Thinking Outside the Hearing Aid: Wireless Microphone Accessories

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Introduction

A sensorineural hearing impairment, acquired during adult life, can have serious impact on function (auditory sensitivity and resolution), activity (especially speech perception and communication), participation (social, vocational, and leisure), and quality of life. The goal of hearing care is to minimize this impact. This goal is pursued through a process with four basic components:

1. Sensory management – the use of hearing aids, cochlear implants, and hearing-assistance technology
2. Instruction – also known as informational counseling
3. Perceptual training – also known as auditory training or communication training.
4. Personal counseling – vocational, emotional, relationship, etc.

The principal focus of the current paper is sensory management. But it behooves us to remember that the success of sensory management is often contingent on the effectiveness of the other three components (Boothroyd in press).

Limitations of Amplification

Modern hearing aids, with multi-channel wide-dynamic-range compression, can do much to optimize audibility, comfort, and quality over a wide range of listening conditions. As is well known, however, poor speech perception in noise tends to remain an unresolved issue.

For the hearing-aid user, the negative effects of noise are exacerbated by distance (which reduces speech-to-noise ratio); by bandwidth limitations (usually loss of high frequencies); by deficits of auditory resolution (both spectral and temporal); and possibly by cognitive and processing deficits (which are likely to increase with age) (see figure 1).

Note that noise and distance are features of the listening context. Bandwidth restriction can be a feature of the hearing aid, the user, or both. Resolution is primarily a feature of the listener but may involve some aspect of hearing aid processing. Cognition and perceptual processing are entirely features of the user.

Because of the five enemies of effective speech perception (distance, noise, bandwidth, resolution, and cognition), unfavorable conditions that are tolerable for a

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Figure 1. The five enemies of speech perception for the hearing aid user are noise, distance, limited bandwidth, reduced spectro-temporal resolution, and cognitive deficits.

1 For present purposes, the term “noise” is used to include both actual noise, and the late components of reverberation, which are, in effect, a noise generated by the speech signal itself.
hearing listener can become intolerable for a hearing-impaired listener. The hearing aid industry has a major interest in helping to solve this problem – mostly, and understandably, with “in-the-aid” solutions.

**In-the-Aid Solutions**

**Wide-Dynamic-Range Compression**

To a certain extent, the distance problem is addressed in the aid with wide-dynamic-range compression, which increases gain for low-level inputs. In a noise-free context, there are clear improvements of function and activity (Jenstad, Seewald, Cornelisse and Shantz 1999; Souza and Bishop 1999). But when noise (including reverberation) is the main enemy, the increase of gain raises speech and noise levels equally – with no improvement of signal-to-noise ratio.

**Digital Noise Reduction**

In-the-aid approaches to enhancing signal-to-noise ratio are of two types: digital noise reduction and directional microphones. Digital noise-reduction algorithms examine the combined signal and noise waveform after the two have been mixed at the hearing-aid input. Decisions are made as to which parts of the mixture are mostly signal and which parts are mostly noise. The former are preserved while the latter are suppressed. The result, in theory, is an increase in signal-to-noise ratio.

The usual assumptions behind these algorithms are: a) the signal is speech, b) the noise is not speech, and c) signal and noise have distinctly different acoustic properties. When these conditions are met, there may be enhancement of sequential signal-to-noise ratio and reduction of perceived noisiness. As will be observed in figures 2 and 3, however, there is no change of actual signal-to-noise ratio at any moment or at any frequency. In other words, these algorithms do not provide increased access to acoustic speech cues. Enhanced comfort or perceived quality may well increase satisfaction, decrease fatigue, and decrease annoyance, but these benefits are unlikely to be accompanied by enhancement of speech intelligibility in noise (Bentler 2005).

A serious concern with noise-reduction algorithms is the definition of signal and noise. As mentioned earlier, the engineer tends to think of the signal as speech and the noise either as random or as multi-talker babble. From a psychological perspective, however, signal is what the listener wants to hear and noise is any sound that interferes with what the listener wants to hear (figure 4). In a restaurant, for example, the signal is typically speech and the noise might be music. But at the symphony, the signal is music and the noise is speech. In some situations both signal and noise are speech. At the present time, no hearing aid algorithm can determine what part of a mixed signal and noise waveform the listener wants to hear.

In summary, time-based noise-reduction algorithms can enhance sequential speech-to-noise ratio, and spectrum-based algorithms may well enhance both frequency the mixed signal is mostly noise (figure 3). Advanced algorithms do both.
simultaneous speech-to-noise ratio and spectral contrasts. But neither can restore missing speech cues once the speech and noise are mixed at the microphone. And both will fail when the signal is non-speech or the noise is speech.

**Directional Microphones**

Given the difficulties of separating signal and noise once they have been mixed in the hearing aid, it makes sense to keep the noise out in the first place. The in-the-aid approach to accomplishing this goal is the directional microphone (Bentler 2005). The expectation of directional benefit is based on the assumption that the signal comes from the direction in which the listener is looking while the noise comes from other directions. This is an assumption on which the engineer and the psychologist are likely to see eye-to-eye (see figure 5).

There are, however, several limitations to this approach. Obviously, it will be ineffective if the signal and noise come from the same direction. Less obvious is the fact that, indoors, any speech-to-noise enhancement will diminish with increasing talker-listener distance. In a room, the useful speech signal has two components (Boothroyd 2004b, 2005). One is the direct speech signal traveling in a straight line from talker to listener. The other consists of signals that arrive at the listener after one or more reflections from the room’s boundaries—and within about 50 msec of the direct signal. The direct signal follows the inverse-square law, that is, its level falls by 6 dB for every doubling of distance from the talker. The level of the early reflections, however, is relatively independent of distance. The critical distance is defined as the distance at which these two components contribute equally. Within the critical distance, the direct signal dominates and a directional microphone can be effective—attenuating noise while leaving the dominant component of the speech signal unchanged. Beyond the critical distance, however, the received signal is dominated by the early reflections—most of which arrive from non-frontal directions. As a result, a directional microphone attenuates both noise and speech and its effectiveness is reduced—falling to zero when the talker-listener distance is around three times the critical distance².

Even within the critical distance, the enhancement of signal-to-noise ratio is limited to around four or five dB—depending on the properties of the directional algorithm and the locations of the noise sources. Nevertheless, directional microphones can provide a clinically-significant expansion of the environments in which a hearing aid user can communicate effectively.

In summary, directional microphones increase signal-to-noise ratio by reducing the level of noise before it and the signal are mixed in the hearing aid. Moreover, they can do so regardless of the nature of the signal and the noise. But the benefit is limited to four or five dB—and it falls once the talker-listener distance exceeds the critical distance.

**Out-of-the-Aid Solutions**

**Remote Wireless Microphones**

A microphone placed close to the mouth of the talker picks up a direct speech signal whose level is 15 to 20 dB higher than at the hearing aid. Moreover, the speech level at this microphone is unaffected by changes of talker-listener distance. Delivery of this signal to the listener over a wireless link (usually using frequency modulation—or FM) essentially removes the issues of distance and noise, as illustrated in figure 6. This solution is simple, elegant, and highly effective and

²There is ample research evidence to support this theoretical analysis (Walden, Surr, and Cord 2003; Walden, Surr, Cord and Dyrlan 2004).
has been used in education, and in the news and entertainment industries, for decades.

Unfortunately, things are not quite so straightforward when the technology is applied to the management of hearing loss in adults. For example:

1. If the hearing aid microphone remains active, it can reintroduce the noise that the remote microphone was intended to eliminate. Minimization of this effect depends on precise equalization of relative gains for the two microphones.

2. To avoid problems of over-modulation, and to minimize electronic noise in the FM link, manufacturers must incorporate some form of amplitude compression in the FM transmitter – making it impossible to maintain the equal-gain criterion for all input levels.

3. If the system is to be used in the FM-only condition, the FM gain may need to be lowered below the equal-gain criterion; otherwise the listener’s perception of noisiness of the environment will be unchanged when switching between Aid-alone and FM-alone modes.

4. The full signal-to-noise benefit applies only to the speech of the person with the FM microphone. This is not a problem in a one-on-one situation but creates difficulties in a group setting.

5. The wireless microphone adds a layer of complexity to the communication situation that involves both listener and talker. Potential beneficiaries of this technology may well be deterred by the complexity and potential intrusiveness.

6. The remote microphone is, in essence, a wandering ear. And the control of this ear is given to another person – a situation that can create unease for the listener.

7. The best that can be accomplished with this technology is that speech perception in a noisy environment is brought to the level that is attained in quiet. Hearing aid users who are looking for something better will be disappointed.

