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An Evidence-Based Systematic Review of Directional Microphones and Digital Noise Reduction Hearing Aids in School-Age Children With Hearing Loss

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Abstract

Purpose—The purpose of this evidence-based systematic review was to evaluate the efficacy of digital noise reduction and directional microphones for outcome measures of audibility, speech recognition, speech and language, and self- or parent-report in pediatric hearing aid users.

Method—The authors searched 26 databases for experimental studies published after 1980 addressing one or more clinical questions and meeting all inclusion criteria. The authors evaluated studies for methodological quality and reported or calculated *p* values and effect sizes when possible.

Results—A systematic search of the literature resulted in the inclusion of 4 digital noise reduction and 7 directional microphone studies (in 9 journal articles) that addressed speech recognition, speech and language, and/or self-or parent-report outcomes. No digital noise reduction or directional microphone studies addressed audibility outcomes.

Conclusions—On the basis of a moderate level of evidence, digital noise reduction was not found to improve or degrade speech understanding. Additional research is needed before conclusions can be drawn regarding the impact of digital noise reduction on important speech, language, hearing, and satisfaction outcomes. Moderate evidence also indicates that directional microphones resulted in improved speech recognition in controlled optimal settings; however, additional research is needed to determine the effectiveness of directional microphones in actual everyday listening environments.

Keywords

children; evidence-based systematic review; digital noise reduction; directional microphones; amplification

The negative perceptual consequences of background noise on speech understanding have been established across numerous studies with children (Elliott, 1979; Johnson, 2000). Children with and without hearing loss experience greater degradation in speech recognition

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than do adults in background noise (McCreery et al., 2010; Stelmachowicz, Pittman, Hoover, & Lewis, 2001); furthermore, children with hearing loss may experience even greater degradation in speech understanding than do their peers with normal hearing (Crandell, 1993; Finitzo-Hieber & Tillman, 1978). Interference from background noise not only influences speech understanding but can also have substantial effects on learning and academic achievement, including reading and mathematics (Shield & Dockrell, 2003, 2008). Classroom noise levels are frequently observed to exceed recommended levels of noise and reverberation, often reaching levels that are likely to degrade speech recognition and make learning more difficult. Whereas the recommended signal-to-noise ratio (SNR) for educational environments is +15 dB to +30 dB, SNRs in most classrooms are only between -6 dB and +6 dB (Knecht, Nelson, Whitelaw, & Feth, 2002; Nelson, Bougatsos, & Nygren, 2008). Frequency modulation (FM) systems can be coupled with hearing aids (HAs) to limit the effects of background noise on speech understanding and learning in classrooms (Lewis & Eiten, 2011); yet, FM systems may not be practical in all listening situations, such as learning environments like classroom discussions with multiple talkers of interest. When FM systems are impractical or not available, HA features such as directional microphones and digital noise reduction (DNR) may help to minimize the negative perceptual consequences of background noise.

Directional microphones and DNR are HA features that were developed to minimize the negative effects of background noise for HA users. DNR includes a wide range of signal processing strategies designed to classify the input to the HA as primarily speech input or noise input, and then reduce gain when the input to the HA is predominantly noise. DNR can be implemented using a wide range of algorithms, including modulation detection and complex filtering. Significant differences in the implementation of DNR between manufacturers and within manufacturers' different products make general predictions about the effect of DNR and related outcomes difficult (Hoetink, Körössi, & Dreschler, 2009).

Directional microphones also have been developed to limit the negative effects of noise on speech understanding and comfort. Directional microphones maintain amplification for sounds originating in front of the listener while limiting amplification for sounds arriving from the sides and behind the listener. Spatial processing is accomplished by having multiple microphones at different locations on the HA or a single microphone with multiple ports. Directional microphones can be assigned to a specific program in the HA, which requires the listener to switch the device to a directional setting for situations with background noise. More recently, manufacturers have developed directional microphone systems that switch automatically from omnidirectional to directional response when the input to the HA has spectral, modulation, and/or level characteristics consistent with background noise. This process often relies on a similar classification signal processing to DNR. Directional microphones can also be fixed, where the direction pattern of the microphones does not change, or be adaptive, where the directional pattern of the microphone changes in response to the location of a speech or noise source in the environment. The advent of programmable directional microphone and DNR settings, as well as adaptive features that change automatically in response to the environment, create novel challenges for clinicians who must decide whether these features should be activated as well as how to verify any impact their use may have on audibility. Recent data support the idea that school-age children can reliably change their HA program in response to changes in the environment (Scollie, 2010), but the efficacy and effectiveness of adaptive signal processing features have yet to be determined.

Although research with pediatric HA users is becoming more prevalent, most DNR research to date has been conducted in the adult population. In general, adult DNR studies reveal that speech recognition typically is not affected by DNR (Bentler, 2005). However, adults can

experience improved ease of listening in noise with DNR compared to conditions without DNR (Boymans & Dreschler, 2000; Ricketts & Hornsby, 2005). For example, Mueller, Weber, and Hornsby (2006) documented that while DNR did not change speech recognition for adults, DNR did result in listeners being able to tolerate a higher acceptable noise level in comparison to conditions without DNR. The lack of improvement or degradation in speech understanding for adults with DNR is not surprising given that most algorithms use modulation detection to reduce gain only for periods of the signal where only noise is present (Kates, 2008). Some DNR algorithms may selectively reduce gain only in frequency regions where noise is the primary signal; however, the spectral characteristics of speech and noise in realistic environments often overlap significantly. Therefore, when both speech and noise are present in the environment, many DNR algorithms do not make significant changes to the signal in order to preserve the audibility of speech (Peeters, Kuk, Lau, & Keenan, 2009). Even if DNR were active when both speech and noise were present in the environment, any reduction in gain would be applied to the combined speech in noise signal, making it unlikely that SNR improvements would be sufficient to improve speech understanding. Therefore, as with adults, the primary objective for using DNR with children should be to maintain speech understanding while limiting the negative impact of background noise on listening effort, cognitive processing, and the child's listening comfort. In cases where DNR does result in decreased speech audibility, the negative effect on speech recognition would likely be greater for children than what would be expected with adults, as children require more audibility to reach the same levels of speech recognition as adults (Stelmachowicz et al., 2001).

Unlike DNR, directional microphones have the potential to improve the SNR for the listener, particularly in situations where the signal of interest and noise sources are spatially separated (Boymans & Dreschler, 2000; Gravel, Fausel, Liskow, & Chobot, 1999). The benefits of directional microphones for improving speech understanding in noise for adults who use HAs have been previously documented in three systematic reviews (Agence d'évaluation des technologies et des modes d'intervention en santé [AETMIS], 2003; Amlani, 2001; Bentler, 2005). Whereas the magnitude of improvement observed with directional microphones varied across studies, reviews by AETMIS (2003), Amlani (2001), and Bentler (2005) all reported that overall directional microphones did provide a statistically significant improvement in speech recognition across studies with adults. In general, the largest improvements in speech recognition were observed for experimental conditions where the stimuli are presented in front of the listener and the noise source was fixed behind the listener. The presence of reverberation, diffuse noise sources, or other more realistic acoustic conditions resulted in smaller improvements in speech recognition in adults.

Although existing studies can provide clinicians with support for using these advanced HA signal processing strategies with adults, the findings are difficult to generalize to children in school-age populations due to the ongoing development of auditory, speech, and language skills coupled with the unique, acoustically complex environments in which they must access auditory information. Changes in audibility that result from DNR and directional microphones may have different effects on children than those previously reported with adult listeners. Since children experience greater degradation in speech understanding from background noise than adults, the degree to which the negative consequences of background noise can be limited may have a greater impact on children than has been observed in adults. Additionally, differences in listening behavior between adults and children have the potential to affect the degree to which similar results can be observed with children. Unless the talker of interest and sources of noise are stationary, improvements in the SNR with directional microphones are predicated on the ability to orient the head toward the signal of interest. Ching and colleagues (2009) evaluated listening behavior in infants and young

children with normal hearing and hearing loss in simulated realistic listening situations. These children looked at the speaker of interest more than 40% of the time, which suggests that young children are able to orient toward a speaker in realistic environments, but may not do so consistently.

Evidence-based systematic reviews (EBSRs) and guidelines of HA signal processing for children are necessary to provide objective, nonbiased summaries of empirical evidence and recommendations for HA selection and clinical management based on empirical evidence. The American Academy of Audiology Pediatric Amplifications Guidelines Task Force has announced a soon-to-be published evidence-based guideline that will likely include information on directional microphones and DNR. Currently available pediatric HA articles, clinical guidelines, and protocols (American Academy of Audiology Task Force, 2003; Bagatto, Scollie, Hyde, & Seewald, 2010; King, 2010; Scollie, 2010) are not based on systematic reviews of the evidence. Additionally, as pointed out by Scollie (2010), current clinical guidelines provide conflicting recommendations regarding the use of HA features with children. Whereas Bagatto and colleagues (2010) recommended decisions about selecting HA features be conducted on an individual basis using clinical judgment, King (2010) recommended that features such as directional microphones and DNR be routinely used with children. Therefore, the purpose of the current EBSR is to systematically review the current research evidence regarding the effect of directional microphones and DNR on relevant hearing, speech, and satisfaction outcomes for school-age children with hearing loss.

Beginning in 2010, ASHA's National Center for Evidence-Based Practice in Communication Disorders began a systematic search of the current, peer-reviewed research to determine the impact of several HA signal processing features on select communication outcomes in school-age children, including: directional microphone response, noise reduction, amplitude compression, and frequency lowering. The results of the literature search are presented in a series of three EBSR reports. This review focuses on the impact of directional microphone response and noise reduction; two additional reviews address frequency lowering and amplitude compression. This series of EBSRs is intended to inform clinical decisions pertaining to the selection and management of the aforementioned HA technology for school-age children.

We developed clinical questions for this review in consideration of the population, intervention, comparison, and outcome. Our population of interest is school-age children, and our intervention comparisons include the use of DNR in HAs versus the use of HAs without DNR and omnidirectional response as compared to directional microphone response. Four categories of outcome measures have been suggested to evaluate the efficacy of HA features with children: audibility, speech recognition, speech and language outcomes, and subjective measures (Hogan, 2007). Audibility, the ability to hear sounds directly, impacts an individual's ability to recognize, learn, and interpret speech. Audibility outcome measures are objective measures of speech audibility, including sound-field testing, real ear measures (gold standard), real-ear-to-coupler difference, Articulation Index (AI; ANSI S3.5-1969) scores, and Speech Intelligibility Index (SII; ANSI S3.5-1997) scores. Because children with hearing impairments are more likely to have limited exposure to audible speech (Arlinger, 2001), they are at increased risk for language difficulty in areas such as vocabulary acquisition (e.g., Briscoe, Bishop, & Norbury, 2001; Pittman, 2008), which is important in developing context for academic subject areas (e.g., Maynard, Pullen, & Coyne, 2010; Myers & Botting, 2008; Scarborough, 1998). Speech recognition outcome measures are objective measures of speech stimuli identification, including phoneme, nonword, word, and sentence materials. The accurate perception of speech underlies the development of spoken and written language skills (Bavin, Grayden, Scott, & Stefanakis,

2010; DesJardin, Ambrose, Martinez, & Eisenberg, 2009). Speech and language outcome measures include standardized measures of communication development. Ultimately, the impact of hearing ability on social interaction becomes a primary focus and is often captured by self-report or parent-report questionnaires. The impact of these outcomes on school-age children fitted with hearing devices is an important consideration for audiologists who provide services to that population.

Two clinical questions were developed as the focus of this EBSR:

1. What are the effects of DNR technology as compared to HAs without DNR on audibility outcomes, speech recognition outcomes, speech and language outcomes, and HA self-report or parent-report outcomes for school-age children with hearing loss?
2. What are the effects of directional microphone response as compared to omnidirectional response on audibility outcomes, speech recognition outcomes, speech and language outcomes, and HA self-report or parent-report outcomes for school-age children with hearing loss?

Method

Literature Search

We obtained articles for this series of reviews from a literature search of HA processing features. The fourth author, experienced in conducting systematic literature searches (e.g., Frymark et al., 2010), developed a search strategy. We searched 26 databases (e.g., PubMed, CINAHL, PsycINFO, ERIC) from January to April 2010 using keywords related to hearing loss, children, and amplification (e.g., *hearing aid*, *hearing instrument*, *amplification*, *child*, *frequency compression*). A full list of the searched databases and search terms are included in a concurrent review within this series, McCreery, Venediktov, Coleman, and Leech (2012). We examined reference lists of all full-text articles retrieved from the initial search to identify additional relevant articles. One author looked for articles citing the studies accepted for inclusion (see McCreery et al., 2012) and searched in the EBSCO database for literature published by 26 prolific authors. The overarching search for the series of reviews was initially completed from January to April 2010; however, given the size and scope of the review series as well as the lapse of time with report of results, the search was updated to include studies published through July 2011.

Study eligibility was based on the following inclusion criteria: (a) experimental or quasi-experimental research designs addressing one or more of the clinical questions; (b) studies written in English that were published in a peer-reviewed journal after 1980; (c) studies including school-aged children between the ages of 5 and 17 years with documented conductive, mixed, or sensorineural hearing loss; (d) studies using wearable HAs and signal processing approaches that are currently available in commercial HAs; and (e) studies providing comparative data on HAs with and without the target technological features. Studies including participants outside of the target age range were excluded unless the mean age fell within the target age range or if the data could be split for separate analyses. Operational definitions of signal processing strategies and outcomes are included in McCreery et al. (2012). Two authors independently applied the inclusion criteria to determine study eligibility based on abstracts. A second independent review of preliminarily accepted full-text articles was completed by the same authors to determine final inclusion. We calculated interrater reliability using the kappa statistic (κ) and percent agreement. Interrater disagreements were resolved by consensus or the advisement of the first author, who also reviewed the final list of included and excluded literature for accuracy and completeness. Landis and Koch's (1977) labels describing relative strength of agreement

were applied to κ statistics: $<.00$ = poor, $.00-.20$ = slight, $.21-.40$ = fair, $.41-.60$ = moderate, $.61-.80$ = substantial, and $.81-1.00$ = almost perfect.

Critical Appraisal

Individual studies—Full-text versions of each included study were independently reviewed by the second and third authors, who have educational training and previous experience (e.g., Gosa, Schooling, & Coleman, 2011; Roush, Frymark, Venediktov, & Wang, 2011); these authors appraised experimental research for quality. Each author rated the quality of the study on up to seven appraisal criteria using an adaptation of the ASHA levels-of-evidence scheme (Cherney, Patterson, Raymer, Frymark, & Schooling, 2008; Fey et al., 2010; Mullen, 2007). The levels-of-evidence scheme was developed by the ASHA National Center for Evidence-Based Practice in Communication Disorders along with the ASHA Advisory Committee for Evidence-Based Practice and was piloted prior to its adoption in 2008. The scheme was adapted for evaluation of within-subject repeated measures designs with special consideration for threats to internal validity arising from these study designs (Portney & Watkins, 2009) and with input from the first author regarding the applicability of each appraisal point to HA research. We calculated interrater reliability using κ (weighted as appropriate) and percent agreement. Neither rater had an extensive audiological background; therefore, they requested the knowledge and experience of the first author as necessary to provide background information to clarify any instances of uncertainty during the quality appraisal process. Individual studies received one point for each appraisal criterion met, and quality ratings were determined for each study on the basis of the total number of points. Appraisal points were awarded for (a) an adequate description of study protocol (i.e., sufficient detail provided for replication), (b) assessor blinding, (c) an adequate description of random sampling of participants, (d) randomization to condition or sequence of conditions, (e) counterbalancing of the order of conditions (applicable only to within-subject designs), (f) reporting of p values (or the provision of data to calculate that statistic), and (g) reporting of effect sizes and their confidence intervals (or the provision of data to calculate those statistics).

