Chapter Nine

Should Digital Noise Reduction be Activated in Pediatric Hearing Aid Fittings?

Ryan W. McCreery, Samantha Gustafson and Patricia G. Stelmachowicz

Introduction

The sophistication of hearing aid (HA) signal processing has increased rapidly in the last decade. Several specific advancements have been developed with the goal of mitigating the negative perceptual and psychological consequences of background noise for HA users. While attempts to reduce unwanted noise for HA users have been made over the last three decades (see Bentler and Chiou 2006 for a review), modern digital noise reduction (DNR) algorithms attempt to limit background noise by initially classifying the input to the HA based on the acoustic characteristics of the listening environment. When noise is the primary signal detected by the HA, DNR algorithms reduce gain to improve listener comfort. Ideally, DNR should maintain audibility for the speech signal if speech and noise are both present in the environment. The sophistication of current DNR algorithms allows for these changes to be made independently across multiple frequency bands simultaneously. Optimization across frequency bands minimizes distortion of the speech signal by only providing DNR in the frequency bands where noise dominates the input signal (Hoetink , Korossy and Dreschler 2009). Although these goals may sound simple in theory, overlap between the frequency spectra of speech and noise in realistic environments (Koopman, Franck and Dreschler 2001) has the potential to limit the algorithm from achieving these goals. Specifically, the expected improvements in the signal-to-noise ratio (SNR) and speech perception in noise may not be realized outside of laboratory settings.

Because DNR has been made a standard feature available in most digital hearing aids within the last decade, scrutiny regarding the efficacy and appropriateness of such algorithms for children who wear hearing aids has surfaced. Studies of DNR with adult listeners have begun to illustrate the potential advantages of DNR in terms of listener comfort in noise, showing that improved comfort can be achieved without negatively impacting speech understanding. Unfortunately, research evaluating the efficacy of DNR for pediatric hearing aid users has been limited. Lack of substantive evidence to support the use of DNR with children has led to recommendations that DNR be implemented with caution (Palmer and Grimes 2005). Clinicians must determine if DNR should be activated for their pediatric hearing aid clients despite limited evidence to support their decision to use this widely available feature. If an audiologist determines that DNR may be appropriate for a given child, it is important that the effects of the processing on the speech signal be included in the verification process. Just as verification is important for other advanced signal processing strategies, it is necessary with DNR so any potential changes in the speech signal be identified and optimal settings obtained.

The purpose of this article is to provide a brief review of how DNR is implemented in HAs. Previous studies with adult listeners are highlighted in addition to a more detailed discussion regarding outcomes of the limited number of recent DNR studies completed with children. A practical verification procedure for clinicians to evaluate DNR with their pediatric clients is presented. Strategies for optimizing DNR algorithms to minimize the impact on speech audibility are discussed, as well as

---

Address correspondence to: Ryan W. McCreery, M.S., CCC-A, Boys Town National Research Hospital, 555 North 30th Street, Omaha, NE 68131, Email: ryan.mccreery@boystown.org.

considerations for future studies evaluating the efficacy and effectiveness of DNR for children.

Digital Noise Reduction in Hearing Aids

Noise reduction has long been a goal of HA manufacturers due to the negative consequences of noise for both listener comfort and speech understanding. Early attempts to reduce background noise in analog devices were based on limiting low-frequency gain at high input levels through either amplitude compression or adaptive filtering. Improvements in speech recognition with these systems were typically not realized since decreased gain at low frequencies also decreased the audibility of the speech signal (Tyler and Kuk 1989). With the development of digital HA signal processing, the sophistication of DNR algorithms has increased significantly; however, the goal of reducing interference from noise has remained unchanged. Many modern DNR algorithms use some form of amplitude modulation detection to analyze the input to the HA (see Kates 2008 for a review). The differences in amplitude modulation between speech and noise spectra allow the HA to estimate whether the input is comprised of speech or noise and then to adjust the amount of gain provided by the HA. Devices with multiple channels of signal processing can perform these analyses for discrete frequency regions and reduce gain in only the channels where noise dominates the input. Such precision allows algorithms to provide gain reduction in the frequency regions where the noise is present, while attempting to maintain audibility for speech. The analysis of the signal characteristics by the HA is an on-going process, allowing the algorithms to adapt to changes in the acoustic environment.

In order to improve speech understanding in noise significantly through signal processing, algorithms would need to effectively improve the SNR. DNR operates by reducing gain, which means that any improvements in SNR would only be achieved by maintaining the amount of gain for speech, while reducing gain for noise. Because of the significant spectral overlap between speech and noise in everyday listening situations, current DNR algorithms must analyze and manipulate a signal that contains both speech and noise. Any changes in gain made by the algorithm are applied to the combined noisy speech signal. Independent manipulation of the speech and noise signal would be required to change the SNR in each band; therefore, it is unclear if significant improvement of the overall SNR can be achieved with current DNR technology unless the noise is isolated to a limited frequency region. Methods for quantifying the change in SNR improvement with DNR processing have been proposed (Hagerman and Olofson 2004), but have not been extensively evaluated in formal studies of DNR.

Although many DNR systems use modulation detection as the primary method of signal analysis, the implementation of DNR algorithms varies substantially across manufacturers and devices. Hoetink and colleagues (2009) systematically evaluated the characteristics of DNR in twelve different HAs to quantify variations in how these algorithms are implemented in different devices. Results from measurements using modulated and unmodulated ICRA (International Collegium for Rehabilitative Audiology; Dreschler, Verschuure, Ludvigsen and Westermann 2001) noise stimuli indicated that DNR systems in hearing aids vary based on a number of different parameters including the amount of gain reduction, number of channels where DNR is active, frequency range where noise reduction occurs, input level where DNR is activated, and the wearer's audiometric thresholds. Results from a comparison of the two types of ICRA noise revealed that different DNR algorithms can have distinct effects on the amount of gain for speech signals in noise, varying from algorithms that preserve the speech signal with limited gain reduction to those which significantly reduce gain. The amount of time required for onset and release of DNR algorithms also varies considerably across manufacturers. DNR systems with faster attack and release times have been found to improve speech understanding and listener ratings of sound quality in real world environments (Woods, Nooraei, Galster and Edwards 2010). Presumably, algorithms with faster time constants have the ability to adapt more rapidly to acoustic changes in speech or noise in the environment, which may result in a more rapid gain reduction with the onset of noise and less persistence of noise reduction with the onset of speech.

