

# Hearing Aid Accessories for Adults: The Remote FM Microphone

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**Objective:** The primary goal was to determine the benefits and limitations of a remote FM microphone as a hearing aid accessory. A secondary goal was to determine the predictors of aided and FM-assisted speech perception by adults with hearing loss, in quiet and in noise, using methods derived from Articulation Index theory.

**Design:** Twelve adults with mild to severe hearing loss, aged 52 to 85, were fit with behind-the-ear FM hearing aids and used them for a minimum of 2 wk. Phoneme recognition was measured before and after the trial period at several speech levels under three conditions: aided in quiet, aided in spectrally matched noise, and FM-assisted in noise. A single session of counseling, instruction and demonstration was provided before the trial period. Perceived benefit was assessed by questionnaire at the end of the trial period. Measured and perceived benefit were examined in relation to age and pure-tone thresholds.

**Results:** FM-assisted phoneme recognition in noise equaled aided phoneme recognition in quiet. Both were very well predicted by the average pure-tone threshold at 2 and 4 kHz, under a model that assumes Articulation Index (AI) falls with increasing high-frequency threshold at the rate of about 1 percentage point per dB. Aided phoneme recognition in noise was quite well predicted by the same average threshold, under a model that assumes a signal-to-noise ratio of 0 dB reduces Articulation Index to one third of that in quiet. Average perceived benefit was highest for one talker, at a distance, in quiet or in noise. It was lowest for multiple talkers (where the system would be expected to be ineffective) and one close talker in quiet (where the system should be unnecessary). Older subjects and subjects with poorer aided recognition in noise tended to express lower perceived benefit. Many subjects reported that the system was ineffective in reducing background noise. This finding was attributed to use of an "equal gain" criterion in adjusting relative gains via the hearing aid and FM microphones. The single pretrial session of counseling, instruction and demonstration was clearly inadequate for many of the subjects. None expressed an intention to acquire an FM system.

**Conclusions:** The expected benefits of a remote FM microphone in reducing the negative effects of distance and noise, for a single talker, can be demonstrated under both laboratory and field conditions. The effects of hearing loss, noise and FM assistance, on aided phoneme recognition, are well predicted by methods derived from Articulation Index theory. Considerable counseling, instruction and coaching will be needed, however, to ensure optimal use of this technology. In addition, the relative gains via FM and hearing aid microphones must be adjusted with care.

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Remote wireless microphones have a long history of application in the education of children with hearing loss (Ross, 1992). Their use in that context has three goals: a) eliminating the negative effects of noise and reverberation on speech perception, b) increasing speech output levels for children with severe and profound hearing loss and c) maintaining constant speech input regardless of distance between talker and listener. These goals are attained by placement of the microphone within a few inches of the talker's mouth. As a result the speech level and signal-to-noise ratio are typically 15 to 20 dB higher than at the listener's location. They also remain constant as the talker moves around. Wireless transmission of the resulting signal is not essential but is obviously more convenient than a wired connection (Boothroyd, 1992).

In recent years miniature FM receivers have been introduced that can be attached to, or built into, behind-the-ear hearing aids. This development has enhanced the possibility of the application of remote, wireless microphones as hearing aid accessories by adults with hearing loss. There are, however, several potential limitations in this application. Obvious examples are intrusiveness and the fact that enhanced reception only applies to the speech of the person wearing the microphone. Less obvious are the loss of control of the microphone by the hearing aid user, and the difficulties of balancing gains via the remote microphone and the hearing aid's own microphone (American Speech-Language-Hearing Association, 2002). Whether the benefits might outweigh the limitations, and for what type of hearing aid user, is uncertain.

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TABLE 1. Background data for 12 subjects

Subject	Gender	Age (yr)	Frequency in kHz						Right PTA	Frequency in kHz						Left PTA	
			0.25	0.5	1	2	4	8		0.25	0.5	1	2	4	8		
s1	F	73	30	30	40	35	40	75	35	25	20	30	25	30	70	25	
s2	F	73	25	20	50	40	30	20	37	35	35	55	45	40	25	45	
s3	M	83	15	20	70	70	70	60	53	20	30	65	75	65	70	57	
s4	M	73	30	40	45	35	45	50	40	35	40	40	35	40	60	38	
s5	F	69	80	75	75	65	60	65	72	85	75	75	70	60	65	73	
s6	M	79	Total loss						—	—	25	25	50	60	105	90	45
s7	M	73	90	85	90	75	80	85	83	80	75	75	75	80	105	75	
s8	M	80	30	45	55	60	65	70	53	30	40	55	65	80	90	53	
s9	M	73	45	60	65	85	90	115	70	50	55	65	90	100	115	70	
s10	M	52	45	55	75	75	75	60	68	40	45	80	70	75	55	65	
s11	F	85	Total loss						—	—	20	15	25	45	55	80	28
s12	M	62	5	10	15	15	70	60	13	0	5	15	5	70	65	8	
Mean		73	40	44	58	56	63	66	53	37	38	53	55	67	74	49	
Max		85	90	85	90	85	90	115	83	85	75	80	90	105	115	75	
Min		52	5	10	15	15	30	20	13	0	5	15	5	30	25	8	

The present study was designed to assess the benefits and limitations of a remote wireless microphone, as a hearing aid accessory for adults, in both laboratory and field tests. Speech perception was assessed as a function of input level, under controlled listening conditions, before and after a trial period with a behind-the-ear FM system. Perceived benefits were assessed at the end of the trial period by questionnaire. Specific research questions were as follows.

1. Are laboratory measures consistent with the expected effects of signal level and signal-to-noise ratio on aided speech perception in quiet and noise, and on FM-assisted speech perception in noise?
2. To what extent do unaided pure-tone thresholds and age account for individual differences in speech perception measures?
3. To what extent can the effects of hearing loss and noise on speech perception be modeled using Articulation Index theory?
4. How does listening condition affect perceived benefit during everyday use?
5. To what extent can individual differences of perceived benefit be accounted for by unaided pure-tone threshold, laboratory measures of speech perception, and age?
6. What are the benefits and limitations of such a system as identified by users during everyday use?

