J Am Acad Audiol 17:519–530 (2006)

Improving Speech Intelligibility in Background Noise with an Adaptive Directional Microphone

Peter J. Blamey*
Hayley J. Fiket*
Brenton R. Steele*

Abstract

Omnidirectional, supercardioid, and adaptive directional microphones (ADM) were evaluated in combination with the ADRO® amplification scheme for eight participants with moderate sloping hearing losses. The ADM produced better speech perception scores than the other two microphones in all noise conditions. Participants performed the Hearing in Noise Test sentences at -4.5 dB SNR or better, which is similar to the level achievable with normal hearing. The Speech, Spatial and Qualities of Hearing Scale indicated no disadvantages of using the ADM relative to the omnidirectional microphone in real-life situations. The ADM was preferred over the omnidirectional microphone in 54% of situations, compared to 17% preferences for the omnidirectional microphone, and 29% no preference. The combination of the ADM to improve SNR, and ADRO® to keep the signal output comfortable and audible provided near-normal hearing performance for people with moderate hearing loss. The ADM is the recommended microphone configuration for ADRO hearing aids.

Key Words: Directional microphones, hearing aids

Abbreviations: ADM = adaptive directional microphone; ADRO = adaptive dynamic range optimization; CUNY = City University of New York; HINT = Hearing in Noise Test; PTA = average of the pure-tone threshold hearing levels at 500, 1000, and 2000 Hz; SNR = signal-to-noise ratio, SSQ = Speech, Spatial and Qualities of Hearing Scale

Sumario

Se evaluaron micrófonos omnidireccionales, supercardioides y micrófonos direccionales adaptativos (ADM) en combinación con el esquema de amplificación ADRO® en ocho participantes con hipoacusias de pendiente moderada. El ADM produjo mejores puntajes de percepción del lenguaje que los otros dos micrófonos en todas las condiciones ruidosas. Los participantes realizaron la Prueba de Audición en Ruido a – 4.5 dB SNR o mejor, que equivale al nivel alcanzable con audición normal. La escala de percepción del lenguaje, percepción espacial y de calidad de la audición (SSQ) no mostró desventajas del uso del ADM en relación con el micrófono omnidireccional en situaciones de la vida real. Se prefirió el ADM sobre el micrófono omnidireccional en 54% de las situaciones, comparado con un 17% de preferencia por el omnidireccional y un 29% sin preferencia. La combinación del ADM para mejorar la SNR, y el ADRO® para mantener la salida de la señal confortable y audible aportó un desempeño auditivo cercano a la normalidad en las personas con una hipoacusia moderada. La configuración de micrófono ADM es la recomendada para auxiliares auditivos ADRO.

Palabras Clave: Micrófonos direccionales, auxiliares auditivos

Abreviaturas: ADM = micrófono direccional adaptativo; ADRO = optimización adaptativa del rango dinámico; CUNY = Universidad de la Ciudad de Nueva York; HINT = Prueba de Audición en Ruido; PTA = promedio de los niveles auditivos para umbrales de tonos puros a 500, 1000 y 2000 Hz; SNR = tasa señal-ruido; SSQ = Escala de percepción del lenguaje, percepción espacial y de calidad de la audición

*Dynamic Hearing Pty Ltd, Richmond, Australia

Peter Blamey, Dynamic Hearing Pty Ltd, 2 Chapel Street, Richmond 3121, Australia; Phone: (+61 3) 8420 8500; Fax (+61 3) 8420 8599; E-mail: pblamey@dynamichearing.com.au

Hearing impairment often results in a loss of frequency resolution in addition to the elevation of hearing thresholds (Zwicker and Schorn, 1978). One of the consequences of reduced frequency resolution is that listeners with impaired hearing require a higher signal-to-noise ratio (SNR) to understand speech than people with normal hearing (Plomp, 1986). Market surveys confirm that the majority of hearing aid users seek improved intelligibility of speech in background noise (e.g., Kochkin, 2002), and even listeners with normal hearing are affected by noise if the SNR falls below 0 dB. Designers of hearing instruments have developed noise reduction and compression algorithms with the goals of making listening in noise more comfortable and improving the intelligibility of speech in noise. Unfortunately, many noise reduction and compression schemes that improve comfort for loud sounds also reduce speech intelligibility in noise rather than enhancing it (Nabelek, 1983; Van Tasell and Trine, 1996; Verschuure et al, 1998; Hornsby and Ricketts, 2001). There are, however, two complementary technologies that can achieve both goals when used together. The adaptive dynamic range optimization (ADRO®) amplifier has been shown to provide comfortable listening in loud or noisy conditions and to improve speech intelligibility in noise compared with alternative linear and nonlinear amplification schemes in multiple scientific studies (reviewed by Blamey, 2005). The ADRO amplifier has noise reduction "built in." The second technique to improve speech intelligibility in noise is the use of a directional microphone.

It is well known that directional microphones can improve SNR when the speech signal and the noise come from different directions in a laboratory setting, but there is still controversy over some aspects of this technology in real-life conditions. In addition, the compression amplification schemes in most hearing aids may reduce the SNR advantage produced by a directional microphone because they tend to amplify lower level sounds more than the higher level sounds. When a directional microphone reduces the intensity of sounds from behind the listener to a level that is lower than sounds in front of the listener, WDRC will tend to reduce this intensity difference, thus reducing the benefit derived from the microphone.