Because the characteristics of each manufacturer's DNR systems are proprietary, variations in these characteristics may not be evident to clinicians without extensive and systematic testing. These differences have the potential to significantly impact the amount of gain that is applied in different situations, directly impacting the audibility of speech for the HA user. The wide range of implementations and proprietary nature of these algorithms support the need for an individualized verification approach to determine how DNR may impact the audibility of speech. However, the assessment of various parameters of DNR for each manufacturer presents multiple challenges for clinicians.

Studies of DNR with Adult Listeners

A growing body of literature assessing the effects of DNR algorithms with adult listeners has started to emerge over the past 10 years because the availability of these algorithms in digital hearing aids has become standard. Studies of DNR with adult listeners have focused on three main categories of outcome variables: speech recognition, listener ratings of comfort or preference in noise, and ease of listening or listening effort. Although improvements in speech understanding in noise is a desirable outcome for individuals with hearing loss, the extant literature suggests that DNR algorithms do not significantly improve or degrade speech understanding in noise for adult listeners (Alcantara, Moore, Kuhnel and Launer 2003; Boymans and Dreschler 2000; Ricketts and Hornsby 2005; Hu and Loizou 2007). Given that most approaches of DNR either decrease or maintain amplification based on the presence, intensity and spectral characteristics of noise, the best potential outcome of this processing would be to maintain the audibility of the speech signal. With reduction in gain, there is also potential to reduce overall audibility. Therefore, the limited improvements in speech understanding in noise that have been reported with DNR to date may not be surprising.

Although DNR has not been demonstrated to decrease speech understanding in noise, the positive impact of DNR on *listener comfort* in background noise, as well as measures of ease of listening in adults have been much more widely reported. Mueller, Weber and Hornsby (2006) determined that adults with hearing loss demonstrated increased Acceptable Noise Level (ANL) with DNR enabled. In previous studies with hearing-impaired adults, the ability of listeners to tolerate a higher ANL has been linked with increased likelihood of hearing aid use (Nábělek, Freyaldenhoven, Tampas, Burchfield and Muenchen 2006). In another study of DNR with adults, Ricketts and Hornsby (2005) used a paired comparison task to measure listener preference for speech in noise at two different signal-to-noise ratios (SNRs). While results did not indicate an improvement in speech understanding for their participants, listeners demonstrated a very strong preference for speech in noise processed using DNR over those signals without DNR.

Given the fact that listening in background noise is a significant complaint that has been reported for many hearing aid users, improvements in listener preference or comfort in noise are encouraging, particularly if the algorithms do not degrade speech understanding. More recent studies have attempted to demonstrate the impact of DNR for reducing listening effort in adults. Such studies are based on the theory that listening in background noise requires the listener to dedicate more cognitive processing resources to decoding the speech signal relative to listening in quiet. The increased effort required for listening in noise leaves the listener with fewer remaining cognitive resources to perform other important processes, such as committing stimuli to short-term memory. Therefore, interference from noise has been demonstrated to result in decreased recall, even at SNRs where recognition remains intact (Conlin, Gathercole and Adams 2005). The method that is most often used to measure a listener's allocation of cognitive resources is a dual-task paradigm, where a listener is instructed to perform two tasks. When the primary task increases in difficulty, performance on the secondary task decreases as individuals allocate more cognitive resources to performing the primary task. Sarampalis and colleagues (Sarampalis, Kalluri, Edwards and Hafter 2009) used two different dual-task paradigms to measure the influence of DNR on short-term memory and listening effort. In one experiment, adult listeners were required to repeat words or sentences as the primary task and hold the words in memory for later recall. Additionally, speed of processing was estimated in another task by measuring responses on a visual task completed while performing speech recognition in noise. DNR did not have a significant effect on the speech recognition; however, free word recall and reaction time for the secondary task improved at the lowest signal-to-noise ratio in each task when DNR was applied to the auditory stimuli. Although the statistical effect sizes for each task were relatively small, these results suggest that positive benefits of DNR may extend beyond the traditional outcome measure of improved speech recognition.

Evidence from DNR research with adults has important implications for clinical decisions regarding the application of this technology in hearing aid fittings. Although DNR does not affect speech understanding, benefits in terms of listener comfort, preference and ease of listening have been demonstrated. Few studies of DNR with adults have attempted to quantify the effects of DNR on the speech and noise signals in an attempt to predict which algorithms have the greatest potential for perceptual improvement. The relationship between ease of listening and speech recognition is also not well understood. It is possible that improvements in listener comfort or ease of listening may have the potential to offset changes in audibility through reduction in gain that may occur with DNR. This trade-off could result in a maintained level of speech understanding with much less effort on the part of the listener. The relationship between listening effort and speech understanding may have significant implications for using DNR with children, but requires additional investigation.

Despite the emergence of promising evidence to support the use of DNR with adults, it is important to note that DNR signal processing strategies continue to become more sophisticated. Because the pace of innovation often exceeds the rate at which studies of these algorithms can be designed, completed and published, it will be difficult for practicing clinicians to evaluate the efficacy of these algorithms. Overall, DNR studies with adults have suggested that, while DNR algorithms do not significantly alter speech understanding, adult listeners do report improvements in listening comfort, tolerance of background noise, and reduced listening effort with DNR. While studies with adult listeners are important for our understanding of how these algorithms may benefit adult hearing aid users, application of these results to a pediatric population is tenuous because the listening needs of children are distinct from those of adults.

DNR for Children who Wear Hearing Aids

Data from adult studies related to DNR would suggest that such processing might be beneficial to children at least in terms of improving listening comfort in noise. Unfortunately, previous studies of children with hearing loss have demonstrated the limitations of attempting to predict performance of children based on adult behavioral data. Therefore, the potential benefits and negative consequences of DNR for children must be carefully considered using data from studies with pediatric participants. Children with hearing loss require amplification to promote development of speech and language; therefore, the impact of any signal processing strategy on the audibility of speech must be considered prior to implementation in pediatric hearing aid fittings. Because children require more audibility than adults to achieve levels of speech recognition similar to those of adults (Stelmachowicz, Hoover, Lewis, Kortekaas and Pittman 2000), any reduction in audibility for the speech signal occurring as a consequence of an attempt to reduce background noise could have a greater negative impact on children compared to adult listeners. Data also suggest that children are frequently listening in classrooms and other environments where background noise is present at levels that could negatively impact perception (Bradley and Sato, 2008). Neuman and colleagues (Neuman, Wroblewski, Hajicek and Rubinstein 2010) found that children show greater degradation of speech understanding in background noise and reverberation than adults. Thus, the potential to reduce the negative perceptual consequences of background noise using DNR may be even greater for children than for adult listeners.

