMA than other types of receivers. The authors proposed that the sequential-testing protocol used in verification may have affected the results for some units. A sequential-testing protocol dictates measuring hearing aid output for a composite input of 65 dB SPL to the hearing aid local microphone, then measuring the hearing aid and FM system output for a composite input to the FM microphone of 80 dB SPL (ASHA, 2002). As the authors pointed out, data from Platz (2004, 2006) suggested that sequential testing did not replicate real-world inputs to both microphones. Additionally, they suggested that the use of input compression or wide-dynamic range compression in both the hearing instrument and the transmitter may have resulted in reductions in the measured FMA when the signals were added.

Although all agree that FM systems can result in improvements in speech perception in noise, the question of whether increases in FMA are associated with significant improvements in speech perception in noise remains unanswered. The purpose of the present study was to determine the relationships between changes in programmable FMA and speech perception in noise in adults with normal hearing and those with mild-to-severe sensorineural hearing loss. Based on the current understanding of the relationship of SNR to speech perception in noise (Finitzo-Hieber & Tillman, 1978; Nabelek & Pickett, 1974), it was predicted that all participants would show improvement with the addition of an FM system, and that people without hearing impairment would show greater improvement than listeners with hearing impairment, as FMA increased.

Method

Participants

Control participants included ten adults (four males and six females, age 19 to 35 years, mean = 26 years) with normal hearing, as defined by passing a hearing screening at 15 dB HL at 1000, 2000, and 4000 Hz. None had a history of hearing problems, nor had any experience using personal FM systems. Control participants were recruited from an available graduate student population. This group was included to see what optimal performance could be achieved without the effects of hearing loss or age. Experimental participants included ten adults (five males and five females, age 44 to 75 years, mean = 58.7 years) with bilateral sensorineural hearing impairment, as defined by the better-ear pure tone average (500, 1000, and 2000 Hz) ranging from 18 to 70 dB HL (mean = 34.6 dB HL). Experimental participants were recruited from those who had participated in past research at the University of Texas at Dallas. As shown in Table 1, nine of ten participants were experienced bilateral hearing-instrument users. Two participants (Participants 2 and 4) had experience using FM systems, and four had participated in hearing-related research studies, though none were familiar with the specific test materials.

Table 1. Demographic information on the experimental participants, their age, better ear pure-tone average (PTA), personal hearing-aid type, and initial SNR used during testing.

Participant	Age (years)	Better Ear PTA (dB HL)	Personal Hearing Aid	Initial SNR
1	61	25	Open-fit BTE	54
2	48	65	BTE	64
3	55	20	None	54
4	56	70	BTE	49
5	67	28	BTE	64
6	75	18	Open-fit BTE	52
7	44	33	Open-fit BTE	50
8	49	25	Open-fit BTE	54
9	71	30	CIC	44
10	71	32	Open-fit BTE	44
Mean (SD)	58.7 (10.66)	34.6 (18.03)	--	52.9 (6.94)

Note: dB HL = decibel hearing level; BTE = behind-the-ear; CIC = completely-in-the-canal; SNR = signal-to-noise ratio

Amplification Systems

Although there is current FM technology in which the FMA fluctuates or adapts, depending on the background noise level, an examination of the effects of small changes in FMA would be difficult with an adaptive system. Additionally, there are several FM systems with programmable settings that adjust the FMA to a certain fixed level. To conduct an investigation of FMA settings, a convenient instrument to program for both normal and impaired hearing was selected. Ten Phonak iLink S-311 hearing instruments with integrated FM receivers were programmed using Phonak PFG software, version 8.6, and Phonak FM Successware, version 4.0. For control participants, the study's hearing instruments were programmed to meet National Acoustic Laboratories Non-Linear version 1 (NAL-NL1: Byrne, Dillon, Ching, Katsch, & Keidser, 2001; Dillon, 1999) targets for a hearing level of 15 dB HL across the frequencies of 250 Hz to 8000 Hz. ER-3A tips with size 13 tubing were used to couple the hearing instruments to each ear. For experimental participants, the study hearing instruments were programmed to match the settings of their personal hearing instruments when possible. For those without personal hearing instruments (Participant 3) or with open-fit behind-the-ear aids (Participants 1, 8, and 10), the study aids were programmed to meet NAL-NL1 targets for their hearing loss, and then adjusted for comfort. Four of the ten participants had personal earmolds that were used to couple the study's hearing instruments to their ears; the other six participants used the same type of temporary ER-3A eartips as the control participants.