This study was designed to evaluate three different microphone configurations used together with the ADRO sound processing strategy. Previously published ADRO studies for hearing aids have all used an omnidirectional microphone. The three microphones in the present study were omnidirectional, fixed supercardioid, and a newly designed adaptive directional microphone with a unique combination of features (Steele, 2004). In addition to its adaptive directionality, the ADM (adaptive directional microphone) has a flat frequency response, adopts an omnidirectional mode when it is advantageous to do so, and has relatively low power consumption. The participants in the study were evaluated with speech in noise in a variety of conditions in the laboratory, and with questionnaires to assess their performance and preferences outside the laboratory.

DIRECTIONAL MICROPHONES

Amplification alone does not overcome speech perception difficulties in noisy listening environments. Adverse signal-to-noise ratios for any type or degree of hearing loss can be improved with the use of directional microphones (Ricketts and Mueller, 2000). Directional microphones operate on the assumption that desired speech signals arrive from the front of the listener and competing noise sources arrive at the microphone from other directions. Evaluations in sound-treated booths have seen directional microphones improve SNRs from 3.4 dB to 8.5 dB (Valente et al, 1995; Wouters et al, 1999). Factors such as the level of reverberation, signal location, signal distance, and the location of noise influence directional microphone performance. Performance is easier to optimize in the sound booth than in the real world (Compton-Conley et al, 2004; Walden et al, 2004).

In quiet situations, a directional microphone has the disadvantage that sounds from behind are not heard as easily as sounds from the front. For hearing aid users to gain the most benefit from a conventional directional microphone, they must be able to correctly identify appropriate listening situations. The responsibility for manually switching between omnidirectional and directional microphones in a hearing aid to suit listening environments requires not just physical skills but cognitive ones as well. Automatic directional microphones eliminate the need for manual switching of microphones.

Adaptive directional microphones automatically adapt their directional response pattern so that the SNR is optimized in continuously changing environments. Various evaluations have shown that adaptive directional microphones improve the SNR when tested in a sound booth environment (Wouters et al, 2002; Valente and Mispagel, 2004). Furthermore, an investigation by Ricketts and Henry (2002a) found that in many situations, an adaptive directional microphone outperformed a fixed directional microphone. In that study, 20 participants with binaural behind-the-ear hearing aids completed the Connected Speech Test and the Hearing in Noise Test (HINT) in four noise environments designed to represent the real world. In conditions where the competing noise was presented from the listener's side, a significant speech recognition advantage was measured for the adaptive mode.

In the present study, the adaptive directional microphone (ADM) was both adaptive and automatic (Steele, 2004). When the input sound level was below 65 dB SPL, the microphone automatically adopted an omnidirectional response pattern. For input sound levels above 65 dB SPL, the microphone adapted its directional response pattern to minimize the total input sound level while keeping the response from the front constant. The effect is to maximize the SNR for signals in front of the listener. The ADM has several advantages over other directional microphones. It has a flat frequency response from the front, unlike most directional microphones that introduce a 6 dB per octave slope (Ricketts and Henry, 2002b). The flat response means that the hearing aid fitting can be exactly the same for the ADM and the omnidirectional microphone, and the fitting does not need to adapt as the ADM changes its response pattern. The ADM will take up an omnidirectional pattern in windy conditions, because this minimizes the total input sound level. Most other directional microphones are more susceptible to wind noise. The ADM is also very efficient, using less battery power than other designs. The efficiency is achieved by using a fixed delay in the processing, compared to other schemes where the delay is variable, requiring more complex calculations.

ADRO AMPLIFICATION

The rationale and algorithm for ADRO processing are described in detail elsewhere (Blamey, 2005; Blamey et al, 1999, 2004; Martin et al, 2001). Briefly, ADRO splits the sound into 64 or 32 narrow frequency channels and statistically analyses the output level distribution in each channel. The statistical information is used to optimize the output levels in each channel independently of the others, using four fuzzy logic rules. The comfort rule ensures that the output level does not exceed the comfort target more than 10% of the time. The audibility rule ensures that the output level does not fall below the audibility target more than 30% of the time. The hearing protection rule ensures that the output level does not ever exceed the maximum output level. The background noise rule ensures that very soft noises are not amplified to an annoying level, by restricting the maximum gain of the instrument in each channel. To fit ADRO, the audiologist or dispenser finds the optimum settings for the comfort targets, audibility targets, maximum output levels, and maximum gains. The 64-channel version of ADRO was used in this study.

EXPERIMENTAL DESIGN

The study was conducted in two parts. The first part of the study compared an omnidirectional microphone with a fixed directional microphone. The participants were fitted with a BTE hearing aid containing an omnidirectional microphone in one program and a fixed directional supercardioid microphone in the second program. Both programs were used in speech perception testing. Participants did not take the hearing aids home during this phase.

The second part of the study was designed to evaluate the performance of the ADM relative to the other two microphones with ADRO. In this phase of testing, the participants wore the hearing aids in their daily life for a period of four to five weeks. The hearing aids they wore home featured an omnidirectional microphone in program one and the ADM in program two. For the evaluation sessions, the omnidirectional, fixed directional supercardioid, and the ADM were compared using two speech perception tests. The participants also responded to two questionnaires assessing their use of the omnidirectional and adaptive directional microphones with ADRO in everyday life.

PARTICIPANTS

Eight participants (three females and five males) took part in the study. Ages ranged from 36 to 82 years (mean = 69.6, SD = 15.8). All participants had a bilateral sensorineural hearing loss. Air- and bone-conduction pure-tone thresholds were obtained for all participants in both ears from 250 to 6000 Hz. Figure 1 shows the mean air-conduction threshold at each frequency. All participants had previously worn hearing aids, with a mean of 12 years of experience (range four months to 28 years). All participants were fitted binaurally.