While modern DNR algorithms are designed to limit the amount of gain reduction when speech is present in the environment, reduced audibility is still a potential negative outcome. For example, Figure 1 shows the reduction in gain for speech in noise when DNR is activated in two devices that utilize spectral subtraction DNR. While there is no change in the amount of gain for the HA in Panel A, the HA in Panel B shows a broadband reduction in gain of approximately 6 dB when speech and noise are presented to the HA with DNR activated. Such a significant reduction in gain would limit the audibility for speech in noise, potentially limiting speech understanding in noisy situations. Unfortunately, the differences between the outputs of these two DNR algorithms for speech in background noise would not be apparent using most pediatric hearing aid verification protocols for DNR.

To date, relatively few studies have evaluated the effects of DNR on speech understanding or ease of listening on children. Marcoux and colleagues (Marcoux, Yathiraj, Cote and Logan 2006) utilized a cross-language paradigm where adult listeners with normal hearing were exposed to a novel, non-native speech contrast that is sufficiently difficult for adult English speakers to perceive. This method is frequently used in studies of speech sound acquisition. In their study, speech was processed through a commercially-available hearing aid. The goal of the study was to determine if DNR would interfere with the ability of listeners to perceive and learn acoustic contrasts needed for speech and language development, which is a primary concern for any hearing aid signal processing strategy that has the potential to be implemented with children. Results after four sessions of exposure to the contrast suggested that adult subjects were able to learn the speech contrast regardless of whether DNR processing was utilized, suggesting that DNR did not *interfere* with the perception and acquisition of a novel phonetic cue. The authors cite a number of specific limitations in generalizing these findings to pediatric hearing aid users, including most importantly the use of adult listeners. Although these findings may not predict specific outcomes in children

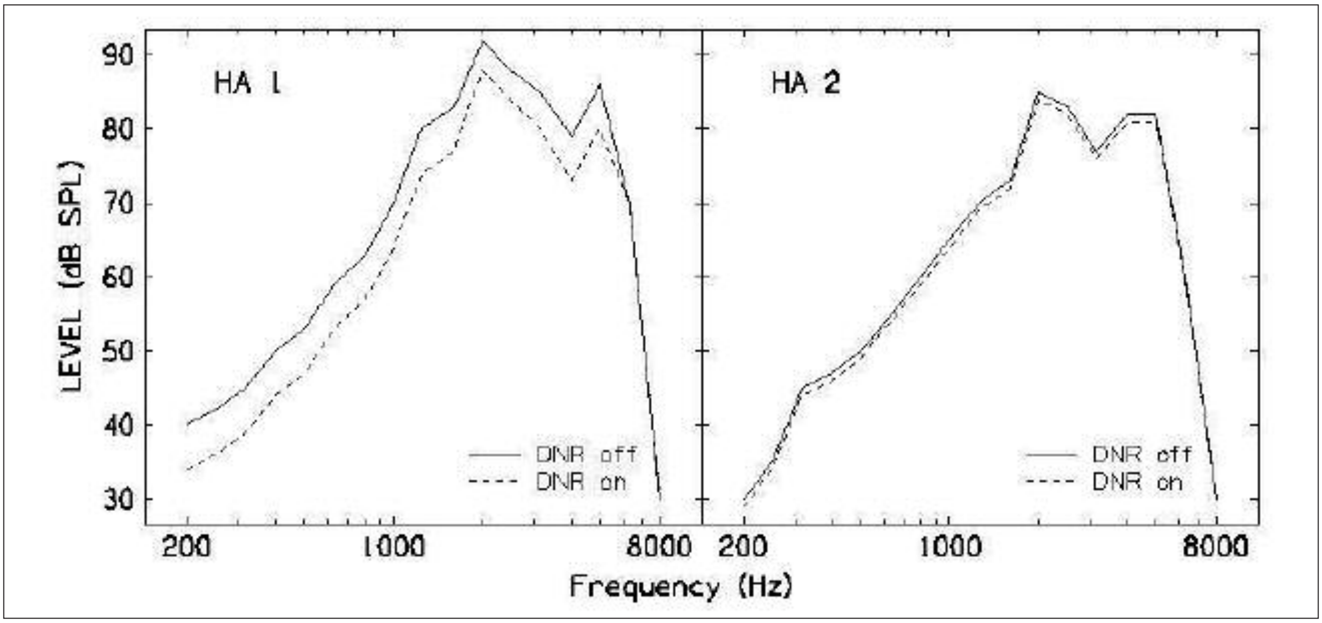

Figure 1. Hearing aid output level (dB SPL) in a 2cc coupler for a 60 dB speech signal in steady-state noise at a +3 dB SNR plotted as a function of frequency (Hz) for two hearing aids. The solid line in each panel is the hearing aid response with DNR off, while the dashed line is the response with DNR on. The difference between the two responses for HA 1 (left panel) represents a reduction in gain for speech in noise with DNR on. Changes in gain with DNR on are minimal for HA 2 (right panel).

with hearing loss, the implementation of DNR used by Marcoux and colleagues did preserve the acoustic cues in the speech signal sufficiently to allow listeners to learn a novel speech contrast, suggesting that DNR can be applied without negatively impacting cues important for learning phonetic contrasts.

One of the first attempts to evaluate DNR processing for school-age children with hearing loss reported in the literature was completed by Auriemmo and colleagues (2009) as part of a study evaluating multiple advanced hearing aid features. Multiple dependent measures were used to quantify the influence of DNR on listening behavior in children, including speech recognition, as well as subjective ratings of everyday listening situations by parents and the child HA users. Results revealed no differences in speech recognition between conditions with DNR and without DNR, consistent with previous adult studies. Differences in subjective ratings for DNR were found only for questions related to sounds originating from behind the listener, which children rated as less bothersome with DNR. The main strengths of this study were the use of both laboratory speech perception measures and children's subjective ratings from extended use in realistic situations. Additionally, because the effectiveness of DNR is not dependent on spatial separation between the signal and noise as it is for directional microphones, DNR may provide additional advantages for children in background noise beyond what could be realized with a directional microphone alone. Auriemmo and colleagues reported no additional improvement in speech recognition with DNR compared to the directional microphone condition in their study. However, the laboratory speech recognition measures used in this study did not include acoustic conditions that would be expected to provide an advantage over a directional microphone, such as spatially diffuse noise or speech signals originating from the sides or behind the listener. These conditions have been shown to limit the advantage of directional microphones in previous studies with school-age children (Ricketts, Galster and Tharpe 2007), but the relative advantage of DNR under these conditions has not been investigated.

