Comparison of Performance on the Hearing in Noise Test Using Directional Microphones and Digital Noise Reduction Algorithms

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Purpose: Difficulty understanding speech in background noise is one of the most common complaints of hearing aid users. In modern hearing aids, directional microphones (d-mics) are considered the method of choice in improving signal-to-noise ratio, with demonstrated improvement in speech-perception-in-noise tasks. On the other hand, digital noise reduction (DNR) algorithms, in commercially available products, are considered to provide comfort but not significant assistance in improving speech perception in noise. In practice, these 2 technologies are often used in conjunction, but few studies have evaluated their interaction and the resultant effect on speech perception in noise. The purpose of this study was to evaluate the effect on speech performance of using d-mics and DNR in isolation as well as in conjunction in the presence of background noise.

Method: This study evaluates the performance of 16 experienced adult hearing aid users on the Hearing in Noise Test when each technology was activated independently and then simultaneously in 4 commercially available hearing aids.

Result: Approximately 50% of our participants performed better with both d-mics and DNR activated in conjunction, while the other 50% performed best in the d-mic-only condition. When considering statistically significant differences in performance only, a reduction or improvement in performance was observed in 17% and 14% of the conditions, respectively.

Conclusion: A direction for further research would be to identify predictive variables that could help the audiologist determine an individual's preference a priori.

Key Words: speech in noise, directional microphones, digital noise reduction algorithms

Aging listeners process sound signals in a markedly different manner as compared with younger listeners due to age-related physiological changes in the auditory periphery and the central nervous system (Snell & Frisina, 2000). Peripherally, age-related changes within the cochlea occur in the organ of Corti, the afferent and efferent nervous systems serving the cochlea, and the stria vascularis (Schuknecht & Gacek, 1993). Centrally, processing of rapid level and spectral fluctuations of acoustic signals degrades with age (Snell & Frisina, 2000). These differences help explain the difficulties in speech understanding, particularly in the presence of background noise, reported by aging listeners (Walton, Simon, & Frisina, 2002). Such problems in auditory processing are only heightened by the presence of a hearing loss.

Individuals with hearing loss due to the aging process, or presbyacusis, perform poorly compared with their counterparts with normal hearing thresholds on various psychoacoustic tasks, including auditory backward masking, duration discrimination, gap detection, discrimination of temporal differences in speech, modulation detection, and speech recognition with temporal waveform detection (Stuart & Phillips, 1996). These findings are suggestive of a decreased ability to process both spectral and temporal cues—critical to understanding speech in noise, the most often noted complaint of aging individuals with any degree of sensorineural hearing loss (Alacantara, Moore, Kuhnel, & Launer, 2003; Kochkin, 2005; Ricketts & Dhar, 1999).

In addition to these auditory processing changes in older adults with hearing loss, speech understanding in noise is dependent on memory demands and available speech contextual information (Gordon-Salant & Fitzgibbons, 1997). Thus, the problem of speech perception in the presence of background noise, common to all individuals with impaired hearing, is magnified by age-related changes in older adults who happen to compose the overwhelming majority of hearing aid users.

Hearing Aid Technology

In practical terms, for equivalent performance in speech perception tasks in the presence of background noise, listeners with impaired hearing typically require a much higher signal-to-noise ratio (SNR) than listeners with normal hearing. In recent times, a major thrust in hearing aid development has been to do just that—provide a better SNR to hearing aid users in a variety of listening environments. Two technologies relevant to these efforts are directional microphones (d-mics) and digital noise reduction (DNR) algorithms.[1]

D-mics rely on spatial separation of a signal of interest (i.e., speech) and an unwanted signal (i.e., noise). Note that the critical variable, from the perspective of a d-mic, is the spatial origin of a signal and not its physical characteristics. For instance, a steady state noise or a speech source not of current interest to the listener would both be categorized as noise by a d-mic provided they originated in the hemisphere behind the hearing aid wearer's head (given the appropriate polar pattern of the d-mic in use). Today's generation of d-mics are constructed either with two ports on a single microphone or with multiple independent microphones whose outputs are mixed electronically. In all cases, the signal entering the rear microphone or the rear port in a single microphone is delayed by an electronic or mechanical filter in the directional mode. The spatial directivity pattern of a microphone depends on the relationship between this internal delay and the external delay required for any sound to travel in the atmosphere between the two microphones or ports. Use of more than two microphones in creating greater directionality is also being explored (for a thorough review of d-mic technologies, see Ricketts, 2001).

DNR algorithms, on the other hand, rely on differences in physical characteristics of a signal to distinguish speech from noise. The earliest attempts relied on the assumption that unwanted noise typically existed at the lower frequencies, and attenuated and/or compressed the output of the hearing aid at these frequencies to achieve an SNR advantage. However, such pure frequency-based algorithms are not effective under a majority of circumstances (Boymans & Dreschler, 2000; Kuk, Ludvigsen, & Paludan-Muller, 2002). Another approach is to analyze the intensity distribution of the signal. This algorithm type assumes greater variability in the intensity of speech as compared with noise. Other similar methods attempt to identify noise by analyzing modulation depth or frequency (Kuk et al., 2002). Thus, these algorithms identify any steady state signal as noise. When the signal in any frequency channel is detected to be predominantly noise, gain is reduced for that channel, often proportionately to the level of the noise. Although this does not improve within-channel SNR, it attempts to reduce direct masking within the channel, as well as any spread of masking to adjacent channels (Kuk et al., 2002).

Second-generation applications of DNR feature additional means of detecting speech in an incoming signal, including rapid analysis of multiple components of the signal. One technology currently available monitors higher frequency channels for synchronous energy. As such energy is suggestive of formants, its presence is used to infer the presence of speech in the signal (Chung, 2004).

Today's digital platforms afford flexibility in hearing aid design never seen before (for a recent review of DNR technologies, see Bentler, 2005). The bandwidth of the hearing aid is often divided into several channels, operating as independently as desired. Signal processing algorithms can operate at speeds close to real time in modifying the incoming signal. However, as always, there are trade-offs. Increasing the number of channels offers greater capability to fine-tune the frequency response of the hearing aid as well as reduce gain in a (narrowly) localized frequency region when performing feedback or noise management tasks, thereby leaving gain in other frequency regions relatively unaffected. However, with narrower filters comes greater group delay, or the amount of time taken for a circuit to deliver a signal from the microphone to the receiver. Although estimates of tolerable group delay vary, the negative effects of exceedingly large group delays are manifest in perception of signals as "hollow" or echoic, which in turn has a negative impact on speech perception (Kuk et al., 2002). The speed of processing is also of critical interest. Understandably, the processor has to be fast enough to effectively operate on samples of noise embedded in natural gaps in speech, but a processor that is too fast could also cause spectral smearing (Kuk et al., 2002). Finally, increased complexity and/or speed of signal processing in a hearing aid will demand more power, leading to reduction in battery life, an unwelcome side effect from the standpoint of the end user.

Benefits of D-mics and DNR

Directional benefit is a term that is commonly used to describe improvement in performance when a hearing aid operates in its directional setting as compared with the omnidirectional setting. Often computed as the difference in the results of matched speech-perception-in-noise tests, this is a behavioral measure that incorporates the listener, the environment, and the hearing aid with all technologies and their interactions accounted for. It should be pointed out that directional benefit measured from a hearing aid is not independent of its performance in omnidirectional or directional modes. For example, two hearing aids may demonstrate the same directional benefit (omnidirectional – directional scores), even if one hearing aid's overall scores (omnidirectional and directional) are poorer than the other.

[1]We use the term *d-mics* to refer to directional microphones in general. The term is not used to refer to any specific configuration or design of directional microphones.

Physical directivity of a hearing aid can be quantified using a variety of techniques such as the directivity index, the front-to-back ratio, or the polar plot (refer to Ricketts, Lindly, & Henry, 2001, for a recent review of these methods).

Empirical, anecdotal, and incidental accounts of directional benefit are abundant in the literature. Over the last decade, directional benefit from hearing aids has been quantified to be between 2 and 11 dB, depending on the test environment, reverberation, variations in noise, noise source location, and number of noise sources (Bentler, 2005; Hawkins & Yacullo, 1984; Ricketts & Dhar, 1999). A corresponding improvement in speech perception performance in background noise between 40% and 70% has also been reported (Ricketts et al., 2001). This great improvement observed under laboratory conditions is tempered to a great extent in the real world (Bentler, 2005; Cord, Surr, Walden, & Dyrlund, 2004; Killion et al., 1998) and by acoustic and extra-acoustic factors (Dhar, Humes, Calandruccio, Barlow, & Hipskind, 2004) not fully understood as of yet.

In contrast, studies of the efficacy of DNR algorithms are less frequent in the literature, and their conclusions are often inconsistent. Although listeners often demonstrate a strong tendency for subjective preference for DNR algorithms (Boymans & Dreschler, 2000), actual improvement in speech perception is reportedly unreliable. Negative effects of DNR algorithms (algorithms that include spectral subtraction, spectral enhancement, and adaptive noise cancellation) on speech perception tasks have been reported. In many cases, though, the signal is reportedly more comfortable to listen to under measurably improved SNR (Alcantara et al., 2003; Ricketts & Hornsby, 2005). The examination of interactions between DNR algorithms and other signal processing such as compression within a hearing aid is at its infancy but perhaps holds the key to the concomitant use of these technologies (Galster & Ricketts, 2004). Finally, isolated findings from a few recent studies (*not* peer reviewed) suggest DNR algorithms may be effective in improving speech perception in noise when the speech and noise sources are not spatially separated (Bray, Sandridge, Newman, & Kornhass, 2002) or when the noise field is isotropic (Bray & Nilsson, 2001).

The maturation of the two technologies under scrutiny here, d-mic and DNR algorithms, is occurring in parallel and, some suggest, may be directed toward disparate end points. However, in reality, the two technologies are often used simultaneously by the hearing aid user. This in itself motivates the examination of their compatibility and interactions. Our survey of the literature reveals great variability in published results based on the hearing aid in question and the test conditions. Some studies have demonstrated additivity of benefit from these two technologies (e.g., Bray & Nilsson, 2001 [*not* peer reviewed]), while others have not (e.g., Walden, Surr, Cord, Edwards, & Olsen, 2000).

Both technologies are highly dynamic, and as new generations evolve the audiologist and the consumer are routinely overwhelmed with the extolled virtues of the newer systems. The process of evaluating efficacy of these technologies must be repeated as newer generations of technology emerge. The purpose of the study was to compare the performance of a group of adults with impaired hearing on the Hearing in Noise Test (HINT) when using d-mic and DNR technologies in isolation and in conjunction in modern hearing aids.

Method

Sixteen adults between the ages of 58 and 90 years ($M = 79.56$) were recruited from the Northwestern University Hearing Clinic. All had symmetric, moderate to severe sensorineural hearing loss with no significant air–bone gaps, and all had a minimum of 12 months' experience using hearing aids. Of the 16 participants, 8 were using hearing aids with d-mics. Each participant signed an informed consent form prior to the commencement of the experiment in accordance with the institutional review board procedures at Northwestern University. Speech-perception-in-noise ability was measured using a modified version of the HINT (Nilsson, Soli, & Sullivan, 1994) as described below.

Four commercially available digital behind-the-ear hearing aids were used in this investigation. These instruments—the GN ReSound Canta 7, Oticon Syncro, Phonak Perseo, and Siemens Acuris—were equipped with specialized algorithms for noise identification and reduction as well as switchable (i.e., between omnidirectional and directional) microphones. These instruments present a representative sample of the high-end products from four of the six largest hearing aid manufacturers in the world. The DNR algorithms used in these instruments also represent a variety of approaches prevalent in the industry today. As our results did not demonstrate significant differences in performance and/or benefit between instruments, we refer to them in generic code, HA1 through HA4 in no particular order, in the remainder of this article. Table 1 outlines characteristics of each hearing aid in terms of type of noise reduction algorithm, number of channels, and time constants related to activation of DNR. This information was provided by the manufacturer or has been gleaned from the literature. The hearing aids were programmed using the manufacturer-supplied "first fit" algorithm on the NOAH platform using pure-tone thresholds measured prior to the commencement of the experiments for each subject. Each hearing aid was programmed for the following four conditions: (a) omnidirectional, (b) d-mic, (c) DNR, and (d) d-mic + DNR. Automatic algorithm or microphone-mode selection was disabled in all instruments. The hearing aids were coupled to the participants' ears using custom earmolds with a 1–2-mm vent. All measurements were made while the participant was seated in a double-walled sound-treated audiometric test booth using the speaker setup described below.

