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Subjective and Objective Evaluation of Noise Management Algorithms

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Abstract

Purpose: To measure the subjective and objective improvement of speech intelligibility in noise offered by a commercial hearing aid that uses a fully adaptive directional microphone and a noise reduction algorithm that optimizes the Speech Intelligibility Index (SII).

Research Design: Comparison of results on the Hearing in Noise Test (HINT) and the Acceptable Noise Level task (ANL).

Study Sample: Eighteen participants with varying configurations of sensorineural hearing loss.

Results: Both the directional microphone and the noise reduction algorithm improved the speech-in-noise performance of the participants. The benefits reported were higher for the directional microphone than the noise reduction algorithm. A moderate correlation was noted between the benefits measured on the HINT and the ANL for the directional microphone condition, the noise reduction condition, and the directional microphone plus noise reduction conditions.

Conclusions: These results suggest that the directional microphone and the SII-based noise reduction algorithm may improve the SNR of the listening environments, and both the HINT and the ANL may be used to study their benefits.

Key Words: Acceptable noise level, directional microphone, hearing aids, noise reduction, Speech Intelligibility Index

Abbreviations: ANL = acceptable noise level; BNL = background noise level; CST = Connected Speech Test; dir = directional microphones; HINT = Hearing in Noise Test; MCL = most comfortable level; NR = noise reduction; omni = omnidirectional microphones; SE = speech enhancer; SII = Speech Intelligibility Index; SNR = signal-to-noise ratio

The inability to hear well in noise has been one of the top reasons for hearing aid dissatisfaction (Kochkin, 2002). Fortunately, with the application of digital signal processing (DSP) technology, processing algorithms are available that can improve the signal-to-noise ratio (SNR) of the listening environment. In this paper, we reported on the subjective and objective efficacy of such a processing algorithm, as well as its interaction with other processing algorithms in the hearing aid.

Speech in noise is generally managed by two approaches: the use of a directional microphone and the use of noise reduction (NR) algorithms. The former approach involves the use of multiple microphones (or a single microphone with multiple port openings) and is based on the assumption of spatial separation between desirable and undesirable signals (e.g., noise). The latter approach involves the use of a single microphone and assumes frequency separation between desirable and undesirable signals.

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The algorithms studied in this manuscript are manufactured by Widex Hearing Aid Company.

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The efficacy of both approaches has been evaluated in the last 20 years. In the case of directional microphones, it has been conclusively demonstrated that this technology improves the SNR of the listening environments (Ricketts, 2001). Such improvements have been reported in adults (e.g., Freyaldenhoven et al, 2005; Kuk, 2005) and children (e.g., Gravel et al, 1999; Kuk et al, 1999) and the magnitude of the improvement varied somewhat depending on the "openness" of the earmold/shell that the wearers used (Kuk and Keenan, 2006). The benefits provided by a directional microphone have been measured on objective SNR tests such as the Hearing in Noise Test (HINT; Nilsson et al, 1994) and the Speech in Noise (SIN; Killion, 1997) test.

The efficacy of a typical "noise reduction" (NR) algorithm is less clear (Chung, 2004). Traditionally, a NR algorithm operates by first identifying the nature of the input signal ("noise" versus "non-noise," or "speech"). Gain on the hearing aid is maintained for a speech or non-noise signal. Gain on the hearing aid is reduced proportionately when noise is identified, depending on the level of the noise. In this regard, the gain of both the noise signal and any speech signals occurring with the noise will be attenuated regardless of the degree of hearing loss of the wearer.

Traditional noise reduction algorithms have been shown to provide consistent improvements under subjective measurement procedures. For example, Boymans and Dreschler (2000) examined speech recognition and preference for NR using background noise matching the spectral shape of the speech signal and background noise differing in spectral shape from that of the speech signal. Results did not show any benefits of NR when measured objectively or subjectively for each noise type. However, the NR "On" condition showed improvement in the area of "aversiveness" on the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire over the NR "Off" condition.

Alcantara et al (2003) examined the efficacy of a NR algorithm in four different noise backgrounds using subjective and objective measures. The objective task involved determining the SNR for 50% correct sentence identification in a fixed noise background. In addition, participants rated each NR condition while listening to sentences using five response categories from "very dissatisfied" to "very satisfied." While there was no objective SNR improvement between NR On and Off, listening comfort was rated higher for NR On than NR Off in all noise conditions. Ricketts and Hornsby (2005) also found significant preference for NR when subjects were forced to choose their preferred setting (NR On vs. Off) when no improvement was found in the speech recognition score in noise using the Connected Speech Test (CST; Cox et al, 1987).

There can be several reasons for the lack of objective improvement or the objective-subjective discrepancy seen in today's NR algorithms. The first and most obvious reason is that today's NR algorithms cannot improve speech intelligibility in noise. This is likely because most speech and noise signals occupy the same frequency range. By reducing gain in the frequency regions where noise is identified, gain for speech in the same frequency region is affected to the same extent. This results in no net improvement in SNR (e.g., Fabry and van Tasell, 1990). On the other hand, because the net output of the hearing aid is reduced consequent to the activation of the NR algorithm, subjective listening comfort may be improved.