## METHOD

### Subjects

Eight men and four women participated in this study. Table 1 provides background data. Ages

ranged from 52 to 85 yr with a mean of 73 yr. Better-ear, three-frequency-average hearing loss ranged from 8 to 75 dB with a mean of 48 dB. Six of the subjects had sloping audiograms, defined, here, as a difference of 30 dB or more between better-ear thresholds at 500 and 4000 Hz. Eleven of the subjects were experienced hearing aid users. All subjects had previously participated in a Rehabilitation Research Training Center project on Living with Hearing Loss at the California School of Professional Psychology. Participation in the present study was voluntary, by informed consent. Subjects were paid a small fee to offset travel expenses.

### Amplification

For purposes of this study, all subjects were fitted with behind-the-ear hearing aids having built-in FM receivers (the Free Ear from Phonic Ear\*). These were linear, single-channel, analog aids with adjustable compression limiting. Apart from the compression limiting, these aids employed no adaptive signal processing. Subjects were also provided with a Free Ear microphone/transmitter. This transmitter includes compression limiting giving a compression threshold in the region of 75 dB SPL. Gains via the hearing aid and FM microphones were adjusted to be equal for inputs below the compression threshold of the FM transmitter. Above this threshold, the gain via the FM microphone falls in relation to that via the hearing aid microphone. Gains, Saturation Sound Pressure Levels, and frequency response of

\*This study was not designed as a clinical trial of a specific product. It was an NIDRR-funded study of a technology, of which the Free Ear was an example.

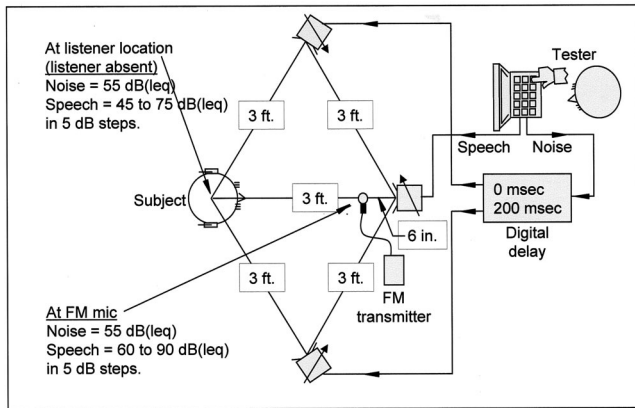


Figure 1. Set-up for laboratory testing.

the aids were initially adjusted according to individual needs by matching to NAL targets as closely as possible.

### Laboratory Testing

**Equipment** • The set-up for laboratory testing is illustrated in Figure 1. Speech and noise were presented from digital stereo files via a laptop computer and amplified single-cone loudspeakers (Roland 12C). Speech was presented at a distance of 3 feet and 0° azimuth. Noise was presented from two loudspeakers at 3 feet and +60° and -60° azimuth. The two noise sources were desynchronized by insertion of a 200 msec delay in one channel. When testing via FM, the microphone was placed at a distance of 6 inches from the speech loudspeaker, thus increasing speech input without increasing noise input. Root-mean-square (rms) noise level at both the listener's location and the FM microphone was 55 dB SPL. The long-term rms speech level at the listener's location was varied under computer control from 45 to 75 dB SPL in 5 dB steps. The lowest level was intended to represent input from a talker at around 17 feet in a non-reverberant environment. The highest level was intended to represent input from self-generated speech. The middle level (60 dB SPL) was intended to represent conversational input at around 3 feet. The speech level at the FM microphone was always 15 dB higher than at the listener's location.

**Speech Perception Measures** • During laboratory testing, speech perception was assessed in terms of phoneme recognition in a word-repetition task. Words were presented with a short carrier phrase. Subjects were instructed to repeat the test words, or any portion recognized, and were encouraged to guess if not sure. The stimuli consisted of 20 isophonemic lists of 10 consonant-vowel-consonant words recorded by a female talker from the north-

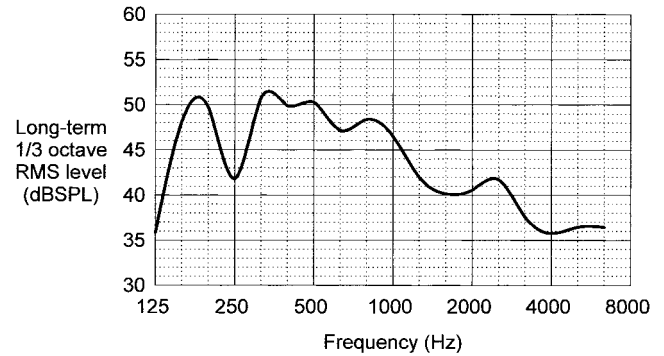


Figure 2. Long-term average spectrum of the speech stimuli at the listener's location in dB per 1/3 octave band. Overall RMS level = 60 dB SPL

eastern United States and digitized at 16 bits and 22,050 Hz. The long-term average spectrum of these stimuli is shown in Figure 2. Using custom software, random noise was generated with the same spectrum. The purpose of spectral matching was to ensure that signal-to-noise ratio was independent of frequency. Seven sets of stimuli were created in which the noise level remained constant but the signal-to-noise ratio varied in 5 dB steps from -10 to +20 dB. Four different carrier phrases were prepared for each set, with and without noise. Stimulus presentation, list randomization, word randomization within lists, response scoring, and data logging were under computer control, using software for Computer-Assisted Speech Perception Assessment (CASPA) developed for this and related projects (Mackersie, Boothroyd, & Minnear, 2001).

### Procedure

Each subject was seen three times. Activities at the three sessions were as follows:

First session:

1. Pure-tone audiometry.
2. Tympanometry (to rule out a conductive involvement).
3. Earmold impressions.

Second session:

1. Administration of a brief questionnaire to identify difficult listening situations and their importance to the subject.
2. Generation of unaided performance versus intensity functions in quiet. This was done in the sound field, under earphones, or both.
3. Generation of aided performance versus intensity functions, in quiet, using the subjects' own aids, as normally worn. This was done to confirm that performance with the experimental aids was at least as good as that with the subjects' own aids.

4. Fitting of the experimental aids, initially to NAL targets but with adjustments based on subjects' reactions.
5. Generation of performance versus intensity functions, in quiet and noise, using the experimental aids. One list of 10 words was presented at each level. Scores were based on 30 phonemes.
6. Generation of a performance versus intensity function in noise using the FM wireless microphone, without activation of the hearing aid microphone.
7. Counseling, demonstration and instruction in use of the FM system.
8. Provision of illustrated written instructions on use of the FM system, together with a diary for keeping a log of experience with it.

Final session (at least 2 wk after the previous session):

1. Administration of a brief questionnaire to assess perceived benefits and limitations of the FM system in various listening situations (see the Appendix).
2. Generation of performance versus intensity functions, in quiet and noise, using the experimental aids.
3. Generation of a performance versus intensity function in noise using the FM wireless microphone.
4. Provision of manufacturers' brochures describing all of the BTE FM systems that were commercially available at the time this study was conducted.

## RESULTS

### Laboratory Study

**Performance versus Intensity Functions** • Figure 3 shows performance versus intensity functions for each subject under three conditions: a) aided in quiet, b) aided in noise, and c) FM-assisted in noise. Noise level was 55 dB SPL at the listener's location, and at the FM microphone. Speech level at the FM microphone was 15 dB higher than at the listener's location. Also shown is the average performance in noise for adults with normal hearing (Boothroyd and Guerrero, Reference Note 1). Each data point was averaged across Sessions 2 and 3 (except for Subjects 6, 11, and 12, who did not complete testing at the third session). The subjects have been arranged in descending order of aided phoneme recognition in quiet for a conversational input level of 60 dB SPL. Note that the FM-assisted data apply to FM input only. In other words, the hearing aid microphone was not activated. The lines in Figure 3 show least-

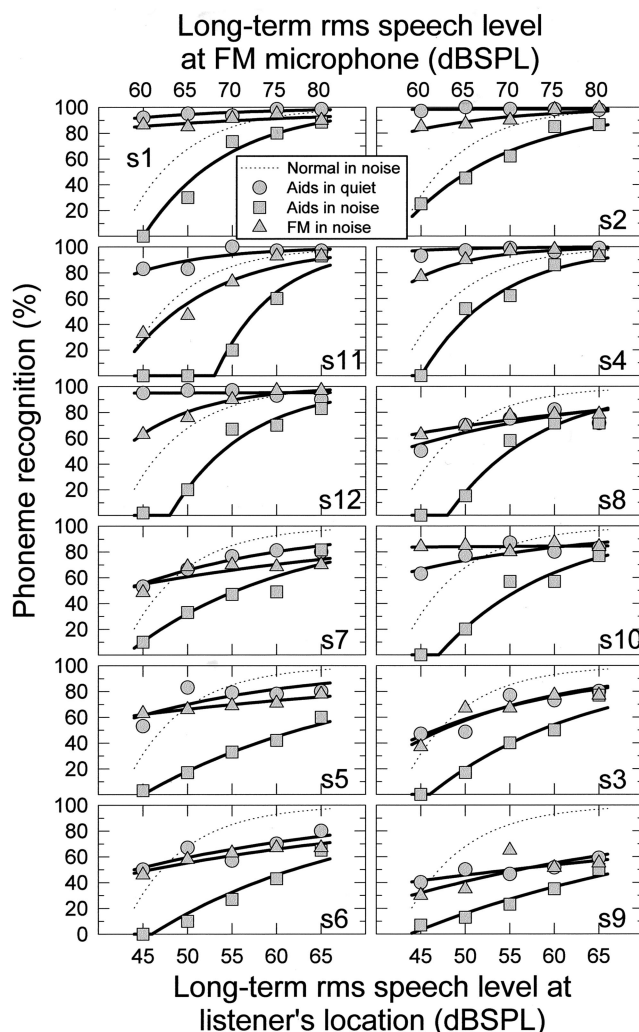


Figure 3. Performance versus intensity functions of 12 subjects under three listening conditions. Noise level at both the listener's location and the FM microphone was 55 dB SPL

squares fits to an exponential function derived from Articulation Index theory.

It will be seen from Figure 3 that all subjects suffered a noise penalty relative to young adults with normal hearing. All subjects also showed a dramatic improvement under the FM-assisted condition. In many cases FM-assisted performance in noise was at or close to aided performance in quiet for all input levels. Figure 4 shows group-means for the same three listening conditions. Subject 11 was omitted from the means for the noise data because of unusually high noise susceptibility.

The data illustrated in Figures 3 and 4, excluding Subject 11, were examined using repeated-measures analyses of variance. The main effects of level and condition were highly significant, as was the interaction between them ( $F[4,40] = 146$ ,  $F[2,20] = 206$ , and  $F[8,80] = 27.5$ , respectively,  $p < 0.000005$ ). In post hoc testing, using the least-significant-differ-

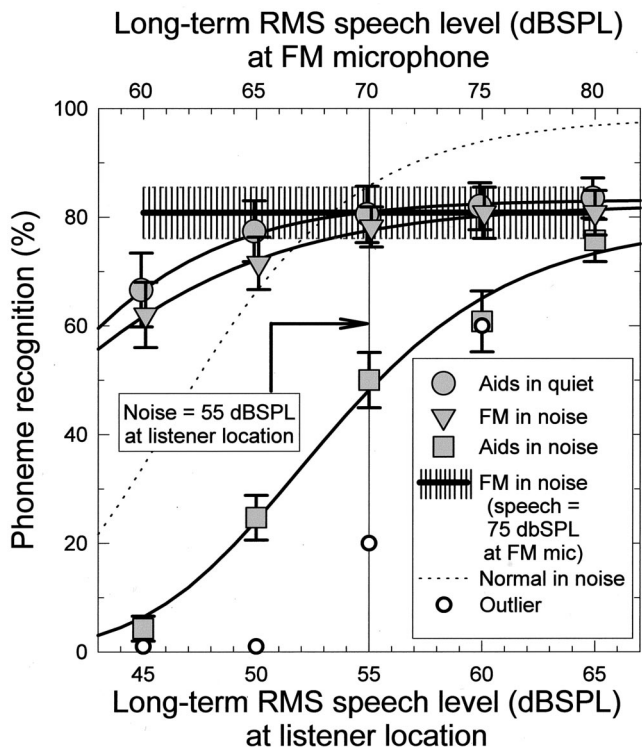


Figure 4. Group mean phoneme recognition ( $\pm 1$  standard error) as a function of speech level at the listener's location for 11 adults under three listening conditions. Note that speech level at the FM microphone was 15 dB higher than at the listener's location. The horizontal shaded area shows FM performance under conditions in which input to the FM microphone remains at 75 dB SPL, independent of changes of distance between talker and listener.

ence test, the difference between aided performance in quiet and noise was highly significant ( $p < 0.000005$ ) at speech levels of 45 through 60 dB SPL (s/n ratio  $-10$  through  $+5$  dB). The difference was marginally significant ( $p = 0.024$ ) at a speech level of 65 dB SPL (s/n =  $+10$  dB). The difference between FM-assisted performance in noise and aided performance in quiet failed to reach the 5% level of significance at any input level.