All efforts were made to manipulate the hearing aids in specific, consistent ways to make conditions as similar as possible across hearing aids. HA3 and HA4 allowed adjustment of noise reduction level. For those hearing aids, DNR was set to the highest level for the DNR and d-mic + DNR conditions. The default DNR setting was used for HA1

Table 1. Technical specifications of hearing aids used in this study.

Variable	HA1	HA2	HA3	HA4
Noise detection/ reduction algorithm	Multichannel modulation detection in 12-s analysis windows; steady state noise is identified via modulation rate, and SNR is calculated	Multichannel synchrony detection, modulation detection, and noise level detector; noise reduction is not applied or limited if speech is in the signal	Multichannel modulation detection; 2 modulation detectors are applied: 1 follows the minima and 1 the maxima to provide baseline for estimating SNR.	Multichannel modulation detection. Signal center of gravity is estimated as is overall input level.
Number of channels	16	8	14	20
Speed of gain reduction	3–8 s	To switch from noise only to Speech/Speech in Noise: 0.2–0.9 s From Speech modes to Noise only: 1.8–7 s	10 s	Dependent on signal type and other programmed parameters. Approximately 8 s when programmed for average thresholds from our participants.
Information sources	Communication with manufacturer's research and development personnel.	Chung, 2004	Chung, 2004	Communication with manufacturer's research and development personnel.

Note. SNR = signal-to-noise ratio.

and HA2. Directionality in each hearing aid was configured to be nonadaptive with a cardioid polar pattern. Because one of the hearing aids did not present the option of a cardioid polar pattern, a hypercardioid pattern was chosen in that case. When given an option to set the degree of directionality, this setting was always set to "full" or "maximum." When an option, hearing aid acclimatization level was set to the highest level allowed in the fitting software. Venting size specification options also varied; HA1 was set to 1.5 mm, HA2 was set to 1.8 mm, and HA4 was set to "medium vent." HA2 allowed for the specification of various parameters in a "personal profile." Under this option, the age range of 70–79 was chosen, and hearing aid experience was set to long-term nonlinear user. "Personality" specifications were left at the default settings. In this particular hearing aid, age and personality factors were used to categorize individuals on a continuum from "energetic" to "calm." Time constants for compression, noise reduction, and so on were varied from short to long, and magnitudes of change, in gain, for example, were gradually decreased along this continuum. By specifying the same age range and personality type for all our participants, we avoided the introduction of yet another uncontrolled variable in the data set.

Speech perception in noise was measured using the HINT (Nilsson et al., 1994). We modified the standard HINT recording by adding two additional channels of noise, thereby creating a total of four channels. The first channel carried the speech signal, while the other three channels carried uncorrelated versions of the standard speech-shaped noise supplied with the HINT recording. The three noise channels were further modified by adding a 12-s noise lead-in before the onset of each sentence to allow all signal processing schema to be fully activated prior to the presentation of the speech signal. A commensurate 12-s period of silence was added to the beginning of each sentence in the first channel. The length of lead-in noise was determined by measuring the time required for the output of each hearing aid to stabilize after the onset of the speech-shaped noise. The longest delay measured, using a Fonix 7000cx, was approximately 11 s, in general agreement with Chung (2004).

The signal (speech and noise) was delivered through the four channels of an M-audio Quattro input/output USB device from the hard disk of a computer. The presentation was controlled on the computer using the commercially available sound-editing software package Tracktion. The HINT sentences were presented from a speaker at 0° azimuth, 1 m from the listener at a height of 36 in. The three channels of uncorrelated noise were presented from matched Realistic Minimus 7 speakers at 90°, 180°, and 270° azimuth, also 1 m from the listener at a height of 36 in. Presentation levels were calibrated using the calibration tracks provided with the HINT CD. Test blocks of 10 sentences were presented for 16 conditions: four hearing aids in four modes. Note that the typical application of the HINT involves the use of two sentence blocks, or 20 sentences. We were forced to reduce the number of sentences to 10 due to time constraints. Using one instead of two lists increased the 95% confidence interval from ±1.41 to ±2.49 (Nilsson et al., 1994). Our results should be interpreted in light of this "broadened" confidence interval. As will be seen below in the Results, the contrasts reported to be significant in this report accommodate this departure from custom in this area of research. The results from 3 participants (additional to the 16) were not included in the data analyses because we observed significant problems during the administration of the HINT. These participants typically showed nonreversals or inconsistent reversals during the presentation of the HINT sentences for more than one hearing aid and/or condition.

The hearing aids and the conditions within each hearing aid were counterbalanced across participants. The HINT lists used were also counterbalanced across participants. The noise level was fixed at 65 dBA, and the level of the speech was varied by 4 and 2 dB depending on the subject's response, in accordance with the standard HINT protocol. The HINT test is an adaptive speech-in-noise test. While background noise remains at a constant 65 dBA, the presentation level of the HINT sentences varies based on performance accuracy on each sentence (i.e., for a correct answer, presentation level is decreased, and for an incorrect answer the presentation level is increased). The noise level (65 dBA) was subtracted from the averaged presentation levels for Sentences 5–11 to compute the SNR threshold. Per standard protocol, the (would-be) presentation level for the 11th sentence is factored into the computation, but a sentence is not presented.

HINT performance and benefit (with reference to omnidirectional performance) were statistically compared across hearing aids and conditions using a general linear model with repeated measures. Individual hearing aids and the conditions within each hearing aid were the factors used in the primary analysis. Age, hearing loss, and previous hearing aid use were used as factors in a secondary analysis to examine differences between two groups of participants. Comparison of individual conditions was made using a Tukey honestly significant difference (HSD) post hoc analysis. All statistical tests were performed using SPSS Version 9.0.

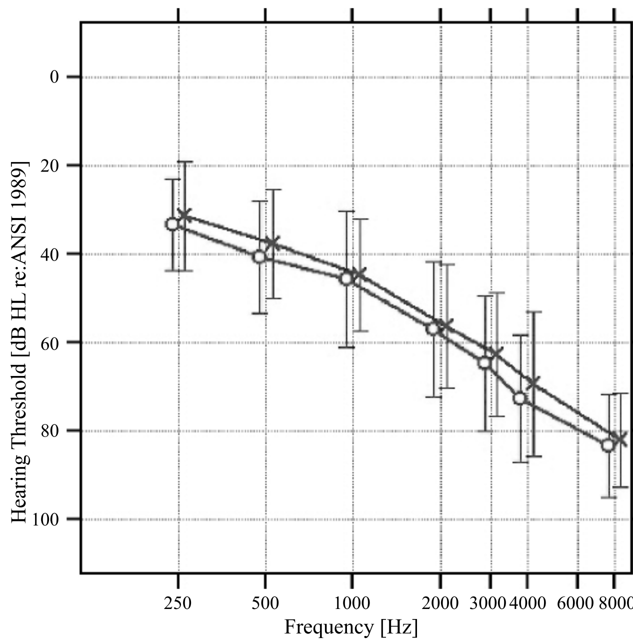
Results

Mean hearing thresholds from the participants ($N = 16$), separated by right and left ears, are displayed in Figure 1. Note the gradually sloping configuration and the symmetry between ears. Any conductive component was ruled out through immittance measures.