More recently, additional evidence to support the use of DNR with school-age children was reported by Stelmachowicz and colleagues (2010). Children with mild-to-moderate hearing loss between 5 and 10 years of age were asked to repeat nonsense vowel-consonant-vowel (VCV) syllables, monosyllables, and sentences at three different SNRs. The speech stimuli were processed using a commercially-available HA with a modified spectral subtraction DNR algorithm implemented over sixteen frequency bands. HA gain and output characteristics were optimized using Desired Sensation Level (DSL) targets for average speech for each child's audiogram. On average, speech recognition in noise did not change when DNR was activated for any of the stimulus types or SNRs. Despite the fact that there was no observed effect of DNR overall, significant individual variability in speech recognition was observed, particularly for children in the 5 to 7 year-old age range. Although speech recognition was highly variable across subjects, none of the children in the study showed a consistent improvement or degradation in speech understanding across conditions when DNR was activated.

Another study of DNR with children conducted by Bentler, Kirby and Stiles (2010) attempted to assess the potential impact of DNR on speech recognition, novel word learning, and subjective ratings of sound quality in normal hearing school-age children. While the results for speech recognition demonstrated no effect of the DNR processing, novel word learning rates and children's subjective ratings of sound quality of speech in noise were both improved in the DNR conditions compared to the conditions without DNR. Results from this investigation support the previous studies' findings of limited impact on speech understanding with the additional benefits of improved sound quality ratings and word learning rates in children. The researchers speculated that the improvements observed in novel word learning rates with DNR were related to a decrease in the cognitive processing load afforded by the DNR signal processing.

Although these preliminary DNR findings support the implementation of this feature with school-age children, the limitations of these studies should be considered when determining the appropriateness of DNR for pediatric hearing aid users. Specifically, despite the fact that DNR is implemented differently across manufacturers, the studies by Auriemmo, et al. (2009) and Stelmachowicz, et al. (2010) each evaluated only a single DNR algorithm, limiting the potential generalization of these findings to other DNR algorithms. Additionally, comparative data for different algorithms on the same task to assess various aspects of DNR algorithms and how they may impact that algorithm's effectiveness with children are not possible when only a single algorithm is assessed. Although studies by both Auriemmo, et al. and Bentler, et al. (2010) included children's ratings of comfort, additional listener ratings of comfort and sound quality in children have not been widely reported in pediatric studies of DNR. In both cases, improvements in children's ratings of sound quality occurred without improvements in speech understanding, suggesting that children may be sensitive to improvements in signal quality that are not significant enough to improve perception.

The ability of researchers to generate informed hypotheses about how children perform with DNR has been hindered by the difficulty quantifying the effect of these algorithms on the speech signal. As discussed previously, improvements in SNR with DNR are a desired outcome that would be required in order to improve speech recognition. Quantifying specific changes in audibility related to DNR would allow for hypotheses about the impact of these algorithms on speech understanding. For example, an algorithm that reduced the signal quality above 3000 Hz could have a negative impact on fricative perception. In order to determine if DNR improves the SNR after the signal has been processed by the hearing aid, the speech and noise signals would have to be evaluated separately, as the combined speech and noise output may not reflect alterations of important speech cues that may have occurred during signal processing. Analysis of the effects of DNR on the speech and noise signals independently may allow estimation of any changes in SNR that might not be observable from the combined speech and noise signal.

In an attempt to address some of the limitations from previous studies of DNR and children, Gustafson and colleagues (Gustafson, McCreery, Hoover, Kopun and Stelmachowicz in preparation) conducted an investigation of the impact of two DNR algorithms on speech recognition, listening effort, and ratings of sound clarity for a group of 7 to 12 year-old children with normal hearing. Multiple candidate DNR algorithms in commercially available devices from different manufacturers were considered for the study. Based on their signal processing characteristics, two devices were selected. One major limitation of previous DNR studies is the lack of attempts to quantify the impact of the processing on the speech signal. Hagerman and Olofson (2004) developed a procedure known as the inversion method to quantify the effects of digital signal processing strategies such as DNR on the integrity of the speech signal when measured in noise. The inversion method requires two samples of speech in background noise that are identical except that the phase of the noise is inverted in one sample. When the two samples are added together, the noise signals cancel and the resulting waveform contains only the speech signal. When the two samples are subtracted, the speech signals cancel, leaving only the noise signal. From these two extracted signals, the effects of signal processing on both the speech and noise signals can be estimated, including changes in the SNR by measuring relative changes in the level of the two signals. The inversion method has also been previously used to evaluate the effects of amplitude compression on the relative levels of speech and noise (Souza, Jenstad and Boike 2006). The two algorithms selected by Gustafson and colleagues had different effects on the SNR following processing with DNR. As measured by the inversion method, HA1 had minimal impact on the SNR while HA2 resulted in an improvement in the SNR of 7 dB. The hypotheses of the study were that the HA providing the largest SNR improvement would show the greatest improvement in speech recognition, reduction in verbal response time, and improvements in children's ratings of clarity.

Another significant limitation of previous studies was the use of either closed-set stimuli or stimuli with high linguistic redundancy when estimating performance changes with DNR. While providing stimuli with linguistic context can help to support children in difficult listening environments and provides a valid estimation of what children are able to do in realistic situations with contextual cues, the availability of context could potentially overshadow the effects related to subtle changes in signal processing. To limit the available semantic cues during the speech recognition task, nonword consonant-vowel-consonant (CVC) stimuli were utilized to require children to rely more heavily on the acoustic-phonetic representation and use bottom-up decoding skills rather than top-down linguistic knowledge. Children must be able to perceive these acoustic-phonetic cues as they develop speech and language.

Results from the study showed a slightly different pattern than was predicted from the inversion method. Although HA2 resulted in a 7 dB improvement in SNR, phoneme recognition improved by only 6.5% compared to HA1. While this difference in performance was statistically significant, previous studies of phoneme recognition for normal-hearing children in this age range have demonstrated approximately a 20% improvement in phoneme recognition with a 7 dB improvement in SNR (McCreery, Spratford, Lewis, Hoover and Stelmachowicz 2010). Additionally, verbal response time and ratings of sound clarity were improved with both algorithms, even without a significant improvement in the SNR in HA1 as predicted by the inversion method. In an effort to explain the differences in speech recognition between the two algorithms, further analysis of the extracted speech signal from the inversion method was completed using magnitude squared coherence. Coherence compares the spectra of two signals to determine the degree of similarity as a function of frequency and varies between one, suggesting that the signals are spectrally identical, and zero, suggesting that the two spectra are completely dissimilar. Coherence measures have previously been used to evaluate equivalent input noise in hearing aids (Lewis, Goodman and Bentler 2010). Coherence measures comparing the extracted speech signals with DNR active versus inactive for HA1 and HA2 revealed that the high-frequency region of the speech spectrum was better preserved by HA2 when DNR was activated. Decreased perception of phonemes with energy in the high frequencies such as fricatives would be anticipated for DNR processors that did not maintain the level of the speech spectrum above 3 kHz. Future studies could potentially use coherence measures to predict perceptual performance for algorithms that significantly alter the speech spectrum.