If the discrepancy between objective and subjective benefits is a reflection of the NR processing algorithm itself, a change in the processing algorithm may show an improvement in objective SNR benefit and/or narrow the subjective-objective benefit discrepancy. More specifically, if the algorithm can improve the availability of intelligibility cues, the hearing aid wearer may be more likely to experience an improvement in objective SNR while also reporting a subjective improvement when listening in noise.

Recently, Widex introduced a new noise reduction algorithm called the speech enhancer (SE). Once a noise condition is identified, the SE algorithm performs gain reduction in noise after an iterative calculation of the resulting Speech Intelligibility Index (SII; American National Standards Institute, 1997) based on the estimate of the noise spectrum, the extrapolated speech spectrum, and the hearing loss of the wearer (Kuk and Paludan-Müller, 2006). A maximum gain reduction of 12 dB may occur when the listening environment is "noise" only. In situations where there are both "noise" and "speech" signals, a gain increase of 5 dB may result in some frequency channels. This will occur if the gain increase (1) improves the predicted SII of the given channel, (2) does not increase the likelihood of feedback, and (3) does not cause loudness discomfort. The goal is to have the maximum potential for speech intelligibility for the wearer in the specific noise background. It is likely that the action of the SE algorithm will have more available speech cues than the traditional NR algorithm where gain reduction is independent of the wearer's hearing loss. It suggests the possibility that the SE may result in a significant SNR improvement in noise. The effect of microphone types should also be included as the relative efficacy of the SE may be affected by input-limiting devices such as a directional microphone (vs. an omnidirectional microphone).

In this study, we compared the efficacy of two noise management algorithms measured with the Acceptable Noise Level (ANL, subjective measure) and HINT (objective measure) in order to determine if each

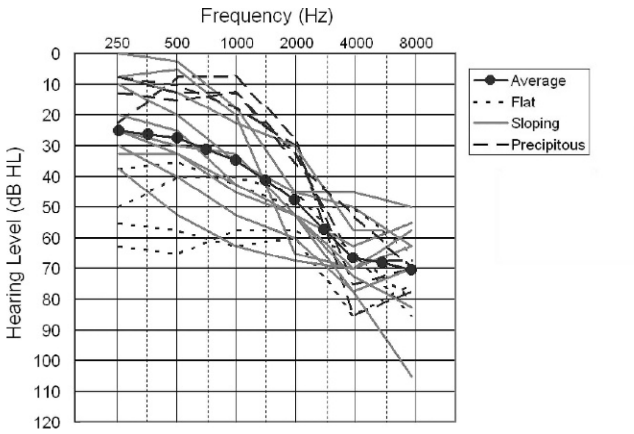

Figure 1. Audiogram thresholds averaged for left and right ears for each participant. Dark dashed lines represent precipitous configurations, solid gray lines represent sloping configurations, and dark dotted lines represent flat configurations. The dark solid line represents the average hearing level for all participants.

algorithm could improve speech recognition in noise. The ANL test has been advocated as an alternative approach to evaluating the efficacy of hearing aid algorithms because of its purported ability to predict successful hearing aid use (Nabelek et al, 1991). In addition, the correlations of the performance between both measures were examined. A high correlation would suggest that similar perceptual mechanisms may be at work during the two measures.

METHODS

Study Participants

Eighteen adults with bilaterally symmetrical (±5 dB) sensorineural hearing loss participated in the study (12 males and 6 females). Among them, four had a precipitously sloping hearing loss, ten had a mild-to-moderate sloping hearing loss, and four had a flat hearing loss. Figure 1 shows the audiogram thresholds averaged for right and left ears for all participants. All participants were native English speakers. Seven had not worn hearing aids previously, and eleven had 1 to 43 years of experience. Their ages ranged from 44 to 89 years with a mean age of 68.6 years (SD = 11.7). All participants signed an informed consent with an explanation of the purpose of the study as well as the benefits and risks prior to their participation. Participants were financially reimbursed.

Hearing Aids

Two models of the Widex Inteo hearing aids were used in the study based on the degree of hearing loss in the low frequencies. Those participants (N = 8) with relatively normal hearing at 500 Hz and a high frequency hearing loss were fitted with binaural Inteo IN-9e open-ear BTEs. Those with more than 30 dB HL at 500 Hz were fitted with binaural Inteo in-the-canal models (IN-X) with the appropriate vent diameter (N = 10). The fitting software Compass (v4.0.1) was used to program the hearing aids.

The Inteo is a 15-channel hearing aid with an input dynamic range of 107 dB SPL, a compression threshold as low as 0 dB HL, and an active feedback cancellation algorithm that estimates feedback in both microphone paths. The directional microphone system uses dual microphones and is capable of frequency specific, fully adaptive directivity in each of its 15 channels. This allows each channel to form its own polar pattern at any time with the goal of optimizing the signal coming from the front. The directional microphones may be set in a fixed hypercardioid polar pattern or fully adaptive polarity. Microphone matching is continuous to ensure the accuracy of the intended directivity. In addition, a speech preservation feature that maintains an omnidirectional polar pattern when the environment has only speech input is utilized.

As indicated, the Inteo has the speech enhancer noise reduction algorithm. This patented feature differs from the traditional noise reduction in that it considers the wearer's hearing loss and the SII (in noise) in its gain adjustment algorithm. The SE estimates the best combination of gain parameter settings in order to maximize SII. The SE provides a maximum of 12 dB gain reduction and up to 5 dB of gain increase.