Mean HINT SNR threshold values (performance) for each hearing aid are displayed in Figure 2 for each condition. HINT SNR threshold values are calculated as the decibel difference between the threshold level of speech (for 50% performance) and the 65-dBA background noise level. Lower HINT SNR threshold values reflect better speech perception in noise. Across hearing aids, performance for d-mic and d-mic + DNR conditions were better than in the omnidirectional and DNR conditions. Significant differences between hearing aids were *not* observed for matched conditions. Significant differences, $F(3, 252) = 38.652$, $p < .01$, were found when comparing SNR threshold between conditions. Thresholds for D-mic and d-mic + DNR conditions were significantly better than omnidirectional and DNR conditions. However, differences in thresholds between d-mic and d-mic + DNR as well as between omnidirectional and DNR conditions were not significant.

Comparison of HINT SNR performance across individual instrument-condition pairs is presented in Table 2. The

Figure 1. Mean audiometric thresholds (N = 16). Error bars represent the range of thresholds at each frequency.



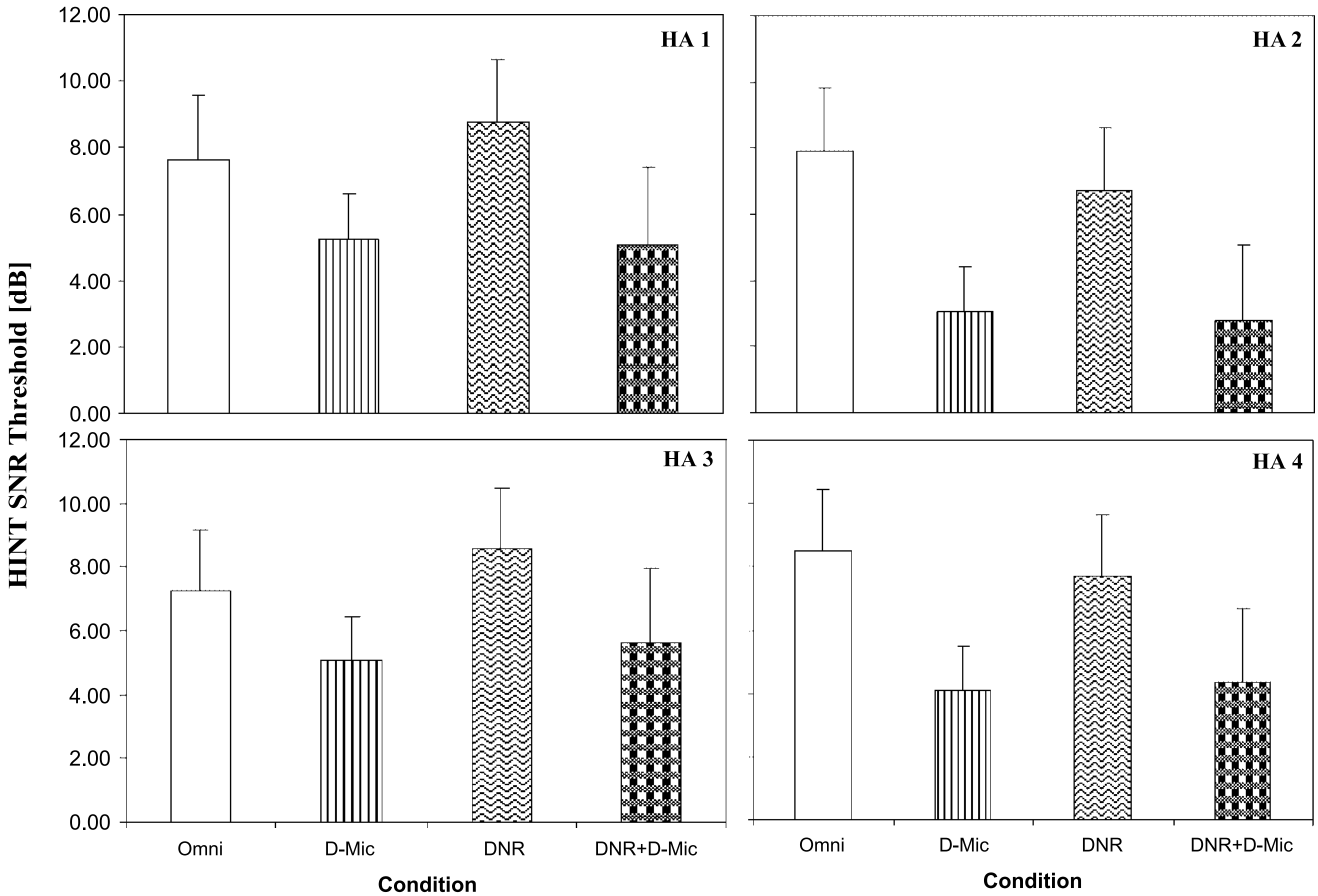
instrument-condition pairs are ranked from best to worst performance based on a Tukey HSD test. Inclusion of a condition in a subgroup (A, B, or C) indicates a statistically similar ($p = .05$) performance. Note that performance for the d-mic and the d-mic + DNR conditions fall in the same subgroup (C) for all hearing aids.

HINT SNR *benefit,* displayed in Figure 3, was calculated for d-mic, DNR, and d-mic + DNR conditions with the performance in the omnidirectional condition as the reference. The interpretation of Figure 3 is different from Figure 2 as greater benefit is demonstrated by higher values. Differences in SNR benefit within condition were *not* found to be significant across hearing aids. Differences among conditions in each hearing aid, however, were found to be significant, $F(2, 61) = 29.359$, $p < .01$, with d-mic and d-mic + DNR showing the greatest improvement over the omnidirectional condition.