The FMA of iLink S-311 hearing instruments can be adjusted in 2-dB steps, from 0 to 18. A clinically-feasible step size of 4 dB was chosen, resulting in the following FMAs: 18, 14, 10, 6, or 0 dB. The decision was made to eliminate the FMA 2 condition rather than including a final step size of less than 4 dB. As a result, there was a 6 dB step size from FMA 6 to FMA 0. All participants were fit bilaterally at the beginning of each listening condition with a pair of the study's hearing instruments programmed for their hearing loss and for one of the FMA settings. An FM transmitter was selected that was of the same generation of equipment and that would have minimal advanced features that might impact results, such as adaptive FMA, directional microphones, or voice activation. A Phonak Campus S transmitter with MM8 lapel microphone on omnidirectional setting was used on Channel 1.

[1] It should be noted that the American Academy of Audiology Clinical Practice Guidelines for Fitting and Verification of Hearing Assistance Technology (2008) cautions against using adaptive-noise behavioral verification protocols because "resulting noise levels may exceed typical classroom noise levels". However, the literature supports the use of adaptive noise, as occupied-classroom noise levels fluctuate throughout the day. For example, Dockrell and Shield (2004) found that classroom noise levels varied from 55.5 dBA when students were working quietly to 77.3 dBA when students were involved in activities. To mimic the natural fluctuations in noise that occur throughout a listener's day, a modified method of constants approach to manipulating SNR was needed, and thus the BKB-SIN test (Etymotic Research, 2005) was chosen for the present study to determine behavioral changes in speech perception in noise performance.

Electroacoustic Verification Procedure

Electroacoustic characteristics of hearing instruments were verified using a Frye FP-40 hearing-aid analyzer to determine gain/output and equivalent-input-noise characteristics. All study hearing instruments were programmed to match NAL-NL1 simulated real-ear targets using average adult RECD information. One participant with hearing impairment (Participant 2) requested an increase in gain for the left hearing instrument, which resulted in an increase of 7 dB for the three-frequency average at 750, 1000, and 2000 Hz, as measured in a 2cc coupler using an input of 65 dB SPL.

The American Academy of Audiology Clinical Practice Guideline for Fitting and Verification of Hearing Assistance Technology (2008) was used for verification of FM output. Measurements via HA-2 coupler with a 65 dB SPL randomly-interrupted, speech-weighted input were used to compare hearing instrument local-microphone (M) response to hearing-aid-plus-FM (FM+M) response to ensure that programming changes resulted in changes in output. The goal was not to achieve transparency, as recommended in the AAA protocol, but rather to measure the output of the M and FM+M in a consistent way.

Materials

The Bamford-Kowal-Bamford Speech-in-Noise test (BKB-SIN), a test of speech perception in decreasing SNR[1], was used with non-traditional presentation levels to assess the potentially small changes in performance that could occur with the changes in FMA settings. The BKB-SIN uses the Bamford-Kowal-Bench sentences (Bench & Bamford, 1979; Bench, Kowal & Bamford, 1979) spoken by a male talker in four-talker babble (Auditec of St. Louis, 1971) and contains 18 List Pairs, each half of which comprises an 8 to 10 sentence list. The first sentence of each list has four key words, and the remaining sentences each have three. The method for determining the signal-to-noise ratio at 50% correct (SNR-50) score is based on the Tillman-Olsen (Tillman & Olsen, 1973) procedure for obtaining spondee thresholds. In the BKB-SIN, one point is given for each key word repeated correctly, and the total number of correct words per list is subtracted from 23.5 (this number is derived from the starting SNR = 21, plus half the step size = 1.5, plus the extra word from the first sentence = 1). If modifications were made to the initial intensity of the background babble (see Behavioral Verification section for more information on signal levels), then the formula was adjusted as follows: Total number of words correct was subtracted from [23.5 - (65- x), when 65 = initial signal presentation level and x = initial SNR]. The SNR-50 scores for both half-lists of the List Pair are averaged to obtain the List Pair score (Etymotic Research, 2005).