HEARING INSTRUMENT FITTING

BTE hearing aids containing the AMIS Toccata Plus open platform DSP chip (Brennan and Schneider, 1998) were programmed for ADRO processing. The hearing aids were fitted to the participants' requirements using the ADROfit fitting software developed by Dynamic Hearing Pty Ltd.

To start the fitting, comfort levels were predicted from the audiogram. The comfort levels were refined using in situ measurements. At 500, 1000, 1500, 2000, 3000, and 4000 Hz, narrow band noise was presented through the hearing aid. Participants were asked to inform the audiologist when each sound was at a comfortable level. Loudness was then balanced across the frequency range.

The ADROfit fitting software automatically calculated initial output targets (maximum output level, comfort target, and audibility target) from the measured comfort levels. Initial values for the maximum gain in each frequency channel were derived from the audiogram. The hearing instruments were turned on, and overall volume for live speech was adjusted to a comfortable level that was not too loud or too soft by varying all four sets of fitting parameters in both ears up and down at the same time. If necessary, fine-tuning of high, low, and mid-frequencies was used to avoid acoustic feedback and to set the sound quality to the preferences of the listener. The adjustments were applied bilaterally while listening to live speech and/or recorded sounds with the omnidirectional microphone.

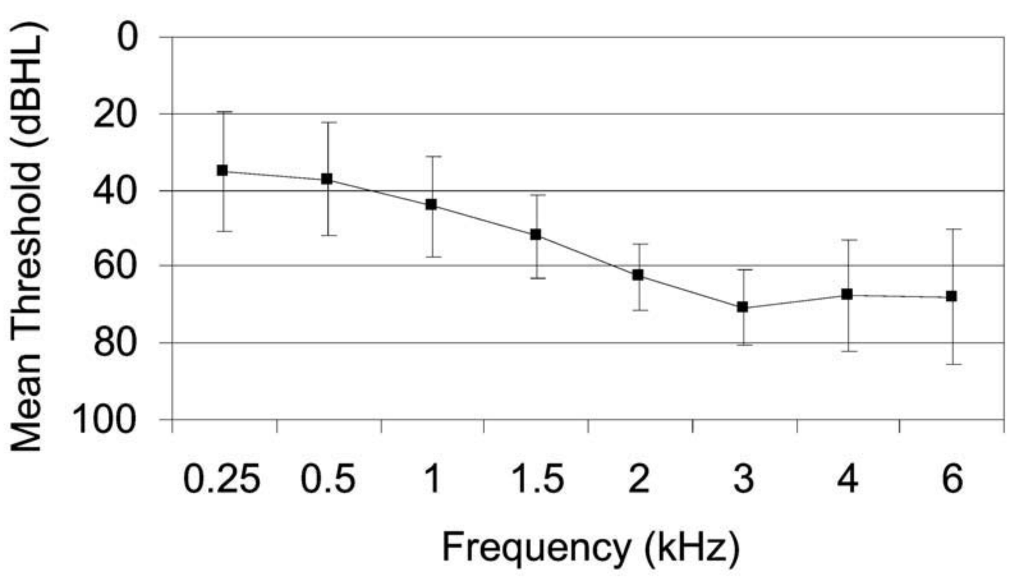

Figure 1. Mean air-conduction pure-tone thresholds for 16 ears.

After fitting, two programs were saved to the hearing aid. Program one always utilized an omnidirectional microphone. Program two used either a fixed supercardioid microphone or the adaptive directional microphone. In the second phase of the experiment, the participants were informed that the hearing instruments had two programs that might sound different from one another in some situations. They were asked to try both programs in different situations and form an opinion about the differences. They were not told anything about the differences that might be expected between the two programs or how the microphones operated.

SPEECH TESTING WITH THE HINT

Speech intelligibility was assessed using the Hearing in Noise Test (Nilsson et al, 1994). The HINT consists of 12 lists, each containing 20 sentences. The sentences are phonetically balanced and are approximately equal in length. Steady-state noise acts as a masker for the sentences. The noise spectrum has been shaped to correspond to the long-term average spectrum of the sentences. The noise was presented to participants at a level of 65 dBA, and the noise onset was five seconds prior to the speech onset. Noise level did not vary throughout the test. The level of the sentences was varied adaptively to find the signal-to-noise ratio where the participant understood 50% of the sentences.

Testing was performed within a sound-treated room having internal dimensions of 2.7 m x 3 m. The reverberation time in the room was 220 msec. Speech was presented from a speaker located at 0° azimuth. Noise was presented from three speaker positions: 90°, 135°, and 180° on the side with the higher pure-tone average thresholds for each listener (PTA at 500, 1000, and 2000 Hz). All speakers were positioned one meter from the center of the participant's head at ear level.

The order of testing speaker positions, microphone types, and sentence lists was randomized between participants. For each condition, participants completed two lists of sentences. The starting signal-to-noise ratio was -5 dB for all conditions and all participants. The speech presentation level was automatically adapted up or down according to participant responses. For the first four sentences in each list, the step size was 4 dB. For the remaining sentences, incorrect responses resulted in the speech presentation level increasing in 2 dB steps, and correct responses resulted in the speech presentation level decreasing in 2 dB steps.

The first part of the study involved participants completing the HINT with the omnidirectional microphone and the fixed directional microphone. As the first session required all lists of sentences to be heard (two microphone conditions x three speaker positions x two lists), a period of at least four weeks elapsed between this session and later evaluations involving the adaptive directional microphone to minimize any learning effects.

The expected polar patterns for the adaptive directional microphone in the three noise source conditions are bipolar (with nulls at 90° and 270°) for noise at 90°; supercardioid (with nulls at 135° and 225°) for noise at 135°; and cardioid (with one null at 180°) for noise at 180°. Polar response patterns measured in a free field were in accord with these expectations (Fortune, 2004). When the hearing instruments are positioned on the head, the polar pattern is significantly affected by the acoustics of the head itself. Theoretically, there should be no difference between the fixed supercardioid microphone and the ADM for noise at 135°. However, the ADM may take up a different configuration if it is advantageous to do so, and it should never perform worse than the fixed directional microphone for noise from any angle. The experimental data confirmed this expectation.

Figure 2 shows that across each of the three speaker locations, the best results (lowest SNR) were always achieved with the adaptive directional microphone. Repeated measures analysis of variance showed that the differences in SNR between the three microphone configurations were highly significant ($F [2, 56] = 93.2$, $p < 0.001$) as were the differences in scores between the three noise locations ($F [2, 56] = 16.8$, $p < 0.001$). For all three microphones, the most difficult listening situation (highest SNR) was for noise presented directly behind the listener. In the other two conditions (noise from one side at 90° or 135°), the head shadow effect provided higher SNR at the ear opposite the noise source. The most difficult listening condition, with noise from 180°, was also the condition in which the directional microphones offered the largest improvements in SNR.

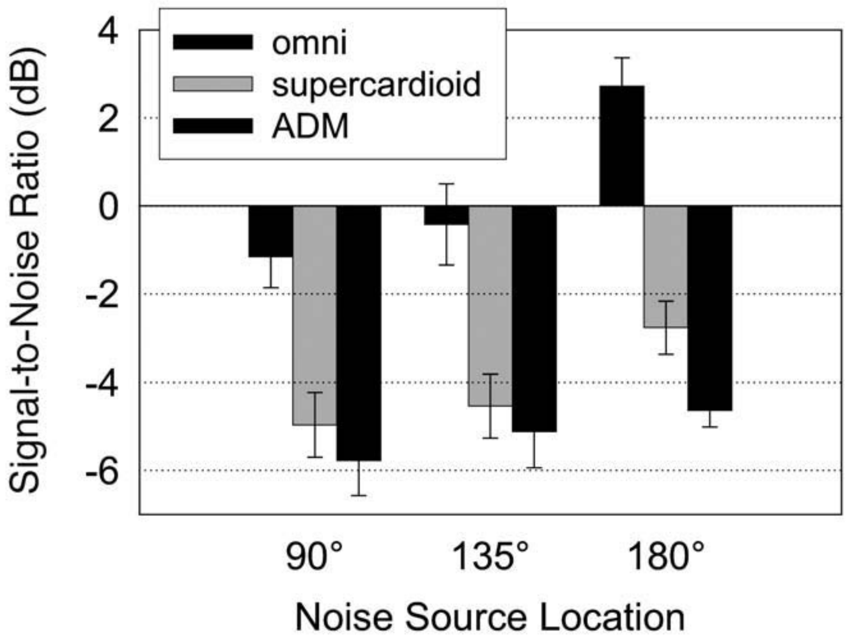

Figure 2. Mean HINT results for three microphones and three noise source locations.

Paired t-tests were used to test the differences between the microphones in the three noise conditions. These tests showed that the fixed directional microphone performed significantly better than the omnidirectional microphone in every noise condition ($t = 10.15$, $p < 0.001$, at 90°; $t = 6.48$, $p < 0.001$, at 135°; $t = 8.57$, $p < 0.001$, at 180°), the adaptive directional microphone performed better than the omnidirectional microphone in every noise condition ($t = 4.7$, $p < 0.05$, at 90°; $t = 6.09$, $p < 0.001$, at 135°; $t = 8.04$, $p < 0.001$, at 180°), and the adaptive microphone performed better than the fixed directional microphone in noise from 180° ($t = 2.59$, $p < 0.05$). Comparisons involving the ADM should be considered cautiously because of the repetition of the HINT sentence lists. If the listeners remembered some sentences or words from the first presentation, they may have performed better with the ADM as a result.

SPEECH TESTING WITH CUNY SENTENCES

City University of New York (CUNY) Sentences (Boothroyd et al, 1985) were also used to assess speech perception in quiet and in noise. One hundred and seventy lists of sentences make up the CUNY speech test. Each list contains 12 sentences having a different number of words (range from 3 to 14). The sentences were recorded by a female Australian speaker. Participants were required to repeat as many words in a sentence as they could. Each list was scored on the total number of words correctly repeated. The CUNY Sentences were presented in four conditions: in quiet, in noise from 90°, in noise from 180°, and in moving noise. Only the fixed and adaptive directional microphones were assessed.

Speech was presented from a speaker located one meter away from the center of the participant's head at ear level. The speaker was located at 0° azimuth. In the quiet condition, participants completed two lists of CUNY Sentences with the hearing aid in fixed directional mode and two lists with the hearing aid in adaptive directional mode. Sentences were presented at 67 dB SPL.