Body of evidence—We used the Cincinnati Children's Hospital Medical Center body of evidence grading scheme (Cincinnati Children's Hospital Medical Center, 2011a) to evaluate the strength of the evidence for the body of literature for each clinical question. This scheme was selected because it considers several important domains: hierarchy, bias, quantity, magnitude of effect, and consistency of evidence (Coleman, Talati, & White, 2009), and offers a clear and objective approach to evaluating bodies of evidence. The second and third authors independently evaluated the quality of individual studies using the Cincinnati Children's Hospital Medical Center Controlled Clinical Trial Appraisal worksheet (Cincinnati Children's Hospital Medical Center, 2011b) to arrive at a quality level for each study. Interrater agreement was calculated using κ and percent agreement. These two authors then independently evaluated the body of evidence for each clinical question using the Cincinnati Children's Hospital Medical Center evidence grading worksheet to arrive at a grade of high, medium, or low. A high grade of evidence is based on a high-quality systematic review, more than one high-quality randomized controlled trial or more than five high-quality nonrandomized controlled trials or cohort studies. If a body of evidence was graded as high, it suggests that future research is not likely to change confidence in the answer to the clinical question. A moderate grade was based on a high-quality randomized controlled trial or multiple high- or low-quality systematic reviews, randomized and nonrandomized controlled trials, cohort studies, or more than five case-control studies. Moderate evidence suggested that future research is likely to have an important impact on answers to the clinical question. A low grade of evidence indicated that there is consensus but no research to answer the question. A grade was not assignable if

there was insufficient evidence to answer a clinical question. Questions and interrater disagreements were resolved by consensus or advisement of the first author.

Data Extraction and Analysis

With the advisement of the first author, a list of discipline-specific data extraction points was developed. The second and third authors summarized these critical features of each study, including study design, characteristics of the population, previous HA usage, test HA features, HA settings (including volume control and equalization), study protocol, outcome measures, findings, and limitations. The first author reviewed summaries for accuracy and completeness. This information is located throughout the text and tables of this review.

Effect size, r , was calculated for all studies providing sufficient data. In studies providing raw data in which the independent variable was dichotomous and the dependent variables were continuous, the point-biserial correlation co-efficient (r_{pb}) effect size was calculated using an online calculator (Lowry, 2010). If raw data were not presented, an approximated effect size, r , was calculated from F -statistics with corresponding degrees of freedom (dfs ; Garbin, n.d.) or from paired t values and df (Rosenthal & DiMatteo, 2001). The number of participants in each study was entered into an online calculator (Garbin, n.d.) to calculate the confidence interval (CI) surrounding each effect size. Effect sizes favoring the experimental technology (i.e., HAs with DNR or a directional microphone response) investigated in each study were assigned a positive value, whereas effect sizes favoring the control condition (i.e., HAs with DNR deactivated or an omnidirectional response) were assigned a negative value. The magnitude of the r effect sizes was interpreted as follows: small (.10 to .29), moderate (.30 to .49), and large (above .50; Cohen, 1992). P values were calculated in several studies in which raw data were provided but statistical significance for our sample of interest was not reported. We used the Wilcoxon signed ranks test due to the small number of participants.

We discuss the statistical significance of included study findings throughout the text of this review. A finding was considered to be statistically significant if the confidence interval surrounding the effect size did not include the null value and/or if the p value was less than or equal to .05. For each clinical question, we further analyzed results to determine whether any data trends were apparent that suggested an impact of study design or study quality on the results.

Results

Study Selection

Of the 376 studies identified, 168 were eliminated during the abstract review and an additional 171 were subsequently excluded after review of the full text. Of the 37 remaining studies, 14 were eliminated after further scrutiny. This process resulted in a total of 23 articles, nine of which are included in this review. Reasons for exclusion were that the study did not directly address a clinical question for this or another review in the series, did not provide sufficient data for analyses, or reported the use of a technology no longer available in commercial HAs. See McCreery et al. (2012) for a flow chart depicting this process.

Ten studies from nine articles were included in this review. Four studies (Auriemma et al., 2009; Pittman, 2011a, 2011b; Stelmachowicz et al., 2010) provided data to address Clinical Question 1 (DNR) and seven studies (Auriemma et al., 2009; Gravel et al., 1999; Hawkins, 1984; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999; Ricketts, Galster, & Tharpe, 2007, Experiments 1 and 3; Wouters, Litière, & van Wieringen, 1999) addressed Clinical Question 2 (directional microphones). One study (Auriemma et al., 2009) investigated both directional microphone response and DNR.

Interrater Reliability

Overall interrater reliability for the inclusion/exclusion process indicated substantial agreement and moderately high percent agreement between raters ($\kappa = .67$, 87.9%). The interrater reliability for the critical appraisal of individual studies and bodies of evidence was also calculated using the κ statistic (weighted as appropriate) and percent agreement. Perfect interrater agreement ($\kappa = 1.00$, 100%) was obtained for three appraisal criteria: blinding, sampling, and random allocation to condition/sequence. Interrater agreement was moderate for the counterbalancing and effect size appraisal criteria ($\kappa = .60$, 80%; $\kappa = .62$, 90%, respectively) and substantial for the statistical (p value) reporting criterion ($\kappa = .48$, 70%). Interrater reliability was poor ($\kappa = 0$) for one appraisal criterion, protocol description, despite a high percent agreement between raters (i.e., 80%). The skewed distribution of responses created a paradox in which the κ statistic was very low despite a fair percentage of agreement (see Feinstein & Cicchetti, 1990, for further explanation). Interrater reliability and percent agreement for individual study quality determinations, conducted as a step in the process of grading the body of evidence for each question, was substantial ($\kappa = .62$, 90%). Individual ratings are included in the supplementary materials associated with this article.

DNR

Clinical Question 1: What is the effect of DNR technology as compared to HAS without DNR on audibility outcomes, speech recognition outcomes, speech and language outcomes, and HA self- or parent-report outcomes on school-age children with hearing loss?—Four studies (Auriemma et al., 2009; Pittman, 2011a, 2011b; Stelmachowicz et al., 2010) that included a total of 65 participants met the inclusion criteria for this clinical question. Participants ranged in age from 5 to 12.8 years and presented with mild to moderately severe hearing loss. The majority of participants had a sensorineural hearing loss and were experienced HA users. Additional details are presented in Table 1. Four different HA models with varying DNR algorithms were identified across the four studies and included the Widex Diva SD9M/19M, Siemens Explorer 500, Starkey Destiny (Model 1200), and a test HA with modulation-based DNR algorithm and Wiener filter. Researchers in two studies (Auriemma et al., 2009, Stelmachowicz et al., 2010) provided speech recognition outcomes, two (Pittman 2011a, 2011b) provided speech and language outcomes, and one (Auriemma et al., 2009) also provided HA self- or parent-report outcomes. Additional details regarding HA features and experimental procedures are located in the appendix. As a result of the heterogeneity (e.g., differences in specific outcome measures used, differences in severity of hearing loss, differences in compression thresholds and stimulus input levels) and small number of included studies for each clinical question, effect sizes were not averaged across studies.

Speech recognition outcomes: Speech recognition outcomes consisted of nonsense syllable, word, and sentence recognition scores measured at several SNRs. Auriemma et al. (2009) tested word recognition in quiet and at +5, 0, and −10 dB SNR. Stelmachowicz et al. (2010) measured recognition of nonsense syllables, words, and sentences at SNRs of 0, +5, and +10 dB. As shown in Table 2, two (of five) effect sizes yielded a small magnitude of effect (favoring DNR); however, no statistically significant mean differences in speech recognition were reported between conditions with DNR compared to those without DNR in either study at any SNR.

Speech and language outcomes: As reported in Table 3, Pittman, in two studies (2011a, 2011b), examined language outcomes for children with hearing loss using DNR. Pittman (2011b) measured children's ability to appropriately categorize words heard in noise while completing a simultaneous visual task with DNR activated versus deactivated. In Pittman (2011a), children's ability to learn novel words was investigated by exposing children to

nonsense words presented in noise with DNR activated versus deactivated. In both studies, effect sizes were small and nonsignificant with the exception of one finding, in which the p value just reached significance ($p = .047$) and favored HAs with DNR for novel word learning in older children (11–12 years; Pittman, 2011a). The magnitude of this effect was large.

HA self-report or parent-report outcomes: Auriemma et al. (2009) used the parent version of the Abbreviated Profile of Hearing Aid Performance (PA-PHAP; Kopun & Stelmachowicz, 1998) to assess parents' perceptions of their child's response to a range of listening situations after each 6-week trial with the HA with DNR versus without DNR. Parents did not report any significant difference between HA conditions on the PA-PHAP. Children in this study also were asked to respond to a directional subscales questionnaire (Ricketts, Henry, & Gnewikow, 2003) designed to evaluate the child's perceived amount of difficulty hearing in different listening environments. The children did not report any significant differences between settings with DNR and those without DNR for the "sound front" scale; however, significant differences ($p = .03$) were reported for the "sound back" scale, which favored the setting with DNR enabled.

Trend analysis by study design and quality: Individual study quality scores ranged from 4/7 to 5/7 across the four studies. All of the studies were within-subject, repeated measures designs, and three studies counterbalanced conditions, further distinguishing them as crossover designs. In the fourth study, Pittman (2011b) randomized participants to a sequence of conditions, also reducing the potential for order effects. None of authors of these studies reported use of random sampling, and only one indicated that assessors were blinded. However, researchers in all four studies did provide adequate protocol descriptions and reported or provided sufficient information to calculate statistical significance (see Table 4). Results from these studies were analyzed to determine whether variations in study quality or study design were associated with variations in effect size. However, because there were only minimal discrepancies among the included studies in quality and design, no conclusions were possible. The ability of users to control the volume of the HA, although not included as an appraisal point, may significantly impact study findings. Study authors indicated that volume control was deactivated in all but one study (Auriemma et al., 2009), which did not provide information regarding the volume control.

Overall quality of body of evidence for DNR: The authors of one low-quality RCT (Pittman, 2011b) and three low-quality controlled clinical trials (Auriemma et al., 2009; Pittman, 2011a; Stelmachowicz et al., 2010) provided information to address Clinical Question 1. Findings from these studies were generally consistent and suggested that DNR did not have a significant impact on speech recognition, speech and language, or parent/child report outcomes. Using the Cincinnati Children's Hospital Medical Center grading scheme, this constitutes a moderate body of evidence, which means that further research is likely to impact the answer to this clinical question.

Directional Microphones

Clinical Question 2: What is the effect of directional microphone response as compared to omnidirectional response on audibility outcomes, speech recognition outcomes, speech and language outcomes, or HA self-report or parent-report outcomes for school-age children with hearing loss?—Seven studies were found to address this clinical question (Auriemma et al., 2009; Gravel et al., 1999; Hawkins, 1984; Kuk et al., 1999; Ricketts et al., 2007 [Experiment 1, Experiment 3]; Wouters et al., 1999). These studies included a total of 97 participants (ages 4.8–17 years) with hearing loss severity ranging from mild to severely profound. As shown in Table 1, the

majority of participants were experienced HA users with a sensorineural hearing loss. Experimental directional response systems included adaptive automatic or fixed systems that used either dual microphones or a single two-port directional microphone. Additional details pertaining to the HA features and experimental procedures are presented in the appendix. All seven studies included speech recognition outcomes and three (Auriemma et al., 2009; Kuk et al., 1999; Ricketts et al., 2007, Experiment 1) also included HA self- or parent-report outcomes.

Speech recognition outcomes: Speech recognition outcomes were reported for word or sentence recognition accuracy at set SNRs as well as SNRs necessary to achieve 50% accurate speech recognition (see Table 5). Effects of directionality are heavily dependent on the azimuth of the signal and noise in relation to the listener. Therefore, results are discussed in the context of the signal/noise azimuth.

Presentation of signal to front and noise to back: Two studies (Auriemma et al., 2009; Kuk et al., 1999) assessed accuracy of word recognition for directional response and omnidirectional response at several positive and negative SNRs. Although Kuk et al. did not provide sufficient information to calculate effect sizes, p values were reported revealing statistical significance across all SNRs and favored use of HAs with a directional response over the participants' own omnidirectional HAs ($p < .05$). Auriemma et al. reported large and statistically significant findings at SNRs of 0 dB ($r = .56$, 95% CI [.14, .81], $p < .05$) and -10 dB ($r = .67$, 95% CI [.31, .86], $p < .05$) in favor of the directional HAs. Findings in quiet and at +5 SNR failed to reach statistical significance; however, the magnitude of the effect at +5 SNR was moderate. Two studies (Gravel et al., 1999; Hawkins, 1984) measured SNRs necessary to achieve 50% accuracy on tests of word or sentence recognition. All p values from these two studies were statistically significant and favored directional response over omnidirectional response ($p < .05$); yet only one of the three effect sizes was significant. Gravel et al. (1999) reported a large and statistically significant effect size for words and sentences combined ($r = .86$, 95% CI [.67, .94], $p < .0001$). Hawkins (1984) examined the effects of omnidirectional and directional microphones in both monaural and binaural conditions. Neither condition produced a statistically significant effect size, although the magnitude of effect was moderate in the monaural condition and large in the binaural condition.

Presentation of signal to front and noise to side: In one study, Wouters and colleagues (1999) presented stimuli to the front (0°) of participants and noise to the side (90°) and measured the SNR necessary to achieve 50% accuracy on tests of word and sentence recognition. Effect sizes ranged from small ($r = .22$) to large ($r = .63$) for words or sentences presented in several types of noise. However, the statistical significance of these effects could not be determined because confidence intervals were not reported or calculable. All p values were statistically nonsignificant.

Presentation of signal to front in diffuse noise: Ricketts and colleagues (2007) simulated several classroom environments within which three different experiments were conducted. Only data from Experiments 1 and 3 provided information to determine the effect of directional response with stimuli and noise coming from various directions. In Experiment 1, omnidirectional and directional response was measured in five simulated conditions: "teacher front," "teacher back," "desk work," "discussion," and "bench seating." The azimuths of stimuli and noise for each condition are provided in Table 5. The SNRs necessary to achieve 50% accuracy on a sentence recognition test were recorded. An overall effect size, calculated across all five listening conditions, was large and statistically significant and favored directional response ($r = .58$, 95% CI [.25, .79], $p < .0017$). Post-hoc

analysis revealed a statistically significant interaction of listening condition and directionality. “Teacher front,” “desk work,” and “discussion” conditions were statistically significant and favored directional response ($p < .05$). “Teacher back” was statistically significant and favored omnidirectional response ($p < .0375$). “Bench seating” was not statistically significant. In Experiment 3, omnidirectional and directional response were measured in a “multiple talkers” condition in which the stimuli were directed to the front, back right, or back left of the participant and noise was presented from four speakers in corners of the room. The overall effect size for this condition was large and statistically significant and favored omnidirectional response ($r = -.79$, 95% CI $[-.90, -.58]$, $p < .0012$). Post hoc analysis revealed a significant interaction between stimuli source and directionality. No statistically significant differences were noted between directional and omnidirectional responses when the stimuli were presented to the front of the listener; although, significant differences ($p < .01$) favoring omnidirectional response were present when the stimuli were presented to the back left and back right of participants.

Summary of speech recognition outcomes: The overall findings indicate that directional microphones were more effective for speech recognition when the signal was presented directly in front (0° azimuth) of the listener and when the noise was presented directly behind the listener (180° azimuth). Use of omnidirectional microphones, however, resulted in better speech recognition when the signal deviated away from the front of the listener.