When an FM microphone is worn by the talker, speech input remains high and constant, regardless of the distance from the listener. In contrast, the direct speech input to the hearing aid microphone falls as the talker-listener distance increases. It is appropriate, therefore, to compare aided performance at each input level with FM-assisted performance using a fixed speech input to the FM microphone of 75 dB SPL—as indicated by the horizontal shaded area of Figure 4. In this case, there is a significant difference between aids in quiet, with speech level of 45 dB SPL at the listener location, and FM in noise, with a speech level of 75 dB SPL at the FM microphone. Under this condition, the score

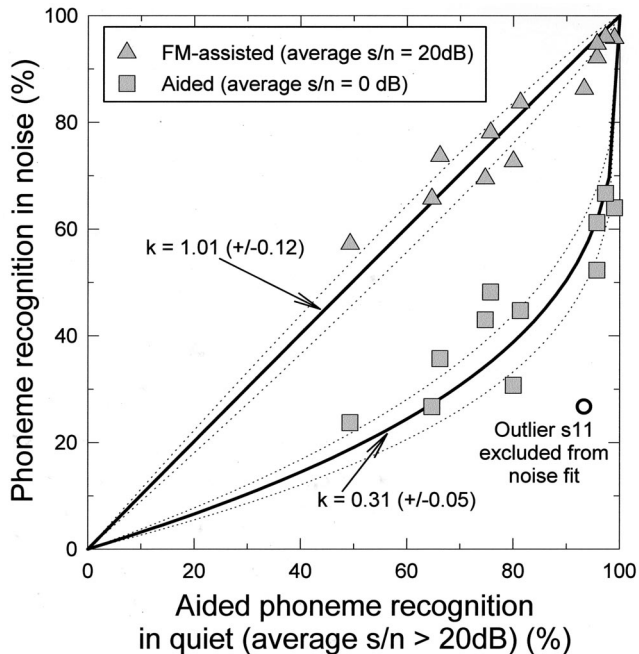


Figure 5. Phoneme recognition in noise as a function of phoneme recognition in quiet for 12 adults. Curves show least-squares fits ( $\pm 95\%$  confidence limits) to Equation 1. The factor  $k$  represents the proportional change in Articulation Index when comparing aided in noise with aided in quiet ( $k = 0.31$ ) and FM-assisted in noise with aided in quiet ( $k = 1.01$ ).

for FM in noise is significantly *higher* than for aids in quiet when the two are compared directly ( $F[1,10] = 20.9, p = 0.0012$ ).

**Performance in Noise as a Function of Performance in Quiet** • Figure 5 shows aided and FM-assisted performance in noise as functions of aided performance in quiet for individual subjects. To reduce error variance, the aided data were averaged across speech inputs at the listener's location of 50, 55, and 60 dB SPL—for an average signal-to-noise ratio, under the aided-in-noise condition, of 0 dB. Similarly, the FM-assisted data were averaged across speech inputs at the FM microphone of 70, 75, and 80 dB SPL—for an average signal-to-noise ratio at the FM microphone of  $+20$  dB.

The curves in Figure 5 are least-squares fits to the equation:

$$p_n = 100 (1 - (1 - (p_q/100))^k) \quad (1)$$

where:

- $p_n$  = percent phoneme recognition in noise, either aided or FM-assisted.
- $p_q$  = percent phoneme recognition, aided, in quiet.
- $k$  = an exponent representing the effect of the noise.

Note that the exponent  $k$  would appear in Articulation Index theory as a “proficiency factor.” In the present context it is the ratio of Articulation Index in noise to that in quiet.<sup>†</sup>

As in Figure 4, subject s11 was omitted from the curve fitting under the aided-in-noise condition because of her extreme noise susceptibility. It will be seen from Figure 5 that the data for the remaining 11 subjects clustered along the curves represented by Equation 1. For these speech and noise levels, the mean aided AI in noise was 0.31 of that in quiet. Thus, the introduction of noise, at a 0 dB signal-to-noise ratio, produced, on average, a 69% reduction of Articulation Index. The mean FM-assisted Articulation Index in noise was 1.01 times that for aided listening in quiet. In other words, listening with FM assistance in noise resulted in an average 1% increase of Articulation Index compared with aided listening in quiet. It should be noted, however, that the 95% confidence limits for the FM data include the diagonal. It cannot be concluded, therefore, that the mean FM-assisted performance for the hypothetical population represented by these 12 subjects is different from aided performance in quiet, under the conditions of this study.

**Performance as a Function of Age and Pure-Tone Threshold** • There was no evidence of a significant association between age and speech perception performance. In multiple regression analyses, however, better-ear pure-tone threshold at 2 kHz was a good predictor of phoneme recognition, under all conditions, with additional and independent contribution from threshold at 4 kHz. These two variables accounted for 84% of the variance ( $p = 0.002$ ) in aided phoneme recognition in quiet (averaged over inputs of 50, 55 and 60 dB SPL), 62% of the variance ( $p = 0.014$ ) in aided phoneme recognition in noise (averaged over inputs of 50, 55 and 60 dB SPL) and 87% of the variance ( $p = 0.0001$ ) in FM-assisted phoneme recognition in noise (averaged over inputs of 60, 75, and 80 dB SPL).

Figure 6 shows percent phoneme recognition under the three listening conditions as functions of the average better-ear threshold at 2 and 4 kHz. As in the previous figure, aided data are averaged across inputs of 50, 55 and 60 dB SPL and FM-assisted data are averaged across FM inputs of 70, 75 and 80 dB SPL. The corresponding average signal-to-noise ratios are 0 dB for aided listening in noise, 20 dB for FM-assisted listening in noise, and well in excess of 20 dB for aided listening in quiet.

Because of the absence of evidence showing a significant difference between aided performance in

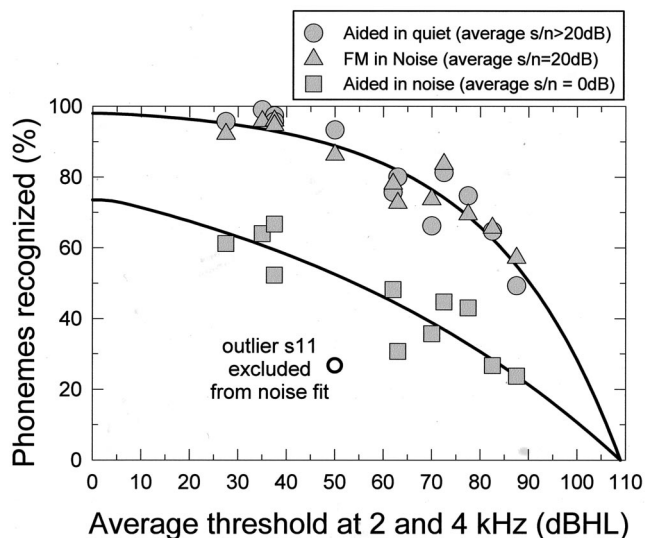


Figure 6. Phoneme recognition under three listening conditions as functions of high-frequency threshold. The upper line is a least-squares fit to Equations 2 and 3 using both aided-in-quiet and FM-assisted-in-noise data. The lower line combines Equations 1, 2, and 3.

quiet and FM-assisted performance in noise, these two sets of data were combined for purposes of curve fitting. The upper line in Figure 6 shows the least-squares fit to the equations:

$$p = 100 (1 - 0.02^{AI}) \tag{2}$$

and

$$AI = 1 - \ln (1 + \exp (a(x - b))) \tag{3}$$

where:

AI = Articulation Index, relative to performance when there is no high-frequency hearing loss

p = percent phoneme recognition

a = rate of change of Articulation Index in percentage points per dB of average threshold at 2 and 4 kHz.

x = average better-ear threshold at 2 and 4 kHz

b = high-frequency threshold below which there is no loss of Articulation Index.

ln = natural logarithm

Several assumptions underlie Equations 2 and 3:

1. The residual error probability for subjects with no hearing loss at 2 and 4 kHz is 0.02, or 2%.
2. Hearing loss at these frequencies has no effect on Articulation Index until a critical value is reached (represented by variable b)
3. Once the critical value of hearing loss is exceeded, Articulation Index falls linearly in percentage points per dB (at a rate represented by variable a).

<sup>†</sup>The k-factor, and Equation 1 have also been used by the author as a metric for context effects in speech perception (Boothroyd, 1985; Boothroyd & Nittrouer, 1988).

Natural logarithms and exponentiation are used in Equation 3 to create the nonlinear function required under assumptions 2 and 3.

Least-squares fitting shows that, on average, Articulation Index in quiet, for these subjects, falls by 0.95 percentage points per dB of loss, averaged at 2 and 4 kHz, after a critical loss of 3.7 dB is exceeded. The resulting fit accounts for a highly significant 90.4% of the variance in the phoneme recognition data ( $df = 10, p < 0.0005$ ). The lower line in Figure 6 is derived from a combination of Equations 1, 2, and 3. The assumption is that the Articulation Index derived for the quiet and FM-assisted conditions is modified, at a 0 dB signal-to-noise ratio, by a constant factor  $k$ . The resulting fit provides a value of  $k = 0.32$  and accounts for a significant 70.8% of the variance in the phoneme recognition data ( $df = 8, p = 0.002$ ). As in previous graphs, Subject 11 has been omitted from the curve fitting under the aided-in-noise condition.

### Field Study

**Perceived Benefit** • Figure 7 shows the distributions of responses to questions about the perceived benefit of the FM system under several conditions of use. The listening conditions have been arranged in descending order of perceived benefit. Also shown are the responses to a question about overall benefit.

It will be seen from Figure 7 that subjects tended to express the greatest perceived benefit when listening to one person at a distance—either in noise or in quiet. The next highest perceived benefit was when listening to one person, close by, in noise. Five of six subjects who used the FM microphone while watching TV expressed considerable perceived benefit, as did five of seven subjects who used the system in meetings. The second lowest level of perceived benefit was in restaurants. Presumably the restaurant condition was complicated either by excessive noise, or by the impracticality of passing the microphone from person to person during group conversation. The lowest level of perceived benefit was when listening to one person close by, in quiet. In this condition a remote microphone should be unnecessary.

All subjects expressed some or considerable perceived benefit overall. There were no conditions under which subjects felt that the FM system made communication worse. There were, however, conditions under which some subjects expressed no perceived benefit. As expected, the majority of these were for listening to one person, close by, especially in quiet but also in noise.

**Predictors of Perceived Benefit** • A single quasi-parametric measure of benefit was derived by as-

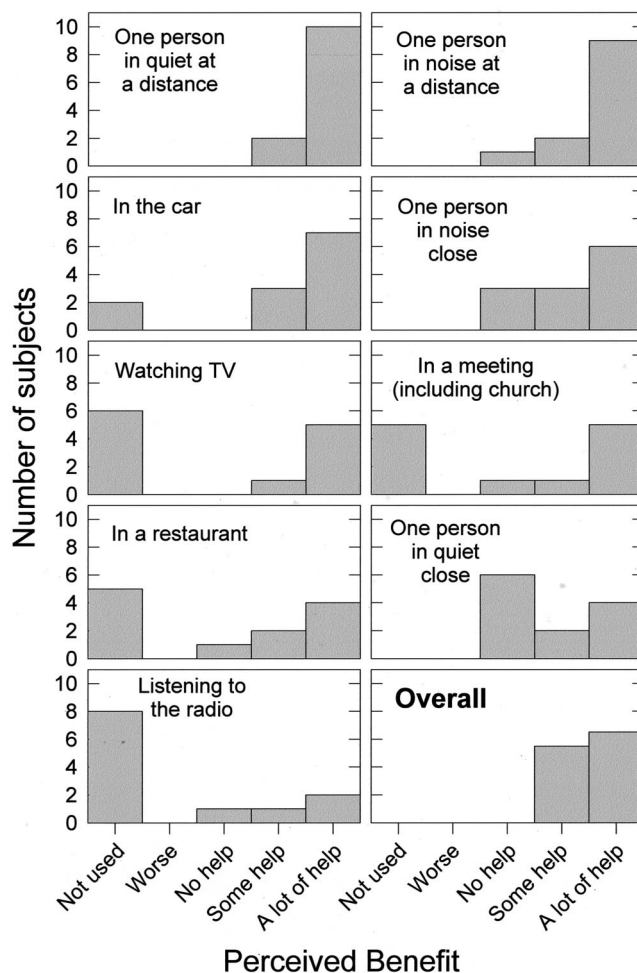
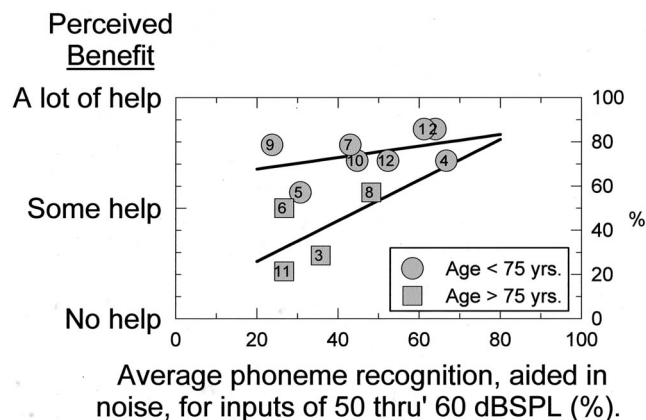