Results of a Tukey HSD analysis for the *benefit* scores are presented in Table 3. The information presented here is similar to that in Table 2, but the organization is slightly different. Instrument-condition pairs are ranked from least to most benefit. The letter groups indicate statistical similarity for an alpha level of .05. Note that the DNR conditions for all hearing aids belong to one statistical group (A). Also note that all d-mic as well as d-mic + DNR conditions belong to one statistical group (E).

Individual HINT thresholds for the unaided and omnidirectional conditions for each participant and each condition across hearing aids are displayed in Figure 4. These data are sorted as a function of the difference between thresholds for the d-mic and d-mic + DNR conditions, this

Figure 2. Hearing in Noise Test (HINT) performance among participants ($N = 16$) within hearing aid (4) across conditions. A lower signal-to-noise ratio (SNR) value equals better performance. Error bars represent 1 *SD*. Statistical analysis revealed performance difference across conditions to be insignificant ($F = 0.542$, $p = .654$).



difference being displayed with the open and closed circles on the graph. Note that each symbol on this trace represents a combination of a participant and a hearing aid, thereby leading to a sample size of 64 (16 subjects and 4 hearing aids); we refer to these subject-instrument combinations as *SI combinations* in the remainder of the article. Negative difference scores (left half of the figure) indicate that an SI combination performed better with d-mic + DNR, while positive scores indicate better HINT performance with d-mic only. The four SI combinations where the two thresholds were equal are marked with closed symbols in Figure 4. The shaded area about the "zero line" demarcates the 95% confidence interval for HINT thresholds obtained with one sentence block. Note the approximately symmetrical distribution of SI combinations on this metric about zero, suggesting that an approximately equal number of SI combinations performed best with d-mic alone ($n = 11$, when considering statistically significant results only) as did with d-mic and DNR activated together ($n = 9$, when considering statistically significant results only). A tally of this metric is also displayed in Table 4, where a count of participants performing best under each condition for each hearing aid is tabulated. Thus, the data presented in Figure 4 are disassociated across participants, hearing aids, and conditions in this table. There is no consistent relationship between performance in the omnidirectional or unaided conditions with a participant's preference for the d-mic or d-mic + DNR conditions, as evident from the random scatter of these data in Figure 4. When scores beyond the 95% confidence band were considered, approximately 17% and 14% of the SI combinations performed better in the d-mic and d-mic + DNR conditions, respectively.

Consistency of "best condition" across hearing aids was examined by tallying the number of individuals performing best in a particular condition for each hearing aid (see Table 4). That is, we asked whether an individual performed best under Condition A for hearing aid *x* and did that translate to hearing aids *y, z,* and so on. Eleven of the 16 participants (69%) consistently performed best for the same condition in at least three out of the four hearing aids. Three participants (19%) demonstrated 100% consistency; that is, their best performance was for the same condition in all four hearing aids. Five participants (31%) were 50% consistent (or inconsistent, in this case), performing best in the d-mic condition with two hearing aids and best in

Table 2. Ranking and homogenous subgroups of *performance* by condition.

Condition	Group		
HA4 (d-mic)			C
HA2 (d-mic)			C
HA4 (d-mic + DNR)			C
HA1 (d-mic + DNR)			C
HA3 (d-mic)			C
HA2 (d-mic + DNR)			C
HA3 (d-mic + DNR)		B	C
HA1 (d-mic)	A	B	C
HA4 (omni)	A	B	
HA4 (DNR)	A	B	
HA3 (DNR)	A	B	
HA1 (omni)	A	B	
HA1 (DNR)	A	B	
HA2 (DNR)	A	B	
HA2 (omni)	A		
HA3 (omni)	A		

Note. Mean Hearing in Noise Test (HINT) performance scores for each condition are ranked (from best to worst) and grouped with conditions where performance was statistically similar. Performance scores within each group are statistically similar as analyzed by a Tukey honestly significant difference (HSD) test with an alpha of .05. Thus all conditions grouped under C were found to be statistically similar, so were all conditions grouped under A and B. Average performance for the HA3 (omni) was worst among all conditions. However, performance for this condition was not statistically significantly different from HA1 (d-mic), as both conditions are grouped under A. Performance for HA3 (omni) was statistically significantly different than HA3 (d-mic + DNR), which is grouped under B and C but not A. Note the overlap in performance between omnidirectional (omni) and digital noise reduction (DNR) conditions; d-mic = directional microphone.

d-mic + DNR condition with the remaining two hearing aids. Surprisingly, 1 participant performed best for the omnidirectional condition for all hearing aids, but we were unable to find any outstanding features in hearing loss, age, or experience with amplification for this person. In our data set, there were 5 participants who performed equally in two or more conditions for a given hearing aid. The reader is cautioned that all results, irrespective of their relationship to the 95% confidence interval, were used in developing this part of the analysis. Our interest was in ascertaining similarity in the direction of the effect of DNR rather than magnitude.