HA self-report or parent-report outcomes: In three studies (Auriemma et al., 2009; Kuk et al., 1999; Ricketts et al., 2007, Experiment 1), researchers evaluated HA self- or parent-report outcomes in the children’s daily environments using subjective questionnaires administered to children, parents, and/or teachers. No effect sizes were calculable for these studies; however, p values were reported in Auriemma et al. (2009) and Ricketts et al. (2007). The p values reported in the Kuk et al. study were based at a .10 significance level, and, therefore, could not be interpreted as significant at the .05 level. The Kuk et al. findings suggested that overall students favored the use of directional microphones over their own omnidirectional HAs for the majority of listening situations. No differences were found for the following situations: group discussion, teacher moving, and talking while hanging coats. Auriemma and Ricketts and their coauthors found no statistically significant differences between directional and omnidirectional response for children or parents.

Trend analysis by study design and quality: As depicted in Table 4, individual study quality scores ranged from 2/7 to 5/7. All of the studies were within-subject, repeated measures designs. Three (Auriemma et al., 2009; Gravel et al., 1999; Ricketts et al., 2007, Experiment 1) were designed to control for order effects by counterbalancing conditions and were therefore classified as crossover studies, whereas in another study, Hawkins (1984) controlled for order effects by randomizing participants to a sequence of conditions. Authors of all studies reported or provided sufficient data to calculate statistical significance, and the majority of studies provided an adequate description of protocol and sufficient data to calculate effect sizes. For many studies, researchers did not indicate assessor blinding, random sampling, randomization and/or counterbalancing procedures. The results of these studies were further analyzed to determine whether study design or quality impacted findings. Despite multiple similarities in study design and quality among select studies, no overall conclusions can be drawn; effect sizes were unavailable or the significance of the effect size was questionable for some of the studies. Although not included in the study critical appraisal, potential confounding variables including volume control settings, frequency response, and use of different devices are important to consider when evaluating study findings. With the exception of two studies in which sufficient information was not provided (Kuk et al., 1999; Wouters et al., 1999), studies did equalize the frequency

response between omnidirectional and directional conditions. Only one study (Hawkins, 1984) reported that volume control was fixed for both conditions; all other studies did not provide this information. One important confound noted by Kuk et al. (1999) was the use of different devices to assess omnidirectional and directional response. Outcomes from directional microphone HAs were compared to outcomes with the children's own omnidirectional HAs.

Overall quality of body of evidence for directional microphones: The body of evidence to answer this clinical question consisted of one low-quality randomized controlled trial (Hawkins, 1984) and six low-quality controlled clinical trials. Findings from these studies were generally consistent across similar signal/noise listening configurations. This constitutes a moderate level of evidence that suggests that future research is likely to impact the answer to the clinical question.

Discussion

The purpose of the current EBSR was to evaluate the impact of DNR and directional microphone technology on a range of communication outcomes for school-age children with hearing loss who use HAs. Our aim in this review as well as the findings from two additional reviews in this series was to inform clinical decisions pertaining to the selection and management of these technologies in the school-age population. DNR and directional microphones are both designed to minimize the negative perceptual consequences of background noise on comfort and perception. Because school-age children listen and learn in environments with significant levels of competing background noise (Knecht et al., 2002), these technologies have the potential to benefit children with hearing loss. We identified four studies that evaluated DNR and seven studies that evaluated directional microphones were identified and analyzed as part of the review.

DNR

DNR is a signal processing strategy designed to reduce the negative perceptual consequences of background noise by lowering the gain of the HA when the input signal is classified as noise. Because DNR typically relies on gain reduction, speech recognition can at best be maintained and may potentially be degraded if the processing significantly alters the audibility of the speech signal (Stelmachowicz et al., 2010). The results of two studies included in this EBSR on the effect of DNR on speech recognition with school-age children with mild to moderately severe hearing loss (Auriemma et al., 2009; Stelmachowicz et al., 2010) indicated that mean speech recognition was not improved or degraded with DNR. Although the younger group of children (ages 5–8 years) in Stelmachowicz et al. (2010) showed considerable individual variability in speech recognition in conditions with and without DNR, none of the participants showed constant patterns of improvement or degradation across nonsense syllables, monosyllabic words, or sentences. Auriemma et al. (2009) also included parent and child ratings of listening difficulty, which were found to improve with DNR for the children's ratings only when sound was located behind them. Although such a finding would be anticipated with directional microphones, it is unexpected for a condition with only DNR activated because DNR adjusts the SNR in a nonlocalized manner. Results from these two studies support the conclusion that the DNR algorithms used in these two studies did not improve or degrade speech recognition in school-age children, but did result in a reduction in the difficulty rating for sounds from behind the listener. These findings are generally congruent with previous studies of the impact of DNR on speech recognition and sound quality in adults with hearing loss.

The author of two other studies included in this EBSR (Pittman, 2011a, 2011b) examined the influence of DNR on complex listening tasks, including word categorization and novel word learning tasks. The outcomes in these two studies were categorized as speech and language outcomes because the tasks were dependent on perceptual and cognitive processes important for spoken and written language development, in addition to speech recognition. For the word categorization study (Pittman, 2011b), participants heard words that were to be categorized as person, food, or animal while also completing a complex connect-the-dots visual task. No improvement or degradation in word categorization was observed when comparing conditions with and without DNR for children with hearing loss. In another study, Pittman (2011a) analyzed the effect of DNR on novel word learning at 0 dB SNR. Whereas there was no improvement or degradation in word learning for 8- to 9-year-old children with hearing loss, 11- to 12-year-olds experienced an enhancement in word learning in the DNR condition only. The age-related differences in DNR benefit were attributed to the higher overall nonword recognition scores in the older group; the process of novel word learning in part is dependent on the accuracy of speech recognition. Because speech recognition in noise has rarely shown improvement with DNR in previous studies, an enhancement in novel word learning may be unlikely to occur if the effect is dependent on DNR improving perception. Collectively, these two studies suggest that DNR does not negatively impact complex listening and word learning tasks and has the potential to improve performance in some conditions and age groups of children. Although word categorization and novel word learning have not been specifically explored in DNR studies with adult listeners, investigators have reported positive outcomes for reduced listening effort at very poor SNRs (Sarampalis, Kalluri, Edwards, & Hafter, 2009) and acquisition of novel speech contrasts (Marcoux, Yathiraj, Côté, & Logan, 2006) for DNR with adults. While further research is needed to specify the underlying mechanisms that result in reduced effort and improved performance on complex tasks in the absence of observable benefits for speech perception, the limited data to date suggest that DNR will not negatively impact learning processes in school-age children. Given the documented negative consequences of noise on academic and learning outcomes in children (Shield & Dockrell, 2008), the use of DNR in classroom settings may help to minimize potential problems.

Overall, a moderate level of evidence from four studies of DNR with school-age children identified in the current review suggest that DNR does not affect speech recognition or complex listening tasks and may result in reduced ratings of difficulty for specific situations (sounds behind the listener) and improved novel word learning in older (11- to 12-year-old) children. Evidence that DNR does not result in reduced outcomes in conjunction with its potential for improvements in sound quality, listening effort, and complex listening and learning tasks provides preliminary support for the use of DNR with school-age children. Further studies of DNR should attempt to replicate the findings from these studies with different DNR algorithms because the characteristics and implementation of DNR vary considerably across manufacturers and devices (Hoetink et al., 2009). The four studies of DNR in the current review also included only children with mild to moderately severe hearing loss. Children with greater degrees of hearing loss may have more limited audibility and experience greater degradation in outcomes with background noise that could lead to different results with DNR.

Three of the four studies addressing this clinical question used the desired sensation level (DSL; Scollie et al., 2005) fitting prescription to determine HA gain and output. Auriemma and colleagues (2009) used a proprietary approach. Differences in audibility for different fitting prescriptions across studies may limit the generalizability of these findings and ability to compare results across studies using different prescriptive methods. The use of proprietary fitting approaches without quantification of aided audibility prevents accurate

predictions regarding the magnitude and pattern of differences that might be observed for different outcome measures in children with hearing loss.

