Published in final edited form as:

Ear Hear. 2010 June ; 31(3): 345–355. doi:10.1097/AUD.0b013e3181cda9ce.

Effects of digital noise reduction on speech perception for children with hearing loss

Patricia Stelmachowicz, Ph.D.,

Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131

Dawna Lewis, Ph.D.,

Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131

Brenda Hoover, M.A.,

Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131

Kanae Nishi, Ph.D.,

Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131

Ryan McCreery, M.S., and

Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131

William Woods, Ph.D.

Starkey Hearing Research Center, 2150 Shattuck Ave #408, Berkeley, California 94704

Abstract

Objective—While numerous studies have investigated the effects of single-microphone digital noise reduction algorithms for adults with hearing loss, similar studies have not been conducted with young hearing-impaired children. The goal of this study was to examine the effects of a commonly-used digital noise reduction scheme (spectral subtraction) in children with mild-moderately severe sensorineural hearing losses. It was hypothesized that the process of spectral subtraction may alter or degrade speech signals in some way. Such degradation may have little influence on the perception of speech by hearing-impaired adults who are likely to use contextual information under such circumstances. For young children who are still developing various language skills, however, signal degradation may have a more detrimental effect on the perception of speech.

Design—Sixteen children (eight 5–7 year olds and eight 8–10 year olds) with mild-moderately severe hearing loss participated in this study. All participants wore binaural behind-the-ear hearing aids where noise reduction processing was performed independently in 16 bands with center frequencies spaced 500 Hz apart up to 7500 Hz. Test stimuli were nonsense syllables, words, and sentences in a background of noise. For all stimuli, data were obtained with noise reduction on and off.

Results—In general, performance improved as a function of SNR for all three speech materials. The main effect for stimulus type was significant and post hoc comparisons of stimulus type indicated

CORRESPONDING AUTHOR: Patricia Stelmachowicz, Boys Town National Research Hospital, 555 N. 30th St. Omaha, Nebraska 68131, (Phone: 402- 498-6522; Fax: 402:452-5015; stelmach@boystown.org.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

⁵In previous studies, we have found that young children will occasionally respond with a phoneme that is not part of the stimulus set. To document these instances, we elected to include an “other” category. In the analysis of both overall performance and phonetic features “other” responses were assumed to be incorrect.

that speech recognition was higher for sentences than for both nonsense syllables and words, but no significant differences were observed between nonsense syllables and words. The main effect for noise reduction and the two-way interaction between noise reduction and stimulus type were not significant. Significant age group effects were observed, but the two-way interaction between NR and age group was not significant.

Conclusions—Consistent with previous findings from studies with adults, results suggest that the form of noise reduction used in the current study does not have a negative effect on the overall perception of nonsense syllables, words, or sentences across the age range (5–10 years) and SNRs (0, +5, and +10 dB) tested.

Keywords

hearing loss; children; hearing aids; noise reduction

INTRODUCTION

A common complaint of individuals with hearing loss is an inability to understand speech in the presence of noise (Kochkin 2000, 2002). Numerous studies with hearing-impaired (HI) listeners have reported significant deficits in speech perception in the presence of noise (Finitzo-Hieber and Tillman 1978; Suter 1985) and the perception of speech in noise has been shown to be particularly difficult for children with hearing loss. In a study designed to determine the speech-to-noise ratio (SNR) required to score 71% correct, Blandy and Lutman (2005) found that 7 year old children required a better SNR (−4 dB) than a group of adults (−6 dB) despite the fact that the children had better audiological thresholds. Note that all subjects had thresholds within the normal range. They concluded that the ability to recognize speech in noise is not fully developed by 7 years of age. Jamieson et al. (2004) examined the speech intelligibility of young school-aged children in the presence of typical classroom noise. Although all children had some difficulty understanding speech under these circumstances, the youngest groups (kindergarten and first graders) had considerably more difficulty than the older children. Hall et al. (2002) compared the effects of a speech-shaped masker and a two-talker masker on perception for both adults and school aged children. Results revealed that the masking effect for the two-talker speech competition was greater in children than in adults. When a continuous masker was used, results revealed higher thresholds for the two-talker masker than for the speech-shaped noise masker in both groups. However, the magnitude of this effect was greater in the children than in the adults. Gravel et al. (1999) examined the ability of twenty children with mild to severe hearing loss (ages 4–11 years) to recognize speech in a background of multi-talker competition for two different hearing-aid microphone configurations (omni-directional and dual-microphone technology). The speech and multi-talker competition was presented at 0 and 180 degrees azimuth respectively. An adaptive procedure was used to estimate the SNR corresponding to 50% correct performance. The SNR was estimated for both words and sentences. Results revealed significant effects for microphone type, speech materials, and age. Specifically, even with directional microphones, the younger children required a more advantageous SNR to achieve the same performance as the older children. Thus, it appears that, in order to achieve equivalent levels of performance, young children with hearing loss require a better SNR than older children and adults.

An important goal in the design and development of advanced hearing instruments is to improve the signal-to-noise ratio (SNR). The largest improvements in speech perception in noise have been shown to occur for FM systems (Hawkins 1984; Anderson and Goldstein 2004; Lewis et al. 2004; Anderson et al. 2005). The goal of an FM system is to reduce the negative consequences of noise, distance, and reverberation by placing a microphone close to the talker's mouth and transmitting the signal (via FM) to an ear-level receiver. Although these

systems have been shown to improve auditory experiences in non-academic settings, practical issues (e.g., target signal is restricted to a single talker, talker must wear a microphone, and a lack of SNR improvements for non-primary talkers) have restricted their widespread use outside the classroom (Boothroyd 2004).

Directional microphones in hearing instruments have been shown to improve the SNR by as much as 7–8 dB for adults (Valente et al. 1995) and by an average of 4.7 dB for 4–11-yr old children with mild-to-severe hearing losses (Gravel et al. 1999). However, the youngest children examined in the Gravel et al. study required a more favorable SNR to achieve the same performance as older children. In addition, directional microphones may limit the ability to “overhear” conversations, impede self-monitoring of speech, and pose a safety risk if environmental sounds cannot be detected and localized (McCreery 2008). While adults typically solve these problems by selecting a directional microphone configuration only when listening in noise, young children may not be able to make these decisions reliably (Ricketts and Galster 2008). Despite continued improvements in directional microphone technology, it has been noted that their ability to improve SNR is diminished in reverberant environments, when the source and noise are not spatially separated, or when multiple noise sources exist (Greenburg and Zurek 1992; Ricketts 2000; Ricketts and Hornsby 2003; Woods and Trine 2004).