Figure 7. Responses of 12 subjects to the questionnaire administered after at least 2 wk of experience with a behind-the-ear FM system.

signing values of 0 to “not used” and “no help,” 1 to “some help,” 2 to “a lot of help,” and summing across the seven listening conditions for which the greatest benefit was reported (i.e., excluding listening to one person close by and listening to the radio). Correlations were examined between this measure and potential predictors including pure-tone thresholds, speech perception performance and age. No significant correlations were found for pure-tone threshold, aided phoneme recognition in quiet, or FM-assisted phoneme recognition in noise. Weak evidence of correlation were found for aided phoneme recognition in noise, averaged at  $-5, 0,$  and  $+5$  dB s/n ( $r[10] = 0.585, p = 0.046$ ) and age ( $r[10] = 0.574, p = 0.051$ ). In multiple regression analysis, performance in noise accounted for 34% of the variance in perceived benefit and age accounted for an additional and independent 18% for a total of 52% ( $p = 0.034$ ). Figure 8 shows average perceived benefit as a function of phoneme recognition in noise. To illustrate the contribution of age, the subjects were



**Figure 8.** Average perceived benefit of the FM system in seven listening conditions as a function of aided phoneme recognition in noise. Lines are linear least-squares fits to data for two age groups.

divided into two groups—eight subjects younger than 75 yr and four subjects older than 75 yr. Figure 8 shows least-squares linear fits to the data for these two groups. It will be seen that the perceived benefit in this subject sample tended to increase with increasing aided phoneme recognition in noise and to decrease with increasing age.

**Subject Comments** • The most common negative report was of persistent noise problems when using the FM microphone. One subject commented that there was “not much improvement when there is a lot of noise.” Similar comments included “picked up air conditioners,” “it is still a problem in a noisy room,” “picked up too much noise in noisy environments,” “easier with no aids in a noisy restaurant,” and “didn’t like hearing my husband chewing his cereal.”

Other comments confirmed the expectation of least benefit when dealing with a group of talkers. One subject commented on the “problem of handing the microphone when eating with many friends.” Another said there were “problems with a group around a table” and “in a car it works for one talker but not for the people in the back.” Some of the subjects tried to address the restaurant problem by leaving the FM microphone in the middle of the table but, as would be expected, they were disappointed by the results.

One subject raised the issue of localization. He said he liked to be able to hear when his wife called “but didn’t know where she was.” Another subject indicated that he was uncomfortable asking his friend to wear the microphone, pointing to the intrusiveness of this technology. Yet another subject enjoyed improved perception when walking with a friend but commented on a problem of wind noise with the FM microphone. Several of the subjects experienced occasional, but annoying, interrupted FM reception.

On the positive side, some of the subjects and their spouses reported using the system as a one-way walkie-talkie. One subject was happy to be able to hear his wife call when he was gardening. Another expressed similar benefit when his wife was in a different room of the house. One subject reported that the system was “wonderful” in a restaurant. Another said she “hated to give it back.” One subject used the system for listening to his car radio by placing the microphone next to the loudspeaker.

Although all subjects expressed some or considerable benefit overall, and several gave very positive comments, none indicated an intention to purchase an FM system. The two subjects with the highest metric for perceived benefit expressed modest interest in the possibility of purchase but felt that technical and human engineering issues needed to be addressed first.

Many of the subjects’ normally wore in-the-ear aids and it was expected that they would express concern about the need to use behind-the-ear aids to take advantage of the FM feature. This did not happen, however. Nor did the subjects express concerns about the large size of the aids or the presence of visible antennas. Nevertheless, these factors may have influenced their lack of enthusiasm for acquiring the technology.

Another factor that was expected to influence enthusiasm was cost but, interestingly, nobody asked about price.

## DISCUSSION

All speech levels in this paper are expressed in terms of long-term rms sound pressure level of the test material. To obtain this value, the digital files containing the test words were concatenated, without gaps or carrier phrases, and the long-term rms level was measured, with linear weighting. The resulting level is some 5 dB lower than the average vowel-peak level that would be estimated by observing the instantaneous output of a VU meter, or a sound level meter on the “fast” setting. Readers who are accustomed to measuring speech levels in terms of average level of the vowel peaks should add 5 dB to the speech levels and signal-to-noise ratios shown or reported here.

The laboratory set-up was designed to ensure that the level of the speech input to the FM microphone was always 15 dB higher than at the listeners’ location. It was expected, therefore that this difference would result in a 15 dB separation of the group mean performance versus intensity functions for aided and FM-assisted listening in noise, shown in Figure 4. The actual separation of these curves falls short of this prediction by around 2 dB. In other

words, the measured FM benefit, expressed in terms of signal-to-noise ratio, is somewhat less than the predicted benefit. Two factors could account for a discrepancy of this amount. First, input to the hearing aid is expressed, throughout this paper, in terms of sound-field level without the listener present. Because of the spatial separation of the speech and noise sources, head-shadow effects could have resulted in an improvement of signal-to-noise ratio at each ear when the listener was present. In contrast, signal-to-noise ratio at the FM microphone would not benefit from such effects. Second, most of the subjects were listening binaurally and some of them may have benefited from binaural phase differences in the aided-in-noise condition. Any such benefit would be absent for the FM-assisted signal.