Test Materials

Hearing in Noise Test

Objective measure of speech-in-noise performance was obtained with the HINT (Nilsson et al, 1994). The spectrum of the noise stimulus on the HINT was matched to the speech spectrum of the male talker used in the test. The noise was modified to be continuous, and its level was fixed at 75 dB SPL(C) while the level of the speech signal was adjusted in 4 dB steps for the first four sentences and 2 dB for the 5th to 20th sentences. The ratio of the average speech level from the 5th to 20th sentence (including that for the 21st sentence) to the noise level of 75 dB SPL defined the SNR for 50% correct. Presentation of the HINT stimuli was controlled with a custom program (written in Delphi object oriented computer language). Stimuli were amplified by a Rotel RMB 1048 power amplifier. Speech stimuli were presented from a loudspeaker at 0° azimuth, while the continuous noise was delivered to three loudspeakers at 90°, 180°, and 270° with reference to the participant's test position, one meter from each speaker. A splitter was used to split the noise from the single channel output into three loudspeakers. To ensure that the signals from the speakers were not correlated, two delay boxes (DigiTech RP50) were used to introduce timing differences among the three signals (delays of 500 and 640 msec). Noise was activated one minute prior to the presentation of the speech stimuli in order to condition the noise reduction algorithm so that it was fully activated.

Acceptable Noise Level Task

Subjective responses to speech-in-noise performance were measured with the Acceptable Noise Level (ANL) task introduced by Nabelek et al (1991). The ANL is the difference between the highest Background Noise Level (BNL) at which the test subject can no longer tolerate the noise without becoming tense or tired and the most comfortable level (MCL) for speech in quiet while the test subject listens to running speech. In this study, speech stimuli were CST passages spoken by a female talker (Cox et al, 1987). A bracketing procedure (Wall and Gans, 1984) was used to measure the MCL for the passages in quiet. In this approach, the direction of the level change was determined by the preferred level. Initially, speech at 60 and 65 dB SPL were compared. If the higher level was chosen, the higher level (i.e., 65 dB SPL) and a level that was 5 dB higher (i.e., 70 dB SPL) would be compared. If the lower level was chosen, the lower level (i.e., 60 dB SPL) and a level that was 5 dB lower (i.e., 55 dB SPL) would be compared. Comparisons continued until three reversals were encountered. The MCL was taken as the average of the last two reversals. The speech stimulus was presented at 0°. To determine the BNL, the speech-shaped noise from the HINT was used as the distraction. It was delivered to three loudspeakers at 90°, 180°, and 270° one meter from the participant. Initially, the noise level was set at 60 dB SPL and was activated 30 seconds prior to the presentation of the speech stimulus (presented at the participant's MCL). The noise level was increased in 5 dB steps until the participants reported that they could no longer tolerate the noise and understand the speech. A 2 dB step size was then used. Participants indicated their responses verbally or with hand gestures (point up or down). The final BNL was calculated as the average of the last four noise levels before ending the task. ANL was calculated as MCL minus BNL. Consequently, the smaller the ANL, the higher the noise level that the participants could tolerate, or better speech recognition in noise.

Instructions used for the ANL task were as follows:

> MCL Task: I want to find out the loudness level that is most comfortable for you. You will be listening to a female talker reading a story. First, you will listen to it at one loudness level. I will call that number 1. Then I will change the loudness level, and I will call that number 2. Your task is to tell me which level is most comfortably loud for you, #1 or #2. Are there any questions?
>
> BNL Task: I want to find out how much background noise you are willing to put up with while you listen to the female talker at the comfortable level which we have established. First, you will hear the female talker read at the comfortable level that we previously determined. While you are listening, I will introduce some background noise behind you and from your sides. I will increase its level gradually until you are no longer willing to tolerate or "put up with" the noise without becoming tense or tired while following the words of the story. To establish a reference I will adjust the level of the background noise to an unacceptable level, and then I will turn down its level so it is softer. I will bracket around this loudness level several times until I have found this to be a stable level. Please give the same amount of attention to the story each time the procedure is completed. You do not need to remember what is said, but you should be able to understand the words.

Procedures

All testing was conducted in a double-wall sound-treated booth (Industrial Acoustics) with internal dimensions of 10′ × 10′ × 6′6″. Monthly calibration of all test equipment was conducted in addition to daily calibration checks during the course of the study.

The participants' in-situ thresholds (sensogram) were measured and feedback tests were performed as part of the preliminary steps necessary in the fitting of the hearing aids. All fittings were binaural and default electroacoustic settings were used. HINT and ANL testing was completed under four hearing aid (microphone by NR mode) conditions: (1) omnidirectional microphone only (omni); (2) omnidirectional with speech enhancer (omni + SE); (3) fixed directional microphone only (dir); and (4) fixed directional microphone with speech enhancer (dir + SE). Order of testing was counterbalanced (hearing aid conditions and type of test) among participants. A single-blind design was used in which participants were not told what hearing aid conditions were being tested. Each participant was tested on the HINT and ANL at two visits separated by at least two weeks. The participants wore the study hearing aids home between the test sessions in order to acclimatize to the hearing aids. Testing at the first visit served as a practice run for the subjects, and the results were not included in this analysis. The results from the second visit were reported here. Statistical analyses were completed with SPSS v12.0.1 software.