A benefit of using the BKB-SIN for this study was that it was possible to use a split-track recording in which the initial intensity of the babble could be changed independently of the intensity of the signal. This was necessary to avoid a "ceiling effect," where the addition of an FM system could allow participants to score 100% correct in even the most difficult SNR conditions.

The stimuli were presented via CD player, with an amplifier (GSI-16 or Crown D75) in a single-walled audiometric booth using single-cone loudspeakers at 0 and 180 degrees azimuth. Initial calibration was completed using a Quest Impulse Integrating Model 1800 sound-level meter placed in the participant's chair to approximate the location of the participant's ears. Subsequent sound level measurements were made prior to testing each participant to confirm uniformity of signal characteristics from one subject to the next using a Radio Shack Digital-Display sound level meter, Model 33-2055. In each calibration, the 1000 Hz calibration tone on the BKB-SIN CD was used to set the volume units (VU) meter for the initial signal and noise output from the loudspeakers via Channel 1 and Channel 2, respectively. Intensity at the level of the participant's ear was also verified using speech-spectrum noise from the BKB-SIN CD to confirm signal and noise intensity prior to beginning the BKB-SIN test. Using these calibration procedures, signal intensity was confirmed to be 65 dBA at the level of the listener's ear and 86 dBA at the level of the FM microphone placed 15.25 cm from the speaker at 0 degrees azimuth.

Behavioral Verification Procedure

The signal and noise loudspeakers were one meter from the participant at 0 and 180 degrees, respectively. The FM microphone was placed 15.25 cm in front of the signal loudspeaker (see Figure 1). This distance was chosen based on recommendations for "typical use," suggesting that lapel microphones be placed six inches from the speaker's mouth (AAA, 2008). The BKB-SIN test was administered as a split-track recording with Channel 1 providing the speaker's voice and Channel 2 providing the background babble. One half-list from List Pairs 9 through 18 was given as a practice list in the microphone-only condition. Participants had to be able to correctly repeat at least 18 out of 22 words presented at a SNR of 3 dB or better. All test participants met inclusion criteria within one practice list. Test lists (from List Pairs 1 through 8) were then administered in computer-generated random order in the following conditions: microphone-only, FMA 0, FMA 6, FMA 10, FMA 14, and FMA 18. Lists were re-randomized for each participant.

For participants with normal hearing, the signal was presented from the front loudspeaker (Channel 1) at a constant level of 65 dBA (as measured at the level of the participant's ear) and the background babble was presented from the rear loudspeaker (Channel 2), beginning at 54 dBA (SNR 11) and was increased by 3 dB for each presentation until the intensity of the babble was 81 dBA (SNR 16) at the final presentation.

For experimental participants, the signal (Channel 1) was again held constant at 65 dBA. Due to the higher variability in performance expected among listeners with hearing loss, the selection of the initial intensity of the background babble level was carefully selected for each individual so that performance with the FM system would still present a challenge across all the FMA settings. The initial babble level was set based on performance on the practice list. Several of the participants with hearing impairment were able to easily complete most of a practice list in the microphone-only condition at a SNR of 0. This suggests that the addition of an FM system would create a ceiling effect, with participant scores reaching a maximum number of words correct in one or more conditions. If the practice list indicated a ceiling effect, additional adjustment to initial background babble level was made such that when the participant was wearing hearing instruments programmed to the highest FMA (18), their BKB-SIN score would approach (but not meet) the maximum number of words correct. The starting level of the background babble ranged from 44 dBA (SNR 21) to 65 dBA (SNR 0) and increased in 3 dB steps until the final level was 27 dB more intense than the initial level (refer to Table 1).

Figure 1. Booth configuration for the behavioral evaluation. The FM microphone was placed 15.25 cm from the signal speaker, and the participant was separated from the signal and noise speakers by one meter in each direction.