8. Unless the user has appropriate understanding and insight into the possibilities and limitations of this technology (including awareness of the situations in which it will or will not offer benefit) there is a strong possibility of inappropriate use, unreasonable expectations, and sub-optimal results.

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3 The problem is partially addressed with the “Companion Mic” system from Etymotic Research. This system takes advantage of spread-spectrum technology to allow three of four wireless microphones to be active simultaneously. It is also possible, though less convenient, to chain two or more traditional FM transmitters to accomplish the same goal.

4 This assumes the same talker-listener distance. A listener who hears well at close range but whose speech performance decreases dramatically with increasing distance, even in quiet, may find great benefit from a wireless microphone – independently of the noise issue.
Serious attempts to apply this technology to the management of adult hearing loss must address these problems.

The foregoing comments were supported by, or inferred from, the results of a laboratory and field study of the FM-wireless microphone, as a hearing aid accessory for hard-of-hearing and late-deafened adults, conducted by the author (Boothroyd 2004a). Twelve adults, ranging in age from 55 through 85 years participated in this study. They had hearing losses of varying degrees and two general audiometric configurations (see figure 7).

In the laboratory, they listened to and repeated Consonant-Vowel-Consonant words presented from a singlecone loudspeaker at a distance of approximately 1 meter. Steady-state noise, spectrally matched to the female talker, was presented from two loudspeakers at around 1 meter from both the listener and the ‘talker’, and at +60 and -60 degrees azimuth as shown in figure 8. Noise level (when present) at the listener location was constant at 55 dB SPL. Speech level varied in 5 dB steps from 45 to 75 dBLeq – giving a signal-to-noise ratio (at the talker) varying from -10 to +20 dB. The FM microphone was placed a few cm from the speech source where the speech level and signal-to-noise ratio were 15 dB higher than at the listener. The outcome measure was the percentage of phonemes correct in the word repetitions.

Figure 9 shows the performance vs. intensity functions under various listening conditions for a typical subject participating in the study of an FM-microphone accessory.

These findings should come as no surprise. The horizontal axis in figure 9 shows speech level at the listener’s location. The input level at the FM microphone was actually 15 dB higher, but without any change in noise level. If we were to shift the “FM-in-noise” data in figure 9 to the right by 15 dB, it would simply overlap and continue the “Aided-in-noise” function. Note, also, that the FM signal-to-noise benefit for aid inputs below 55 dBLeq is actually better than is implied in figure 9. As talker-listener distance increases, the speech level at the aid microphone will fall but the level at the FM microphone will remain the same – increasing the FM benefit above the value of 15 dB seen here.

Figure 10. Perceived benefit of a wireless-microphone accessory as reported by 12 hard-of-hearing or late-deafened adults. Conditions are organized by descending order of benefit.
For the field-trial, participants were provided with the FM accessory to use for 2 or more weeks. They were asked to keep a log of their experiences and to complete a simple post-trial questionnaire. Results of the questionnaire are shown in figure 10.

As expected, the highest reported benefit was for listening to one person in quiet at a distance. Next highest were those conditions involving one person in noise. Overall, the 12 subjects reported some, or a lot of, benefit from the system. When asked, however, whether they might be interested in purchasing such a device, none indicated enthusiasm. Interestingly, nobody enquired about cost.

Several inferences were made, based on the logs and on responses to open-ended questions:

1. Some subjects found the system awkward and intrusive.
2. Some subjects were put off by the external antenna on the hearing aid used for this study.5
3. Several of the older subjects had already adapted their life styles in such a way as to avoid situations in which communication would be compromised by distance and noise. These subjects were not strongly motivated to explore the possibility of re-experiencing these conditions.
4. The amount of counseling, demonstration, and coaching given to the subjects should probably have been much more extensive. In this study instruction was limited to a single demonstration, verbal explanation, and written materials.

In summary, the remote wireless microphone accessory offers an obvious and highly effective way to solve the problems of distance and noise experienced by the hearing aid user. There are, however, several potential limitations including intrusiveness, inconvenience, and the fact that the benefit is limited to the speech of persons with a microphone. General acceptance and application of this technology by hearing-impaired adults will probably require considerable counseling, demonstration, and coaching (Chisolm et al. 2004) as well as application-appropriate design.

External Beam-Forming Microphones

Among the problems associated with the remote wireless microphone are the intrusiveness involved in asking a communication partner to wear it, the discomfort of losing control of one’s 'ear', and the fact that the benefit applies only to the person wearing it. In theory, these problems can be addressed with a highly directional “point-and-shoot” microphone that remains under the listener’s control. Such a microphone, employing beam-forming technology, can be hand-held or head-mounted, and wirelessly coupled to the listener’s hearing aid.