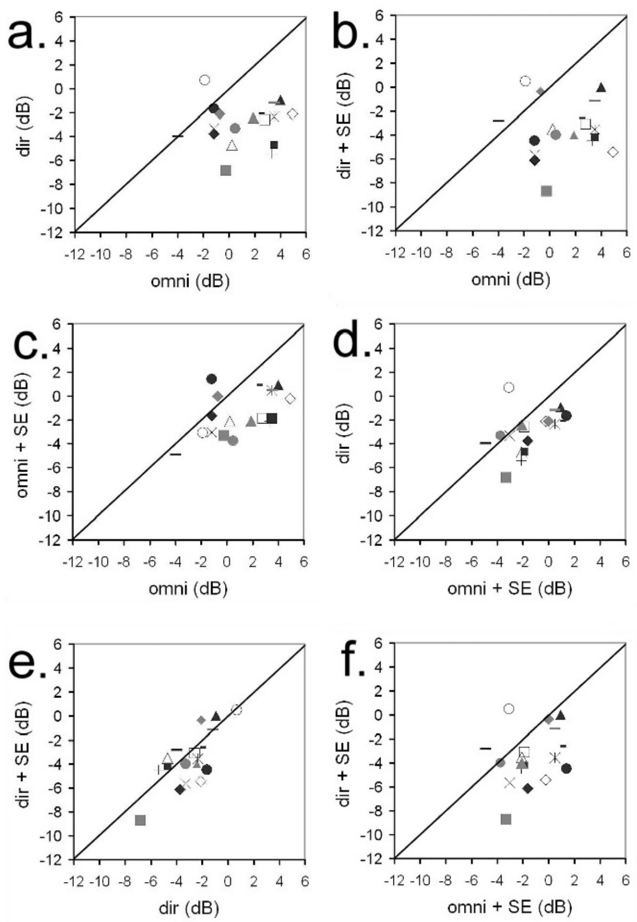

Figure 2. Scatterplot showing the absolute HINT SNR in dB for 50% correct on the HINT for individual participants between two hearing aid conditions (out of a possible four). The comparisons are (a) dir and omni, (b) dir + SE and omni, (c) omni + SE and omni, (d) dir and omni + SE, (e) dir + SE and dir, and (f) omni + SE and dir + SE. Points below the diagonal reflect better performance with the hearing aid condition represented by the vertical axis (y-axis). Points above the diagonal line indicate better performance with the hearing aid condition represented by the horizontal axis (x-axis).

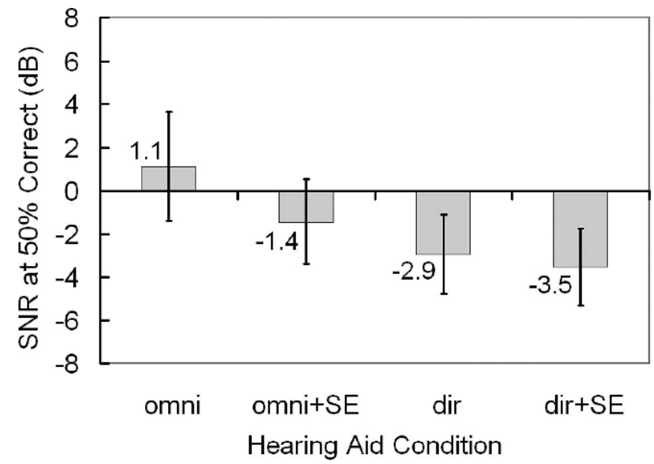

Figure 3. Average SNR in dB for 50% correct on the HINT for all participants in each hearing aid condition. A lower SNR indicates better performance. The error bars indicate one standard deviation.

RESULTS

Objective Speech-in-Noise Performance (HINT)

Scatterplots comparing the individual SNRs required for 50% performance on the HINT for the various hearing aid conditions are displayed in Figure 2. To facilitate comparison, the hearing aid condition that showed the better SNR performance was plotted as the vertical axis (y-axis) while the hearing aid condition for the poorer performance was plotted as the horizontal axis (x-axis). Thus, if the majority of the data points fell below the diagonal, that would suggest that the hearing aid condition defined by the y-axis yielded a better SNR than that represented by the x-axis. For example, Figure 2a shows that the majority of participants required a much smaller SNR when the hearing aid was set to the dir mode versus the omni directional mode. This is illustrated with all data points falling below the diagonal (with one exception). Indeed, if one examines all the subfigures, one would note that with the exception of Figure 2e where it compared the SNR measured between the dir + SE and dir, the majority of data points fell below the diagonal, suggesting that for the majority of subjects, dir was almost always better than omni, and "SE" was almost always better than "no SE."

The average SNRs measured under each of the four hearing aid conditions are reported in Figure 3. The use of the study hearing aid in the omnidirectional microphone alone required an SNR of 1.1 dB for 50% performance on the HINT. When compared to the omni condition, the directional microphones (dir) improved the SNR by 4.0 dB, bringing the required SNR to −2.9 dB. The SE noise reduction improved the average omnidirectional microphone performance by 2.5 dB, bringing the absolute SNR to −1.4 dB. In the directional mode, however, the additional benefit from the SE was only 0.6 dB, with an absolute SNR of −3.5 dB in the dir + SE condition. Despite the reduced benefit of the SE condition in the dir mode, the dir + SE improved the SNR by 4.6 dB when compared to the omni condition.

A one-way repeated measures analysis of variance (ANOVA) of the absolute SNRs of the four hearing aid conditions was significant ($F(3,51) = 25.393$, $p < 0.0005$). Post hoc analysis with adjustment for multiple comparisons using Bonferroni corrections was carried out (Table 1). Significant differences were found among all hearing aid conditions except when dir was compared to dir + SE. That is, SE did not improve the SNR further when it was used with a directional microphone.

Table 1. Summary of HINT Paired Sample *t*-test Post Hoc Analysis of Absolute Scores Using Bonferroni Corrections Based on Adjustments for Multiple Comparisons

		omni	omni + SE	dir
omni + SE	Mean difference	2.56*		
	Standard error	0.516		
	t	4.95		
	Significance *(p)*	<0.001		
	Power (β)	0.99		
dir	Mean difference	4.05*	1.49*	
	Standard error	0.696	0.44	
	t	5.81	3.38	
	Significance *(p)*	<0.001	0.004	
	Power (β)	0.99	0.89	
dir + SE	Mean difference	4.65*	2.10*	0.6
	Standard error	0.782	0.587	0.361
	t	5.95	3.56	1.67
	Significance *(p)*	<0.001	0.002	0.112
	Power (β)	0.99	0.99	-

*Mean difference was significant at the 0.008 level with a power >0.8.

Subjective Speech-in-Noise Performance (ANL)

Figure 4 shows the scatterplots comparing individual ANL results between different hearing aid conditions. The same convention used and described for Figure 2 was used here; that is, the hearing aid condition with the better SNR performance was plotted as the vertical axis (y-axis) while the hearing aid condition for the poorer performance was plotted as the horizontal axis (x-axis). Figure 4a shows that the dir condition was better than omni as most points fell below the diagonal line. In addition, SE performance was better than no SE as Figure 4c also shows that most data points fell below the diagonal.

Figure 5 summarizes the average ANL for the various hearing aid conditions. In the omnidirectional microphone mode (omni) the average participant required an ANL of −1.8 dB. In other words, the BNL was 1.8 dB more intense than the MCL (in quiet) of the average participant. Performance improved to −5.1 dB when the speech enhancer algorithm was activated with the omnidirectional microphone (omni + SE). This produced an SE benefit of 3.3 dB when the SE was used in an omni mode. The average ANL was −4.6 dB when the directional microphone (dir) was utilized. This reflects a directional benefit of 2.8 dB when compared to the omni mode. The average ANL was −7.5 dB when the directional microphone was used in conjunction with the speech enhancer. This reflects an SE benefit of 2.9 dB when a directional microphone was used. This also resulted in a 5.7 dB benefit over the omni mode.

A one-way repeated measures ANOVA was used to evaluate the significance of the observed differences in

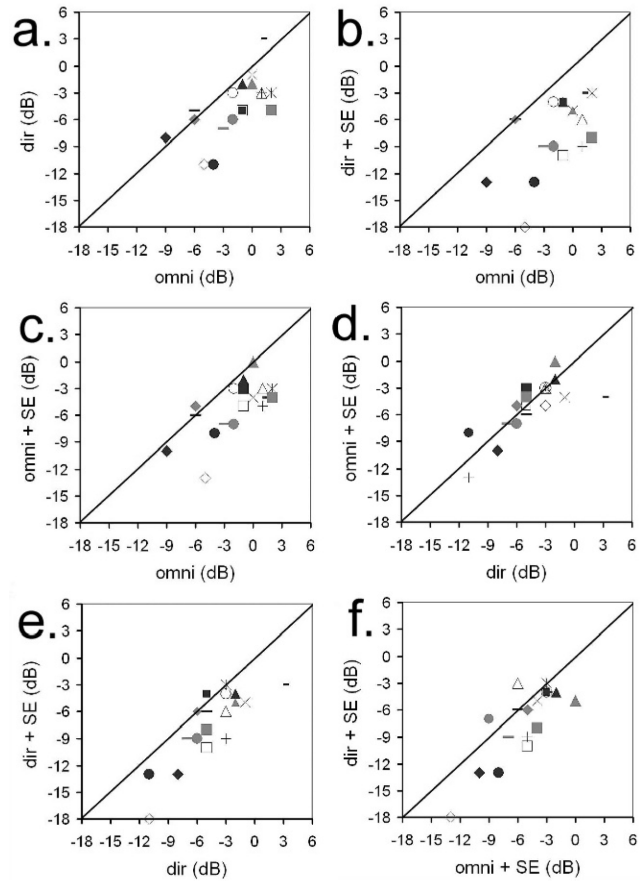

Figure 4. Scatterplot showing the absolute ANL in dB for individual participants between two hearing aid conditions (out of a possible four). The comparisons are: (a) dir and omni, (b) dir + SE and omni, (c) omni + SE and omni, (d) omni + SE and dir, (e) dir + SE and dir, and (f) omni + SE and dir + SE. Points below the diagonal reflect better performance with the hearing aid condition represented by the vertical axis (y-axis). Points above the diagonal line indicate better performance with the hearing aid condition represented by the horizontal axis (x-axis).