In the noise conditions, eight-talker babble was introduced at an SNR determined for each individual so that they were capable of correctly repeating approximately 50% of words in the sentences when the speech and noise were both presented from the front. As for the HINT, the speakers presenting the babble were positioned one meter away from the listener on the side with their highest PTA. Each participant listened to two lists with the noise at 90° for each microphone condition. Two lists were also presented for each microphone condition with the babble coming from the speaker located at 180°. In the moving noise source condition, the eight-talker babble panned back and forth between the speaker at 90° and the speaker at 180°, taking approximately three seconds to move from one speaker to another. Two lists of CUNY Sentences were presented with the fixed directional microphone and two lists with the adaptive directional microphone in the moving noise condition.

Figure 3 shows the means and standard deviations for both microphones and each noise condition used with the CUNY Sentences. In quiet, both microphones produced near perfect speech recognition scores of 99% words correct on average. As for the HINT test, the most difficult listening condition was for noise at 180°, and this condition also produced the largest difference in scores between the two microphones. A two-way repeated measures ANOVA showed that the adaptive directional microphone produced significantly higher scores than the fixed directional microphone, ($F [1, 53] = 21.83$, $p < 0.001$). Paired t-tests showed a statistically significant advantage for the adaptive directional microphone with noise from 180° ($t = 4.54$, $p < 0.001$) and with moving noise ($t = 2.76$, $p < 0.05$). It should be noted that there were no repeated lists of CUNY Sentences, and the pattern of results is similar to that obtained with the HINT.

COMPARATIVE QUESTIONNAIRE

At the end of the second part of the study, the "Comparative Questionnaire" asked each participant which microphone (omnidirectional or ADM) provided the best listening and understanding for 18 common listening situations encountered during their four-week trial. The 18 situations and the participants' responses are summarized in Table 1. At the time that the participants responded to the "Comparative Questionnaire," they did not know what the technical differences were between the two programs in the hearing aid and referred to them only as "Program 1" and "Program 2." In this situation, the most common response bias is for listeners to use Program 1 because this is the program that is selected by default when the hearing aid is switched on. Program 1 was the omnidirectional microphone, so the strong preferences for the ADM are not due to a response bias of this type. If participants had not been exposed to a particular situation, they were able to select a "Not Applicable" option. If there was no perceptible difference between the two microphones, participants were able to select a "No Difference" option.

A total of 144 responses were received for the "Comparative Questionnaire." Twelve "Not Applicable" responses were excluded from further analysis. Of the remaining 132 responses, participants judged that there was

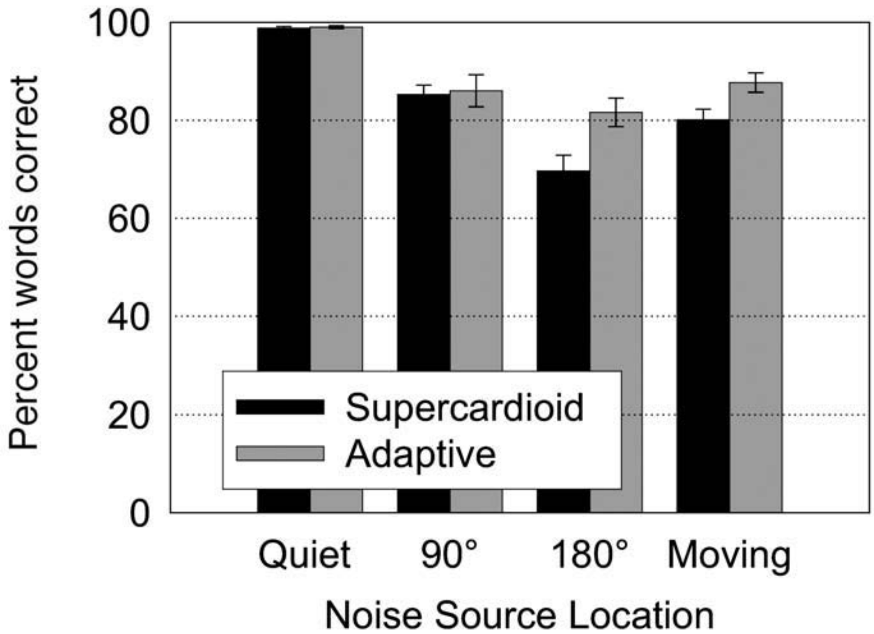

Figure 3. Mean scores and standard deviations for CUNY Sentences in four conditions.

Table 1. "Comparative Questionnaire" Situations and Response Summary

Situation	Omni	ADM	No Difference	Not Applicable
At home, when someone is speaking to me from about 2–3 feet away	1	2	5	0
At home, when someone is speaking to me from across the room	0	4	4	0
At home, when someone is speaking to me from another room	2	2	3	1
At a restaurant, when sitting across from my spouse or friend	1	7	0	0
Several friends or family members talking around the dinner table	1	6	1	0
Talking with a friend or spouse outdoors	2	4	2	0
Talking with friends at a small social gathering	1	5	2	0
Listening to a priest/minister at church or speaker in a meeting (without the use of an FM system)	1	6	0	1
Conversation with my co-workers and supervisor at work	0	3	0	5
Conversation in a car	2	4	2	0
Talking with a particularly soft spoken person	2	4	2	0
A waitress at a restaurant	0	6	2	0
Cashier at the grocery store or department store	0	5	3	0
A child (6–10 years old)	0	3	2	3
Using the telephone	4	1	1	2
Listening to the news on the TV	1	3	4	0
Listening to the news on the radio	2	4	2	0
Detection of soft environmental sounds (i.e. microwave beeping, computer running, door bell, knocking at door)	2	3	3	0
Total	22	72	38	12

"No Difference" between the omnidirectional microphone and the adaptive microphone 29% of the time (38 responses). They also judged that the omnidirectional microphone was preferred 17% of the time (22 responses) and that the adaptive microphone was preferred 54% of the time (72 responses). This difference was highly significant ($\chi^2 = 26.6$, $p < 0.0001$) (see Figure 4).