A microphone of this type6 was evaluated in an unpublished follow-up to the work just described. In terms of laboratory performance, with the noise sources at +60 and -60 degrees azimuth, the average improvement in signal-to-noise ratio was approximately 8 dB. Figure 11 shows performance vs. intensity functions for a typical subject when listening in noise. Results are shown for the aid, the hand-held beam former, and a remote wireless microphone.

![Figure 11. Performance vs. intensity functions of a typical subject listening in noise under three conditions.](image)

The group-mean 8 dB signal-to-noise benefit was less than the 15 dB obtained with the close-talking remote microphone. Nevertheless, it was substantially greater than the 4 or 5 dB that would be expected with in-the-aid directional microphones. This last effect is entirely attributable to the larger separation of individual microphone elements that is possible in an external device.

Questionnaires after a field trial revealed less enthusiasm for this system than for the remote microphone. Subject comments referred to the inconvenience of holding and pointing the microphone and the delay

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5 The hearing aid used was the Free-Ear from Phonic Ear. This aid was actually designed for educational settings and, because of the external antenna, was not ideal for this application.

6 The microphones had five elements in a delay-and-sum beam-forming configuration developed by Soede (1990), and provided for this study by Etymotic Research.

7 The hearing aid was the Sprite from Phonic Ear. Though shorter than in the Free-Ear, the external antenna may still have been a factor in the subjects’ reaction.
involved in locating and pointing at a new talker in a group situation. The number of controls needing to be set correctly, for optimal operation of the complete system, was five on the hearing aid and two on the microphone. The opportunities for inappropriate adjustment and the need for more extensive counseling, demonstration, and coaching were even greater than for the remote wireless microphone.

In summary, hand-held or head-mounted beam-forming microphones, linked wirelessly to the hearing aid, can provide some of the signal-to-noise benefit afforded by a remote wireless microphone while reducing intrusiveness and giving control to the listener. Nevertheless, there are still associated inconveniences, and the potential benefit in group situations is diminished by the problem of locating a new talker and speedily re-aiming the microphone (or the gaze if the microphone is head-mounted). And, as with the remote microphone, the user cannot expect performance to be better than is experienced in quiet.

The Future for Out-of-the-Aid Solutions

In view of the dramatic signal-level advantage and signal-to-noise-ratio benefit that can be provided by a remote wireless microphone, it is appropriate to ask whether steps can be taken to increase convenience, acceptability, and utility. Possibilities include the following:

1. One step is to eliminate the audio-input shoe and external wireless receiver in favor of a fully-integrated internal hearing-aid component. This step would also open up the technology to users of in-the-ear aids.
2. Manufacturing costs could be minimized and application extended by including wireless reception capabilities in all hearing aids and letting the audiologist and client decide whether or when it should be activated.
3. Convenience could be increased by having the receiver detect when an appropriate transmitter is in range and either activating the link automatically or giving the user the opportunity to activate it.
4. The transmitter need not be restricted to a personal microphone but could also be added to such things as radios, TVs, telephones, cell-phones, MP3 players, and public address systems.
5. Reference has already been made to the need for more extensive counseling, demonstration, and coaching of clients in relation to FM accessories.
6. At the same time, professional preparation programs in audiology should pay adequate attention to the possibilities of FM wireless technology within a comprehensive program of adult aural rehabilitation.

Summary

Several possibilities are available for dealing with the difficulties that most hearing aid users experience in noisy surroundings. In-the-aid solutions are convenient and acceptable. In the case of directional microphones, they are capable of providing clinically-significant improvements in the audibility of acoustic speech cues when the talker-listener distance is not too great. Out-of-the-aid solutions, however, are demonstrably more effective. In fact, a remote wireless microphone, properly placed, can virtually eliminate the negative effects of both distance and noise. Unfortunately, this increased benefit is obtained at the expense of convenience and acceptability and carries its own set of limitations. With improvements of design, better client counseling, and improved professional preparation, there is every reason to hope that convenience and acceptability can be improved. We may yet see a time when wireless technology is seen as an automatic component of sensory management, playing a meaningful role in the enhancement of activity, participation, and quality of life for adults with hearing loss.

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8 At the time of writing this step has already been taken in Phonak’s iLink system.
References