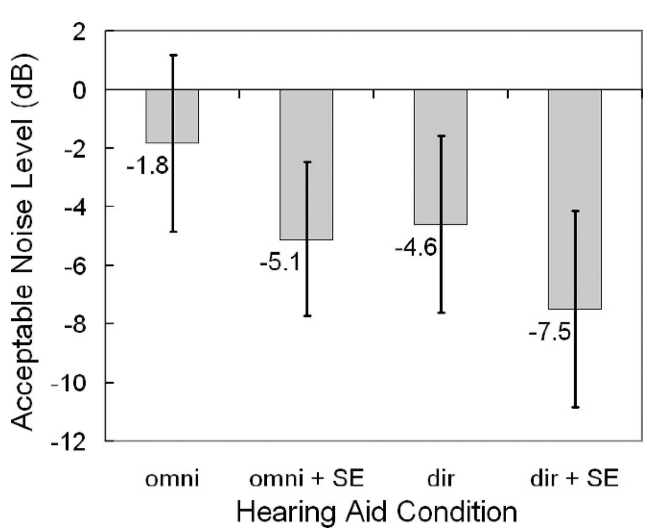

Figure 5. Average ANL in dB for each hearing aid condition. A lower ANL indicates better performance. The error bars indicate one standard deviation.

Table 2. Summary of Post Hoc Paired Sample *t*-test Using Bonferroni Corrections for Absolute ANL Results

		omni	omni + SE	dir
omni + SE	Mean difference	3.28*		
	Standard error	0.587		
	t	5.57		
	Significance *(p)*	<0.001		
	Power (β)	0.99		
dir	Mean difference	2.78*	−0.50	
	Standard error	0.65	0.532	
	t	4.27	−0.94	
	Significance *(p)*	0.001	0.36	
	Power (β)	0.98	-	
dir + SE	Mean difference	5.67*	2.39*	2.89*
	Standard error	0.84	0.458	0.536
	t	6.74	5.21	5.39
	Significance *(p)*	<0.001	<0.001	<0.001
	Power (β)	0.99	0.99	0.99

*Mean difference was significant at the 0.008 level with power >0.8.

absolute ANL scores. The results showed that the within-participant effect of hearing aid condition was significant ($F(3,51) = 28.800$, $p < 0.0005$). Post hoc analysis with adjustments for multiple comparisons using Bonferroni corrections was conducted. Significant differences were revealed among most hearing aid conditions. The exception was the comparison between omni + SE and dir in which no significant difference was found. Table 2 shows the results of the post hoc analysis.

Correlations between Subjective and Objective Measures of Performance

Absolute Performance

Pearson's correlation coefficients were calculated to measure the relationship between the objective and subjective measures of hearing aid performance in noise. As indicated in Table 3, no significant correlations were found in any hearing aid conditions ($r = -0.24$ to 0.42, $n = 17$, $p > 0.05$) when the absolute scores were compared.

Table 3. Correlation Coefficients Measured between Absolute HINT and Absolute ANL Scores

			HINT			
			omni	omni + SE	dir	dir + SE
ANL	omni	r	0.38	−0.01	−0.24	−0.12
		p	0.12	0.95	0.34	0.63
	omni + SE	r	0.01	−0.12	−0.01	0.29
		p	0.97	0.63	0.96	0.24
	dir	r	0.06	−0.1	−0.01	0.24
		p	0.82	0.68	0.96	0.34
	dir + SE	r	−0.09	−0.1	0.96	0.42
		p	0.72	0.69	0.07	0.08

Note: No significant correlations were found at the p = 0.05 level.

Table 4. Correlation Coefficients between Benefit Scores Measured with the HINT and the ANL

			ANL		
			omni + SE	dir	dir + SE
HINT	omni + SE	r	0.42	0.31	0.41
		p	0.08	0.2	0.09
	dir	r	0.56*	0.46*	0.54*
		p	0.02	0.05	0.02
	dir + SE	r	0.70**	0.57**	0.73**
		p	<0.01	0.01	<0.01

*Significance at the 0.05 level.
**Significance at the 0.01 level.

Relative Performance (Benefit)

The correlation coefficients between the SNR benefits (difference in performance between the specific hearing aid condition and the omni condition) measured with the HINT and the ANL for each hearing aid setting were calculated and summarized in Table 4. Subjective and objective benefit scores were found to be significantly correlated ($p < 0.05$) when the hearing aids were in the dir mode ($r = 0.46$, $n = 17$, $p = 0.05$) and dir + SE mode ($r = 0.73$, $n = 17$, $p < 0.0005$). The correlation between HINT and ANL benefits in the omni + SE mode was not significant ($r = 0.42$, $n = 17$, $p = 0.08$).

DISCUSSION

The present study examined the speech-in-noise performance of a fixed directional microphone and an SII-based noise reduction algorithm (SE) using subjective and objective criteria. The results showed a significant improvement in SNR for both features when measured subjectively and objectively. Specifically, on the HINT, the average participant showed an SNR improvement of 4.0 dB with the directional microphones, 2.5 dB with the SE, and 4.6 dB with dir + SE when compared to the omni microphone condition. On the subjective ANL, the average participant showed an SNR improvement of 2.8 dB with the directional microphones, 3.3 dB with the SE, and 5.7 dB with dir + SE over the omni microphone condition. Furthermore, a moderate correlation exists ($r = 0.46$ to 0.73) between the subjective and objective benefits with the directional microphone and the directional microphone with SE. Although these results are encouraging, one must be warned that these benefits may not reflect real-life benefit because of potential reverberation and differences in sound source orientation in the real world.