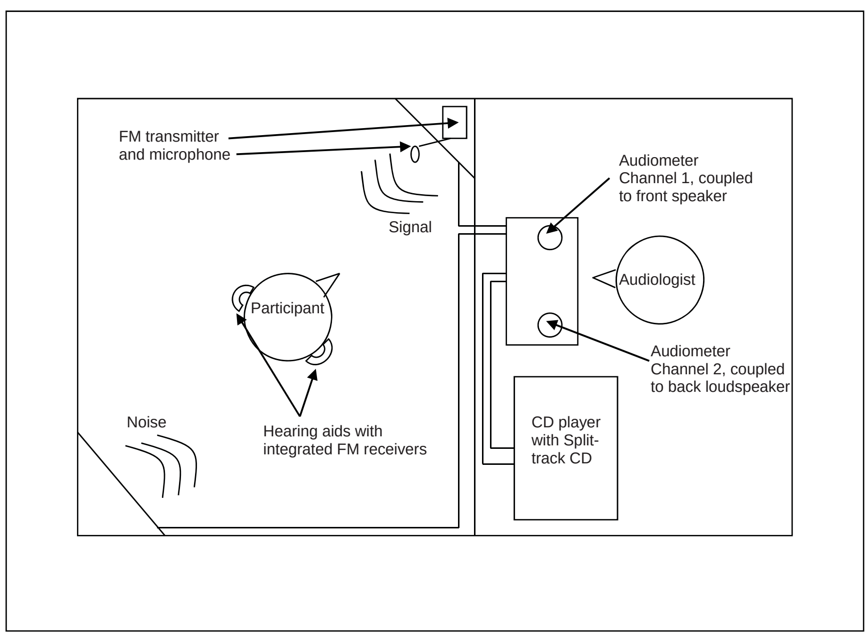
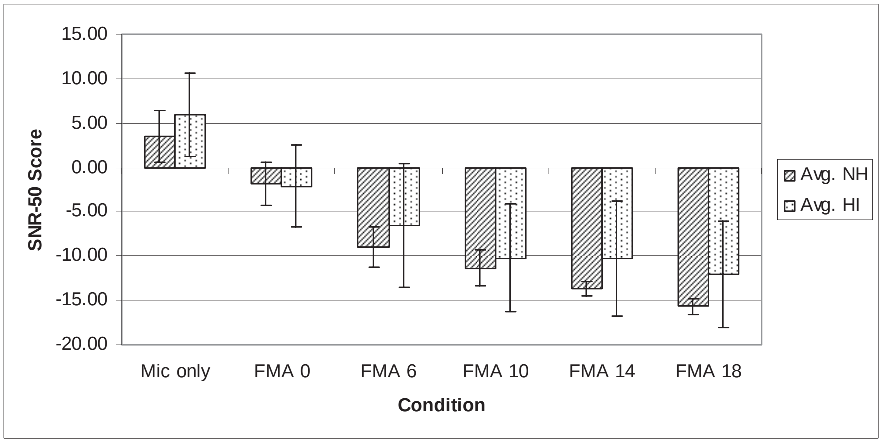


Figure 2. Average SNR at 50% score (SNR-50) for ten control (Avg. NH) and ten experimental participants (Avg. HI).



Note: Errorbars show +/- 1 standard deviation; FMA=FM advantage

Table 2. Average improvement in SNR-50 scores across FM advantage conditions for ten control participants and ten experimental participants.

FMA	Mic-only to 0	0 to 6	6 to 10	10 to 14	14 to 18	Total 0 to 18
Control	-5.35	-7.2	-2.35	-2.35	-2	-19.25
Experimental	-7.45	-4.45	-3.65	-0.10	-1.75	-17.40

Note: FMA = FM advantage; Mic = microphone; SNR = signal-to-noise ratio

Results

The average performance across the conditions for control participants and experimental participants is shown in Figure 2. The SNR-50 scores for each participant are provided in Appendix A. For every condition, the control group could achieve 50% correct performance with greater noise levels (lower SNRs) on average than the experimental group with the exception of the FMA 0 condition. The average improvement from one condition to the next is shown in Table 2. For each group, the use of the FM system resulted in the ability to tolerate more noise relative to the microphone-only condition. Furthermore, increases in FMA resulted in a lower SNR-50 score relative to the previous condition.