There was only one situation (using the telephone) where the omnidirectional microphone was preferred by more participants than the ADM. A special hearing aid program using a telecoil is commonly used for this situation. In all other situations in the "Comparative Questionnaire," the ADM was preferred by at least as many participants as the omnidirectional microphone. As expected, the ADM was strongly preferred in noisy situations, such as a restaurant or grocery store or when there were several people involved in a conversation. Also as expected, there were many "No Difference" responses for quiet situations where the ADM would have adopted an omnidirectional response pattern.

SPEECH, SPATIAL AND QUALITIES OF HEARING SCALE

The Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse and Noble, 2004) is composed of three scales that together cover a spectrum of potential listening situations involving speech, spatial aspects, and sound quality. The SSQ was administered in an interview format. Answers were placed along a continuum from 0 to 10, with scores of "0" indicating the absence of an ability or quality and scores of "10" indicating perfect ability or quality. Across the scales, a high rating indicated fewer problems than a lower rating. The questionnaire was administered twice, once for the omnidirectional microphone and once for the ADM at the end of the study. The order of microphone assessment was balanced across participants.

Responses from the SSQ were collated, and an average rating was obtained for each participant for both microphone conditions across the speech, spatial, and quality

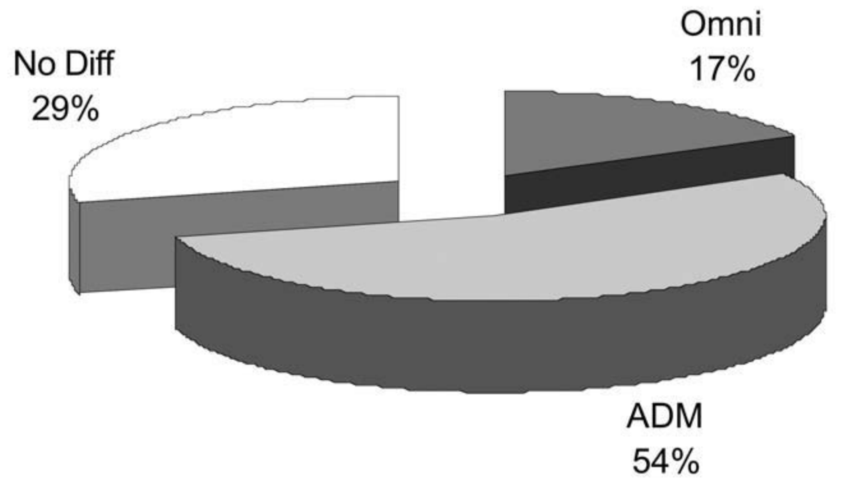

Figure 4. The ADM was preferred three times as often as the omnidirectional microphone.

categories (Figure 5). "Not Applicable" responses were excluded from the analysis. There were no significant differences in the overall ratings for any of the three categories of ratings in the questionnaire.

DISCUSSION

The primary purpose of this study was to evaluate the performance of a new adaptive directional microphone in conjunction with the ADRO amplification scheme. ADRO has already been shown to provide improved speech perception in noise in hearing aids using omnidirectional microphones and in cochlear implants (Blamey, 2005). The results of the present study show that an additional improvement is achieved when ADRO is combined with a supercardioid microphone or an adaptive directional microphone when noise and speech come from different directions. The advantage provided by the supercardioid microphone was 3.8 dB at 90°, 4.1 dB at 135°, and 5.5 dB at 180°. The advantage provided by the adaptive directional microphone was 4.6 dB at 90°, 4.5 dB at 135°, and 7.3 dB at 180°. Averaged over the three noise directions, the ADM provided 1.0 dB advantage over the fixed supercardioid microphone. It is possible that the relative advantage of the ADM may be slightly overestimated in the present study because of the repetition of the HINT sentence lists.

The size of the advantages for the fixed and adaptive directional microphones are similar to other results reported in the literature. For instance, Valente and Mispagel (2004) found an advantage of between 4.5 and 7.2 dB for an adaptive microphone compared to an omnidirectional microphone depending on speaker location. Wouters et al (1999) found a 3.4 dB advantage for a directional microphone over an omnidirectional microphone for noise from 90°. Powers and Hamacher (2004) reported an average of 1.5 dB advantage for an adaptive directional microphone over a fixed directional microphone. Fortune (2004) found improvements of up to 21% on the QuickSIN test in babble at 0 dB SNR comparing the ADM to an omnidirectional microphone, and up to 9% improvement for the ADM over the fixed supercardioid microphone. The mean difference for CUNY Sentences in babble between the supercardioid microphone and the ADM in the current study were 12.0% for noise at 180° and 7.6% for moving noise in good agreement with Fortune (2004).

Using ADRO and the adaptive directional microphone, the participants were able to score 50% correct on the HINT Sentences in noise at an average of -5.1 dB SNR. This is similar to the performance of normally hearing listeners on the HINT. The developers of the HINT reported average SNR results for normally hearing listeners to be -2.92 dB (Nilsson et al, 1994). Bentler et al (2004) reported that normally hearing listeners achieved an average SNR on the HINT of -4.2 dB in stationary diffuse noise and -6.2 dB for a moving noise source.