Although various forms of noise reduction (NR) have been available in hearing aids for many years (Graupe et al. 1987; Fabry 1991), initial improvements for speech perception in noise typically were minimal (Tyler and Kuk 1989; Fabry and Van Tasell 1990). The introduction of digital signal processing provided a means to implement complex algorithms in real time. When spectral and temporal characteristics of the interfering noise are predictable and can be clearly characterized, NR can be quite effective at improving the SNR. In hearing-aid applications where characteristics of both the signal and noise are unknown and time varying, improving speech perception through noise reduction is more challenging (Levitt 2001; Chang et al. 2007). Assuming the target signal is speech, interfering signals may be random noise, another talker, or multiple talkers. Currently, the most common methods of NR use some variation of either spectral subtraction or an assessment of SNR in each band followed by gain reduction. In the former method, the noise spectrum is estimated during pauses between words and is then subtracted from the noisy speech spectrum in either the time domain or frequency domain. In the latter method of NR, the first stage is to determine the SNR within each frequency band. Stationary signals are interpreted as noise while modulated signals are assumed to be speech. Gain reductions then are applied according to pre-determined tolerable SNR values in each band. Across various NR systems, many different parameters (e.g., number of bands, time constants, filtering techniques) can be manipulated at each stage. In general, the ability of these systems to detect the *presence* of noise is quite good. To separate speech from noise without altering the signal of interest, however, is much more challenging. Studies with adults have shown significant improvements in speech perception when the noise is restricted to a narrow frequency region (Van Dijkhuizen et al. 1991; Rankovic et al. 1992). When the long-term spectra of the target signal and noise are similar, most studies have failed to show improvements in speech perception (Levitt et al. 1993; Boymans and Dreschler 2000; Alcantara et al. 2003; Natarajan et al. 2005; Bentler et al. 2008). Kates (2008) reported that, in cases where speech and noise overlap in frequency, speech is likely to be attenuated by spectral subtraction. Since young children require a better SNR to achieve performance equal to that of adults (Stelmachowicz et al., 2000; Picard and Bradley, 2001; Bradley and Sato, 2008), a reduction in the level of speech may impair speech perception in noise.

Despite a lack of improvement in performance, numerous studies have shown improved comfort, a decrease in listening effort (Jamieson et al. 1995; Boymans and Dreschler 2000; Walden et al. 2000) and improvements in perceived signal quality when NR is used (Arehart

et al. 2003; Ricketts and Hornsby 2005). Hochberg et al. (1992) studied the influence of single microphone NR on phoneme recognition in normal-hearing (NH) listeners and cochlear implant users. NR had no effect on performance for either group at high SNRs, but a significant improvement in performance was observed at poorer SNRs for the implanted group only. These results suggest that studies of NR should include a range of SNRs in order to fully examine potential benefits or degradation.

Jamieson et al. (1995) evaluated the effectiveness of an adaptive Wiener filter digital noise reduction algorithm¹ (Wiener 1949) for six adults with sloping sensorineural hearing losses. Two types of speech materials (spondees and nonsense syllables) were presented in broadband noise and in multi-talker babble. Results revealed either no improvement or a slight decrease in performance with NR processing. Mean performance for nonsense syllables in multi-talker babble decreased by 12%, but this difference was not statistically significant. Error analyses revealed that NR processing tended to increase confusions for consonant place of articulation. Interestingly, for continuous discourse in a paired-comparison task, all listeners indicated a strong preference for NR in most listening conditions. Hu and Loizou (2007a) evaluated the intelligibility of sentences and nonsense syllables processed by eight different NR algorithms. Stimuli were presented in four different types of noise at 0 and 5 dB SNRs. The only notable finding was significantly better performance for sentences in one of the eight conditions (car noise at 5 dB SNR) with the Wiener-type algorithm.

Although studies have not been conducted with hearing-impaired children, Marcoux et al. (2006) modeled the effects of NR on language development by evaluating pre-verbal language acquisition of non-native speech contrasts in noise with two groups of English-speaking NH adults. One group listened to speech signals processed with NR while the other heard unprocessed signals. No significant differences in performance were observed between the two groups, suggesting that NR did not degrade the acquisition of novel speech contrasts.

To date, no studies have directly investigated the effects of NR for children with hearing loss. There are many factors to consider when determining how such algorithms might influence auditory access and perceptual learning in young hearing-impaired children. It has been argued that the amplification needs of infants and young children differ from those of adults who generally acquire hearing loss later in life (Stelmachowicz 1991; Seewald et al. 1996; Boothroyd 1997). For children with hearing loss, amplification must facilitate the development of early auditory skills, laying the foundation for the extraction of regularities in the speech signal and the development of language.

The measured efficacy of a specific processing scheme may vary depending upon the language skills of the listener and the outcome measure(s) used. While previous studies with adult listeners have revealed that NR does not improve or impair speech recognition in noise, it is possible that modifications of acoustic speech cues from NR may have a negative impact on speech perception for young hearing-impaired children. For example, Hu and Loizou (2007b) have reported that, in some cases, the algorithms that were found to perform the best in terms of overall quality were not the same algorithms that performed the best in terms of speech intelligibility. They suggested that improvements in quality might be accompanied by a decrease in intelligibility due to the distortion of speech as a result of excessive suppression of the noise + speech signal.

Furthermore, certain aspects of NR processing may actually have a negative impact on speech perception when contextual information is limited. For example, a specific NR algorithm may

¹An adaptive Wiener filter is a commonly-used statistically-based approach to reduce the amount of noise present in a signal by comparison with an estimation of the desired noiseless signal.

be of optimal benefit only for children who have learned to use context to support speech perception under adverse listening conditions. Because of the inherent redundancy of conversational speech, potential degradation of the signal may have little influence on speech perception for adults with post-lingual hearing loss, but may be detrimental to infants and young children who are still in the process of developing speech and language skills. It is for these reasons that NR is not routinely recommended when fitting hearing aids to infants and young children.

To derive a clear picture of the effects of NR for HI children, it may be useful to approach the problem from a developmental perspective. Thus, the goal of the current study was to determine the influence of a NR scheme (i.e., modified spectral subtraction) on the perception of speech in noise for 5–10 year old children with mild-moderate hearing loss using stimuli that vary in terms of contextual information. These results, in conjunction with individual measures of receptive vocabulary, may allow us to speculate on the influence of NR on speech perception in noise at various stages of vocabulary acquisition and to provide insight into the effectiveness of these signal processing techniques for infants and young children with hearing loss.

METHOD

Subjects

Sixteen children with mild-moderately severe hearing loss (no thresholds > 75 dB HL in the better ear) participated in this study. Group 1 consisted of eight 5–7 year olds (mean: 6.5 years, SD = 0.59) and Group 2 consisted of eight 8–10 year olds (mean: 9.2 years, SD = 0.64). These two age groups were included in order to assess the effects of development on the perception of speech materials with varying degrees of contextual information. Figure 1 shows mean better ear auditory thresholds as a function of frequency. The Bankson-Bernthal Quick Screen of Phonology (Bankson and Bernthal 1990) was used to identify children with speech production errors that would influence scoring. Children with multiple production errors were not included in the study. However, children with a few *consistent* production errors (e.g., always substituted /f/ for /θ/) were included; the error(s) were documented to facilitate appropriate scoring. To estimate the language age of each child, the Peabody Picture Vocabulary Test (PPVT-III, Form B; Dunn and Dunn 1997) was administered. The mean language age of Group 1 was 7.15 years (SD= 1.14) and the mean language age of Group 2 was 9.67 years (SD = 2.0). Two children (ages 7 and 9 years, respectively) received below average standard scores on the PPVT-III, while three children (ages 5, 9, and 10 years, respectively) had scores greater than 2 SDs above the mean for their chronological age. In general, the majority of these children with mild-moderate losses had age-appropriate vocabulary skills as measured by the PPVT-III.