A one between-subject, one within-subject repeated measures analysis of variance (ANOVA) was performed and revealed significant main effects for group and condition. Across the six FMA conditions, the control participants (mean SNR-50 score = -7.98 dB) achieved lower SNR-50 scores than the experimental participants (mean SNR-50 score = -5.91 dB), $F(1,5) = 4.95$, $MSE=105.02$, $p=.03$. This difference in performance is consistent with the well-documented finding that people with hearing impairment would have greater difficulty with a speech-perception-in-noise task (Beattie, 1989; Lewis, et al., 2004; Wilson, McArdle, & Smith, 2007). Some of the difference could also be attributed to differences in ages of the two groups, although this was not a main factor of interest in this study.

There was also a significant effect of FMA condition, with the SNR-50 score decreasing as FMA increased from 0 to 18 dB, $F(1,5)=50.12$, $MSE= 974.88$, $p<.0001$. *A posteriori* analysis was completed using the Tukey-Kramer correction for multiple comparisons, and revealed a significant change when comparing low-FMA conditions to higher-FMA conditions (see Table 3). However, there was no change in speech perception performance when instruments were changed from FMA 10 or FMA 14 to higher FMA settings. There was no significant interaction between group and condition, $F(1,5)=0.56$, $MSE=10.93$, $p=0.73$. The change in SNR-50 scores across FMA conditions occurred similarly for control and experimental participants.

The change in FMA measured electroacoustically compared to programmed change is shown in Figure 3, and further detail is provided in Appendix B. A given increase in FMA in the FM Successware program did not always result in a similar (+/- 1dB) increase in FMA when electroacoustically evaluated according to AAA and Phonak guidelines. Changes in electroacoustic response tended to be closer to the programmed change when the hearing aids were programmed for a flat 15-dB hearing level (i.e. for normal hearing). For this programmed level, the electroacoustic change was within +/- 1 dB in two of four FMA comparison conditions (6 to 10 and 14 to 18). However, when the hearing aids were programmed for the respective hearing loss values, the change in electroacoustic response was within +/- 1 dB in only one of the four FMA comparison conditions

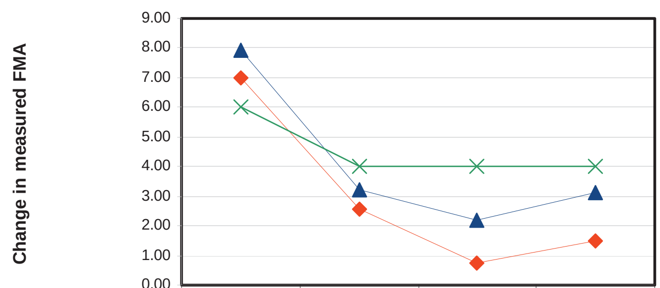
Table 3. Changes in SNR-50 scores between FM advantage conditions for all participants.

	Mic-Only	FMA 0	FMA 6	FMA 10	FMA 14	FMA 18
Mic-only	--	6.40*	12.23*	15.23*	16.45*	18.33*
FMA 0	--	--	5.83*	8.83*	10.05*	11.93*
FMA 6	--	--	--	3.00	4.23*	6.10*
FMA 10	--	--	--	--	1.23	3.10
FMA 14	--	--	--	--	--	1.88

Note: FMA = FM advantage; Mic = microphone; SNR = signal-to-noise ratio: An asterisk (*) indicates a significant difference at the .05 level.

(0 to 6). For three of the comparison FMAs, the change measured electroacoustically was less than the programmed change in FMA. For example, changing the FMA from 10 to 14 in the programming software only resulted in an electroacoustic change of 1.12 dB.

Figure 3. Mean electroacoustic change in FM advantage compared to programmed change in FM advantage, by group.



	0 to 6 dB	6 to 10 dB	10 to 14 dB	14 to 18 dB
Electro NH	7.95	3.23	2.20	3.14
Electro HI	7.01	2.56	0.76	1.51
FMA in DB	6.00	4.00	4.00	4.00

FM Program increase

Note. Electro NH = the difference between the electroacoustic three-frequency average from one condition (such as FMA 0) to the next (such as FMA 6) for the control participants; Electro HI = experimental participants; and FMA in dB = the difference from one programmed FMA (such as 0) to the next (such as 6).