The state of the evidence in any given area of research is suggested to move through several distinct phases including exploratory, efficacy, effectiveness, and cost-effectiveness (see Robey, 2004, for further discussion of stages of research). The DNR studies included in this review were all in the efficacy stage of research, meaning that research was conducted in a controlled manner to maximize the internal validity of the findings. As efficacy has not been established for speech recognition and speech and language outcomes, additional efficacy research examining these outcomes, as well as the effect of DNR on users' self-reported ease of listening and performance on complex listening tasks, is needed to establish the benefit of DNR. Also, as advancements in DNR algorithms are achieved, additional efficacy research on all outcomes will continue to be necessary. Longitudinal studies with children using DNR may provide insight into the effects of experience and acclimatization, and long-term impacts on language and learning processes. Research that addresses these questions would help clinicians to determine the appropriateness of this technology for children because preference ratings have been found to favor DNR for adult listeners in previous studies (Ricketts & Hornsby, 2005). Once efficacy has been established, additional research may focus on effectiveness and cost-effectiveness research.

Directional Microphones

We identified seven studies with school-age children and adolescents that compared an omnidirectional microphone, which is equally sensitive to sounds regardless of their location relative to the listener, to directional microphones for school-age children. Speech recognition in noise was consistently improved when the signal of interest was in front of the listener (Auriemma et al., 2009; Gravel et al., 1999; Hawkins, 1984; Kuk et al., 1999; Ricketts et al., 2007), but was poorer for conditions where the signal of interest was behind the listener (Ricketts et al., 2007). Improvements for speech originating in front of the listener were observed across a wide range of SNRs, stimuli, and configurations of noise: diffuse noise as in Ricketts et al. (2007) and fixed noise behind the listener in Gravel et al. (1999). Because speech recognition is improved when the talker of interest is in front of the listener and is either maintained or degraded for conditions when the talker of interest is beside or behind the listener, the benefit of directional microphones for school-age children is dependent on the ability of the child to orient toward the signal of interest. This ability to orient is particularly important in classroom situations where the speaker of interest may move or change, such as a teacher moving through the classroom or during a class discussion with multiple talkers; it may be dependent on the age of the listener. Ricketts and Galster (2008) demonstrated that school-age children with hearing loss were able to accurately orient toward the signal of interest in classroom settings, indicating that amplification can be maintained using directional microphones in classroom environments. These findings suggest that directional microphones may be beneficial for school-age children in classrooms in situations where an FM system would be impractical, including classroom discussions with multiple talkers of interest.

Despite improvements in speech recognition across multiple studies, no significant differences were observed for subjective measures of sound quality for directional versus omnidirectional responses (Auriemma et al., 2009; Ricketts et al., 2007, Experiment 1). This disparity is counterintuitive considering the importance of speech understanding to communication in everyday situations. However, there are several potential explanations for this difference between objective measures of speech recognition and subjective ratings of satisfaction and sound quality:

1. The amount of improvement from directional microphones in real-world environments may be much smaller than the improvements in a controlled speech recognition task in a laboratory, an explanation that has been mentioned in systematic reviews of directional microphones for adults (Amlani, 2001).
2. Because directional microphones maintain amplification for whatever signal the child is oriented toward, the benefits of directional microphones may be less apparent to the users because they may use visual cues to orient toward the signal of interest throughout the day, which studies with adults have demonstrated can influence the degree of observed directional benefit in the laboratory (Wu & Bentler, 2010).
3. Although in at least one study (Auriemma et al., 2009) researchers used a questionnaire (from Ricketts et al., 2003) that contained items that specifically probed listening situations that would be expected from directional microphones, the overall difference between speech recognition and subjective satisfaction outcomes in the current review may reflect the need for different tools to assess the benefits of this technology in real-world environments and more realistic laboratory outcome measures.

Another important consideration regarding the use of directional microphones in real-world environments is the influence that reduced sensitivity from sounds arriving from the sides or behind the child may have on their ability to use overhearing. Akhtar (2005) suggested that overhearing may be an important mechanism to support novel word learning in young children. By definition, incidental learning through overhearing involves the child's ability to hear and attend to stimuli that may not be directly in front of them. Children with hearing loss are at risk for delays in the acquisition of new vocabulary compared to their peers with normal hearing (Pittman, 2008). Preliminary data from Moeller (2010) suggests that children with hearing loss may face additional challenges using overhearing to support novel word learning compared with children with normal hearing. Although studies that directly evaluate how directional microphones may affect overhearing have not been conducted, potential limitations on children's ability to learn new vocabulary could limit the efficacy of this technology with young children.

Most of the studies relating to this clinical question used a version of the DSL (Scollie et al., 2005) prescriptive formula to prescribe HA gain and output for their participants. Two studies (Auriemma et al., 2009; Kuk et al., 1999) used a proprietary prescriptive approach other than DSL and one study (Wouters et al., 1999) used POGO. The DSL is the most widely used prescriptive method for children, but the extent to which results obtained with one specific prescriptive formula can be generalized to other approaches cannot be determined. As mentioned previously, the use of manufacturer proprietary prescriptive approaches without documenting audibility over a range of input levels limits the ability to determine whether differences in outcomes are related to audibility or the signal processing contrast of interest.

The included studies contribute to a moderate level of evidence that suggests efficacy for the use of directional microphones in school-age children in well-controlled laboratory environments when the sound is directed to the front of the child; however, methodological weaknesses limit our ability to confidently form conclusions without further research. Despite the need for additional high-quality efficacy research, the state of research for directional microphone studies is progressing through a later stage of efficacy and into the realm of effectiveness. Effectiveness research investigates the impact of an intervention when it is implemented in realistic situations, and, often, in typical daily environments. One study (Ricketts et al., 2007) investigated efficacy in several simulated environments, where

the configuration of speech and noise signals more realistically approximated classrooms and other important environments. Authors of three studies (Auriemma et al., 2009; Kuk et al., 1999; Ricketts et al., 2007, Experiment 1) also included real world HA satisfaction measures. The equivocal findings from these later stage investigations highlight the need for additional late efficacy and effectiveness studies that use real world or simulated environments and outcomes. Also, since most HA manufacturers incorporate multiple signal processing techniques into the same device, children may be using DNR and directional microphones simultaneously, whereas most of the current research focuses on the independent effects of these technologies. Future efficacy and effectiveness research should investigate how these strategies may interact to affect listening and satisfaction outcomes.

Limitations of the Current Review

Several limitations of this systematic review should be considered. First, the search criteria for this review were restricted to studies available in English, which likely reduces the quantity of relevant information that could have otherwise been included. Also, although the exclusion of unpublished findings and findings published in non-peer-reviewed journals was intentional to ensure that all included studies were previously vetted in a peer-review process, it has been suggested that this practice increases the likelihood of publication bias and may overrepresent positive treatment effects (McAuley, Tugwell, & Moher, 2000). In addition to the studies discussed in this review, the reader should consider research that was published after completion of the specified dates of this literature search. It is anticipated that future updates to this review will capture evolving research findings. Finally, due to the limited number of studies and differences in technologies and outcome measures used, the effect sizes obtained in this EBSR were not pooled. It is expected that as additional research becomes available, meta-analysis of the findings will be possible, reliable, and meaningful.

Conclusion

When making clinical decisions, clinicians should always use their own expertise to consider the needs and desires of the client in addition to the quality of research evidence, expert consensus opinion, potential benefits/harms, and cost-effectiveness. DNR processing did not improve or degrade speech understanding in school-age children in two studies included in the current review, and outcomes during complex learning tasks were largely unaffected by DNR. There was limited evidence from one study suggesting a potential impact on HA satisfaction; however, additional research is needed to evaluate different DNR processing schemes as well as the influence of these features on comfort and ease of listening in realistic listening situations. Based on these preliminary results from a moderate body of evidence, DNR algorithms that do not reduce the audibility of speech could be used to increase listener comfort in school-age children. Research with younger children and greater degrees of hearing loss are needed before broader evidence-based recommendations can be made.