Hearing instruments and signal processing

All participants wore binaural Starkey Destiny (Model 1200) behind-the-ear hearing aids modified to perform only amplitude compression and noise reduction². With these devices, noise reduction is carried out in the frequency domain using a modified spectral subtraction algorithm which compares ongoing input spectrum levels to an estimated noise level in order to minimize the effect of other processing (e.g., directional microphones). A voice-activity detector is used to detect the speech and stop the noise estimation process. Noise reduction

²While the form of noise reduction in this study (i.e., rapid gain changes acting independently across frequency and driven by input signal statistics) would likely not differ across hearing aids, we note that the specific implementation used here is not present in any current Starkey or other hearing aids. In addition to variations in specific parameter values (e.g., frequency analysis bandwidths or maximum attenuation) across implementations, marketed aids also typically use control logic to turn on NR only in certain situations, or to change the parameters of the noise reduction across situations. Our test case – a steady-state noise at a moderate level – is a situation where NR would typically be applied. See related text in the Discussion section.

processing was performed independently in 16 bands with center frequencies spaced 500 Hz apart up to 7500 Hz. Band levels were computed every 0.5 ms and smoothed with a phonemic-scale time constant³ before comparison to the estimated noise level. Bands with levels equal to or less than their estimated noise level were attenuated by 6 dB. Bands with levels 6 dB or more above the estimated noise level were unaltered (i.e., received 0 dB attenuation). For bands with levels between these ranges, the amount of attenuation gradually decreased in a sigmoidal manner from 6 to 0 dB. Eight-channel, slow-acting compression gain (20 ms attack, 2 sec release) was computed before and applied after the NR gain was computed and applied. Thus, output levels with NR on were always at or below output levels with NR off.

Hearing aid fitting

For each subject, the hearing aids were set to targets based on the Desired Sensation Level (DSL m i/o v.5.0) algorithm (Scollie 2005; Seewald et al. 2005) using Noah-Link and research fitting and communication software (PECS) from Starkey Laboratories. To ensure adequate audibility of test stimuli across frequency, real-ear verification was completed using the Audioscan Verifit probe-microphone system. When necessary, further adjustments were made using the PECS software.

Stimuli

Test stimuli were: 15 VCV nonsense syllables constructed by combining 15 consonants (/p, b, t, d, k, g, l, r, m, n, s, z, ʃ, f, v/) with the vowel /a/⁴; 90 monosyllabic words from the Phonetically Balanced Kindergarten List (PBK) (Haskins, Reference Note 1); and 90 meaningful sentences (BKB), each with 3 key words (Bench et al. 1979). VCVs were used in order to minimize omissions that are expected for CVs and VCs. The PBK words were obtained from recordings (female talker) developed at Brigham Young University (Harris, Reference Note 2). The VCVs and sentences were spoken by two different female talkers and digitally recorded in a sound booth using a condenser microphone (AKG Acoustics C535 EB) with a flat response (+/- 2 dB) from 0.2 to 20 kHz. Speech tokens were amplified (Shure M267) and sampled at a rate of 44.1 kHz with a quantization of 16 bits. Stimulus files were scaled to 65 dB SPL at the calibrated position in the sound booth.

Procedures

Prior to presentation, test stimuli were mixed with speech-shaped noise at the three SNRs (0, +5, +10 dB). These SNRs were selected to represent conditions that are typically encountered by school-aged children. Poorer SNRs were not used in this study because NR algorithms typically are not designed to operate at negative SNRs (Loizou, 2007, chapter 11). To engage noise reduction, a 30-second noise-only precursor was presented prior to each speech-plus-noise stimulus set. Stimuli were presented via a single loudspeaker at 0° azimuth in the sound field. The presentation order of the NR-on and NR-off conditions was counterbalanced across subjects. Each nonsense syllable was heard six times (2 NR conditions × 3 SNRs). To ensure that no subject heard the same word or sentence tokens more than once across the three SNRs, the 90 words and 90 sentences items were divided into six different stimulus sets using a Latin Square design.

An examiner in the adjacent control room initiated stimulus presentations. For all children, the order of presentation was nonsense syllables, words, and sentences. There were a total of 270 presentations per subject (90 presentations each of VCVs, PBK words, and BKB sentences).

³A phonemic time scale is a compromise between too fast (which creates artifacts) and too slow (which decreases the amount of NR that can be achieved).

⁴The vowel /a/ was selected because it was used in previous studies of consonant confusions with adults (Miller and Nicely 1955) and children (Neuman and Hochberg 1983).

Nonsense syllables were presented in a closed-set format with the 16 choices (15 consonants and an “other” category⁴) displayed on a touch-screen monitor. Children were instructed to repeat each VCV and, in most cases, a second examiner (seated next to them) marked their responses. Some of the older children used the touch screen or mouse to mark their own responses. Collapsed across SNR and NR conditions, the category “other” was chosen only 5% and 1% of the time for the 5–7 and 8–10 year olds, respectively. For words and sentences, the children repeated what they heard. In cases where a child was inattentive or vocalizing during stimulus presentation, the test item was repeated once. If a response was unclear, the two examiners conferred to make a decision and/or the child was asked to repeat his/her response. Nonsense syllables were scored as correct or incorrect based on the consonant only. Words were scored as either correct or incorrect and sentences were scored as correct only when all three key words within each sentence were correct. Visual reinforcement was given immediately after each response. For example, each response might be followed by the removal of a puzzle piece on the screen to display an interesting visual image. This feedback was not contingent upon correct responses, but was used only to maintain interest in the task.

RESULTS

To examine the effects of noise reduction on speech recognition, factorial analysis of variance (ANOVA) was conducted with stimuli (nonsense syllables, words, sentences) SNR (0, +5, +10 dB), and NR condition (on, off) as within-subjects factors and age group (5–7 years, 8–10 years) as a between-subject factor. All percent correct scores were converted to Rationalized Arcsine Units (RAU; Studebaker 1985) prior to statistical analyses to normalize covariance as a function of percent correct. For each reported analysis, Mauchly’s test of sphericity was conducted, and Greenhouse-Geisser adjusted values were used if the assumption of sphericity was violated. The only variable that reached significance ($p < 0.05$) on Mauchly’s test (1940) (indicating that the assumption of homogeneity of variance was violated) was SNR. Therefore, the main effect of SNR was tested using Greenhouse-Geisser correction. Figure 2 shows the mean percent correct performance and standard deviations for nonsense syllables, words, and sentences in the NR off (filled bars) and NR on (open bars) conditions for the two age groups (left and right columns) at 0, +5, and +10 dB SNR. As expected, performance improved as a function of SNR for all three speech materials, although the changes from +5 to +10 dB were minimal for the older group. As might be expected, standard deviations for the younger group were larger than for the older children.