As reviewed in the introduction, traditional noise reduction algorithms were able to demonstrate subjective improvements such as listening comfort without providing improvements in speech recognition (Boymans and Dreschler, 2000; Alcantara et al, 2003; Chung, 2004; Mueller and Ricketts, 2005; Ricketts and Hornsby, 2005). The only study that used similar evaluation tools to the current study was conducted by Mueller et al (2006). In their investigation the researchers used the HINT stimuli for both objective and subjective measures. Noise and speech stimuli were presented from 0°. When compared to the omnidirectional mode without noise reduction (omni), their noise reduction algorithm ("omni + NR") reportedly provided an average ANL improvement of 4.2 dB. Unlike the current study, their noise reduction did not result in a significant change in performance on the HINT. The difference between our findings and previous findings is most likely a result of the difference in the noise reduction algorithms. Unlike the SE noise reduction used in the current study, the hearing aid used by Mueller et al (2006) contained a dual algorithm noise reduction system. The first algorithm attempted to filter the speech from the noise using the envelope of the signal and a second algorithm operated similarly to a traditional NR algorithm by reducing gain of frequency channels in which a noise signal was identified. To review, the SE calculates the gain settings needed for the optimal SII.

A Word on the Absolute ANL

While the range of ANL results obtained for our participants was similar to that found in previous studies (a range of 21 dB compared to 26 dB reported in previous studies), the absolute ANLs were much lower than those reported in previous ANL investigations. The ANL reported in previous studies ranged between 2 and 28 dB (Nabelek et al, 2006). In the current study, the absolute ANL ranged from −18 to 3 dB. This difference may have arisen from several possibilities. First, the test conditions were different. In the current study three noise sources from the sides and the back replaced the single noise source from the front that was used in other studies. Secondly, the noise used in the current study was a speech-shaped noise, as opposed to the multitalker babble noise. Such differences would have made the noise used in the current study more "tolerable" because babble noise is more modulated and has a higher potential for informational masking than speech-shaped noise (e.g., Souza et al, 1994, 2007). In addition, all our experienced participants were relatively satisfied with their own hearing aids and would be expected to report low ANLs. Lastly, the current study used the same hearing aids for all the participants, while previous studies used the participants' own hearing aids, which may have ranged widely in technology levels. Thus, it may not be appropriate to compare the absolute ANL values measured in this study with previous studies.

Relative Efficacy of Noise Management Algorithms

Is a Directional Microphone Always Better Than a Noise Reduction Algorithm?

It is not surprising that a directional microphone improves the SNR of the listening situation. Figure 2a shows that 17 of the 18 participants performed better in the dir mode than the omni mode. The average improvement of the dir mode over the omni mode was 4.0 dB as measured on the HINT (objective measure). This is higher than the 2.5 dB improvement offered by the SE algorithm. On the other hand, a directional microphone may not be the most subjectively preferred. This is seen in Figure 4d where the data points were clustered around the diagonal, suggesting that omni + SE condition and dir condition yielded similar efficacy under the current experimental setup for most participants. Indeed, Figure 5 showed that the ANL improvement offered by the dir mode was only 2.8 dB compared to the 3.3 dB offered by the SE. One reason why the SE may be more effective than or equally as effective as the dir mode on the ANL is because SE, by reducing a substantial amount of gain over a broad frequency range, provides listening comfort in noise (Ricketts and Hornsby, 2005). As the participants were asked during the ANL to report the level at which the noise became too loud to tolerate, their decision may have been influenced by the amount of listening comfort (or discomfort) they experienced and not by the consideration of speech intelligibility. In other words, it may be loudness mediated.

Are Directional Benefit and Noise Reduction Benefit Additive?

The present study showed a small but significant improvement in SNR by the SE algorithm. Indeed, Figure 3 shows that on the HINT, an average SNR improvement of 2.5 dB resulted from the SE algorithm when an omnidirectional microphone was used but only 0.6 dB when a directional microphone was used (dir compared with dir + SE). Figure 5 shows that on the ANL, an average SNR improvement of 3.3 dB was provided by the SE algorithm when an omnidirectional microphone was used and 2.8 dB when a directional microphone was used (dir compared with dir + SE).

These observations show that the effect of directional microphone and SE may be additive, albeit the effect of the SE may be modest on the objective task (HINT).

However, the SNRs obtained with the dir + SE were always better than the dir alone or the omni + SE conditions. The decrease in benefit offered by the SE in the directional mode (versus the omnidirectional microphone mode) may be explained by the fact that in the directional mode, postmicrophone input to the hearing aid processor (such as for the SE) would be lower and at a better SNR than in the omnidirectional mode. Consequently, the degree of SNR improvement offered by the SE was less in the directional mode than in the omnidirectional mode.