Overall, preliminary research regarding the efficacy of DNR signal processing for children who wear hearing aids has begun to emerge. Multiple studies have supported findings from the adult literature that DNR does not appear to have an impact on school-age children's speech understanding in noise. Additionally, a few studies have also demonstrated that children's ratings of clarity and sound quality of background noise are also improved with DNR. Studies have suggested that DNR may also improve novel-word learning (Bentler et al. 2010) and verbal response time (Gustafson et al. in preparation). Both of these outcome variables have been attributed to decreased cognitive processing load for children listening in background noise. Furthermore, some researchers have speculated that the presence of background noise can interfere with the rehearsal of auditory stimuli (Sarampalis et al. 2009), an important part of the process for committing auditory stimuli to memory.

Despite significant progress evaluating DNR strategies for children over the past few years, a significant number of questions regarding the efficacy of this technology with children remain unresolved. Currently available studies of DNR with children have included either children with normal hearing or children with mild-to-moderate hearing losses as participants. Further studies should be completed for children with greater degrees of loss, as well as evaluating a wider range of variables in children with all degrees of hearing loss. Children with severe-to-profound hearing loss may be at the greatest risk for experiencing reduced audibility with DNR strategies simply because they have more limited audibility based on their available dynamic range. Furthermore, most of the studies of DNR with children have been completed in the school-age population. Although our knowledge of DNR in this age range is important, studies with infants and younger children would provide clinicians with the evidence and confidence to utilize this technology at an earlier age. However, the current speech recognition and word learning paradigms would likely have to be adapted significantly, or alternative tasks would have to be developed before studies of DNR could be completed in younger children. To date, studies evaluating how experience and training with DNR signal processing could influence children's performance with this technology have also not been established. Finally, additional studies validating the inversion method and coherence measures for evaluating the potential impact of DNR on the speech signal and audibility are needed before firm conclusions can be made from these measurements.

Verification of DNR

The primary purpose of providing amplification to infants and young children is to improve outcomes for speech and language development and provide children with the access to their environment. Maintaining audibility of the speech signal and controlling the level of more intense sounds to prevent discomfort both provide an important foundation for meeting these goals. Therefore, verification procedures for pediatric hearing aid fittings should at least demonstrate that speech is audible and that loudness is adequately controlled to prevent discomfort. With the development of advanced acoustic signal processing features such as DNR, the need to verify the impact of these technologies on audibility has become a critical part of the process. Any advanced feature that may affect the audibility of speech requires verification to quantify the frequency regions where changes in audibility occur and the degree to which audibility is altered. As previously stated, the parameters of DNR algorithms vary considerably both across product lines within the same manufacturer and across different hearing aid companies. The proprietary nature of signal processing strategies means that clinicians are often unable to predict the impact of DNR on audibility. Additionally, some manufacturer's DNR systems vary in the amount of gain reduction provided by the algorithm based on the client's audiogram used to program the hearing aid, providing less reduction in gain as the degree of hearing loss increases in an attempt to preserve audibility (Hoetink et al. 2009). The combination of how DNR processing varies due to individual differences between clients and manufacturers holds clinicians responsible for verifying these features when implemented with a child.

Three different methods of verification for DNR are available to clinicians based on the available verification equipment. Verification of DNR can occur either using a probe microphone to measure the output of the hearing aid in the client's ear or in a 2cc coupler. Although probe microphone measures are recommended whenever possible, performing the additional steps required for DNR verification using probe microphone measurements is likely to be difficult in infants and young children. Therefore, the most practical method of DNR verification is often completed in a 2cc coupler. If the results of DNR verification are to be compared to the client's thresholds, a real-ear-to-coupler-difference (RECD) measurement should be applied to improve estimates of audibility. One advantage to performing DNR verification in a 2cc coupler is that the verification can occur prior to the fitting appointment, leaving more time to provide informational counseling to children and their parents. For the purpose of the current article, the verification procedures will be presented as if the process takes place in a 2cc coupler, keeping in mind that these same measures can be completed using real-ear probe microphone measures in cooperative clients.

Three main types of test stimuli can be used to evaluate the effects of DNR: 1) steady-state broadband noise or speech-shaped noise, 2) recordings of environmental steady-state noise signals, and 3) speech signals with steady-state background noise. Test signals must be calibrated to provide a controlled estimate of how DNR functions at realistic input levels. The availability of these signals will depend on the verification equipment available. Although all three types of test signals can be used for verification of DNR in hearing aids, the information that can be inferred from each test signal is not equivalent. Steady-state broadband and speech-shaped noises, in addition to recordings of steady-state environmental signals, can be used to provide information about the amount of gain reduction provided by the DNR algorithm, frequencies where gain reduction occurs, and DNR time constants. However, only speech signals with steady-state background noise can provide an estimate of how the DNR algorithm will respond when speech and noise are present simultaneously. The amount of gain reduction observed for steady-state noise or recordings of environmental noise should not be assumed to predict the amount of audibility that would be lost for speech. Rather, using steady-state noise signals provides clinicians with an estimate of the maximum effect of DNR that may occur when only noise is present in the environment.

If steady-state noise test signals are to be used for the DNR verification process, the HA should be attached to the 2cc coupler and placed in the test chamber. The HA should be attached to the programming software to allow selection of features during the verification process. Prior to evaluating DNR, directional microphones should be set to a fixed omnidirectional setting in the programming software, ensuring that interactions between DNR and directional microphone processing do not affect the results. First, the HA response to the steady-state signal without DNR activated should be obtained, if possible. Several models of HAs do not allow DNR to be deactivated for verification. In these cases, the default DNR setting can be used as a baseline. The steady-state noise signal should be presented to the hearing aid at a level that would be consistent with environmental noise levels experienced by the client, between 55 – 75 dB SPL. Measurements at multiple input levels can help clinicians to determine if the DNR algorithm has level dependency (i.e., different characteristics for different input levels). Once a baseline measure of the HA response without DNR is obtained, the programming software should be used to activate the DNR setting that will be used with the client. The steady-state noise is then presented to the HA in the coupler again to measure the device's response with DNR activated. For both measures, the signal should be presented to the HA for a minimum of 30 seconds to allow the DNR algorithm to reach its maximum effect and ensure that the algorithm remains engaged. Comparison of the response obtained with and without DNR activated will allow the clinician to make judgments about the impact that the algorithm may have on audibility when the lis-

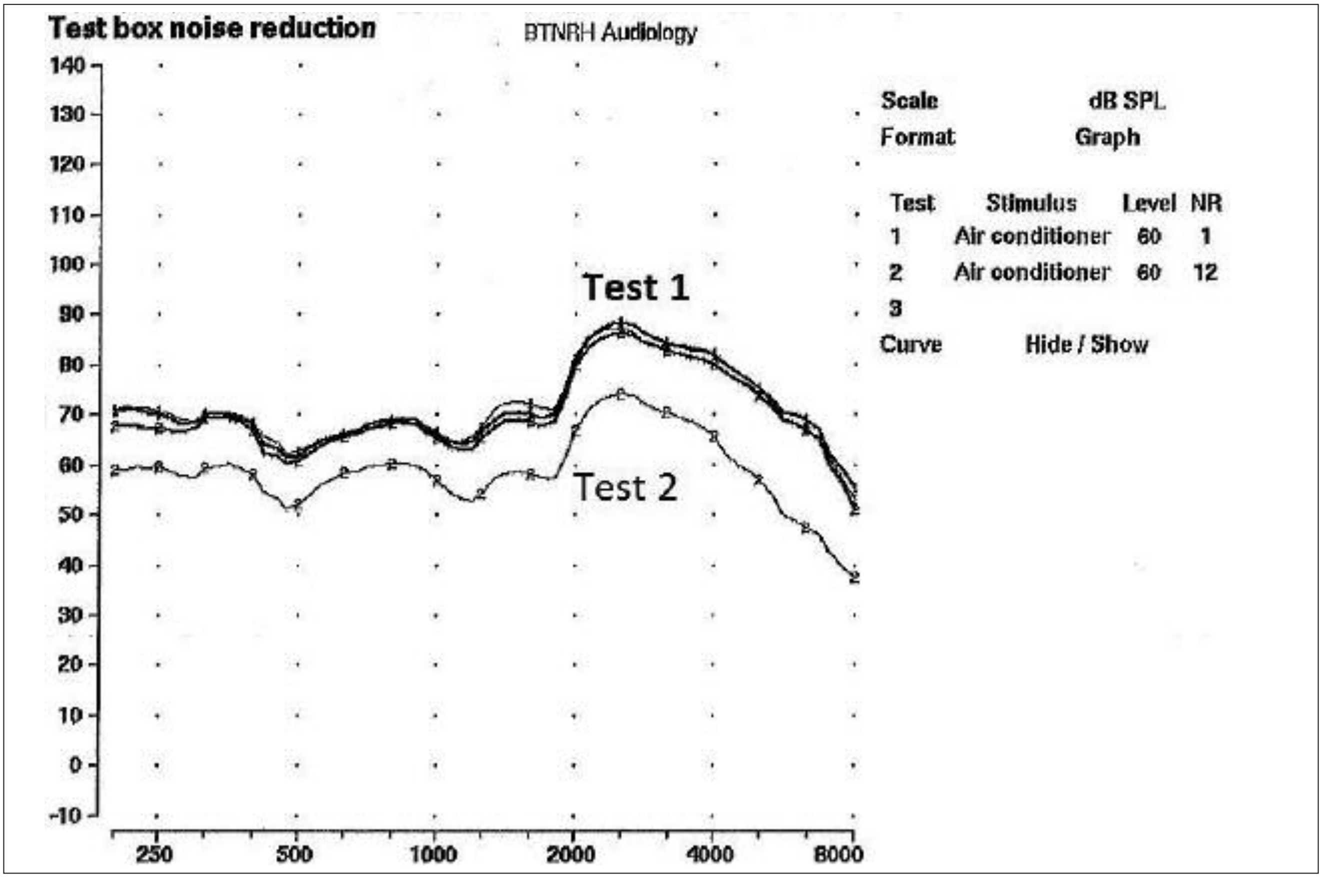

Figure 2. An example of verification of DNR using a steady-state signal using the Audioscan Verifit®. Hearing aid output level (dB SPL) in a 2cc coupler for a 60 dB air conditioner noise plotted as a function of frequency (Hz) with DNR off (Test 1) and DNR on (Test 2). A broadband reduction in gain of approximately 12 dB occurs when a steady-state noise signal is presented to the hearing aid.