Noise reduction

The main effect for NR was not significant [$F_{1,14} = 0.866$; $p = 0.362$; $\eta^2_p = 0.060$], suggesting that the addition of NR did not have negative or positive effects on average speech recognition in noise. The main effect for stimulus type was significant [$F_{2,28} = 137.96$; $p < 0.001$; $\eta^2_p = 0.908$]. Post hoc comparisons of stimulus type using Bonferroni-adjusted alpha levels of 0.017 (0.05/3) indicated that speech recognition was higher for sentences than for both nonsense syllables and words. However, there were no significant differences in performance between nonsense syllables and words. In addition, no significant effects of NR on speech recognition were observed for the two-way interaction between NR and stimulus type [$F_{2,28} = 0.365$; $p = 0.697$; $\eta^2_p = 0.025$], refuting the hypothesis that the efficacy of the NR algorithm in the current study is dependent upon language skills of the listener.

The main effect for age group was significant [$F_{1,14} = 6.897$; $p = 0.020$; $\eta^2_p = 0.330$], suggesting that the 8–10 year-olds exhibited higher speech recognition scores in noise than the younger group. However, the two-way interaction between NR and age group was not significant [$F_{1,14} = 0.132$; $p = 0.722$; $\eta^2_p = 0.009$] indicating that NR did not have a differential effect on performance for the two age groups. As expected, speech recognition varied significantly as a

function of SNR [$F_{1.5, 20.3} = 56.164$; $p < 0.001$; $\eta^2_p = 0.800$]. Post hoc comparisons of stimulus type using Bonferroni-adjusted alpha levels of 0.017 (0.05/3) indicated that speech recognition followed the predicted pattern with the highest performance at +10 dB SNR, followed by +5 dB, and 0 dB, respectively. The NR algorithm used in the current study was designed to provide a consistent amount of gain reduction regardless of SNR. The observed non-significant two-way interaction between NR and SNR [$F_{1,14} = 0.866$; $p = 0.362$; $\eta^2_p = 0.060$] is consistent with the design of this NR algorithm. The two-way interaction between age group and stimulus was not significant [$F_{2,28} = 0.322$; $p = 0.727$; $\eta^2_p = 0.022$], suggesting that the pattern of performance across stimulus type with sentences and nonsense syllables being higher than words was the same for both age groups. None of the higher-order (three-way and four-way) interactions involving NR were significant.

Significant variability in speech recognition across conditions and age groups resulted in several effects that were not statistically significant, but were large enough on an individual basis that such trends might influence a clinician's decision to use NR for a particular child. For example, while the three-way interaction between age, stimulus type and NR was not statistically significant [$F_{2,30} = 2.34$; $p = 0.115$; $\eta^2_p = 0.13$], more than half of the 5–7 year-olds had decreased recognition for words for the NR on condition compared to the NR off condition. To examine the effects of noise reduction for individual listeners, Fig. 3 shows the effects of NR on the perception of nonsense syllables, words, and sentences for the 5–7 year olds (left side) and the 8–10 year olds (right side). Within each age group, subjects are ordered by age in this figure and in Figure 4. Because the effects of NR as a function of SNR were not statistically significant, data were collapsed across the three SNRs. Results for each subject are displayed as a vertical line representing the change in speech recognition from NR off to NR on. Upward arrows indicate an *improvement* in performance with NR on and the downward arrows show *decrements* in performance with NR on. The length of the vertical bars shows the magnitude of change and squares indicate cases where there was no change in performance across the two NR conditions. The bolded arrows indicate cases where the performance differences across the two NR conditions fell outside the 95% confidence interval for all 16 HI subjects. Note that some subjects improved with NR on while others performed more poorly. As might be expected, individual variability was greater for the 5–7 year-olds than for the 8–10 year-olds for all three types of speech materials. Performance for words and nonsense syllables showed greater variability than sentences.

Nonsense syllable data

Relatively large individual differences were observed, particularly for the youngest age group. Specifically, three of the eight 5–7 year olds demonstrated a statistically significant decrease in performance for nonsense syllables while only two children showed statistically significant improvements. Interestingly, the children with the highest performance in the NR off condition showed a decrease in performance with NR on, while children with the poorest performance with NR off showed an increase in performance with NR engaged. For the oldest group, two of the eight children showed significantly better performance with NR on while two other children showed significantly poorer performance.

Despite the lack of a significant main effect for NR, further examination of the nonsense syllable data revealed relatively large effects of NR for specific consonants, particularly at the poorest SNR (0 dB). Hu and Loizou (2007a) have suggested that a feature analysis of consonant confusions can provide valuable information to help identify the weaknesses of current NR algorithms and thus facilitate the design of better processing schemes. In fact, they argue that in order for a noise reduction algorithm to improve speech intelligibility for adults, it would need to improve place and manner feature scores. Thus, additional analyses were conducted to examine errors for the two age groups in terms of phonetic features (place, manner, voicing).

For this analysis, three feature values (see Table I) were assigned to each of the 15 consonants. Using this coding scheme, each subject's responses for each phoneme were analyzed separately for accuracy of consonant place, manner, and voicing features.

The within-subjects effects of NR and SNR on phonetic feature (place, manner and voicing), were examined using multivariate analysis of variance (MANOVA). The effect of NR on the combined dependent variable of phonetic feature was not significant [$F_{3, 13} = 1.58$, $p = 0.243$, Wilks' $\lambda = 0.733$, $\eta^2_p = 0.026$], suggesting that, on average, NR did not systematically affect the accuracy of place, manner and voicing perception. The overall lack of improvement or decrement in speech recognition with NR in the current study is consistent with the above-mentioned predictions of Hu and Loizou (2007a). The effect of SNR on the combined dependent variable of phonetic feature was significant [$F_{6, 56} = 3.12$, $p = 0.013$, Wilks' $\lambda = 0.562$, $\eta^2_p = 0.237$]. Analysis of each dependent variable using a Bonferroni-adjusted alpha level of 0.017 showed that accuracy for place [$F_{2, 30} = 6.95$; $p = 0.003$; $\eta^2_p = 0.317$], manner [$F_{2, 30} = 5.20$; $p = 0.011$; $\eta^2_p = 0.258$], and voicing [$F_{2, 30} = 4.67$; $p = 0.017$; $\eta^2_p = 0.238$] decreased as SNR decreased. This result is consistent with the main effect for SNR which showed that VCV recognition scores decreased as SNR decreased.

Figure 4 shows the feature analysis results for individual subjects as a function of SNR for the 5–7 and 8–10 year olds. Place, manner, and voicing are shown in the top, middle, and lower panels, respectively and the various symbols have the same meaning as in Fig. 3. The gray shaded regions in each panel show the 95% confidence intervals for two comparable groups (5–7 years and 8–9 years) of normal-hearing children ($N = 72$) from a study by Nishi et al. (2009). Note that the test stimuli and procedures related to the perception of nonsense syllables were identical across the two studies, except that 10 year olds were not included in the previous study. With the exception of one 6 year old child (denoted by asterisks), performance for the children with hearing loss was quite good at 5 and 10 dB SNR, often approximating that of the normal-hearing group. Further inspection of the individual data revealed that this participant had poorer hearing sensitivity in the high frequencies than any other participant (better ear thresholds of 75 and 65 dB HL at 4 and 8 kHz, respectively). Although this child had little difficulty producing speech sounds on the Bankson Bernthal Quick Screen of Phonology (which is a picture naming task), in the experiment he was not able to correctly identify any of the five fricatives (/s, z, ʃ, f, v/), regardless of SNR or NR condition. It should be noted that DSL target values in the high frequencies could not be achieved for this child. Thus, as is often the case with moderate-to-severe high-frequency hearing loss, audibility of the fricative class was most likely limited to only the peak energy of high amplitude fricatives (e.g., /s, ʃ, z/), which may not be sufficient to support fricative identification in noise.

Error patterns—In Table II, cases where the error rate was $>50\%$ are shown as a function of SNR for both age groups. Specific errors for a target consonant are shown in parentheses in order of frequency of occurrence. Note that, for a subset of consonants [/r/ at 0 and 5 dB (5–7 yrs); /b/ at 0, 5, and 10 dB and /r/ at 0 dB (8–10 yrs)], even though error rates differed across the two NR conditions, the most common confusions were the same. In these instances, it is likely that the noise (as opposed to NR processing) was most likely responsible for the observed errors. For other consonants, however, error rates and/or error patterns differed for the two NR conditions. Collapsed across age, the error rates for NR on and NR off were equivalent for only one of the 10 comparisons, NR on was better than NR off for 4 of the 10 comparisons, and NR on was poorer than NR off for 5 of the 10 comparisons. When collapsed across age group, SNR, and NR condition, the most frequent errors were /v/ confusions for /b/ and /l/ confusions for /r/. Errors for the consonant /r/ were present at all three SNRs for the youngest group, but occurred only at 0 dB for the older children. Furthermore, the confusions for /r/ were highly variable across both SNR and NR conditions, suggesting that children may have been guessing randomly.

The results for /b/ can be compared with data from Miller and Nicely (1955) for their conditions most comparable to those in the current study (0 and +6 dB SNR). Interestingly, while they also found that the most common error for /b/ was /v/, error rates were substantially lower than in the current study. They reported that /b/ was heard as /v/ only 11% of the time at 0 and +6 dB SNR. Collapsed across age in the current study, /b/ was heard as /v/ 56% of the time at both 0 and +5 dB SNR and 37.5% of the time at +10 dB SNR. Numerous methodological differences across studies may explain the divergent error rates. Miller and Nicely (1955) used noise with a flat spectrum while speech-shaped noise was used in the current study. Thus, the higher proportion of /v/ responses in the current study may be due to the fact that low-frequency energy in the speech noise obscured the acoustic cues for /b/, where the primary spectral energy is also low frequency. However, Cutler et al. (2004), who also found /v/ to be the most common error for /b/ at 0 dB SNR, reported error rates of only 5% (CV) and 15% (VC), despite the fact that speech-shaped noise was used in their investigation. In both of these previous studies participants were normal-hearing adults compared to 5–10 year old children with hearing loss in the current study. Numerous studies have reported that young children exhibit greater difficulties understanding speech in noise compared to adults (Fallon et al. 2000; Hall et al. 2002; Litovsky 2005; Wightman and Kistler 2005; Johnstone and Litovsky 2006) and that children with hearing loss exhibit more difficulties in noise than children with normal hearing (Finitzo-Hieber and Tillman 1978). Another methodological difference is that the stimuli in the current study were processed by hearing aids prior to presentation.

Acoustic analyses—To examine the effects of NR processing on the /b/ - /v/ confusion from an acoustic perspective, the Starkey Destiny hearing aid was programmed to provide appropriate gain in accordance with the mean audiogram shown in Fig. 1. The hearing aid was coupled to a 2 cc coupler (Frye MZ-3) that terminated with a ½-inch microphone and was placed in a test chamber (Fonix 6500). Stimuli were presented to the test chamber and recorded using customized software. Figure 5 shows a series of spectrograms for /b/ (left) and /v/ (right) in three conditions with a partial view of the adjacent vowels. The top row shows spectrograms (in quiet) prior to hearing-aid processing. Note that the silent gap and the release burst for /b/ are clearly visible. Row 2 shows hearing-aid processed signals in a background of speech-shaped noise (at 10 dB SNR) with NR off. Despite the favorable SNR, after hearing aid processing the silent gap and the release burst are obscured by noise. Row 3 shows similar results with NR on. Although the magnitude of noise is markedly reduced with NR on, there is not a clear distinction between /b/ and /v/ in the two spectrograms. It is important to note that these observations should be interpreted with caution since it is known that there are numerous other cues to distinguish between b/ and /v/ and the ability to visualize specific acoustic characteristics in a spectrogram may not necessarily correlate with perception.

Performance for words and sentences

Interestingly, half of the children in the youngest group demonstrated significantly poorer performance for words in the NR on condition while only one child showed a significant improvement in performance. Interestingly, this child's performance in the NR off condition was quite poor (40%). In the older group, performance for words was relatively high in both NR conditions and the differences between the two NR conditions were relatively small.

When sentence materials were used, error rates were relatively low for both age groups suggesting that when lexical, semantic, and syntactic context are available, the negative effects of NR processing are minimal (even for the youngest age group). In general, changes in sentence performance with NR on were smaller than those observed for nonsense syllables and words. The ceiling effects observed for sentences in the older group was expected and is consistent with our hypothesis that, as children mature, their ability to use semantic and syntactic context will facilitate speech perception in noise.

DISCUSSION

Overall, the results of the current study suggest that the effects of NR on speech perception for children as young as 5 years of age may be similar to those reported for adults. As described previously, studies with adults have shown no improvement, but no degradation in performance. It is more difficult, however to speculate on whether NR would be appropriate for younger children and/or at what chronological or language age NR should be implemented. It is unlikely that this type of study could be successfully completed with younger children due to their limited attention span and the likelihood that production errors would complicate interpretation of results. However, it is encouraging that no significant differences were observed across NR conditions for nonsense syllables, words, or sentences for either age group.

In the current study, the highest errors occurred for /f/, /g/, /b/, and /r/, where /f/ was most often confused with /t/, /g/ was confused with /d/, /b/ was confused with /v/, and /r/ was confused with /l/ and /v/. It is important to note that /f/ - /t/, /b/ - /v/ and /r/ - /v/ distinctions would be highly visible on the lips, while /r/ - /l/ and /g/ - /d/ would be indistinguishable. Thus, in typical conversation, young children may be able to use visual cues to supplement acoustic information degraded by noise. However, it is not known to what degree young children rely on visual cues to clarify consonant confusions in adverse listening conditions.

Although not addressed in the current study, as noted previously, studies with adults have found a preference for NR on vs. NR off in terms of sound quality and/or listening effort (Jamieson et al. 1995; Boymans and Dreschler 2000; Walden et al. 2000; Hu and Loizou 2007b; Sarampalis et al. 2009). If this were also found to be the case for young children, a decrease in listening effort might improve attentiveness and/or increase time on task under adverse listening conditions. To date, the effects of NR on attention and listening effort in children have not been directly evaluated.

When interpreting the results of this study it is important to note several potential weaknesses and/or limitations. The design of the study was limited by the attention span of the youngest participants (5 years). Since each child heard a large number of test stimuli (270), it was not feasible to include multiple talkers and/or multiple repetitions of the nonsense syllables. However, as can be seen in Table II, the most commonly observed errors were consistent across subjects and conditions, suggesting that the results would be representative of the target group in this study. In addition, it is possible that factors such as age of identification, age of amplification, and consistency of hearing-aid use may influence the ability to understand speech in noise. Specifically, high quality and consistent auditory experiences in early childhood are likely to establish a solid foundation on which children can develop strategies to maintain relatively high performance in noise. The potential influence of these factors was not investigated in the current study. Finally, the majority of children in the current study had hearing losses in the mild-to-moderate range. It is likely that any negative effects of NR might be greater for children with severe-to-profound hearing loss due to limited audibility. It has been well established that reduced frequency selectivity and a loss of cochlear nonlinearities increases as a function of degree of hearing loss (Horst 1987; Moore 1996; Oxenham and Bacon 2003). Thus, for children with poorer hearing sensitivity, cochlear damage may impair the ability to understand speech in noise to a greater extent than was observed for children in the current study. In fact, some evidence in support of this concern is provided by data from the 6 year old child who had poorer hearing sensitivity in the high frequencies than any other participant (better ear thresholds of 75 and 65 dB HL at 4 and 8 kHz, respectively). Although this child had little difficulty producing sounds on the Bankson Bernthal Quick Screen of Phonology (which is a picture naming task), in the experiment he was not able to correctly identify any of the five fricatives (/s, z, ʃ, f, v/), regardless of SNR or NR condition. As noted previously, DSL target values in the high frequencies could not be achieved for this child. Thus,

as is often the case with moderate-to-severe high-frequency hearing loss, audibility of the fricative class was most likely limited to only the peak energy of high amplitude fricatives (e.g., /s, ʃ, z/), which may not be sufficient to support fricative identification in noise. As can be seen in Fig. 4, marked reductions in performance with NR processing occurred only at 0 dB SNR for this child. At 5 dB SNR performance increased markedly and at 10 dB SNR minimal differences were observed between the NR on and off conditions.

The primary motivation for this study was that, with any single-microphone noise reduction algorithm of this form, the gain reduction used to create the perceived noise reduction may also reduce the audibility of speech energy. While our group data show no adverse effects of the implemented version of noise reduction, several variables will influence the applicability of our results in general. These include: (1) the maximum amount of noise reduction implemented, (2) the level of the input signal relative to the user's absolute threshold, and (3) the user's residual dynamic range of hearing. For instance, it is generally the case that increasing the magnitude of noise reduction also increases the amount of speech attenuation and the audibility of possible artifacts. Our use of a 6 dB maximum attenuation reflects a certain compromise among these effects. As for the second and third variables, while limited speech attenuation may not affect performance when the output speech is already well above the user's threshold, this same attenuation may limit audibility when output speech is near or just above threshold, as is the case when input levels are low. It is also the case, however, that, for the low-level speech to be audible with NR off, any accompanying noise must also be at a low level. In such cases NR would likely not be applied since the noise is already at a low level and thus would not be perceived as disturbing. The constraints represented by the third variable are related to those of the second variable, in that a reduced dynamic range (typically caused by relatively high absolute thresholds) may put even high-level input sounds near a user's threshold. Thus, an "aggressive" noise reduction setting (i.e., one with high maximum attenuation) may yield usable performance for a user with mild hearing loss while making much speech energy inaudible for someone with a moderate-severe loss. In the latter case the noise reduction would either not be used or used with a less aggressive setting. Finally, it is important to note that the results of this study would not necessarily apply to alternate NR algorithms.

CONCLUSIONS

The overall goal of this study was to determine if a common form of NR used in hearing aids (modified spectral subtraction) may have a detrimental effect on the perception of speech for young HI children who are developing speech and language skills. Consistent with previous findings from studies with adults, results suggest that the form of NR used in the current study does not appear to have a negative effect on the overall perception of nonsense syllables, words, or sentences across the age range (5–10 years) and SNRs (0, +5, and +10 dB) tested. Further studies are needed to assess the effects of NR at younger ages, to investigate the effects of NR for children with greater degrees of hearing loss, and to determine if NR can decrease listening effort in children with hearing loss.

Acknowledgments

This work was supported by grants from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health (R01 DC04300, P30 DC04662)

REFERENCES

Alcantara JL, Moore BC, Kuhnel V, et al. Evaluation of the noise reduction system in a commercial digital hearing aid. *Int J Audiol* 2003;42:34–42. [PubMed: 12564514]