Based on a moderate body of evidence, HAs with a directional microphone response were found to improve speech recognition in noise in controlled situations where the target signal is located in front of the listener. However, decreased performance with directional response was noted in one article (Ricketts et al., 2007) when the target signal was located to the side or behind the listener, which highlights the importance of counseling and the ability of the listener to orient toward the target signal for the benefits of this technology to be fully realized. Equivocal real-world satisfaction ratings also call attention to the need for additional research in this area to better understand the use of this technology in typical daily environments. Directional microphones have the potential to improve speech understanding in background noise in specific configurations of talker and background noise. Given the number of potential acoustic environments that a school-age child might experience in

home, academic, and social situations, directional microphones may be beneficial in some situations and equivocal or detrimental in others. Therefore, recommendations regarding directional microphones with school-age children should be based on the child's ability to change the directional setting and the specific acoustic environments encountered by the child.

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*References marked with an asterisk indicate studies included in the EBSR.

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Appendix

HA and Procedural Details

Citation	HA model	Experimental feature	Other features	Fitting prescription	Duration
Auriemmo et al. (2009) (CQ1)	Widex Diva SD9M or SD19M	DNR	Digital; active feedback cancellation system; speech intensification feature; optional adaptive directional microphone system off, slow-acting WDRC, 15 channels	Audioscan Verifit HA analyzer	6 weeks in each condition
Auriemmo et al. (2009) (CQ2)	Widex Diva SD9M or SD19M	Directional response	Digital, active feedback cancellation system, speech intensification feature, DNR off, slow-acting WDRC, 15 channels	Audioscan Verifit HA analyzer	6 weeks in each condition
Gravel et al. (1999)	Phonak PiCS 332x Audio Zoom Sono-Forte	Directional response	Multi-memory, peak clipping output limiting	DSL v3.1	2–3 test sessions
Hawkins (1984)	Phonic Ear 805 CD	Directional response	Wide range of frequency response settings, direct audio input capability, telephone switch, sliding directionality switch	Modified half-gain rule	Total testing time was 2.5 hr
Kuk et al. (1999)	Widex Senso C9 and C19 (directional) Own HAS- various models (omni)	Directional response	Digital (directional), slow-acting WDRC (directional), speech enhancement algorithm (directional), 3 channel (directional), analog (omni), amplitude compression (omni)	Sensogram (directional) NR (omni)	30–35 days (directional) NR (omni)
Pittman (2011a)	Experimental HA	DNR	16 channels, volume control deactivated, all other advanced processing features disabled	DSL 5.0	1 test session
Pittman (2011b)	Siemens Explorer 500	DNR	Amplitude compression, advanced processing features disabled	DSL 5.0	1 test session
Ricketts et al. (2007) Exp. 1	Oticon Gaia or Phonak Supero	Directional response	Digital (Oticon Gaia and Phonak Supero), frequency	DSL v. 4.1	1 month

Citation	HA model	Experimental feature	Other features	Fitting prescription	Duration
Ricketts et al. (2007) Exp. 3	Oticon Gaia or PhonakSupero	Directional response	shaping in seven bands (Oticon Gaia), 2 channel (Oticon Gaia), amplitude compression (Oticon Gaia), 5 channel (PhonakSupero), WDRC (PhonakSupero) Digital (Oticon Gaia and PhonakSupero), frequency shaping in seven bands (Oticon Gaia), 2 channel (Oticon Gaia), amplitude compression (Oticon Gaia), 5 channel (PhonakSupero), WDRC (PhonakSupero)	DSL v. 4.1	1 month
Stelmachowicz et al. (2010)	Starkey Destiny BTE HAs (model 1200)	DNR	8 channels, slow-acting amplitude compression	DSL v5.0 [i/o]	1 test session
Wouters et al. (1999)	Phonak PiCS 232 AZ HA	Directional response	AGC combined with adaptive recovery time Digital handy control Digitally programmable	POGO 2	2-week period in which participants could freely switch between omnidirectional and directional conditions

Note. AGC = automatic gain control; BTE = behind the ear; CQ = clinical question; DNR = digital noise reduction; DSL = Desired Sensation Level; Exp. = experiment; HA = hearing aid; [i/o] = input/output; NR = not reported; Omni = omnidirectional; POGO = Prescription of Gain/Output; WDRC = wide dynamic range compression.

Table 1

Participant characteristics.

Citation	Number of participants	Age range (avg) in years	Gender	Hearing loss type and severity	Previous HA use
Auriemma et al. (2009)	19	6.1–12.8 (10)	NR	Mild to moderately severe SNHL	All children with the exception of one were experienced HA users wearing a variety of digital technology; 15 children used FM systems along with their HAs in the classroom
Gravel et al. (1999)	20	4.8–11.1 (7.4)	14F/6M	Bilateral, mild to severe SNHL	Regular users of binaural BTE HAs
Hawkins (1984)	9	8.3–14.6 (12.1)	NR	Bilateral mild to moderate SNHL	Experienced omnidirectional HA users; 7/9 binaural; 2/9 monaural; 7/9 used HA + FM at school
Kuk et al. (1999)	20	7.5–13.7 (11.25)	NR	Nine with mild to moderately severe hearing loss (C9 HA users); 11 with moderate to severely profound hearing loss (C19 HA users)	Binaural, moderate-high gain, BTE, analog HA users from age of 3–4 years 3/20 reported consistent use with FM + HA
Pittman (2011a)	26	8.08–9.92 (9.08) (N = 13) 11–12.92 (11.92) (N = 13)	15F/11M	Mild to moderately severe hearing loss	25/26 with personal HAs; one with experience with DNR
Pittman (2011b)	30	8–12 (10.42)	16F/14M	Mild to moderately severe hearing loss; 23 sensorineural; 4 conductive; 3 mixed	29/30 with personal HAs; one with experience with DNR
Ricketts et al. (2007) Exp. 1	26	10–17 (14)	NR	One child with conductive component; remaining children had air-bone gap 15 dB	24 had previous experience with binaural amplification; none had experience with directional HAs
Ricketts et al. (2007) Exp. 3	12 (of 26 from Exp. 1)	NR	NR	NR	NR
Stelmachowicz et al. (2010)	16	5–10	NR	Mild to moderately severe SNHL	NR
Wouters et al. (1999)	3	12–14 (13)	3M	Bilateral, symmetrical mild to moderate sloping pure SNHL	Experience with various omnidirectional HA models

Note. BTE = behind the ear; dB= decibel; DNR= digital noise reduction; Exp. = experiment; F = female; FM = frequency modulation; HA = hearing aid; M = male; NR = not reported; SNHL = sensorineural hearing loss.

Table 2

Comparison of DNR on versus DNR off on speech recognition outcomes.

Citation	Conditions	Volume control	Stimuli	Presentation level	SNR	Effect size ^d [95% CI]	<i>p</i>
Auriemma et al. (2009)	DNR on: uses a speech intelligibility weighting rule, triggered above 60 dB SPL with long time constraints DNR off	NR	Monosyllabic words	50 dB HL	Quiet +5 0 -10 dB	$r = .09$, [-.38, .52] ^b $r = .19$, [-.29, .59] ^b $r = -.04$, [-.49, .42] ^b $r = .06$, [-.41, .50] ^b	NS NS NS NS
Stelmachowicz et al. (2010)	DNR on: uses modified spectral subtraction with Wiener filter DNR off	Deactivated	Nonsense syllables, words, and sentences	65 dB SPL	0, +5, and +10 dB	$r = .24$, [-.29, .66] ^c There was no interaction between noise reduction and stimulus type and between noise reduction and SNR	NS

Note. CI = confidence interval; dB = decibel; DNR = digital noise reduction; HL = hearing level; NR = not reported; NS = not significant; SNR = signal to noise ratio; SPL = sound pressure level.

^aPositive effect sizes indicate that the direction of the effect favors DNR. Negative effect sizes indicate that the direction of the effect favors hearing aids without DNR effect size.

^b r , calculated using the paired-samples t test statistic and df provided in the study.

^cEffect size. r calculated using the F statistic and df provided in the study.

Table 3

Comparison of DNR on versus DNR off on speech and language outcomes.

Citation	Conditions	Volume control	Stimuli	Presentation level	Nominal SNR	Outcomes	Effect size ^d [95% CI]	<i>p</i>
Pittman (2011a)	DNR on: uses a modulation-based DNR algorithm with Wiener filter that operates simultaneously in 16 channels, adjusted to engage any time noise is detected DNR off	Deactivated	Nonsense words	50 dB SPL	0 dB	Novel word learning	Younger children: $r = .10$, $[-.48, .62]$ ^c Older children: $r = .54$, $[-.02, .84]$ ^c	NS $p = .05$ (favors DNR)
Pittman (2011b)	DNR on: adjusted to engage DNR with noise detection regardless of the presence or absence of speech DNR off	Deactivated	Words	50 dB SPL	0 dB	Word categorization	$r = .20$, $[-.17, .52]$ ^b	NS

Note. CI = confidence interval; dB = decibel; DNR = digital noise reduction; NS = not significant; SNR = signal to noise ratio; SPL = sound pressure level.

^aPositive effect sizes indicate that the direction of the effect favors DNR. Negative effect sizes indicate that the direction of the effect favors hearing aids without DNR.

^bEffect size, r , calculated using the paired-samples t test statistic and df provided in the study.

^cEffect size, r , calculated using the F statistic and df provided in the study.

Table 4

Study characteristics.

Citation	Study design	Protocol description	Assessors blinded	Sampling	Critical appraisal points			Appraisal score
					Allocation	Counterbalancing	p value	
Aurienno et al. (2009)	Crossover	Adequate	Blinded	Conv/HP/NR	Not random/NR	Counterbalanced	Rep/calc	ES/CI rep/calc 5/7
Gravel et al. (1999)	Crossover	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Counterbalanced	Rep/calc	ES/CI rep/calc 4/7
Hawkins (1984)	Repeated measures	Adequate	Not blinded	Conv/HP/NR	Random	Not counterbalanced/NR	Rep/calc	ES/CI rep/calc 4/7
Kuk et al. (1999)	Repeated measures	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	Rep/calc	ES/CI not rep/calc 2/7
Pittman (2011a)	Crossover	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Counterbalanced	Rep/calc	ES/CI rep/calc 4/7
Pittman (2011b)	Repeated measures	Adequate	Not blinded	Conv/HP/NR	Random	Not counterbalanced/NR	Rep/calc	ES/CI rep/calc 4/7
Ricketts et al. (2007) Exp. 1	Crossover	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Counterbalanced	Rep/calc	ES/CI rep/calc 4/7
Ricketts et al. (2007) Exp. 3	Repeated measures	Inadequate	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	Rep/calc	ES/CI rep/calc 2/7
Stelmachowicz et al. (2010)	Crossover	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Counterbalanced	Rep/calc	ES/CI rep/calc 4/7
Wouters et al. (1999)	Repeated measures	Adequate	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	Rep/calc	Only ES or only CI rep/calc 2/7

Note. Items in boldface type represent the highest quality level for each appraisal point; each is awarded one point toward the appraisal score. Calc = calculable; CI = confidence interval; Conv = convenience; ES = effect size; Exp. = experiment; HP = hand-picked; NR = not reported; Rep = reported.

Table 5
Comparison of directional microphone response versus omnidirectional response on speech recognition outcomes.

Citation	Conditions	Equalization	Volume control	Stimuli	Presentation level	Outcomes	Azimuth	SNR	Effect size ^d [95% CI]	p values
Aurienmo et al. (2009)	Directional (dir) response; adaptive automatic directional microphone system, activated above 50 dB SPL Omnidirectional response	Yes	NR	Monosyllabic words	50 dB HL	Word recognition	0° signal/180° noise	quiet +5 dB 0 dB -10 dB	$r = .05$, [-, 41, .49] ^b $r = .34$, [-, 14, .69] ^b $r = .56$, [-, 14, .81] ^b $r = .67$, [-, 31, .86] ^b	NS NS $p < .05$ (favors dir) $p < .05$ (favors dir)
Gravel et al. (1999)	Directional response: fixed dual-microphone directional response Omnidirectional response	Yes	NR	Monosyllabic words and sentences	50 dB HL	SNR for 50% performance	0° signal/180° noise	varied	$r = .86$, [.67 to .94] ^c	$p < .0001$ (favors dir)
Hawkins (1984)	Directional response: fixed directional mode Omnidirectional response	Yes	Fixed	Spondee words	65 dB SPL	SNR for 50% performance	0° signal/180° noise	varied	Mon dir vs. omni: $r_{pb} = .38$, [-.38, .83] ^d Bin dir vs. omni: $r_{pb} = .63$, [-.06, .91] ^d	$p < .05$ (favors dir) $p < .05$ (favors dir)
Kuk et al. (1999)	Directional response: fixed single-microphone, two-port, directional design Own omnidirectional response HAs	NR	NR	Words	Noise: 65 dB SPL	Word recognition	0° signal/180° noise	overall +7 dB 0 dB -7 dB	NR/NC NR/NC NR/NC NR/NC	$p = .003$ (favors dir) $p < .05$ (favors dir) $p < .05$ (favors dir) $p < .05$ (favors dir)
Ricketts et al. (2007) Exp. 1	Directional response: fixed directional mode Omnidirectional response: fixed	Yes	NR	Sentences	Noise: TF: 55 dB SPL TB: 55 dB SPL DW: 55 dB SPL Disc: 65 dB SPL BS: 65 dB SPL	SNR for 50% performance	Signal: TF: 0° TB: 180° DW: 0° Disc: 0° and ± 50° BS: ± 90°	varied	Overall: $r = .58$, [.25, .79] ^c Effect sizes for each environment	Overall: $p < .0017$ (favors dir) TF: $p < .0436$

Citation	Conditions	Equalization	Volume control	Stimuli	Presentation level	Outcomes	Azimuth	SNR	Effect size ^d [95% CI]	p values
							Noise: four corners of room		are not calculable	(favors dir) TB: $p < .0375$ (favors omni) DW: $p < .0001$ (favors dir) Disc: $p < .0001$ (favors dir) BS: NS
Ricketts et al. (2007) Exp. 3	Directional response: fixed directional mode Omnidirectional response: fixed	Yes	NR	Words	63 dB SPL	Word recognition	Signal: BL: 225° BR: 135° F: 0° Noise: four corners of room	+6 dB	Overall: $r = -.79$, [-90, -58] ^c Effect sizes for each signal source are not calculable	Overall: $p < .0012$ (favors omni) BL: $p < .0078$ (favors omni) BR: $p < .0036$ (favors omni) F: NS
Wouters et al. (1999)	Directional response: via two omnidirectional microphones Omnidirectional response: only the front microphone is active	NR	NR	Words and sentences	65 dBA	SNR for 50% performance	0° signal/90° noise	varied	At fitting: Words in speech noise: $r_{pb} = .62de$ After 2 wk trial: Words in speech noise: $r_{pb} = .63de$ Words in traffic noise: $r_{pb} = .22de$ Words in babble: $r_{pb} = .26de$ Sentences in speech: $r_{pb} = .39de$	At fitting: Words in speech noise: NS ^f After 2 wk trial: Words in speech noise: NS ^f Words in traffic noise: NS ^f Words in babble: NS ^f Sentences in speech: NS ^f

Note. BL = source back left; BR = source back right; BS = bench seating condition; CI = confidence interval; dB = decibel; Disc = discussion condition; DW = desk work condition; Exp. = experiment; F = source front; HA = hearing aid; HL = hearing level; NC = not calculable NR = not reported; NS = not significant; SNR = signal to noise ratio; SPL = sound pressure level; wk = week; TB = teacher back condition; TF = teacher front condition.

^aPositive effect sizes indicate that the direction of the effect favors directional response. Negative effect sizes favor omnidirectional response.

^bEffect size, r , calculated using the paired-samples t test statistic and d' provided in the study.

^cEffect size, r , calculated using the F statistic and d' provided in the study.

^dEffect size, rpb (point-biserial correlation coefficient), calculated from individual participant data provided in the study.

^eUnable to calculate confidence intervals.

^f p values calculated using the Wilcoxon Signed-Ranks Test from individual participant data provided in the study.