Discussion

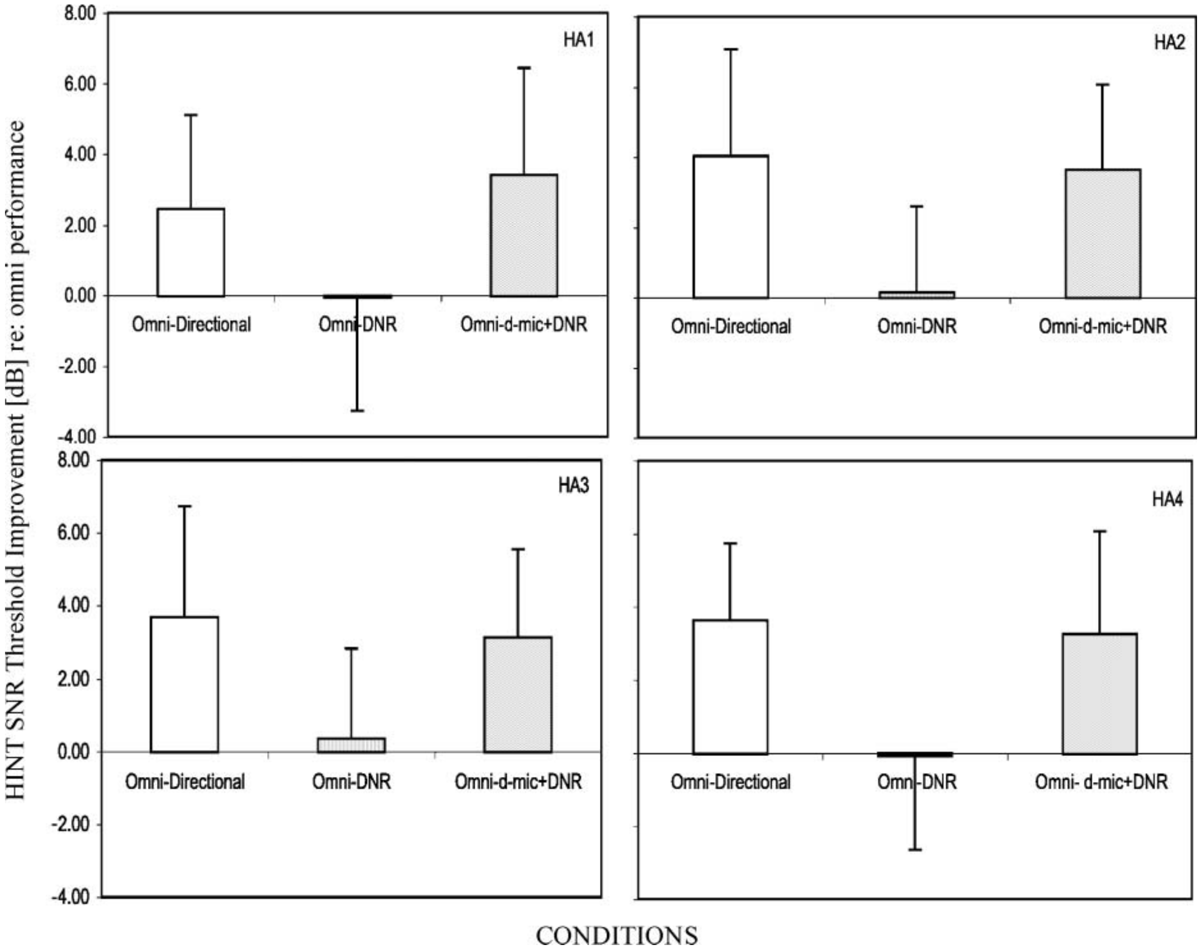
The purpose of this investigation was to evaluate the improvement in hearing-in-noise performance that adult hearing aid users experience when using two technologies: d-mics and DNR, in isolation or in combination. Past reports have indicated significant improvement in hearing-in-noise performance with the use of d-mics. Algorithms for DNR have been shown to improve comfort (e.g., Ricketts & Hornsby, 2005). Most reports to date have not shown significant improvement in speech perception in noise when using a DNR algorithm in isolation or in conjunction with d-mics (e.g., Walden et al., 2000), with the exception of one non-peer-reviewed study (Bray & Nilsson, 2001). Algorithms for DNR are perhaps the most dynamic aspect of hearing aid development today, and their efficacy needs to be evaluated on a timely basis. While our results are consistent with the majority opinion in the literature, we find an interesting trend when individual rather than group mean data are considered. Approximately 50% of the participants in our data pool showed added improvement when the DNR algorithm was activated in conjunction with a d-mic. The number of individuals performing best with d-mic alone (11) or for the d-mic + DNR condition (9) was also approximately equal when scores beyond the 95% confidence interval were considered alone.

The HINT directional benefit scores reported here range between −4.57 and 8.57 dB ($M = 3.46$). The amount of directional benefit measured in this investigation is in good agreement with previous studies under comparable conditions (Cord et al., 2004; Preves, Sammeth, & Wynne, 1999; Valente, Fabry, & Potts, 1995; Walden et al., 2000). The lack of significant differences in directional benefit across hearing aids along with the similarity of our results with studies conducted over the last decade appear to suggest a plateau in directional benefit (at least under laboratory conditions). The average directional benefit reported from different laboratories, under different conditions, for successive generation of d-mics has hovered between 2 and 5 dB. Do these results indicate that we have achieved an asymptote in human performance with d-mics? Of course, the data that drive us to pose this question do not, to a large extent, account for the most recent innovations such as automatic and adaptive directionality.

In a similar vein, our results are consistent with previous reports of HINT benefit, or lack thereof, from DNR algorithms. Bray and Valente (2002) demonstrated a mean improvement of 2 dB using DNR in a Sonic Innovations Natura 2 SE instrument in a non-peer-reviewed report. To the contrary, several other reports have reported no improvement in speech perception in noise from the use of DNR algorithms, or when DNR algorithms are added to d-mics. Our results are consistent with this latter category (e.g., Walden, Surr, Cord, & Dyrlund, 2004) when group average data are considered.

In addition to the general analyses involving group means, we examined data from each individual separately. After all, performance on tasks related to hearing is anything but consistent across individuals. Neglecting the 95% confidence interval temporarily, this analysis suggests that approximately 50% of our participants performed best when the d-mic and DNR algorithm were active in unison. The other 50% performed best when the d-mic was active in isolation. A particular hearing aid and the accompanying DNR algorithm did not appear to be the determinant factor here. In other words, individuals who performed best with both technologies activated did so across hearing aid brand. These findings suggest that the DNR algorithms used in our study do offer additional benefit for some listeners when activated in conjunction with d-mics. Our results have to be interpreted with the limitation that one block

Figure 3. Benefit of d-mic, DNR, and d-mic + DNR as compared with the omnidirectional microphone condition. A positive score indicates better than omnidirectional-only performance, while a negative score indicates worse than omnidirectional-only performance. Error bars represent 1 *SD*. Statistical analysis revealed performance difference across conditions to be insignificant (F = 0.461, p = .710).



of HINT sentences was used for each condition, thereby increasing the 95% confidence interval. However, even after considering the increased confidence interval, an approximately equal number of SI combinations performed best with d-mic alone (n = 11) as did with DNR and d-mic in conjunction (n = 9).