- Anderson KL, Goldstein H. Speech perception benefits of FM and infrared devices to children with hearing aids in a typical classroom. *Lang Speech Hear Serv School* 2004;35:169–184.
- Anderson KL, Goldstein H, Colodzin L, et al. Benefit of SNR enhancing devices to speech perception of children listening in a typical classroom with hearing aids or a cochlear implant. *J Educ Audiol* 2005;12:14–28.
- Arehart KH, Hansen JHL, Gallant S, et al. Evaluation of an auditory masked threshold suppression algorithm in normal-hearing and hearing-impaired listeners. *Speech Comm* 2003;40:575–592.
- Bankson, NW.; Bernthal, JE. Quick Screen of Phonology. San Antonio, TX: Special Press, Inc; 1990.
- Bench J, Kowal A, Bamford J. The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children. *Brit J Audiol* 1979;13:108–112. [PubMed: 486816]
- Bentler R, Wu Y-H, Kettel J, et al. Digital noise reduction: Outcomes from laboratory and field studies. *Int J Audiol* 2008;47:447–460. [PubMed: 18698521]
- Blandy S, Lutman M. Hearing threshold levels and speech recognition in noise in 7-year-olds. *Int J Audiol* 2005;44:435–443. [PubMed: 16149238]
- Boothroyd A. Auditory development of the hearing child. *Scand Audiol Suppl* 1997;46:9–16. [PubMed: 9309833]
- Boothroyd A. Hearing aid accessories for adults: The remote FM microphone. *Ear Hear* 2004;25:22–33. [PubMed: 14770015]
- Boymans M, Dreschler WA. Field trials using a digital hearing aid with active noise reduction and dual-microphone directionality. *Audiol* 2000;39:260–268.
- Bradley JS, Sato H. The intelligibility of speech in elementary school classrooms. *J Acoust Soc Am* 2008;123:2078–2086. [PubMed: 18397015]
- Chang HY, Koh SN, Rahardja S. Subband Kalman filtering incorporating masking properties for noisy speech signal. *Speech Communication* 2007;49:558–573.
- Cutler A, Weber A, Smits R, et al. Patterns of English phoneme confusions by native and non-native listeners. *J Acoust Soc Am* 2004;116:3668–3678. [PubMed: 15658717]
- Dunn, LM.; Dunn, LM. Peabody Picture Vocabulary Test. Third Edition ed.. Circle Pines, MN: American Guidance Service, Inc; 1997.
- Fabry DA, Van Tasell DJ. Evaluation of an articulation-index based model for predicting the effects of adaptive frequency response hearing aids. *J Speech Hear Res* 1990;33:676–689. [PubMed: 2273883]
- Fabry, DA. In: Feigin, JA.; Stelmachowicz, PG., editors. Signal processing hearing aids with the pediatric population; Pediatric amplification: Proceedings of the 1991 National Conference; Omaha, NE: Boys Town National Research Hospital; 1991. p. 49–60.
- Fallon M, Trehub SE, Schneider BA. Children's perception of speech in multitalker babble. *J Acoust Soc Am* 2000;108:3023–3029. [PubMed: 11144594]
- Finitzo-Hieber T, Tillman T. Room acoustics effects on monosyllabic word discrimination ability for normal and hearing-impaired children. *J Speech Hear Res* 1978;21:440–458. [PubMed: 713515]
- Graupe D, Grosspietsch JK, Basseas SP. A single-microphone-based self-adaptive filter of noise from speech and its performance evaluation. *J Rehab Res Dev* 1987;24:119–126.
- Gravel JS, Fausel N, Liskow C, et al. Children's speech recognition in noise using omni-directional and dual-microphone hearing aid technology. *Ear Hear* 1999;20:1–11. [PubMed: 10037061]
- Greenburg JE, Zurek P. Evaluation of an adaptive beam forming method for hearing aids. *J Amer Acad Audiol* 1992;91:1662–1676.
- Hall JW III, Grose JH, Buss E, et al. Spondee recognition in a two-talker masker and a speech-shaped noise masker in adults and children. *Ear Hear* 2002;23:159–165. [PubMed: 11951851]
- Hawkins DB. Comparisons of speech recognition in noise by mildly-to-moderately hearing-impaired children using hearing aids and FM systems. *J Speech Lang Hear Dis* 1984;49:409–418.
- Hochberg I, Boothroyd A, Weiss M, et al. Effects of noise and noise suppression on speech perception by cochlear implant users. *Ear Hear* 1992;13:263–271. [PubMed: 1397769]
- Horst JW. Frequency discrimination of complex signals, frequency selectivity, and speech perception in hearing-impaired subjects. *J Acoust Soc Am* 1987;82:874–885. [PubMed: 3655121]
- Hu Y, Loizou P. Subjective comparison and evaluation of speech enhancement algorithms. *Speech Comm* 2007a;49:588–601.

- Hu Y, Loizou P. A comparative intelligibility study of single-microphone noise reduction algorithms. *J Acoust Soc Am* 2007b;122:1777–1786. [PubMed: 17927437]
- Jamieson DG, Brennan RL, Cornelisse LE. Evaluation of a speech enhancement strategy with normal-hearing and hearing-impaired listeners. *Ear Hear* 1995;16:274–286. [PubMed: 7672476]
- Jamieson DG, Kranjc G, Yu K, Hodgetts WE. Speech intelligibility of young school-aged children in the presences of real-life classroom noise. *J Am Acad Audiol* 2004;15:508–517. [PubMed: 15484600]
- Johnstone PM, Litovsky RY. Effect of masker type and age on speech intelligibility and spatial release from masking in children and adults. *J Acoust Soc Am* 2006;122:2177–2189. [PubMed: 17069314]
- Kates, JM. *Digital Hearing Aids*. Katz, JM., editor. San Diego: Plural Publishing; 2008.
- Kochkin S. MarkeTrak V: Why my hearing aids are in the drawer: The consumer's perspective. *Hear Journal* 2000;53:34–42.
- Kochkin S. MarkeTrak VI: 10-Year customer satisfaction trends in the U.S. market. *Hear Rev* 2002;9:14–25. 46.
- Levitt H. Noise reduction in hearing aids: a review. *J Rehabil Res Dev* 2001;38:111–121. [PubMed: 11322463]
- Levitt H, Bakke M, Kates J, et al. Signal processing for hearing impairment. *Scand Audiol Suppl* 1993;38:7–19. [PubMed: 8153567]
- Lewis MS, Crandell CC, Valente M, et al. Speech perception in Noise: Directional microphones versus frequency modulation (FM) systems. *J Amer Acad Audiol* 2004;15:426–439. [PubMed: 15341224]
- Litovsky RY. Speech intelligibility and spatial release from masking in young children. *J Acoust Soc Am* 2005;117:3091–3099. [PubMed: 15957777]
- Loizou, P. *Speech Enhancement: Theory and Practice*. Boca Raton, FL: CRC Press, Taylor and Francis; 2007.
- Marcoux AM, Yathiraj A, Cote I, et al. The effect of a hearing aid noise reduction algorithm on the acquisition of novel speech contrasts. *Int J Audiol* 2006;45:707–714. [PubMed: 17132559]
- Mauchly JW. Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics* 1940;11:204–209.
- McCreery, RW. Pediatric hearing aid verification: Innovative trends. 2008. Audiology Online Retrieved 11/7/08 from: http://www.audiologyonline.com/articles/article_detail.asp?article_id=2063 (last viewed 12/10/08)
- Miller GA, Nicely PE. An analysis of perceptual confusions among some English consonants. *J Acoust Soc Am* 1955;27:338–352.
- Moore BC. Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. *Ear Hear* 1996;17:133–161. [PubMed: 8698160]
- Natarajan A, Hansen J, Arehart K, et al. An auditory-masking-threshold-based noise suppression algorithm GMMSE-AMT[ERB] for listeners with sensorineural hearing loss. *EURASIP J. Appl. Signal Proc* 2005;18:2938–2953.
- Neuman AC, Hochberg I. Children's perception of speech in reverberation. *J. Acoust. Soc. Am* 1983;73:2145–2149. [PubMed: 6875100]
- Nishi K, Lewis DE, Hoover BM, et al. Children's perception of American English consonants in noise. *J Acoust Soc Am* 2009;122:3032.
- Oxenham AJ, Bacon SP. Cochlear compression: perceptual measures and implications for normal and impaired hearing. *Ear Hear* 2003;24:352–366. [PubMed: 14534407]
- Picard M, Bradley JS. Revisiting speech interference in classrooms. *Audiology* 2001;40:221–244. [PubMed: 11688542]
- Rankovic CM, Freyman RL, Zurek PM. Potential benefits of adaptive frequency-gain characteristics for speech reception in noise. *J Acoust Soc Am* 1992;91:354–362. [PubMed: 1737884]
- Ricketts TA. Impact of noise source configuration on directional hearing aid benefit and performance. *Ear Hear* 2000;21:194–205. [PubMed: 10890727]
- Ricketts TA, Hornsby WY. Distance and reverberation effects on directional benefit. *Ear Hear* 2003;24:472–484. [PubMed: 14663347]
- Ricketts TA, Hornsby WY. Sound quality measures for speech in noise through a commercial hearing aid implementing digital noise reduction. *J Am Acad Audiol* 2005;16:270–277. [PubMed: 16119254]