Discussion

The purpose of this study was to examine the listening-in-noise performance of adults with normal hearing compared to adults with hearing impairment for various FM advantage (FMA) settings. For both groups, there was significant improvement in performance across all conditions as FMA increased.

Clinical Implications

This study has several implications for clinicians working with programmable FM systems. First, the data confirmed that the addition of an FM system improved speech perception in noise for all participants, whether they had normal hearing or hearing impairment (see Appendix C). In all FMA conditions, improvements were achieved by seven of the ten control participants relative to the microphone-only condition, and nine of the ten experimental participants achieved improvements in the FMA 0 condition relative to the microphone-only condition. These results indicate that individuals who use an FM system can tolerate greater noise levels and still maintain 50% speech recognition. This finding supports prior research findings that the addition of an FM system is an effective means of addressing the issue of listening in noise (Anderson & Goldstein, 2004; Arnold & Canning, 1999; Boothroyd & Iglehart, 1998; Lewis et al, 2004).

While the results showed that, in general, FM systems provide advantages to people with and without hearing impairment, the findings described above suggest a great deal of variability between programmed settings and behavioral performance on a speech-perception-in-noise task. With this in mind, a clinician cannot always expect that changes beyond the default settings in the programmed FMA will result in an improvement in their patient's performance.

Interestingly, improvements in performance related to changes in FMA were less consistent for participants with hearing impairment than for participants with normal hearing. This may be due, in part, to compression characteristics of the hearing instrument and FM system. For listeners without hearing impairment, the compression settings were the same across all aids. This most likely resulted in a more consistent SNR improvement with fluctuating inputs. For listeners with hearing impairment, the compression settings varied with degree of loss, which could account for some of the increased variability seen in the participants with hearing impairment. These findings suggest that, in addition to other amplification characteristics, the compression settings of the hearing instrument may interact with those of the FM system.

For the group with normal hearing, most participants showed an improvement in performance as FMA increased. However, the group with hearing impairment achieved greater change more often with the initial addition of an FM system, as seen by comparing microphone-only to FMA 0. However, fewer participants were able to achieve improvements with the addition of greater FM advantage. This suggests that increasing the FM advantage in small increments (i.e., 4 dB or less beyond FMA 6) may not result in significant benefits in speech perception in noise for patients. Also, the variability in results, particularly with the hearing-impaired group, suggests that sensitive measures of speech perception in noise (such as the BKB-SIN) are necessary when fitting FM systems.

Finally, programmed changes in FMA did not always result in equal changes in FMA when measured electroacoustically, especially for participants with hearing impairment. This may have been related to the fixed output sound pressure at 90 dB (OSPL90) of the device. As shown by Schafer, et al (2007), the OSPL90 when receiving an FM signal does not exceed the OSPL90 in the microphone-only setting. Thus, when the speech input for a hearing aid is nearing saturation levels (as is possible for listeners with hearing impairment), the FM system is likely to be in compression and may not be able to generate a signal significantly different in intensity from the microphone-only signal, particularly at high FMA settings.

Limitations

This study was completed using a relatively small sample size of 20 adults. There was more variability in performance with hearing-impaired participants, which could be attributable to differing degrees of hearing loss, varying amounts of prior experience with amplification, compression settings, or central auditory processing issues (due to aging). Another concern is the age difference between the control group (M=26 years, SD=4.74) and the experimental group (M= 60.3 years, SD=9.89). It is well understood that speech perception in noise declines with age (Jerger, Jerger, Oliver, & Pirozzolo, 1989; Martin & Jerger, 2005), so it cannot be ruled out that the performance differences between the control group and the experimental group were confounded by age difference. Additionally, only one type of speech-in-noise test was used, which had an adaptive noise level; results may differ when using different tests and/or when adaptive signal/speech levels are used, as changing the intensity of the signal may affect the compression characteristics of hearing instruments and/or FM systems (see Schafer et. al, 2007). Finally, a specific type of hearing instrument and FM system was used; it is possible that results could vary considerably with different amplification systems as direct audio input characteristics, microphone sensitivities, and impedance characteristics change from one system to the next.