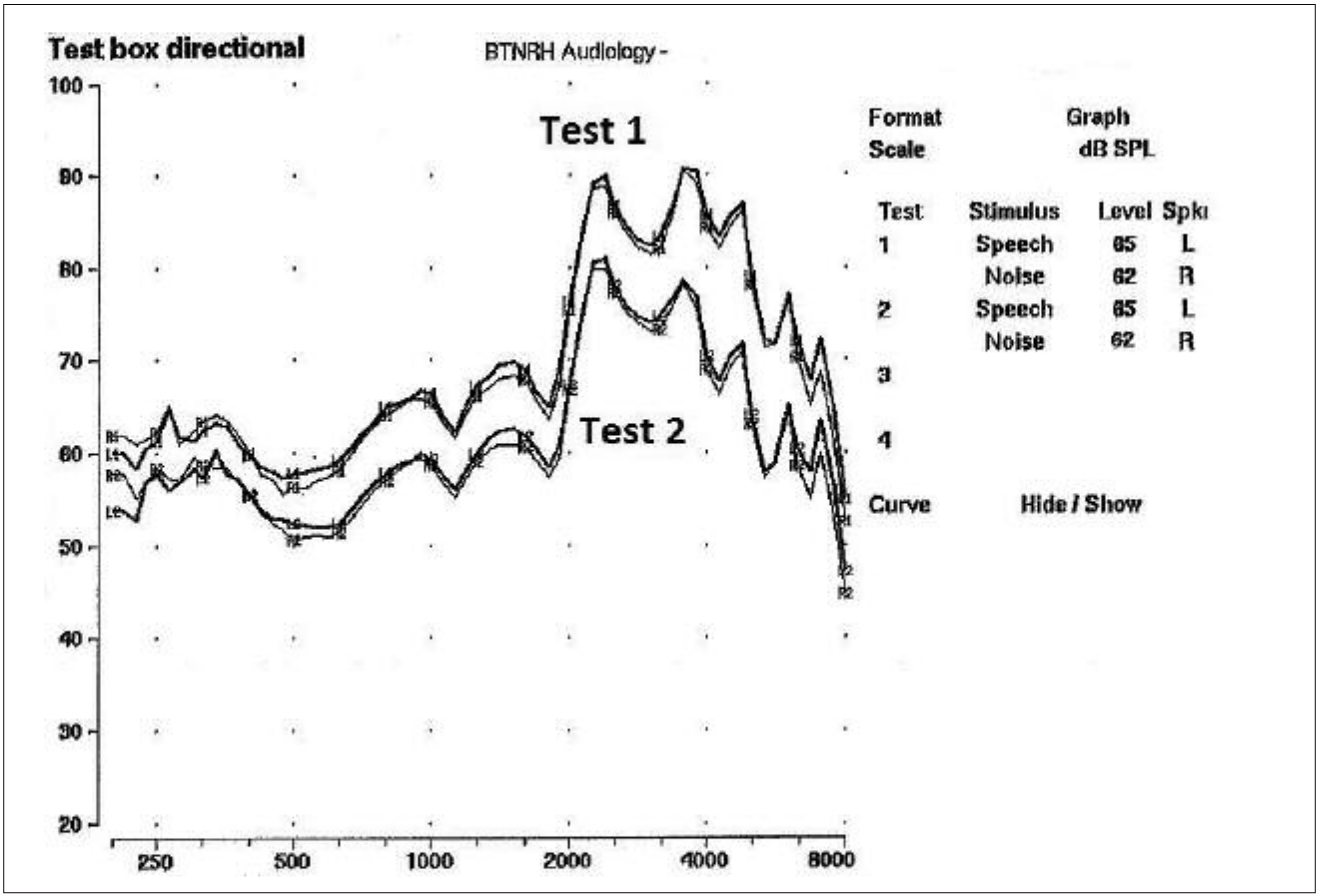

Figure 3. An example of verification of DNR using speech plus steady-state noise using the directional test mode on the Audioscan Verifit®. Hearing aid output level (dB SPL) in a 2cc coupler for a 65 dB speech signal with a 62 dB steady-state noise plotted as a function of frequency (Hz) with DNR off (Test 1) and DNR on (Test 2). The difference between the two responses reflects a reduction in gain when speech and noise are presented to the hearing aid.

tener is in background noise. Changes that occur with steady-state signals should not be assumed to reflect the response of the HA when speech is present. Figure 2 shows the results of a verification procedure for DNR using steady-state signals.

In order to estimate the effect of DNR on speech in background noise, the clinician must use a verification procedure that includes speech and steady-state background noise at calibrated levels. Although not specifically developed for DNR verification, the Audioscan Verifit® Directional Test Mode allows the user to present steady-state noise and speech simultaneously at an adjustable SNR in the test box. With the hearing aid attached to the 2cc coupler and programmed to an omnidirectional microphone setting, sequential measurements of the HA response with DNR activated and deactivated can be completed with both speech and steady-state noise presented to the hearing aid. A positive SNR should be selected for the stimulus presentation to ensure that the speech is the primary signal in the test box. Ideally, the level and frequency characteristics of the response from the HA with DNR activated should be very similar to the response without DNR, reflecting that audibility is preserved when the listener is in an environment with both speech and noise present. Any differences that are observed between the lines corresponding with the left and right speakers in the Verifit® test box are related to the fact that the hearing aid response differs for the stimuli being presented from each speaker. If the HA is set to a fixed omnidirectional response, differences between the left and right speaker response should not occur. Differences between the left and right speaker responses with an omnidirectional setting may indicate a microphone problem or that the device has adaptively changed into a directional response. Figure 3 plots the verification results for speech and steady-state noise obtained for two different hearing aids.

Unfortunately, using speech signals in addition to steady-state noise is not without limitations. The HA response obtained using this method represents a combined input of speech and noise to the hearing aid; therefore, relative changes between the levels of the speech and noise that could be observed using other measurement techniques, such as the inversion method or coherence, are not apparent to the clinician. This method also does not predict how specific DNR algorithms will perform in realistic environments where the amplitude modulation spectrum of the background noise is more similar to speech, such as in background noise comprised of multiple talkers. Fortunately, most DNR algorithms do not activate unless the background noise has amplitude modulation characteristics that differ from speech. However, additional research is needed to understand how these algorithms behave when the assumptions about the modulation spectra of background noise are violated.

Clinical Recommendations

The title of this chapter poses an important clinical question that should be considered by clinicians who fit amplification for infants, children and adolescents. Unfortunately, the current state of evidence regarding DNR with children and the limitations of our verification procedures do not allow for a straightforward answer to the question. However, the limited body of research does provide some consistent findings that can help clinicians to determine the best approach to use with their pediatric clients. Based on the results from several studies completed with school-age children, DNR does not appear to have a negative impact on speech understanding, while providing improved or equivocal ratings of comfort and sound quality. Although the evidence to support the use of DNR to reduce listening effort is only in the most fundamental stages and has only been evaluated with normal-hearing children, there appears to be some indication that DNR may help to improve ease of listening, although much more work with children with hearing loss is necessary before firm conclusions can be reached. Based on the current data, DNR would be appropriate for school-age children as long as verification methods can demonstrate that audibility is not compromised when speech and noise are presented to the device simultaneously.

DNR should be applied with caution for younger children and infants, primarily because there have not been studies to show that speech recognition is preserved within this critical time frame for speech and language acquisition. School-age children, even those with hearing loss, have developed a significant amount of speech and language knowledge that can be used to support top-down processing if distortion of the speech signal occurs during processing by the HA. However, infants and young children are still developing these foundational skills. The decision to implement any signal processing feature that could alter this process should not be taken lightly or without strong evidence to support it. Future studies of DNR should attempt to adapt experimental paradigms to answer some of these critical questions for younger groups of children.

Finally, DNR should not be viewed as the only solution that audiologists have at their disposal to reduce the negative impacts of background noise on children. The evidence regarding directional microphones and frequency-modulation (FM) systems suggests that both of those technologies may be appropriate solutions for children who wear hearing aids, depending on the listening situation. If background noise is a concern, the audiologist should consider all potential solutions, characteristics of the child's likely listening situations, as well as the effectiveness of each of these tools when making decisions about appropriate implementation of technology for a specific child. DNR does have limited advantages over directional microphones and FM systems in specific situations. Unlike directional microphones, DNR does not require spatial separation of the background noise and signal of interest in order to be effective. DNR can also be implemented in situations with multiple talkers of interest, a situation where most current FM technology would be impractical. Audiologists should also consider counseling teachers, parents and children about strategies to reduce background noise in classrooms and in the home, as well as positioning in the environment to maximize audibility of the signal of interest.