- Ricketts TA, Galster J. Head angle and elevation in classroom environments: implications for amplification. *J Speech Lang Hear Res* 2008;15:516–525. [PubMed: 18367693]
- Sarampalis A, Kalluri S, Edwards B, Hafter E. Objective measures of listening effort: Effects of background noise and noise reduction. *J Speech Lang Hear Res*. 2009
- Scollie S. The Desired Sensation Level Multistage Input/Output Algorithm. *Trends Amplif* 2005;9:159–197. [PubMed: 16424945]
- Seewald, RC.; Moodie, KS.; Sinclair, S., et al. Traditional and theoretical approaches to selecting amplification for infants and young children. In: Bess, FH.; Gravel, JS.; Tharpe, AM., editors. *Amplification for Children with Auditory Deficits*. Nashville, TN: Bill Wilkerson Center Press; 1996. p. 161-191.
- Seewald R, Moodie S, Scollie S, et al. The DSL method for pediatric hearing instrument fitting: historical perspective and current issues. *Trends Amplif* 2005;9:145–157. [PubMed: 16424944]
- Stelmachowicz, PG. Current issues in pediatric amplification. In: Feigin, J.; Stelmachowicz, PG., editors. *Pediatric Amplification: Proceedings of the 1991 National Conference*; Omaha, NE: Boys Town National Research Hospital; 1991. p. 1-17.
- Stelmachowicz P, Hoover B, Lewis D, Kortekaas R, Pittman A. The relationship between stimulus context, speech audibility, and perception for normal and hearing impaired children. *Journal of Speech, Language and Hearing Research* 2000;43:902–914.
- Studebaker GA. Rationalized arcsine transform. *J Speech Hear Res* 1985;28:455–462. [PubMed: 4046587]
- Suter A. Speech recognition in noise by individuals with mild hearing impairments. *J Acoust Soc Am* 1985;78:887–900. [PubMed: 4031259]
- Tyler RS, Kuk FK. The effects of ‘noise suppression’ hearing aids on consonant recognition in speech-babble and low frequency noise. *Ear Hear* 1989;10:243–249. [PubMed: 2619801]
- Valente M, Fabry DA, Potts LG. Recognition of speech in noise with hearing aids using dual microphones. *J Amer Acad Audiol* 1995;6:440–449. [PubMed: 8580504]
- van Dijkhuizen JN, Festen JM, Plomp R. The effect of frequency-selective attenuation on the speech-reception threshold of sentences in conditions of low-frequency noise. *J Acoust Soc Am* 1991;90(2 Pt 1):885–894. [PubMed: 1939893]
- Walden BE, Surr RK, Cord MT, et al. Comparison of benefits provided by different hearing aid technologies. *J Amer Acad Audiol* 2000;11:540–560. [PubMed: 11198072]
- Wiener, N. *Extrapolation, Interpolation, and Smoothing of Stationary Time Series*. New York: Wiley; 1949.
- Wightman FL, Kistler DJ. Informational masking of speech in children: effects of ipsilateral and contralateral distracters. *J Acoust Soc Am* 2005;118:3164–3176. [PubMed: 16334898]
- Woods WS, Trine TD. Limitations of theoretical benefit from an adaptive directional system in reverberant environments. *Acoust. Res Letters Online* 2004;5:153–157.

REFERENCE NOTES

- Haskins, HA. Master’s thesis. Evanston, IL: Northwestern University; 1949. A phonetically balanced test of speech discrimination for children.
- Harris, RW. *Speech Audiometry Materials*. Provo, UT: Hearing and Speech Sciences Laboratory, Brigham Young University; 1991.

Fig. 1. Mean hearing level (in dB HL) as a function of frequency for the 16 participants in the current study.

Fig. 2. Mean percent correct performance as a function of SNR for the 5-7 and 8-10 year olds (left and right columns, respectively). Data are shown for nonsense syllables, words, and sentences for the NR off (filled bars) and NR on (open bars) conditions. Error bars denote ± 1 S.D. from the mean.

Fig. 3.

Individual data for both age groups are plotted for all three stimulus types. The arrows denote the direction of change (improvement, decrement) between the NR on and NR off conditions. The line length + arrow indicate the magnitude of the change. Bolded lines/arrows denote changes that are statistically significant. Within each panel, subjects are ordered by age.

Fig. 4. Nonsense syllable data (collapsed across SNR) analyzed in terms of place, manner, and voicing for the two age groups. Line length, arrows, and subject order by age follow the convention noted in Fig. 3. Shaded region shows the 5-95th percentile for the total group.

Fig. 5.

Top row shows the unprocessed spectrograms in quiet for /aba/ and /ava/. Row 2 shows results in noise (at 10 dB SNR) after processing by the hearing aid with NR off. Row 3 shows similar results with NR on.

TABLE I

Phonetic feature coding used in the current study.

Feature	Values	Phonemes
Manner	stop	/p k b d g/
	fricative	/f s ʃ v z/
	liquid	/l r/
	nasal	/m n/
Place	front	/p f b v m/
	mid	/s t z d l n/
	back	/k g ʒ r/
Voicing	voiced	/b d g v z l m n r/
	voiceless	/p t k f s ʃ/

TABLE II

Percent errors and confusions for conditions where performance fell in the lower half of the observed scores (>50%) for *either* NR on or NR off. Results are shown as a function of SNR for both age groups and specific errors are shown in parentheses in order of frequency of occurrence. Gray areas denote error rates <50%, O indicates responses in the “Other” category, and bold numbers indicate the condition (either NR on or NR off) with the fewest errors.

5–7 yrs				
NR off			NR on	
SNR	Phoneme (Errors)	% Errors	Phoneme (Errors)	% Errors
0	g (d, b, t)	62.5%	g (b,d,l)	37.5%
0	r (l, z, b)	50.0%	r (l, O)	62.5%
0	b (v)	37.5%	b (l, v, m,O)	87.5%
0	f (O, t, v)	50.0%	f (t, b, v, O)	62.5%
5	r (l, v, O)	62.5%	r (l, O)	50.0%
10	r (v, m, n, l, O)	62.5%	r (l, O)	50.0%
8–10 yrs				
0	b (v)	75.0%	b (v)	75.0%
0	r (v, g, l)	50.0%	r (v, p, l)	62.5%
5	b (v)	87.5%	b (v, f)	100.0%
10	b (v)	50.0%	b (v)	62.5%