Noise source positioning influences speech perception even when the microphone is omnidirectional. The phenomenon seen in this study where speech intelligibility was always best when noise came from 90° can be explained by the head shadow effect. The head acts as an acoustic barrier to noise from the side. Noise from the front or from 180° is able to reach both ears without being attenuated and so has a greater masking effect than noise from other angles. A similar pattern of results has been reported in many other studies.

The head shadow effect provides an advantage to the listener when voice and noise come from different directions. The best situation is when the noise comes from one side at 90° and the speech comes from the opposite hemisphere. Thus, the listener should position herself facing at right angles to the direction of the noise, and towards the talker. Facing the talker will maximize the information from both lipreading and the acoustic speech signal. Note that if speech and noise are coming from opposite directions, one of the worst listening positions is to be facing the talker with the listener's back to the noise. This advice is valid for a bilateral hearing aid user regardless of the type of microphone on the hearing aid. This is important because it means that a listener used to omnidirectional microphones does not need to modify her behavior when using directional ones.

For all microphone types, noise from 180° had a greater masking effect than 90° or 135°, but the effect was smallest for the ADM. This means that the ADM is more forgiving when the noise source is directly behind the listener, and the listener does not need to be so conscious of her body position relative to the noise and the speaker.

The adaptive directional microphone used in this study differs from most others available in commercial hearing aids. Most directional microphones, whether they are fixed or adaptive, cannot adopt an omnidirectional response pattern. Hearing aids with these microphones usually require at least two programs, one with an omnidirectional microphone, the second with the directional microphone. The ADM in this study is capable of moving from an omni mode to any directional mode provided the input level exceeds the 65 dB SPL activation level. This means wearers of hearing aids, including those with manual dexterity problems, benefit from the different advantages that omni and directional microphones provide.

This advantage of the ADM is clearly shown by the results of the comparative questionnaire. Only 17% of responses reflected situations where the omnidirectional microphone was preferred to the ADM. There was a quite large proportion of responses (29%) where there was no difference. This was expected since the ADM adopted an omnidirectional response pattern identical to the omnidirectional microphone whenever the total input level was below 65 dB SPL. Because of the predominance of conditions in which the ADM was preferred or there was no difference (83%), it is highly recommended that the ADM should be the default microphone for the ADRO hearing aid. This suggestion is in accord with the recommendations of Walden et al (2004) who found that "the vast majority of daily listening time is typically with the signal source in front of and relatively close to the listener, and with the background noise source spatially separated from the signal source"(p.393). Walden et al recommend an omnidirectional microphone in quiet and a directional microphone in most common noise environments.

The only situations in which the ADM is likely to be disadvantageous compared to an omnidirectional microphone are on the telephone or when the listener wants to hear loud sounds (greater than 65 dB SPL) at their full volume, coming from behind. One example is when listening to someone talking from the back seat of the car. The omnidirectional microphone (or a telecoil in the case of the telephone) should be available for use on these occasions.

The ADM obviously changes the relative loudness of sounds from different directions. ADRO also changes the relative loudness of sounds in the environment to keep them audible and comfortable. It is reasonable to ask whether these changes affect listeners' abilities to make spatial and directional judgments about sounds in their environment. The SSQ is an instrument designed to answer these types of questions. There was no statistically significant difference between the SSQ responses for the omnidirectional microphone and the ADM, indicating that the adaptive nature of the microphone did not produce any discernable difference in the subjects' abilities. The overall level of the ratings in Figure 5 indicates that the participants felt they had good (but not perfect) spatial and qualitative

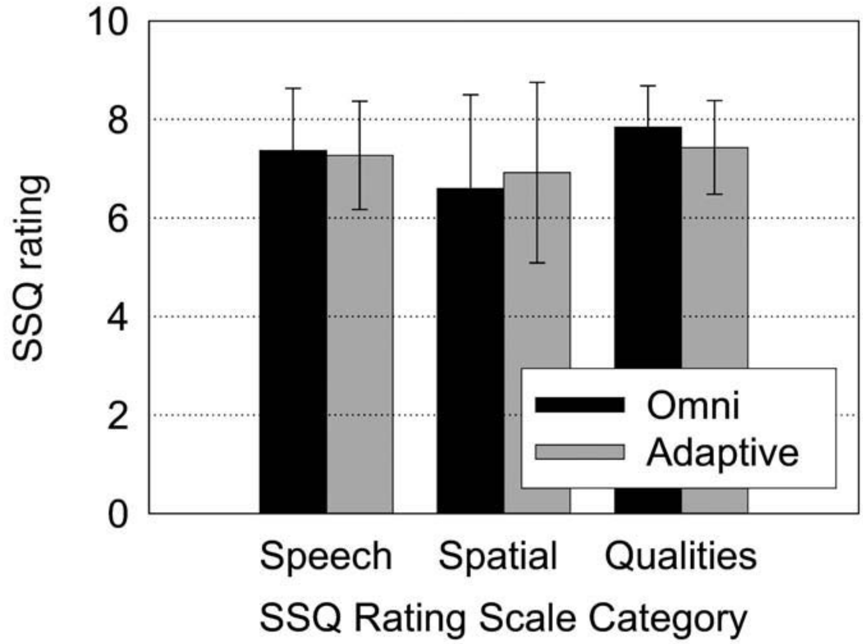

Figure 5. Average SSQ rating for each microphone condition.

hearing capacities with both microphones.

CONCLUSIONS

The adaptive directional microphone has been shown to provide strong benefits in the majority of listening situations. Speech perception performance in noise with the ADM is comparable to performance of listeners with normal hearing. Hearing aid users are not required to switch programs to obtain the benefits of the ADM. The audiologist is not required to fit the ADM any differently from the omnidirectional program. The benefits of the ADM are accompanied by the comfort, audibility, and sound quality afforded by ADRO.

Acknowledgments. The authors wish to thank the participants in this study. The research was approved by the Human Research and Ethics Committee of the Royal Victorian Eye and Ear Hospital (Project 03/529H). ADRO® is the registered trademark of Dynamic Hearing Pty Ltd.

REFERENCES

Bentler RA, Palmer C, Dittberner AB. (2004) Hearing in noise: comparison of listeners with normal and (aided) impaired hearing. *J Am Acad Audiol* 15(3):216–225.

Blamey PJ. (2005) Adaptive dynamic range optimization (ADRO): a digital amplification strategy for hearing aids and cochlear implants. *Trends Amplif* 9(2):77–98.

Blamey PJ, James CJ, Wildi K, McDermott HJ, Martin LFA. (1999) Adaptive dynamic range optimization sound processor. Australian Patent Application PCT/AU99/00076, International Patent Application WO 00/47014, filed Feb. 5, 1999, and published Aug. 10, 2000.

Blamey PJ, Martin LFA, Fiket HJ. (2004) A digital processing strategy to optimize hearing aid outputs directly. *J Am Acad Audiol* 15(10):716–728.

Boothroyd A, Hanin L, Hnath T. (1985) *A Sentence Test of Speech Perception: Reliability, Set Equivalence, and Short Term Learning* (Internal report, RCI 10). New York: City University of New York.

Brennan R, Schneider T. (1998) A flexible filterbank structure for extensive signal manipulations in digital hearing aids. *Proceedings of the 1998 IEEE International Symposium on Circuits and Systems* 6:569–572.

Compton-Conley CL, Neuman AC, Killion MC, Levitt H. (2004) Performance of directional microphones for hearing aids: real-world versus simulation. *J Am Acad Audiol* 15:440–455.

Fortune T. (2004) Adaptive Dynamic Range Optimisation with beamforming: an interesting combination. Paper presented at Europaische Union der Horgerateakustiker, 49th International Congress of Hearing Aid Acousticians, Frankfurt.

Gatehouse S, Noble W. (2004) The Speech, Spatial and Qualities of Hearing Scale (SSQ). *Int J Audiol* 43(2):85–99.

Hornsby BW, Ricketts TA. (2001) The effects of compression ratio, signal-to-noise ratio, and level on speech recognition with normal-hearing listeners. *J Acoust Soc Am* 109(6):2964–2973.

Kochkin S. (2002) MarkeTrak VI: consumers rate improvements sought in hearing instruments. *Hear Rev* 9:18–22.

Martin LFA, Blamey PJ, James CJ, Galvin KL, Macfarlane DS. (2001) Adaptive Dynamic Range Optimization for hearing aids. *Acoust Aust* 29:1–21.

Nabelek IV. (1983) Performance of hearing-impaired listeners under various types of amplitude compression. *J Acoust Soc Am* 74(3):776–791.

Nilsson M, Soli SD, Sullivan JA. (1994) Development of the Hearing In Noise Test for the measurement of speech reception thresholds in quiet and in noise. *J Acoust Soc Am* 95:1085–1099.

Plomp R. (1986) A signal-to-noise-ratio model of the speech-reception threshold of the hearing impaired. *J Speech Hear Res* 29(2):146–154.

Powers TA, Hamacher V. (2004) Proving adaptive directional technology works: a review of studies. *Hear Rev* 11(4).

Ricketts T, Henry P. (2002a) Evaluation of an adaptive, directional microphone hearing aid. *Int J Audiol* 41(2):100–112.

Ricketts T, Henry P. (2002b) Low-frequency gain compensation in directional hearing aids. *Am J Audiol* 11(1):29–41.

Ricketts T, Mueller HG. (2000) Predicting directional hearing aid benefit for individual listeners. *J Am Acad Audiol* 11(10):561–569.

Steele B. (2004) Method and apparatus for producing adaptive directional signals. International Patent PCT/AU2004/001071, World Intellectual Property Organization WO 2005/055644 A1, filed Aug. 11, 2004.

Valente M, Fabry DA, Potts LG. (1995) Recognition of speech in noise with hearing aids using dual microphones. *J Am Acad Audiol* 6(6):440–449.

Valente M, Mispagel K. (2004) Performance of an automatic adaptive dual-microphone ITC digital hearing aid. *Hear Rev* 11(2).

Van Tasell DJ, Trine TD. (1996) Effects of single-band syllabic amplitude compression on temporal speech information in nonsense syllables and in sentences. *J Speech Hear Res* 39(5):912–922.

Verschuure J, Benning FJ, Van Cappellen M, Dreschler WA, Boeremans PP. (1998) Speech intelligibility in noise with fast compression hearing aids. *Audiology* 37(3):127–150.

Walden BE, Surr RK, Cord MT, Dyrlund O. (2004) Predicting hearing aid microphone preference in everyday listening. *J Am Acad Audiol* 15(5):365–396.

Wouters J, Berghe JV, Maj JB. (2002) Adaptive noise suppression for a dual-microphone hearing aid. *Int J Audiol* 41(7):401–407.

Wouters J, Litiere L, van Wieringen A. (1999) Speech intelligibility in noisy environments with one- and two-microphone hearing aids. *Audiology* 38(2):91–98.

Zwicker E, Schorn K. (1978) Psychoacoustical tuning curves in audiology. *Audiology* 17:120–140.