Conclusion

Minimizing the negative perceptual and psychological consequences of background noise is an important goal for audiologists who provide amplification for children. DNR is a widely-available signal processing strategy that adjusts the gain of the hearing aid in an attempt to minimize noise and maintain the integrity of the speech signal. Preliminary research evaluating the efficacy of DNR for children who wear hearing aids indicates that, for school-age children, DNR can improve listener ratings of sound quality and reduce listening effort without negatively affecting speech understanding. If DNR is determined to be appropriate, clinicians must verify the impact of this signal processing strategy on the audibility of speech, preferably using a speech signal in steady-state background noise. Additional evidence is needed to support the use of DNR for younger children, as well as children with severe-to-profound hearing loss, since DNR research has not yet been completed with these groups.

Acknowledgements

Special thanks to Brenda Hoover for reviewing a previous version of this manuscript. Research reported in this chapter was supported by the National Institute for Deafness and Communication Disorders grants RO1 DC4300 10, T35 DC8757, P30 DC4662, and F31 DC010505.

References

Alcantara, J.L., Moore, B.C., Kuhnel,V., and Launer, S. 2003. Evaluation of the noise reduction system in a commercial digital hearing aid. *International Journal of Audiology* 42(1): 34–42.

Auriemmo, J., Kuk, F., Lau, C., Dornan, B.K., Sweeton, S., Marshall, S., and Stenger, P. 2009. Efficacy of an adaptive directional microphone and a noise reduction system for school-aged children. *Journal of Educational Audiology* 15: 15–27.

Bentler, B., Kirby, B., and Stiles, D. 2010. Impact of digital noise reduction on pediatric performance. Poster session presented at the annual conference of the American Academy of Audiology, San Diego, CA.

Bentler, R., and Chiou, L.K. 2006. Digital noise reduction: An overview. *Trends in Amplification* 10(2): 67–82.

Boymans, M., and Dreschler, W.A. 2000. Field trials using a digital hearing aid with active noise reduction and dual-microphone directionality. *Audiology* 39(5): 260–8.

Bradley, J.S., and Sato, H. 2008. The intelligibility of speech in elementary school classrooms. *Journal of the Acoustical Society of America* 123(4): 2078–86.

Conlin, J.A., Gathercole, S.E., and Adams, J.W. 2005. Children's working memory: Investigating performance limitations in complex span tasks. *Journal of Experimental Child Psychology* 90(4): 303–17.

Dreschler, W.A., Verschuure, H., Ludvigsen, C., and Westermann, S. 2001. ICRA noises: Artificial noise signals with speech-like spectral and temporal properties for hearing instrument assessment. International Collegium for Rehabilitative Audiology. *Audiology* 40(3): 148–57.

Gustafson, S., McCreery, R., Hoover, B., Kopun, J.G., and Stelmachowicz, P. in preparation. Ease of listening and speech recognition for normal hearing children with the use of digital noise reduction.

Hagerman, B., and Olofson, A. 2004. A method to measure the effect of noise reduction algorithms using simultaneuous speech and noise. *Acta Acustica* 90: 356–361.

Hoetink, A.E., Korossy, L., and Dreschler, W.A. 2009. Classification of steady state gain reduction produced by amplitude modulation based noise reduction in digital hearing aids. *International Journal of Audiology* 48(7): 444–55.

Hu, Y., and Loizou, P.C. 2007. A comparative intelligibility study of single-microphone noise reduction algorithms. *Journal of the Acoustical Society of America* 122(3): 1777.

Kates, J.M. 2008. *Digital hearing aids.* San Diego, CA: Plural Publishing, Inc.

Koopman, J., Franck, B.A., and Dreschler, W.A. 2001. Toward a representative set of «real-life» noises. *Audiology* 40(2): 78–91.

Lewis, J.D., Goodman, S.S., and Bentler, R.A. 2010. Measurement of hearing aid internal noise. *Journal of the Acoustical Society of America* 127(4): 2521–8.

Marcoux, A.M., Yathiraj, A., Cote, I., and Logan, J. 2006. The effect of a hearing aid noise reduction algorithm on the acquisition of novel speech contrasts. *International Journal of Audiology* 45(12): 707–14.

McCreery, R., Ito, R., Spratford, M., Lewis, D., Hoover, B., and Stelmachowicz, P.G. 2010. Performance-intensity functions for normal-hearing adults and children using computer-aided speech perception assessment. *Ear and Hearing* 31(1): 95–101.

Mueller, H.G., Weber, J., and Hornsby, B.W. 2006. The effects of digital noise reduction on the acceptance of background noise. *Trends in Amplification* 10(2): 83–93.

Nábělek, A.K., Freyaldenhoven, M.C., Tampas, J.W., Burchfield, S.B., and Muenchen, R.A. 2006. Acceptable noise level as a predictor of hearing aid use. *Journal of the American Academy of Audiology* 17(9): 626–39.

Neuman, A.C., Wroblewski, M., Hajicek, J., and Rubinstein, A. 2010. Combined effects of noise and reverberation on speech recognition performance of normal-hearing children and adults. *Ear and Hearing* 31(3): 336–44.

Palmer, C.V., and Grimes, A.M. 2005. Effectiveness of signal processing strategies for the pediatric population: A systematic review of the evidence. *Journal of the American Academy of Audiology* 16(7): 505–14.

Ricketts, T., Galster, J., and Tharpe, A.M. 2007. Directional benefit in simulated classroom environments. *American Journal of Audiology* 16(2): 130–44.

Ricketts, T.A., and 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(5): 270–7.

Sarampalis A, Kalluri S, Edwards B, Hafter E. 2009. Objective measures of listening effort: Effects of background noise and noise reduction. *Journal of Speech, Language, and Hearing Research* 52(5): 1230–40.

Souza, P.E., Jenstad, L.M., and Boike, K.T. 2006. Measuring the acoustic effects of compression amplification on speech in noise. *Journal of the Acoustical Society of America* 119(1): 41–4.

Stelmachowicz, P., Lewis, D., Hoover, B., Nishi, K., McCreery, R., and Woods, W. 2010. Effects of digital noise reduction on speech perception for children with hearing loss. *Ear and Hearing* 31 (3): 345–355.

Stelmachowicz, P.G., Hoover, B.M., Lewis, D.E., Kortekaas, R.W., and Pittman, A.L. 2000. The relation between stimulus context, speech audibility, and perception for normal-hearing and hearing-impaired children. *Journal of Speech, Language, and Hearing Research* 43(4): 902–14.

Tyler, R.S., and Kuk, F.K. 1989. The effects of «noise suppression» hearing aids on consonant recognition in speech-babble and low-frequency noise. *Ear and Hearing* 10(4): 243–9.

Woods, W., Nooraei, N., Galster, J., and Edwards, B. 2010. Real-world listening preference for an optimized digital noise reduction algorithm. *Hearing Review* 17(9): 38–43.