The data in Figure 4 show FM-assisted performance for speech inputs to the FM microphone between 60 and 80 dB SPL. It is important to remember, however, that proper placement of the FM microphone, within a few inches of the talker's mouth, would result in an input to the FM microphone of around 75 dB SPL. Moreover, this level would remain constant as the distance between talker and listener changed. If we accept constant FM input and varying hearing aid input as an appropriate representation of proper use, then three predictable but important points are apparent from Figure 4. First, the FM benefit, expressed in terms of phoneme recognition, increases as the distance between talker and listener increases. This fact would account for the high ratings of perceived benefit for one talker at a distance. Second, FM-assisted performance, even under proper conditions of use, is limited to optimum aided performance in quiet. This fact could account for the less-than-enthusiastic responses of some of the more severely impaired subjects. They were probably expecting the FM technology to provide a "better" hearing aid in spite of counseling to the contrary. Third, for very low inputs to the hearing aid, and high inputs to the FM microphone, FM-assisted performance exceeded aided performance. This observation, however, applies to the specific aid used in this study. Had this study been carried out with aids using wide-dynamic-range compression, the increased hearing aid gain for low inputs would almost certainly have reduced this effect.

The analysis illustrated in Figure 5 showed the group-mean aided noise penalty, for a signal-to-noise ratio of 0 dB, to be equivalent, on average, to a reduction of Articulation Index to 0.31 of its value in quiet. The broken lines in Figures 3 and 4 show mean phoneme recognition, using these test materials and procedures, for a group of young adults with normal hearing (Boothroyd & Guerrero, Reference Note 1). When the same analysis is applied to these

normative data, a signal-to-noise ratio of 0 dB is found to reduce the Articulation Index to 0.5 of its value in quiet. As a group, therefore, these subjects show a noise susceptibility that is greater than can be explained solely on the basis of the effects of noise on audibility. This finding is consistent with previous research on the perceptual consequences of sensorineural hearing loss (for example, Festen & Plomp, 1990; Glasberg & Moore, 1989).

Average pure-tone threshold at 2 and 4 kHz was a remarkably good predictor of aided phoneme recognition in quiet—at least in this sample of subjects (Fig. 6). This finding presumably reflects the importance of the second vocal tract formant to speech recognition, combined with the fact that pure-tone threshold and suprathreshold phoneme recognition provide independent indications of the extent of the underlying cochlear pathology.

The results of curve fitting further suggest that the effects of hearing loss on aided phoneme recognition in quiet can be modeled in terms of a linear reduction of Articulation Index with increasing unaided high-frequency threshold at the rate of roughly 1 percentage point per dB above a critical threshold of about 4 dB. This was, however, a very small sample of subjects and more extensive studies would be needed to establish the validity of this model. Although aided phoneme recognition in noise was less well predicted by unaided pure-tone threshold, it is noteworthy that this same model, with a single correction for the effect of noise on Articulation index, accounted for approximately 70% of the variance in these data.

In spite of the potential heterogeneity of this subject sample, the data in Figure 6 suggest remarkable homogeneity in terms of aided phoneme recognition in quiet and FM-assisted recognition in noise, once the effects of high-frequency threshold are taken into account. Subject 11, however, was a clear outlier in terms of noise susceptibility. Complete data for this subject are shown in Figure 9.

It will be seen from Figure 9 that, in spite of excellent aided performance in quiet, Subject 11's performance in noise dropped to zero when the signal-to-noise ratio fell below 0 dB. Moreover, her FM-assisted performance in noise fell far short of her aided performance in quiet for FM inputs of 70 dB or less (i.e., speech level at the listener's location of 55 dB or less). The combination of excellent performance in quiet and unusually poor performance in noise is, perhaps, consistent with an unusually high ratio of outer hair cell damage to inner hair cell damage. It should be noted, however, that at 85 yr, s11 was the oldest in the group. In addition, she had only one usable ear—possibly the non-dominant ear. Non-peripheral factors could, there-

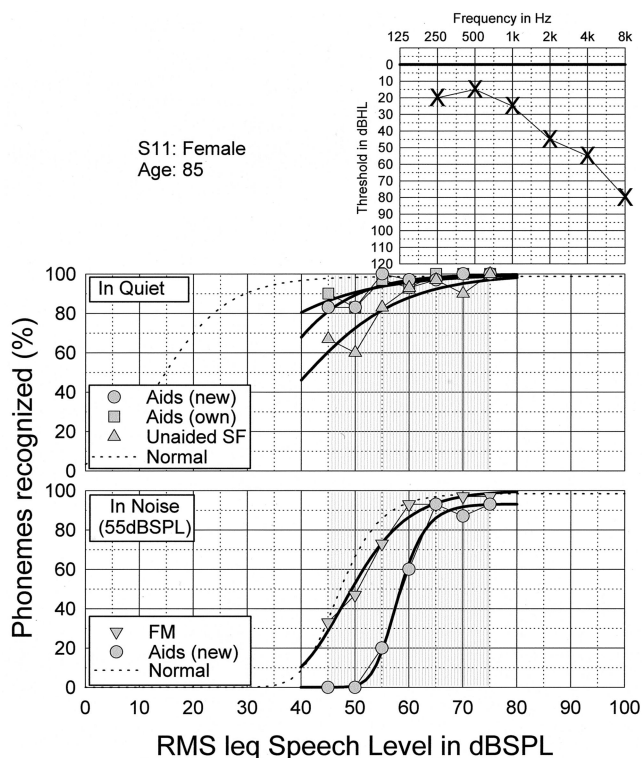


Figure 9. Complete data for Subject 11. This subject was especially susceptible to noise.

fore, also be invoked as possible reasons for her extreme noise susceptibility. Whatever the reason, the data for this subject serve to emphasize the limitations of pure-tone-threshold as a predictor of noise susceptibility, and the importance of recognizing individual differences when providing sensory assistance.

As anticipated, the greatest perceived benefit in this subject sample was when listening to one person at a distance. This outcome is consistent with the laboratory data for low speech input levels illustrated in Figure 4. Also anticipated was the high perceived benefit when listening to one person in noise—including in the car. Also anticipated was the fact that the lowest perceived benefit was in group situations in noise, when the FM microphone is either ineffective or impractical, and when listening to one person close by in quiet, when the FM microphone is unnecessary.

