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An Evidence-Based Systematic Review of Frequency Lowering in Hearing Aids for School-Age Children With Hearing Loss

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Abstract

Purpose—We developed 1 clinical question for this review, which addressed the comparison of hearing aids using frequency lowering compared to conventional processing amplification for outcomes of audibility, speech recognition, speech and language, and self- or parent-report for children with hearing loss.

Method—We systematically searched 26 databases for studies addressing a clinical question and meeting all inclusion criteria. We evaluated studies for methodological quality and reported or calculated effect sizes when possible.

Results—The literature search resulted in the inclusion of 5 studies. We implemented several different frequency-lowering strategies across studies; 2 studies used nonlinear frequency compression, 2 used frequency transposition, and 1 used frequency compression with dynamic consonant boost.

Conclusions—Whereas methodological limitations of the included studies preclude the formulation of strong conclusions, findings were generally positive across frequency-lowering strategies and outcomes. Additional high-quality research is needed in this area.

Keywords

children; evidence-based systematic review; frequency compression; frequency transposition; nonlinear frequency compression; dynamic consonant boost; frequency lowering; amplification

The primary goal of providing early and appropriate amplification for children is to provide access to the acoustic cues needed to support the acquisition of speech and language abilities. Although children who receive amplification and early intervention before 6 months of age generally have better communicative outcomes than cohorts who are identified or fit with hearing aids (HAs) after 6 months of age (e.g., Nelson, Bougatsos, & Nygren, 2008), children who receive early amplification still exhibit delays compared to their peers with normal hearing. Further, Moeller and colleagues (2007) found that children who received amplification before 6 months of age had significantly delayed phonological development for the fricative class of phonemes, despite acquiring other classes of speech

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sounds later than, but at a rate similar to, children with normal hearing. The authors attributed delayed fricative acquisition to the limited bandwidth of conventional processing (CP) HAs. Additional research supports the notion that early phonological delays may impact the acquisition of morphosyntax (Moeller et al., 2010) as well as having implications for speech perception in school-age children with hearing loss. Stelmachowicz, Pittman, Hoover, and Lewis (2001) demonstrated that audibility of a frequency range from 2 to 4 kHz was important for perception of fricatives in male speakers and a range from 2 to 8 kHz in female and child speakers. Given that hearing amplification is typically restricted to approximately 5 kHz (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004), children with hearing loss may not adequately perceive high-frequency sounds such as /s/ and /z/, especially when listening to female speakers or their own productions. Several studies have examined the impact of extending bandwidth into the 9–10 kHz region. These studies suggest that extended bandwidth may improve word learning (Pittman, 2008; Pittman, Lewis, