Performance of a Fully Adaptive Directional Microphone to Signals Presented from Various Azimuths

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Abstract

The signal-to-noise ratio advantage of a directional microphone is achieved by reducing the sensitivity of the microphone to sounds from the sides and back. A fully adaptive directional microphone (one that automatically switches between an omnidirectional mode and various directional polar patterns) may allow the achievement of signal-to-noise (SNR) improvement with minimal loss on audibility to sounds that originate from the sides and back. To demonstrate such possibilities, this study compared the soundfield aided thresholds, speech in quiet at different input levels, and speech in noise performance of 17 hearing-impaired participants under three microphone modes (omnidirectional, fixed hypercardioid, and fully [or automatic] adaptive) as the stimuli were presented from 0° to 180° in 45° intervals. The results showed a significant azimuth effect only with the fixed directional microphone. In quiet, the fully adaptive microphone performed similarly as the omnidirectional microphone at all frequencies, input levels, and azimuths. In noise, the fully adaptive microphone achieved similar SNR improvement as the fixed directional microphone. Clinical implications of the results of this study were discussed.

Key Words: Audibility, automatic switching, fully adaptive directional microphone, signal-to-noise ratio

Abbreviations: BTE = behind the ear; CASPA = computer assisted speech perception assessment; HINT = hearing in noise test; MCL = most comfortable listening level; SIN = speech in noise test; SNR = signal-to-noise ratio; SPIN = speech perception in noise test

Sumario

La ventaja en cuanto a la relación señal-ruido de un micrófono direccional se logra al reducir la sensibilidad del micrófono para sonidos que proviene de los lados y de atrás. Un micrófono direccional totalmente adaptable (uno que cambia automáticamente entre un modo omni-direccional y varios patrones polares direccionales) puede lograr una mejoría en la relación señal-ruido (SNR) con mínima pérdida de audibilidad de los sonidos que se originan a los lados y atrás. Para demostrar tales posibilidades, este estudio compara los umbrales amplificados en campo libre, y el desempeño ante lenguaje en silencio a diferentes niveles de presentación y con lenguaje en ruido, de 17 participantes hipoacúsicos, estimulados con tres tipos de micrófonos (omni-direccional, hipercardiode fijo y totalmente [o automáticamente] adaptable), conforme el estímulo fue presentado de 0° a 180°, en intervalos de 45°. Los resultados mostraron un efecto de azimut significativo sólo con el micrófono direccional...
It is generally accepted that hearing aids with a directional microphone improve the signal-to-noise ratio (SNR) of structured listening environments (see Ricketts 2001; Valente 1999 for a review) and the wearers’ real-world satisfaction with their hearing aids (Kochkin, 2000). While the SNR benefit of this feature for people with a hearing impairment is recognized, the discussion on the potential negative impact from the decreased sensitivity for sounds that originate from directions other than the front is only emerging (Lee et al, 1998; Ricketts et al, 2003). The present report demonstrates this negative potential and illustrates one approach to minimize its impact.

In a simplistic sense, a directional microphone achieves its intended function by reducing its sensitivity to sounds that originate from the sides and back. An SNR improvement can be expected if the desirable sounds originate from the front while the undesirable sounds (or noise) originate from the sides and back. On the other hand, when the desirable signal originates from any other directions but the front, the reduced microphone sensitivity could lead to a loss of audibility for the wearers. Indeed, one would speculate that the directional hearing aids with a higher directivity index are more likely to result in more audibility loss than hearing aids with a lower directivity index (Gravel et al, 1999). Such speculations have been indirectly demonstrated. For example, Kuk (1996) showed that people with a hearing loss preferred a directional microphone in noisy situations but an omnidirectional microphone in quiet situations or noisy situations where the desired signals originate from the sides or the back. Lee et al (1998) showed as much as 24% difference in speech recognition scores between an omnidirectional microphone and a directional microphone (on the same programmable hearing aid) to speech presented from the back at 50 dB SPL. Ricketts et al (2003) showed that their test subjects indicated a lower satisfaction for a directional microphone when the desirable sounds originated from the sides or the back. These questionnaire reports demonstrated the possibility that wearers of a fixed directional microphone may encounter potential audibility problems in real life with sounds that originate from anywhere but the front. Considering that as much as 40% of an adult’s listening environments were absent from background noise, and as much as 20% of the time the signal of interest is from locations other than the front (Walden et al, 2004), a directional hearing aid should be designed with features to overcome the potential audibility loss in listening situations that may violate the assumptions of such a microphone, even though these listening environments may not be the most frequently occurring ones.

Hearing aids with a manually switchable directional microphone could provide a
solution to the problem in that the wearer is given the choice to select the optimal microphone mode. Indeed, Walden (2003) recommended that wearers of switchable directional hearing aids wear the hearing aids in the omnidirectional mode in typical daily situations and switch to the directional mode in noisy situations. This may be a good solution to preserve audibility and improve signal to noise on a need basis. However, its dependence on the dexterity of the wearers could exclude its applications for young children and older adults. Furthermore, the wearers may not recognize the need to switch microphones if they are not made aware of the missing signals (if they frequently leave the hearing aids in the directional mode).

Hearing aids with automatic directional microphones or those that automatically switch from an omnidirectional mode to a fixed directional mode may be necessary to ensure audibility while providing an SNR improvement under specific noise locations. Hearing aids with adaptive directional microphones or those that change their polar patterns in the directional mode only may be effective in ensuring a more favorable SNR than a fixed directional microphone with changing noise sources (Ricketts and Henry, 2002). However, they may not be adequate in ensuring audibility because none of the directional polar patterns is omnidirectional. Consequently, a fully adaptive directional microphone, or one that is both automatic (changes from an omnidirectional polar pattern to a directional polar pattern) and adaptive (changes among different polar patterns) may have the best chance of minimizing the loss of audibility while enhancing the SNR of the listening environment because it moves from an omnidirectional pattern to any directional pattern depending on the listening condition. This design may further have the advantage of preserving the same frequency response in all polar patterns and minimizing any processing artifacts as the microphone changes its polar pattern.

Recently, a fully adaptive directional microphone is introduced that changes its polar pattern from an omnidirectional pattern to any polar patterns depending on the nature, intensity, and azimuth of presentation of the stimulus. When the sound source is presented directly from the front, when the sound level at the microphone is below 50-60 dB SPL, or when the source is wind noise, an omnidirectional microphone is automatically selected to preserve audibility and minimize the perception of circuit noise and wind noise. In other situations with a single noise source, the appropriate polar pattern will result. In a diffuse field where there may be multiple noise sources, a hypercardioid polar pattern is assumed. Meanwhile, the response in the low frequency is compensated such that the same frontal frequency response (as the omnidirectional microphone) is used in all directional polar patterns. To further preserve audibility of the desirable signals that may originate from the sides and back, the microphone uses a switching time of 5–10 seconds to change from an omnidirectional mode to the appropriate directional mode (much shorter time is needed to change among different directional polar patterns). Intuitively, the “long” switching time should give the wearers enough time to detect the presence of the sound source from the sides and back in quiet and make a decision if they should turn toward the sound source. If the source is undesirable and they choose not to turn, the fully adaptive microphone will switch to the correct polar pattern by forming a “null” at the direction of the sound source after the ten seconds. If the sound source is desirable and the wearers turn their heads, the sound source that once originated from the sides or back now originates from the front. This keeps the fully adaptive microphone in an omnidirectional mode and minimizes the loss of audibility. It is estimated that five to ten seconds should be a good compromise between giving the wearers enough time to respond (thus preserving audibility) and sufficient responsiveness to the changing listening situation. It will be desirable to examine if the chosen activation criteria used in this microphone system indeed preserves audibility.

It is recognized that laboratory findings may not always be observed in daily life (e.g., Walden et al, 2000) because of the interactions of many uncontrolled factors. On the other hand, the potential sensitivity limitation of a fixed directional microphone has been reported in daily listening situations (e.g., Kuk, 1996; Ricketts et al, 2003), and yet no laboratory studies have been reported to help one understand how stimulus factors such as input levels and azimuth of presentation may affect the degree of sensitivity limitation.
Consequently, this study was conducted to demonstrate the sensitivity limitation of a fixed directional microphone as well as to evaluate the clinical efficacy of the fully adaptive directional microphone. Specifically, the objectives of this study were to determine:

1. Aided soundfield thresholds measured with an omnidirectional microphone, a fixed hypercardioid directional microphone, and a fully adaptive directional microphone when the stimuli are presented from 0° to 180° in 45° increments.

2. Speech recognition in quiet (on the CASPA [computer assisted speech perception assessment] test) measured at 50 dB SPL, 65 dB SPL, and 75 dB SPL with an omnidirectional microphone, a fixed hypercardioid directional microphone, and a fully adaptive directional microphone when the stimuli are presented from 0° to 180° in 45° increments.

3. Speech recognition in noise (on the HINT [hearing in noise test]) measured with an omnidirectional microphone, a fixed hypercardioid directional microphone, and a fully adaptive directional microphone when the noise is presented to the sides and back (45° to 180° in 45° increments) at an overall level of 68 dB SPL.

### METHOD

#### Study Participants

Seventeen hearing-impaired persons with a symmetrical (within +/- 10 dB) mild-to-moderate sensorineural hearing loss participated. Their individual audiograms and the averaged audiogram for all participants (dark thick line) are shown in Figure 1. All but four participants had worn hearing aids prior to their enrollment at our research office. Table 1 summarizes the participants' demographics including their age, brand and style of own hearing aids.
years of hearing aid use, and averaged speech recognition score in quiet at MCL (most comfortable listening level) using the W-22 word list (full list). All the participants were research volunteers at the research office who signed a written informed consent describing the study prior to their enrollment. However, they were not informed of the specific nature of the study or the identity of the study hearing aids. All the participants were compensated on an hourly basis for their participation. As part of this study, all the participants wore custom-fit, binaural Senso Diva in-the-canal style hearing aids (in the default settings) in their daily listening environments for at least one month prior to data collection in order to acclimatize to the signal processing and sound quality of the study hearing aids.

**Hearing Aids**

A Widex Senso Diva BTE (behind-the-ear) hearing aid was used in the study. This is a 15-channel digital hearing aid that uses primarily slow-acting compression with a compression threshold at 0 dB HL. It has an active feedback cancellation algorithm that minimizes the occurrence of feedback by canceling the feedback signal (Kuk et al., 2002a), a noise reduction algorithm that uses level distribution function for noise identification (Kuk et al., 2002b), and an occlusion manager that minimizes the perception of hollowness of one’s own voice through gain adjustment (Kuk and Ludvigsen 2002). None of these algorithms were active during the data collection.

The fully adaptive directional microphone uses inputs from two omnidirectional microphones that are separated by 10 mm. The directivity index (DI) of the fixed directional microphone (a hypercardioid pattern), or the ratio of the sound pressure from the frontal incidence to that from other azimuths, was estimated from the polar plots of the microphone recorded in the horizontal plane while it is suspended in an anechoic chamber and the results calculated using the following formula:

\[
DI = -10 \log_{10} \left[ \sum | \sin(\phi) | \Delta \phi \cdot p^2(\phi) / 2 \cdot p^2(0) \right],
\]

where

- \( \phi \) is azimuth (\( \phi = 0 \) corresponds to a frontal incidence),
- \( \Delta \phi \) is the angular step-size,
- \( p(\phi) \) is the sound pressure recorded at azimuth \( \phi \),
- summation from \( \phi = -\pi \) to \( \phi = \pi \).

The DI of the omnidirectional microphone and the fixed directional microphone is shown in Figure 2.

During normal operation, a microphone matching algorithm at the input stage continuously monitors (and adjusts) the sensitivity and phase characteristics of both microphones in order to ensure consistent and predictable performance of the dual microphones. Then, the statistical properties of the inputs are examined in order to estimate if they are wind noise, circuit noise, or typical environmental sounds (i.e., speech and other sounds). If the signal is identified as wind noise or circuit noise, the microphone system automatically switches to an omnidirectional mode. The same omnidirectional mode is retained if the input level is below 50–60 dB SPL regardless of signal azimuths. If typical environmental sounds are identified, the levels of the two inputs are compared in order to form the right polar pattern (from an omnidirectional pattern to a cardioid, supercardioid, hypercardioid, bidirectional, or any patterns in between). Meanwhile, the low-frequency sensitivity of the hearing aid is compensated so that the same frontal frequency response as the omnidirectional microphone is used in all polar patterns. To allow time for the wearers to respond to desirable signals, the switching time from an omnidirectional

![Figure 2. Directivity index (DI) of the omnidirectional (thick line) and fixed directional (thick line) microphones across frequencies.](image-url)
pattern to a bidirectional pattern is designed to range between five and ten seconds. A shorter adaptation time is allowed for smaller changes in the noise locations. In a diffuse environment with multiple sound sources, it defaults to a hypercardioid polar pattern. A detailed description of the rationale and mechanism of this fully adaptive microphone can be found in Kuk et al (2002c).

Fitting of Study Hearing Aids

All the participants were fit with the same study hearing aid on the right ear with an EAR foam plug as the earmold during the clinical evaluation. A foam earmold was used to ensure complete occlusion of the ear canal so that (a) variability from external acoustic input that may enter via slits formed between the earmold and the ear canal is minimized, and (b) the noted directional effect may be maximized. The depth of insertion of the foam earmold was marked so the same depth was used for all participants at all visits. Monaural testing was conducted to avoid participation of the ear not facing the test loudspeaker. Thus, the non-test ear (left ear) was occluded with an ear plug during the clinical evaluation. It is assumed that observations made on the right ear can be extended to the left ear.

The participants’ in situ hearing thresholds with the study hearing aid were measured at 500, 1000, 2000, and 4000 Hz using frequency modulated sinusoids generated from within the hearing aids. A bracketing procedure was used to estimate thresholds. The in situ thresholds were used by the fitting software to specify gain targets at various input levels. A feedback test was performed afterwards to estimate the initial feedback path and to ensure maximum available gain without feedback for the participants. No adjustment in the default gain setting was made for any participant.

Equipment and Test Materials

In order to examine the audibility loss from the directional microphone, soundfield aided thresholds and speech intelligibility in quiet at different input levels were determined. The HINT (Nilsson et al, 1994) was used in order to examine the efficacy of the directional microphone in noise.

All testing was conducted in a double-wall sound-treated booth (Industrial Acoustics) that has internal dimensions of 10’ x 10’ x 6’6”. In addition, fabric-wrapped panels were installed on the upper half of the internal walls for acoustic and cosmetic purposes. With the current arrangement, the reverberation time of the booth was 0.24 sec at 125 Hz, 0.15 sec at 250 Hz, 0.09 sec at 500 Hz, and 0.08 sec from 1000 Hz to 4000 Hz. During aided threshold and speech testing, participants were seated one meter from each of the test loudspeakers (Cerwin-Vega, model E-705, 11 1/2” x 6 3/4” x 8”). The critical distance below 500 Hz was calculated to be around 1.2 m using the formula:

\[ \text{Critical Distance} = \sqrt{\text{speaker constant for free-field} \times \text{vol. of room}/(100 \times \pi \times \text{rev time})} \]

To measure the aided thresholds, warble tones at 500, 1000, 2000, and 4000 Hz that were generated from a GSI 61 clinical audiometer were presented in an ascending manner. The audiometer dial was set at 10 dB below the known headphone-thresholds and was increased in 5 dB steps until a threshold response was indicated. The level was decreased by 5 dB, and another ascending trial began. The participants raised their hands when they detected the tones. Threshold was taken as the lowest dial setting when consistent response occurred. The stimulus duration was set to at least 1 sec in duration with an interstimulus interval of 5 sec. These steps were necessary to ensure that the attack time (for complete gain reduction) and the release time (for complete gain recovery prior to next presentation) of the nonlinear circuit is exceeded in order to minimize measurement variability (Kuk, 2002).

The CASPA (v 3.0) test was used to estimate speech intelligibility in quiet. This is a CVC word test designed by Boothroyd et al (Mackersie et al, 2001) for the purpose of examining speech recognition over different signal and noise levels. There are 20 lists of ten phonemically balanced CVC words. Stimulus presentation and response scoring are computerized (Compaq Pentium III). In this study, audio output (of each stimulus .wav file) from the computer was taken through the GSI 61 clinical audiometer that allowed conditioning and adjustment of the stimulus level. Each word was presented with a carrier phrase, “Please say the word ____.” The examiner typed the participants’ responses.
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into the computer to allow automatic calculation of the intelligibility score for the particular listening condition. A unique advantage of the CASPA is its efficient scoring method. Instead of only scoring at a word level, scoring can be done at a phoneme level as well. A word that has three phonemes (e.g., CVC) is counted as three items on this test. This reduces the number of necessary items on a test while achieving a stated level of reliability (Thornton and Raffin, 1978). For the purpose of this study, the CASPA words were presented at 50 dB SPL, 65 dB SPL, and 75 dB SPL in quiet only. The choice of these speech levels was intended to demonstrate that the limitations of a directional microphone were dependent on the input intensity.

The HINT is a sentence test that estimates the signal-to-noise ratio required for 50% recognition of the speech materials. It was used to estimate the SNR required by each microphone mode used in this study. Although the HINT typically comes with a gated speech-shaped noise, the competing noise was replaced with a continuous speech-shaped noise that was formed by looping the noise segment. The continuous noise was used to approximate real-life noise situations and to ensure that the study hearing aid was set to the appropriate polar pattern. A custom MATLAB program was written to use with a Tucker-Davis System 3 unit for the delivery of HINT sentences and the competing noise at the appropriate levels (using Tucker-Davis PA5 programmable attenuators) and to the designated loudspeakers (Cerwin-Vega) via the SA-1 power amplifiers. Calibration of the speech and noise level was achieved with a 1000 Hz warble tone that has the same RMS level as the stimuli. In administering the test, the noise level was fixed at an overall level of 68 dB SPL while the level of speech was adaptively changed to yield the 50% recognition score. The HINT noise from the four loudspeakers was uncorrelated with the use of different start times (milliseconds apart) for each loudspeaker. The continuous noise was “on” for about one minute before the first HINT sentence was presented to ensure that the fully adaptive microphone have sufficient time to adapt to the “optimal” polar pattern (in this case, a hypercardioid pattern).

Test Conditions

The performance of the three microphone modes—omnidirectional, fixed hypercardioid, and the fully adaptive directional—was examined. Stimuli, to include warble tones (at 500, 1000, 2000, and 4000 Hz) and CASPA words, were presented from the loudspeakers placed one meter from the participants at 0°, 45°, 90°, 135°, and 180°. The left ear of all the participants was occluded with a foam plug during the testing.

Speech in noise testing was conducted with the HINT sentences presented in front (i.e., 0°) and noise presented to the sides and back (i.e., 45°, 90°, 135°, and 180°). The overall noise level from all four loudspeakers was fixed at 68 dB SPL, while the level of speech was adaptively changed to yield the 50% recognition score. The HINT noise from the four loudspeakers was uncorrelated with the use of different start times (milliseconds apart) for each loudspeaker. The continuous noise was “on” for about one minute before the first HINT sentence was presented to ensure that the fully adaptive microphone have sufficient time to adapt to the “optimal” polar pattern (in this case, a hypercardioid pattern).

Procedure

All participants spent at least three visits to complete data collection with all three microphone modes. However, only one microphone mode was tested during each visit. The ordering of the microphone modes was counterbalanced among participants. During each visit, the study hearing aid was first fit with the foam earmold (in situ thresholds and feedback test). To ensure consistent insertion depth of the foam earmold, the study audiologist aligned the
lateral surface of the foam with the tragus prior to any data collection. The aided thresholds (at 500, 1000, 2000, and 4000 Hz) and speech in quiet testing with the CASPA words at all five loudspeaker azimuths were measured. The SNR for 50% correct on the HINT was also measured on the same day. All the test variables, including the microphone modes tested, the test materials used (i.e., aided threshold by CASPA by HINT), the test frequencies, the CASPA and HINT lists, as well as the azimuth of presentation, were counterbalanced in order to minimize any order effect.

RESULTS

Repeated-measures ANOVAs were performed on the aided thresholds, CASPA scores in quiet, and HINT scores. The within-subject variables (independent variables) included three microphone modes (omni-, fixed, and adaptive), five azimuths of presentation (0°, 45°, 90°, 135°, 180°), four frequencies (500, 1000, 2000, and 4000 Hz) for the aided threshold measure, and three intensity levels (50, 65, and 75 dB SPL) for the CASPA in quiet. Statistical significance was set at 0.05 level, and post hoc Bonferroni corrections were made for the number of independent variables.

Aided Thresholds

Figure 3 summarizes the effect of azimuths on the soundfield aided thresholds for each microphone mode (omni-, fixed, and adaptive) at the four test frequencies (A, B, C, and D for 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, respectively). Three observations were immediately apparent. First, the aided thresholds for the fixed directional microphone were poorer than those of the omnidirectional and adaptive microphones at all frequencies and azimuths. Secondly, the aided thresholds at 500 Hz and 1000 Hz obtained with the fixed directional microphone were poorer than those obtained with an omnidirectional and fully adaptive microphone even at the 0° azimuth. Lastly, the aided thresholds for the omnidirectional microphone and the fully adaptive microphone were similar across all azimuths and test frequencies.

A three-factor, repeated measures analysis of variance (ANOVA) was performed to study the significance of the three main factors (microphone mode, test frequency, and azimuth of presentation) on aided
The results suggest that the overall interaction of the three main factors was significant ($F_{[24, 384]} = 5.18, p < 0.001$). In addition, each of the three main factors was also significant (Microphone effect - $F_{[2,34]} = 264.29, p < 0.001$; Azimuth effect - $F_{[4,64]} = 27.46, p < 0.001$; Frequency effect - $F_{[3, 48]} = 19.72, p < 0.001$). The interactions between two main factors, namely, microphone x azimuth ($F_{[8, 128]} = 63.66, p < 0.001$), microphone x frequency ($F_{[6,96]} = 21.57, p < 0.001$), and azimuth x frequency ($F_{[12, 192]} = 8.04, p < 0.001$) were significant also.

Post hoc paired t-tests with Bonferroni correction to the probability was used to compare data from the three microphone modes. The results suggest no significant differences between the omnidirectional and adaptive microphones ($t = -2.01$ to $1.13, df = 17, p > 0.017$) but a significant difference between the fixed directional microphone and the adaptive microphone ($t = 4.40$ to $18.35, df = 17, p < 0.017$) and the fixed directional microphone and the omnidirectional microphone ($t = 2.66$ to $17.32, df = 17, p < 0.017$) across all azimuths and test frequencies (except 4000 Hz at 45° azimuth).

Post hoc paired t-tests also showed many of the ten combinations of azimuth were significantly different. The only exceptions were the comparison between 0° and 45° and the comparisons in the fully adaptive and omnidirectional microphone modes.

**Speech Recognition Scores in Quiet**

Speech recognition (on the CASPA) scores were calculated on a phoneme level as well as on a word level. Because the same pattern was seen for both methods of scoring, and because phoneme scoring would have increased the number of items from ten words to 30 phonemes in a list, phoneme scores were reported here. Figure 4 showed the phoneme scores as a function of azimuth of presentation at the three intensity levels (50, 65, and 75 dB SPL presentation levels).

Several observations are apparent. First, the phoneme scores were similar for the omnidirectional and the adaptive microphone across all azimuths. Second, the phoneme scores for the omnidirectional (and adaptive) microphone were different from the fixed directional microphone. Third, the difference between the fixed directional microphone and the omnidirectional microphone was the greatest at the 50 dB SPL input level, decreasing as the input level increased. Fourth, maximum effect was noted at an azimuth of 135°. This pattern is similar to the changes in aided thresholds across azimuths.

A three-factor, repeated measures ANOVA was performed to study the significance of the three main factors (microphone modes, intensity levels, and azimuth of presentation) on the CASPA scores. The results suggest that the overall
interaction of the three main factors was
significant ($F_{[16, 272]} = 9.37, p < 0.001$). In
addition, each of the three main factors was
significant (microphone effect - $F_{[2,34]} = 52.63$,
p $< 0.001$; intensity effect - $F_{[2,34]} = 117.03$,
p $< 0.001$; and azimuth effect, $F_{[4, 68]} = 17.87$,
p $< 0.001$). The interactions between
microphone x intensity ($F_{[4, 68]} = 41.24$,
p $< 0.001$), microphone x azimuth ($F_{[8,136]} = 24.93$,p
$< 0.001$), and intensity x azimuth ($F_{[8,136]} = 2.57$,p
$< 0.05$) were significant also.

Post hoc analysis using paired t-tests showed that at a 50 dB SPL input level,
scores for the fixed directional microphone
were significantly poorer than the
omnidirectional microphone and the adaptive
microphone for all but the 0° azimuth of
presentation (p $< 0.017$). At a 65 dB SPL
presentation level, the differences were only
significant at the 135° and 180° azimuth of
presentation. At a 75 dB SPL presentation
level, the differences were only significant at the 90° and 135° azimuth of presentation.
Comparisons between the adaptive and
omnidirectional microphones were nonsignificant at all azimuths and
presentation levels.

Post hoc paired t-test showed that the
effect at the 50 dB SPL presentation level was
significantly different from the other two
intensity levels ($t = -3.44$ to -11.49, df = 17,
p $< 0.017$). The comparisons between the
presentations at 65 dB SPL and 75 dB SPL showed that they were only significantly
different ($t = -3.71$ and -3.04, df = 17,
p $< 0.017$) for the fixed microphone mode and at azimuths of 0° and 135°.

The effect of azimuth was only significant for the fixed directional microphone
(p $< 0.05$). Post hoc paired t-test showed that the azimuth effect was most noticeable at the 50 dB SPL presentation level and nonsignificant at the 75 dB SPL presentation level.

**Speech Recognition in Noise**

Figure 5 compares the required SNR for
the three microphone modes (omni, fixed, and adaptive) to achieve 50% on the HINT presented in a 68 dB SPL continuous speech-shaped noise background. An SNR of 5.27 dB was required for the omnidirectional microphone mode. An SNR of 1.96 dB was required for the fixed directional microphone mode, and an SNR of 1.47 dB was required for the fully adaptive mode. Compared to the omnidirectional microphone, an SNR improvement of 3.8 dB was achieved with the fully adaptive microphone mode in this noise condition.

A one-factor, repeated measures ANOVA showed that the difference among microphone modes was significant ($F_{[2,32]} = 27.62$, p $< 0.001$). Post hoc analysis revealed that the omnidirectional mode was significantly different from the fixed directional ($F_{[1,16]} = 26.62$, p $< 0.001$) and the adaptive modes ($F_{[1,16]} = 41.68$, p $< 0.001$). The difference between the fixed directional and the adaptive modes was not significant ($F_{[1,16]} = 1.43$, p $> 0.05$).

**DISCUSSION**

Under the current test conditions, the
present study demonstrated that the reduced sensitivity of a fixed directional microphone would result in elevated aided thresholds and decreases in speech recognition scores in quiet for stimuli presented from the sides and back. For the fixed hypercardioid microphone, the effect was most noticeable for stimuli presented at 135° and at the 50 dB SPL input level. The effect on speech intelligibility was less detrimental at higher presentation levels. These negative effects were not seen in the fully adaptive directional microphone. Furthermore, the adaptive microphone yielded
a significant 3.8 dB improvement in SNR over the omnidirectional microphone in a continuous noise background. These results showed that the fully adaptive microphone functioned like an omnidirectional microphone when it was quiet, and as a directional microphone when the test environment was noisy. While the results of this study demonstrated the potential efficacy of this microphone design in the sound booth, they do not necessarily imply that a fully adaptive microphone is the only optimal microphone design in daily life. Real-life listening situations with different reverberation, and/or the use of directional microphones with different directivity indices, and/or adaptive microphones with different criteria for activation may lead to different observations and efficacies.

**Confirmation of Design Rationale**

The present observations are not unexpected. A directional microphone with a hypercardioid polar pattern assumes a “null” or poorest sensitivity around 135°. This suggests that the intensity of any acoustic stimuli presented at this angle will be transmitted less efficiently. This is verified in Figure 3, which shows that the aided thresholds determined at this azimuth were 10–15 dB higher than those measured at 0° or 45°. The intelligibility of CASPA words (at 50 dB SPL) presented at this azimuth was over 50% poorer than that of the same stimuli presented from the front or to an omnidirectional microphone (Figure 4). The poorer speech score at 135° agreed with the poorer aided thresholds at that azimuth.

The polar pattern of the fixed directional microphone cannot explain the elevated aided thresholds at 500 and 1000 Hz when these sinusoids were presented at 0° and 45°. Rather, it is related to the increased noise floor associated with a compensated, fixed directional microphone (Kuk et al, 2002c). In an effort to minimize the potential negative effects of the low-frequency roll-off in a directional microphone (over an omnidirectional one), many directional hearing aids compensate by amplifying the low-frequency region so the frontal frequency response in the directional mode is identical to that of the omnidirectional mode. A negative consequence is an increase in circuit noise at the output of the hearing aid. Depending on the hearing thresholds of the wearers, this circuit noise may mask the true thresholds to result in higher aided thresholds. Considering that many participants in this study had normal-to-mild hearing loss in the low frequencies, it is not surprising to find that their aided thresholds in the directional mode were elevated.

The drastically poorer speech recognition scores seen at 50 dB SPL in the fixed directional mode can be attributed to the reduced sensitivity from these azimuths as well. For the same amount of sensitivity reduction, the effects will be more noticeable at the lower input level than at the higher input levels because less audible information is available. Thus, the reduction in intelligibility was especially noted at the 50 dB SPL input, and the effect decreased as input levels increased.

The similarity in performance between the fully adaptive directional microphone and the omnidirectional microphone in quiet confirms the design objective of this directional microphone. That is, the microphone should assume an omnidirectional polar pattern when the overall input level to the microphone is below the conversational level. Since the test environment is quiet during aided threshold measurements (overall ambient noise level below 35–40 dB SPL) and the level of the test stimuli (warble tones and CASPA at 50 dB SPL) were typically low, the fully adaptive microphone remained in an omnidirectional mode during all testing in quiet. This explains why the fully adaptive microphone has similar aided thresholds and speech scores as the omnidirectional microphone at the 50 dB SPL presentation level. The short duration of the CASPA words (including the carrier phrase), in relation to the required microphone switching time (5–10 sec), would suggest that the fully adaptive microphone remained in an omnidirectional mode during the speech in quiet testing at the 65 and 75 dB SPL presentation levels as well. The possibility that the fully adaptive microphone was indeed functional during the evaluation was confirmed by the noted 3.8 dB improvement in SNR over the omnidirectional mode during HINT testing in noise.
Clinical Implications

Is It Adaptive or Is It Automatic?