While that may be true for the HINT, the results on the ANL did not show a reduction in SE effectiveness when it was used in conjunction with the directional microphone. SNR improvements of 3.3 dB and 2.8 dB were provided by the SE when the hearing aid was in the omnidirectional mode and directional mode, respectively. It is unclear why such a discrepancy in benefit existed between results of the HINT and the ANL tasks. Perhaps the action of the directional microphone (enhancement of SNR and diminishment in loudness) still left sufficient loudness cues for the SE to act upon when a subjective task was used; but these same loudness cues were not sufficient to result in an intelligibility difference as evaluated on the HINT.

There are several implications to the above findings. First, in order to evaluate the true efficacy of the SE algorithm, it may be the most optimal to examine it in conjunction with an omnidirectional microphone instead of a directional microphone. Secondly, and perhaps more importantly, a directional microphone can be used with additional signal processing algorithms (such as SE) to ensure the greatest SNR advantage in a greater variety of situations. In those situations where both algorithms may be activated, pairing the two would ensure the best SNR possible. In situations where the directional microphone may operate suboptimally (such as in a reverberant situation, or when the noise source originates from the front as well), the postprocessing SE algorithm may complement the action of the directional microphone and yield an SNR that might not be possible otherwise.

Relationship between Subjective and Objective Measures

One of the objectives of this study was to determine if subjective and objective measures of speech-in-noise performance resulting from different noise management algorithms were correlative. This study confirmed that this was the case for directional microphone (dir) and dir + SE when SNR benefit was compared. Benefit results were supported by Freyaldenhoven et al (2005), who reported a significant correlation between subjective (ANL) and objective (HINT) measures of directional benefit ($r = 0.62$, $p < 0.05$). Taken together, these results provide some promises for linking the results of objective measures with subjective measures in evaluating directional benefits.

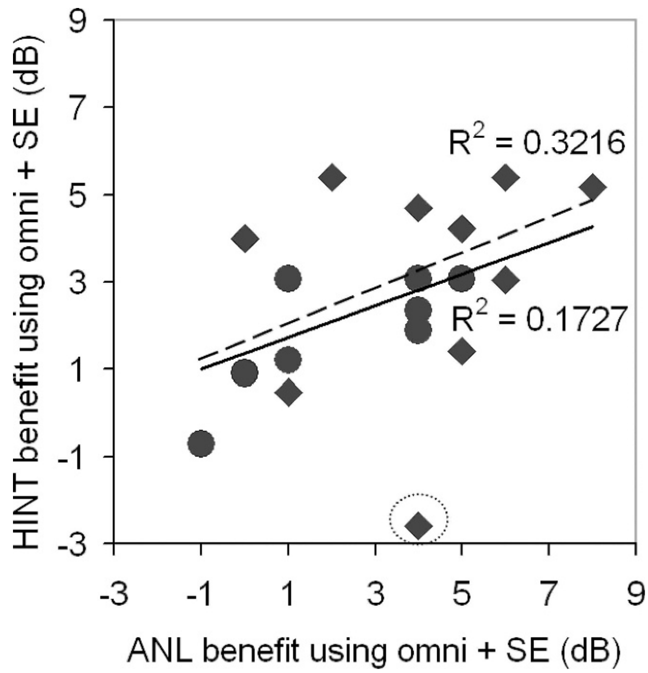

Figure 6. Scatterplot of HINT and ANL benefit data for the omni + SE condition. Circles represent BTE open fittings data, and diamonds represent ITE fitting data. Significant correlation ($r = 0.56$ ($n = 17$, $p < 0.05$)) resulted when the outlier (circled on the plot) was removed. The solid line represents the regression line before the outlier was removed ($R^2 = 0.1727$), and the dashed line represents the regression line when the outlier was removed ($R^2 = 0.3216$).

We investigated further to understand why a low correlation existed between HINT and ANL for the omni + SE condition. Figure 6 shows a scatterplot of the participants' SNR benefits reported on the HINT and ANL. While the majority of data points were clustered together, one participant's data point (circled on the scatterplot) clearly departed from the rest. When this data point was removed from the analysis, a correlation of $r = 0.56$ ($n = 17$, $p < 0.05$) was found between HINT and ANL. This suggests that the subjective benefits reported by the SE may be correlated to the objective benefit as well.

Significant correlations between the subjective and objective measures in this investigation suggest that these measures were evaluating similar attributes or processes triggered by similarities in the information that the hearing aid provided to the wearer. Considering that the correlations were seen for the directional microphone and the SE, it is likely that both of these algorithms provide significant speech cues to the wearer through their processing.

Future testing may seek to uncover if certain algorithms fail to correlate between the subjective and objective measures of performance. For example, while we found a correlation for SE results, the traditional noise reduction examined by Mueller et al (2006) did not yield a correlation between HINT and ANL. The difference might be explained by the differences in the algorithms, but future investigations are needed to verify this. In addition, test conditions in which different types of noise, and noise presented from the front as well as the back, will provide further information on the use of subjective measures with noise reduction algorithms in the presence of directionality.

In conclusion, the use of SII-based noise reduction and directional microphones significantly improved speech-in-noise performance on subjective and objective measures compared to an omnidirectional hearing aid condition. The combination of SE noise reduction and directional microphones was the most effective condition in improving SNR in noise. From the results of this investigation it appears that either the subjective ANL measure or the objective HINT measure may be used to evaluate the benefits offered by noise management algorithms.

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