Many subjects, however, were negative about the system’s ability to combat noise. These reactions may have resulted from the fact that, in this study, the gains for low inputs to the FM and hearing aid microphones were equal. This condition meets the “equal gain” criterion as recommended in the current ASHA guidelines when FM systems are operated in the FM+Aid mode (American Speech-Language-Hearing Association, 2002). A consequence of

the “equal gain” criterion, however, is that there is no perceived reduction of background noise when switching from Aid-only to FM-only mode. The benefits of increased input level and improved signal-to-noise ratio will be present at the FM microphone when it receives close speech input. And compression limiting in the hearing aid will then cause a reduction of gain, which will keep the FM-transmitted speech within a comfortable range while lowering the simultaneous background noise. But gain will rise when the person wearing the FM microphone stops speaking. As a result, the signal-to-non-simultaneous-noise ratio will be poor. It is probable that this was the principal source of the negative comments about noise. In retrospect, it would have been advisable, at least for some of the subjects, to reduce the FM gain relative to the hearing aid gain—perhaps approaching an “equal-output” criterion (Dillon 2001). Such an approach was advocated in the 1994 ASHA guidelines (American Speech-Language-Hearing Association, 1994). It is also supported in the current ASHA guidelines for FM-only listening. It is clear from the mixed reactions of these subjects, however, that the relative gain via hearing aid and FM microphones should be adjusted according to individual preferences and characteristics. It should also, perhaps, be under user control for adaptation to different listening conditions. In fact, subjects in the present study were advised to reduce overall gain manually when in the FM mode but, for some, this suggestion may simply have added one more complexity to an already overly complex system.

In calculating a single metric for perceived benefit, no distinction was made between “not used” and “used but no help.” While this approach is valid in terms of actual benefit, it may have underestimated potential benefit. It became clear to the experimenter that some of the subjects, especially the older ones, had already adjusted their lifestyles to avoid many of the difficult listening situations in which an FM system might have helped. Unless they are anxious to reverse these adaptations, and they are provided with adequate counseling, instruction and coaching, the actual benefit of an FM system is automatically reduced for such subjects.

The finding that perceived benefit tended to fall with increasing age was predictable. The tendency, however, for higher perceived benefit to be associated with better, rather than poorer, perception in noise was not expected. Several factors could have contributed to this last finding. First, subjects with better perception in noise will, in general, have more satisfying listening experiences. Second, as mentioned earlier, the relative gains via the hearing aid and FM microphones may not have been optimal for those subjects with greater noise susceptibility. Third,

subjects with greater noise susceptibility are the ones who are more likely to have developed lifestyles that avoid situations in which the FM system's signal-to-noise benefits would be most apparent.

Although many subjects were positive about the benefits of the FM microphone, the ultimate test of perceived benefit—an intent to acquire one—was failed. Possible reasons include the fact that many of the subjects would have had to buy new hearing aids. Some were already wearing in-the-ear models. Others were wearing behind-the-ear models without either a telecoil, or the option for a shoe to accept a plug-in FM receiver. It is also possible that the size and appearance of the specific aids used in this study was a deterrent, in spite of the fact that the final counseling included information about all the manufacturers and options that were available at the time.

At the final session, it became apparent that the brief period of explanation, instruction and demonstration included in the present study, even with the addition of illustrated written instructions, was inadequate for many of these subjects. Some still did not fully understand the need for the microphone to be within a few inches of the talker's mouth for optimum benefit, nor could they distinguish situations in which an FM system might be beneficial and those in which it would be either unnecessary or counterproductive. Moreover the number of switches and controls created an obvious problem for some of the older subjects. It was also clear that some of the subjects with the poorest speech perception in quiet were hoping, in spite of counseling to the contrary, that the FM microphone would result in a "better" hearing aid, in the sense of returning them closer to their goal of restored normal hearing. The overriding impression left by the results of the field study was of the need for considerable counseling, instruction and coaching, extended over several sessions, if remote wireless microphones are to become widely accepted as hearing aid accessories by adults with hearing loss.

### SUMMARY AND CONCLUSIONS

1. Under laboratory conditions, FM-assisted phoneme recognition in noise was as good as (or, for very low input levels to the hearing aid, better than) aided phoneme recognition in quiet.
2. The average of pure-tone thresholds at 2 and 4 kHz was an excellent predictor of both aided phoneme recognition in quiet and FM-assisted phoneme recognition in noise (under a model that assumes a linear reduction of Articulation Index with increasing threshold at the rate of roughly 1 percentage point per

dB of average loss at 2 and 4 kHz, above a critical value of 4 dB).

3. The average of pure-tone thresholds at 2 and 4 kHz was a good predictor of individual aided phoneme recognition in noise (under a model that assumes that noise, at a 0 dB signal-to-noise ratio, introduces a subject-independent reduction of Articulation Index to about one third of its value in quiet).
4. Under field conditions, the highest reported benefit was associated with a single talker at a distance, in quiet or in noise.
5. The second lowest reported benefit was associated with multiple talkers, when an FM system would be expected to be impractical.
6. The lowest reported benefit was associated with one close talker in quiet, when an FM system would be expected to be unnecessary.
7. Although all subjects in this study reported some or considerable overall benefit, many drawbacks were reported and none expressed an intention to acquire the technology.
8. Many subjects reported failure of the FM microphone to combat noise—probably because of unnecessarily high gain via the FM microphone.
9. Older subjects and subjects with poorer aided performance in noise tended to report less perceived benefit from the FM system.
10. Optimal benefit from these and similar accessories will require considerable counseling, instruction and coaching.
11. Careful, individualized, adjustment of relative gains via FM and hearing aid microphones will also be needed.

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**APPENDIX. Perceived-Benefit Questionnaire Administered at the Third Session**

How helpful was the FM microphone:	Not used	Made things worse	No help	Some help	A lot of help
Overall?					
Listening to one person in quiet at a few feet?					
Listening to one person in quiet at several yards?					
Listening to one person in noise at a few feet?					
Listening to one person in noise at several yards?					
Watching TV?					
Listening to the radio?					
At the movies?					
In a meeting or at church?					
In a restaurant?					
In a car?					
Other? _____					
Other? _____					
What did you like about this equipment?					
What problems did you encounter?					
Is this something you might wish to acquire?					