The study hearing aid was designed as a fully adaptive directional hearing aid in that both automatic switching (between omnidirectional and directional modes) and adaptive beamforming (among various directional polar patterns) are integrated into the design of the microphone. In this study, it was mainly the result of the automatic switching mechanism (i.e., from omnidirectional to directional) and not the adaptive mechanism (i.e., among various directional polar patterns) that preserved audibility (seen from the results of aided thresholds and speech intelligibility in quiet tests). Indeed, the current study was not designed to evaluate the benefits of an adaptive directional microphone. Such benefits have been reported elsewhere on the same study hearing aid (Valente and Mispagel, 2004) and other adaptive directional hearing aids (e.g., Ricketts and Henry, 2002). Rather, this study was designed to demonstrate the limitation of a fixed directional microphone and to evaluate the potential benefit of the “automatic” feature of a fully adaptive directional microphone.

Choice for a Fully Adaptive or Automatically Switching Directional Hearing Aid?

The present study demonstrated the potential negative consequences of a fixed directional microphone—that of raised aided thresholds and decreased sensitivity for low-input level sounds that originate from the sides and back. Furthermore, there could be increased circuit noise from the hearing aid. This is an important consideration when selecting the appropriate microphone for a hearing aid wearer. This study also demonstrated that directional microphones may be designed to function like an omnidirectional microphone in quiet and a directional microphone in noise. An important question is whether a directional hearing aid that has the potential of automatically adapting from an omnidirectional microphone mode to various polar patterns in the directional mode in real-life is necessary and preferable to a fixed or manually switchable directional microphone.

To address that question, it is beneficial to understand real-life wearer behaviors and environmental factors that may govern the use of directional microphones. Walden et al (2004) asked a group of 17 experienced hearing aid wearers of a switchable directional hearing aid to group their listening environments according to five criteria—presence/absence of noise, location of signal (front/back), distance from speaker (near/far), amount of reverberation (low/high), and location of noise (front/other), if present. Their study showed that noise originated from the sides and back in as many as 90% of the listed noisy situations. This confirms the design rationale of a directional microphone.

On the other hand, their study also showed that as much as 40% of the participants’ environments did not have any noise and the desirable signals originated from directions other than the front in over 20% of the situations. In these situations, the use of an omnidirectional microphone would have been desirable whereas the use of a fixed directional microphone could result in audibility problems and dissatisfaction. Ricketts et al (2003) also showed that wearers of a fixed directional hearing aid reported lower satisfaction scores on questions that described sounds that originated from the sides and backs of the wearers. These studies confirmed the occurrence of real-life listening situations that favor the use of both omnidirectional and directional microphones. In addition, Surr et al (2002) reported that wearers are able to identify listening situations that favored a directional microphone over an omnidirectional microphone.

Both the Walden et al (2004) and the Ricketts et al (2003) studies addressed daily use of directional microphone for sounds that are fairly typical in intensity levels, that is, medium or conversational. This study showed that while audibility is compromised at a medium input level (but <15%), the most decrease in speech intelligibility was seen at a low input level (50 dB SPL) where intelligibility with the fixed directional microphone was more than 50% poorer than that of the omnidirectional microphone. The impact of the sensitivity loss decreases as the intensity of presentation increases. This suggests that the observations in the Ricketts et al (2003) and Walden et al (2004) studies may have
underestimated the severity of the impact of the audibility loss for soft sounds (such as someone calling from another room at a normal volume, or someone whispering behind the wearer's back) that may occur in daily life. In these situations, the wearer may not even perceive the sounds to make negative remarks on the performance of the fixed directional hearing aids or to make a compensatory head turn to restore audibility. Thus, despite the lower occurrence of soft sounds in daily life, the need to hear them and the potential that their audibility may be compromised with a fixed directional microphone is real.

But can a switchable directional microphone that allows the wearer to manually switch between microphone modes be the answer? Cord et al (2002) showed that 23% of 112 new wearers of a switchable directional hearing aid did not switch between microphones (and 20% did not use the hearing aids at all). Of the 57 participants who frequently switched microphones, 48 provided additional usage information in that the microphone was in an omnidirectional mode 78% of the time (22% of the time in a directional mode). Mueller and Ricketts (2000) also reported that at least half of the wearers of a manually switchable directional hearing aid would not switch between microphone modes. These studies confirmed that many wearers of manually switchable directional hearing aids would not switch microphone modes. A manually switchable directional hearing aid is not the solution to ensure both audibility and signal-to-noise ratio advantages. An automatic switching mechanism that switches from an omnidirectional mode to a directional mode (fixed or adaptive) may be an alternative solution for many wearers. This may be even more important for older adults and young children (Bentler and Dittberner, 2003).