Future Research

The focus of this study was on the performance of adults with hearing loss, but there is a clear need to do similar research with children with and without hearing loss, as children tend to be the most frequent users of FM technology (Smaldino & Crandell, 2000). Also, further research into electroacoustic evaluation using speech-like inputs at varying intensities may help explain how compression characteristics affect outputs with and without FM systems. Finally, with the emergence of new technology (such as dynamic or adaptive FM systems), additional research will be needed to determine how to effectively evaluate benefit, both electroacoustically and behaviorally. Ultimately, in order to maximize user benefit, careful monitoring of electroacoustic and behavioral benefit of programmable FM systems is warranted.

Acknowledgements

The authors would like to thank Phonak Hearing Systems for the donation of the FM receivers and transmitters used in this study.

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Appendix A

SNR-50 scores for participants from control group (top) and experimental group (bottom).

Participant	NH-1	NH-2	NH-3	NH-4	NH-5	NH-6	NH-7	NH-8	NH-9	NH-10
Mic-only	3.50	-0.50	1.00	4.50	-1.50	5.00	4.50	7.00	5.50	6.50
FMA 0	1.00	-6.00	-3.50	-2.50	-1.50	3.00	-1.50	-2.50	-2.50	-2.00
FMA 6	-6.50	-11.00	-9.00	-7.00	-11.00	-5.50	-10.50	-7.00	-12.00	-10.50
FMA 10	-10.50	-10.00	-16.00	-10.50	-10.50	-9.00	-12.50	-10.00	-12.50	-12.00
FMA 14	-12.50	-13.50	-15.00	-15.00	-14.00	-14.00	-13.00	-13.00	-13.00	-14.00
FMA 18	-14.00	-15.50	-17.00	-15.00	-16.00	-15.50	-15.00	-16.00	-16.00	-17.00
Mean	-6.50	-9.42	-9.92	-7.58	-9.08	-6.00	-8.00	-6.92	-8.42	-8.17

Participant	HI-1	HI-2	HI-3	HI-4	HI-5	HI-6	HI-7	HI-8	HI-9	HI-10
Mic-only	10.50	10.50	6.50	-1.50	0.00	-0.50	9.50	10.50	4.00	4.00
FMA 0	3.50	-1.00	-0.50	-2.50	5.00	-7.00	0.50	-5.00	-10.00	-4.00
FMA 6	-2.50	-4.50	0.00	-9.00	7.00	-5.50	-10.00	-12.00	-17.50	-11.50
FMA 10	-6.50	-7.00	-8.00	-9.50	2.00	-13.00	-10.50	-14.00	-21.00	-14.50
FMA 14	-11.50	-7.00	-6.00	-10.00	3.50	-13.00	-13.00	-10.00	-21.00	-15.00
FMA 18	-8.00	-7.50	-8.50	-15.00	-1.50	-15.00	-10.50	-15.50	-22.50	-16.50
Mean	-2.42	-2.75	-2.75	-7.92	2.67	-9.00	-5.67	-7.67	-14.67	-9.58

Average SNR-50 Scores

	NH	SD	HI	SD
Mic-only	3.55	2.92	5.35	4.85
FMA 0	-1.80	2.43	-2.10	4.61
FMA 6	-9.00	2.31	-6.55	6.99
FMA 10	-11.35	2.00	-10.20	6.11
FMA 14	-13.70	0.86	-10.30	6.43
FMA 18	-15.70	0.92	-12.05	5.98
Mean	-8.00		-5.88	

Note: FMA = FM advantage; Mic = local microphone NH = control group; HI = experimental group

Appendix B

Behavioral SNR improvement and electroacoustic differences as FM advantage changes, by subject.