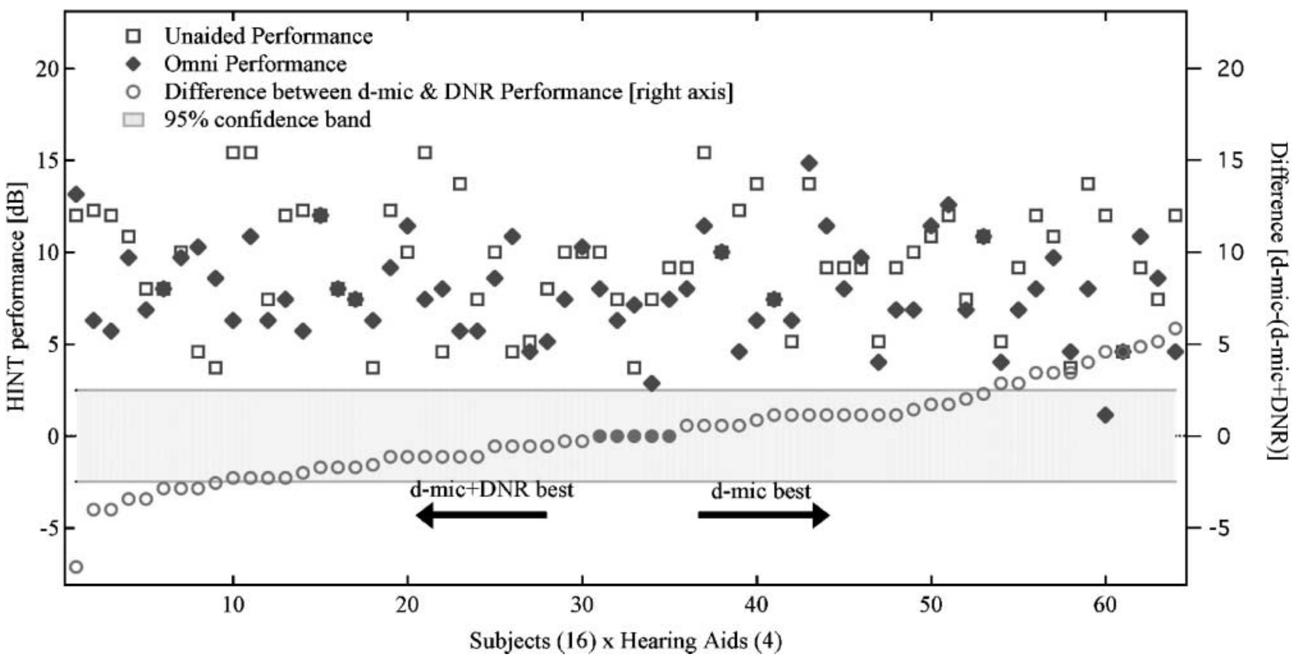
It is perhaps a worthwhile exercise to identify physiological correlates, if any, for this observation. In other words, could differences in physiology or pathophysiology account for an individual being able to take greater advantage of DNR as compared with others? The distinguishing factor between DNR and d-mics is that while d-mics are able to improve SNR within a frequency band, DNR is only able to do so across frequency bands. Individuals who are able to extract meaningful information from a signal that may be *sparse* in the frequency domain could arguably benefit more from DNR as the levels of certain bands of frequency (with poor SNR) are lowered. An alternate interpretation of the same data would be that the performance of these individuals is hindered to a greater extent due to cross-channel masking effects when DNR is not activated. Two

Table 3. Ranking and homogenous subgroups of HINT *benefit* by condition.

Condition	Group				
HA4 (DNR)	A				
HA1 (DNR)	A	B			
HA2 (DNR)	A	B	C		
HA3 (DNR)	A	B	C	D	
HA1 (d-mic)	A	B	C	D	E
HA3 (d-mic + DNR)	A	B	C	D	E
HA4 (d-mic + DNR)		B	C	D	E
HA1 (d-mic + DNR)			C	D	E
HA4 (d-mic)				D	E
HA2 (d-mic + DNR)				D	E
HA3 (d-mic)					E
HA2 (d-mic)					E

Note. Mean HINT benefit score (difference between d-mic, DNR, or d-mic + DNR and omni) for each condition is ranked (from least to most) and grouped with conditions where performance was statistically similar. The general structure of the table is similar to Table 2. Group E represents greatest benefit. Benefit scores within each group are statistically similar as analyzed by a Tukey HSD test with an alpha of .05.

Figure 4. Unaided and omnidirectional performance on the HINT for every participant (*N* = 16) and hearing aid (4) sorted according to the difference between their d-mic and DNR performance. Negative difference-scores indicate that the participant performed better with both d-mic and DNR activated. On the other hand, positive difference scores indicate better performance with only d-mic activated. The shaded band about the "zero line" indicates the 95% confidence interval for single block testing.



explanations could be put forward to explain the data for individuals who perform best with d-mic in isolation. First, the performance in this group of individuals could have reached an asymptote, and adding DNR does not yield greater benefit. Another possibility could be that taking away information in some frequency bands hampers performance in this group—these individuals depend on the information present in all frequency bands, noisy or otherwise. Our data provide some insights that may allow us to begin to discern these issues. A vast majority of the individuals who performed best with both the d-mic and DNR activated in unison demonstrated an improvement in performance when DNR was added to the d-mic. This would be consistent with a negative impact of cross-band masking effects in the d-mic condition, which are ameliorated by the activation of DNR. The individuals who performed best with d-mic alone overwhelmingly showed a decline in performance when DNR was added to the d-mic condition. This observation would be consistent with a deleterious effect of "taking away" information in certain frequency regions even when such information is "noisy."

From a practitioner's standpoint, it would be useful to be able to predict an individual's preference when determining the optimal configuration of the hearing aid for speech perception in noise. Pertinent to our experiments, we examined several factors in an attempt to identify predictor variables for preference of d-mic alone versus the d-mic/DNR combination. These two groups were matched in age, hearing thresholds, and experience with hearing aid use, except for a 10-dB difference in average thresholds at 4000 Hz. Aware of the wide age range of the participants in our study, we compared the ages of two groups and found them to be statistically similar ($p > .05$). Hearing thresholds and experience with amplification were likewise found to be statistically similar between the two groups, irrespective of whether data were collapsed across hearing aids in the analysis. We were also unable to identify any predictive relationship from omnidirectional or unaided performance on the HINT (see Figure 4). While DNR will probably be an automatic choice while configuring a "comfort" memory in a multimemory instrument, our results appear to suggest that DNR could play a significant role in improving speech

Table 4. Tally of "best performance" conditions for each hearing aid.

[A] Best performance	HA1	HA2	HA3	HA4
Omni	1	1	1	1
D-mic	8	9	10	7
DNR	1	1	0	0
D-mic + DNR	9	8	6	8

Note. Each cell displays the number of participants who performed best for a given condition. The numbers in the columns and/or rows do not add up to 16 as individuals may have performed equally well for more than one condition. Note that one (the same) individual performed best in the omnidirectional condition for all hearing aids. These results were compiled including all data, irrespective of their relationship to the 95% confidence interval as shown in Figure 4.

understanding in noise for some individuals. Based on these results, our recommendation would be to evaluate speech perception in noise for each individual with d-mic alone and with the d-mic/DNR combination. We make this recommendation cognizant of the time limitations clinicians face in configuring the many parameters of a modern digital hearing aid. To that end, it would be beneficial to continue our search for predictive measures that would allow the clinician to optimize the aided hearing for an individual.

Our results offer an insight into the complexities involved in human performance with hearing aids. We are encouraged to have identified a group of individuals who receive measurable benefit in speech perception tasks from DNR algorithms when used concurrently with d-mics. These results, however, come with the usual caveats of natural versus contrived test environments and the lack of longitudinal monitoring of performance as an individual acclimatizes to a hearing aid. We close with hope and expectation that scientists will continue to develop technologies capable of improving speech-in-noise performance, that the industry will continue implementing these technologies in their product lines, and that we will continue to aggressively and objectively evaluate the efficacy of these strategies. As a result of this collaboration, newer and more effective technologies will emerge, as will objective measures of evaluation and configuration of amplification systems for individuals with impaired hearing.

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References

Alacantara, J., Moore, B., Kuhnel, V., & Launer, S. (2003). Evaluation of the noise reduction system in a commercial digital hearing aid. *International Journal of Audiology, 42,* 34–42.

Bentler, R. A. (2005). Effectiveness of directional microphones and noise reduction schemes in hearing aids: A systematic review of the evidence. *Journal of the American Academy of Audiology, 16,* 473–484.

Boymans, M., & Dreschler, W. A. (2000). Field trials using a digital hearing aid with active noise reduction and dual-microphone directionality. *Audiology, 39,* 260–268.

Bray, V., & Nilsson, M. (2001). Additive SNR benefits of signal processing in a directional DSP aid. *The Hearing Review, 8,* 12.

Bray, V., Sandridge, S., Newman, C., & Kornhass, S. (2002, September 9). Clinical research findings confirm benefits of advanced signal processing. *Audiology Online.* Retrieved August 15, 2005, from http://www.audiologyonline.com

Bray, V., & Valente, M. (2002, September 24). Can omni-directional hearing aids improve speech understanding in noise? *Audiology Online.* Retrieved August 15, 2005, from http://www.audiologyonline.com

Chung, K. (2004). Challenges and recent developments in hearing aids: Part I. Speech understanding in noise, microphone technologies and noise reduction algorithms. *Trends in Amplification, 8,* 3.

Cord, M., Surr, R., Walden, B., & Dyrlund, O. (2004). Relationship between laboratory measures of directional advantage and everyday success with directional microphone hearing aids. *Journal of the American Academy of Audiology, 15*(5), 353–364.

Dhar, S., Humes, L., Calandruccio, L., Barlow, N., & Hipskind, N. (2004). Predictability of speech-in-noise performance from real ear measures of directional hearing aids. *Ear & Hearing, 25*(2), 147–158.

Galster, J., & Ricketts, T. (2004, August). *The effect of digital noise reduction time constants on speech recognition in noise.* Poster presented at the 2004 International Hearing Aid Research Conference (IHCON), Lake Tahoe, CA.

Gordon-Salant, S., & Fitzgibbons, P. (1997). Selected cognitive factors and speech recognition performance among young and elderly listeners. *Journal of Speech, Language, and Hearing Research, 40,* 423–431.

Hawkins, D., & Yacullo, W. (1984). Signal-to-noise ratio advantage of binaural hearing aids and directional microphones under different levels of reverberation. *Journal of Speech and Hearing Disorders, 49,* 278–286.

Killion, M. C., Schulien, R., Christensen, L., Fabry, D., Revit, L., Niquette, P., & Chung, K. (1998). Real world performance of an ITE directional microphone. *Hearing Journal, 51*(4), 24–26, 30, 32–36, 38.

Kochkin, S. (2005). Marke Trak VII: Hearing loss population tops 31 million people. *Hearing Review, 127,* 16–29.

Kuk, F., Ludvigsen, C., & Paludan-Muller, C. (2002). Improving hearing aid performance in noise: Challenges and strategies. *The Hearing Journal, 55*(4), 34–46.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *Journal of the Acoustical Society of America, 95,* 1085–1099.

Preves, D., Sammeth, C., & Wynne, M. (1999). Field trial evaluations of a switched directional/omnidirectional in-the-ear hearing instrument. *Journal of the American Academy of Audiology, 10,* 273–284.

Ricketts, T. (2001). Directional hearing aids. *Trends in Amplification, 5*(4), 139–174.

Ricketts, T., & Dhar, S. (1999). Comparison of performance across three directional hearing aids. *Journal of the American Academy of Audiology, 10,* 180–189.

Ricketts, T. A., & Hornsby, B. W. (2005). Sound quality measures for speech in noise through a commercial hearing aid implementing digital noise reduction. *Journal of the American Academy of Audiology, 16,* 270–277.

Ricketts, T. A., Lindly, G., & Henry, P. (2001). Impact of compression and hearing aid style on directional hearing aid benefit and performance. *Ear & Hearing, 22,* 348–361.

Schuknecht, H., & Gacek, M. (1993). Cochlear pathology in presbycusis. *Annals of Otology, Rhinology, and Laryngology, 102,* 1–16.

Snell, K., & Frisina, R. D. (2000). Relationships among age-related differences in gap detection and speech perception. *Journal of the Acoustical Society of America, 107,* 1615–1626.

Stuart, A., & Phillips, D. (1996). Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal-hearing, and presbyacusic listeners. *Ear & Hearing, 17,* 478–489.

Valente, M., Fabry, D. A., & Potts, L. G. (1995). Recognition of speech in noise with hearing aids using dual microphones. *Journal of the American Academy of Audiology, 6,* 440–449.

Walden, B., Surr, R., Cord, M., & Dyrlund, O. (2004). Predicting microphone preference in everyday living. *Journal of the American Academy of Audiology, 15,* 365–396.

Walden, B., Surr, R., Cord, M., Edwards, B., & Olson, L. (2000). Comparison of benefits provided by different hearing aid technologies. *Journal of the American Academy of Audiology, 11,* 540–560.

Walton, J., Simon, H., & Frisina, R. D. (2002). Age-related alterations in the neural coding of envelope periodicities. *Journal of Neurophysiology, 88,* 565–578.

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