**Issues with Automatic Microphone Switching**

A potential issue with an adaptive directional microphone that automatically switches from an omnidirectional mode to the various directional modes is the “correctness” of the switching. The incidence of incorrect switching must be minimized. If that is not possible, at least the consequence of incorrect switching must be minimized. One solution is to choose the “optimal” activation time for the system to automatically switch from an omnidirectional mode to a directional mode. Intuitively, if the objective is to improve the SNR of the listening environment, or to prevent the listener from hearing background noise, a quick or short switching time would be desirable. The short switching time would achieve a desirable polar pattern sooner if the signal that needs to be attenuated is indeed undesirable. Ricketts and Henry (2002) showed that a 100 msec switching time is fast enough for an adaptive microphone to track and provide a good SNR over the fixed directional mode. On the other hand, if the signal is desirable, such as soft speech or a low intensity warning signal presented from the position of the null, a short switching time could potentially reduce the intensity of the speech signal to below the threshold of audibility so the listener may not be aware of its occurrence.

Consequently, the switching time may need to be long enough so that it gives the listener a chance to respond to the sounds regardless of its desirability. If the sound source from the sides and back is undesirable, the wearer will have to hear the “noise” for the duration of the switching time. If the sound is desirable, the wearers will turn their heads toward the sound source for additional information. This way, audibility (and thus intelligibility) may be preserved. Obviously, the wearers must be instructed on the mechanism of the automatic directional microphone and counseled on proper head turning to maximize understanding and minimize audibility loss.

**Verification and Validation Protocol**

The use of hearing aids with directional microphones, especially those with an automatically switching fixed or adaptive mechanism, would require us to reconsider the protocol we use for the verification and validation of hearing aid fittings.

**Soundfield Aided Threshold Determination**

One common evaluation measure is the soundfield aided threshold that estimates the hearing sensitivity with hearing aid use. Typically, warble tones are presented in the sound field at either 0° or 45°. The results from this study would suggest that one may
expect similar aided thresholds between an omnidirectional and this fully adaptive directional microphone (and possibly other automatically switching fixed or adaptive directional microphones) when stimuli are presented from any azimuth as long as the patients are tested at the calibrated position. For a fixed directional microphone, however, the observed thresholds for stimuli that are presented at any angles but 0° would be elevated to result in an underestimation of the individual’s true hearing sensitivity (exceptions are the low-frequency thresholds from masking noise). Obviously, the polar pattern of the fixed directional hearing aid, the activation time, and the threshold of activation of the automatic directional hearing aid would affect the outcome.

Along the same lines, the increased circuit noise from some directional hearing aids may increase the soundfield aided thresholds below 1000 Hz for some patients, even at 0° and 45° azimuths. Those with a normal-to-mild hearing loss in the low frequencies are especially susceptible to the elevated aided thresholds. These individuals may also hear the increased circuit noise in a quiet environment. However, not all directional microphones would result in an elevated aided threshold. In this study, the fully adaptive microphone did not raise the soundfield aided threshold because it behaved like an omnidirectional microphone under the circumstances. Consequently, one should be cognizant of the type of directional microphone (fixed, switchable [manual or automatic], or fully adaptive) that the patient wears during aided threshold measures and interpret the findings accordingly. This is especially true if the directional microphone allows manual switching between omnidirectional and directional modes.

Speech in Noise Testing

An automatic microphone with a long switching time may be problematic during speech in noise testing. Currently, many of the speech in noise tests such as the HINT (Nilsson et al, 1994), speech in noise (Etymotic Research, 2001), and speech perception in noise (SPIN, Kalikow et al, 1977) use gated noise as the competing signal. That is, noise only occurs during the presentation of speech. While this condition is unremarkable for evaluating hearing aids with omnidirectional and fixed directional microphones, the same test conditions (of using gated noise) to evaluate an automatic microphone system may be problematic. The brevity of the test stimuli (which are sentences that typically last for less than five seconds per sentence) compared to the switching time would leave the automatic hearing aid in the omnidirectional microphone mode, or in an intermediate polar pattern. This would result in no (or partial) SNR improvement over the omnidirectional microphone. Consequently, use of a continuous noise, rather than a gated noise, is necessary to evaluate an automatic microphone in order to avoid underestimation of the efficacy of such a system. Furthermore, the noise must be presented for a duration that exceeds the maximum switching time of the automatic microphone in order to ensure that the optimal polar pattern is used. After all, continuous noise is encountered more frequently in daily life than gated noise.

Real-Ear Measurement

One needs to be cautious as well when evaluating the real-ear output of an adaptive directional microphone (automatic switching or fully) when the test loudspeaker is placed at different azimuths. Because of the duration dependency (of adaptive microphone), the real-ear test stimuli should be presented for a sufficient duration to allow the adaptive microphone to adapt to the appropriate polar pattern. Otherwise, this could lead to unreliability in the test measure as well as a false finding. As a general rule, the duration of any test stimulus should be longer than the longest activation and adaptation times of these adaptive systems to ensure reliability and accuracy of measure.

CONCLUSION

This study demonstrated the potential limitation in audibility of a fixed directional microphone and confirmed the potential advantage of a fully adaptive directional microphone in minimizing this limitation while ensuring a good SNR improvement. It indicates that directional hearing aid designs, in addition to increasing the magnitude of SNR improvement, should also consider the potential issue of audibility loss as well. At the same time, as directional microphones are designed to function
automatically, our current practice in verification and validation of directional hearing aid fittings must also be modified to reflect the change in technology.

REFERENCES