FMA		NH-1	NH-2	NH-3	NH-4	NH-5	NH-6	NH-7	NH-8	NH-9	NH-10
0 to 6	Beh	7.50	5.00	5.50	4.50	9.50	8.50	9.00	4.50	9.50	8.50
	Elec	7.00	7.00	7.00	7.00	7.00	7.00	7.00	10.17	10.17	10.17
	Diff	0.50	-2.00	-1.50	-2.50	2.50	1.50	2.00	-5.67	-0.67	-1.67
6 to 10	Beh	4.00	-1.00	7.00	3.50	-0.50	3.50	2.00	3.00	0.50	1.50
	Elec	3.33	3.33	3.33	3.33	3.33	3.33	3.33	3.00	3.00	3.00
	Diff	0.67	-4.33	3.67	0.17	-3.83	0.17	-1.33	0.00	-2.50	-1.50
10 to 14	Beh	2.00	3.50	-1.00	4.50	3.50	5.00	0.50	3.00	0.50	2.00
	Elec	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.67	2.67	2.67
	Diff	0.00	1.50	-3.00	2.50	1.50	3.00	-1.50	0.33	-2.17	-0.67
14 to 18	Beh	1.50	2.00	2.00	0.00	2.00	1.50	2.00	3.00	3.00	3.00
	Elec	3.42	3.42	3.42	3.42	3.42	3.42	3.42	2.50	2.50	2.50
	Diff	-1.92	-1.42	-1.42	-3.42	-1.42	-1.92	-1.42	0.50	0.50	0.50

FMA		HI-1	HI-2	HI-3	HI-4	HI-5	HI-6	HI-7	HI-8	HI-9	HI-10
0 to 6	Beh	6.00	3.50	-0.50	6.50	-2.00	-1.50	10.50	7.00	7.50	7.50
	Elec	5.83	6.67	8.50	7.17	7.00	8.17	7.67	8.33	3.47	7.33
	Diff	0.17	-3.17	-9.00	-0.67	-9.00	-9.67	2.83	-1.33	4.03	0.17
6 to 10	Beh	4.00	2.50	8.00	0.50	5.00	7.50	0.50	2.00	3.50	3.00
	Elec	2.17	1.50	3.50	1.33	4.17	3.67	3.38	4.00	1.83	0.05
	Diff	1.83	1.00	4.50	-0.83	0.83	3.83	-2.88	-2.00	1.67	2.95
10 to 14	Beh	5.00	0.00	-2.00	0.50	-1.50	0.00	2.50	-4.00	0.00	0.50
	Elec	0.67	1.00	0.33	1.50	0.33	2.50	-0.75	-0.42	0.60	1.83
	Diff	4.33	-1.00	-2.33	-1.00	-1.83	-2.50	3.25	-3.58	-0.60	-1.33
14 to 18	Beh	-3.50	0.50	2.50	5.00	5.00	2.00	-2.50	5.50	1.50	1.50
	Elec	1.50	0.67	-0.50	2.83	-1.83	2.17	2.17	3.97	2.07	2.10
	Diff	-5.00	-0.17	3.00	2.17	6.83	-0.17	-4.67	1.53	-0.57	-0.60

Note: Beh = Change in SNR-50 score from one FMA condition to the next;
Elec = change in the 3-frequency average (750, 1000, 2000 Hz) difference between hearing aid and hearing aid plus FM, from one FMA condition to the next;
Diff = difference between behavioral change and electroacoustic change from one FMA condition to the next.

Appendix C

Individual participants who exceeded the 95% confidence interval for change in speech-recognition-in-noise score as FM advantage was changed.

FMA comparison	Group	CI	1	2	3	4	5	6	7	8	9	10	Total no. of participants exceeding CI
Mic-only to 0	Control	1.81	+	+	+	+	-	+	+	+	+	+	9
	Experimental	3.00	+	+	+	-	-	+	+	+	+	+	8
0 to 6	Control	1.51	+	+	+	+	+	+	+	+	+	+	10
	Experimental	2.85	+	+	-	+	-	-	+	+	+	+	5
6 to 10	Control	1.43	+	-	+	+	-	+	+	+	-	+	7
	Experimental	4.33	-	-	+	-	+	+	-	-	-	-	3
10 to 14	Control	1.24	+	+	-	+	+	+	-	+	-	+	7
	Experimental	3.78	+	-	-	-	-	-	-	-	-	-	1
14 to 18	Control	0.53	+	+	+	-	+	+	+	+	+	+	9
	Experimental	3.99	-	-	-	+	+	-	-	+	-	-	3

Note: FMA = FM advantage; Mic = microphone; CI = confidence interval; (+) = change in score exceeded 95% confidence interval; (-) = change in score did not exceed 95% confidence interval.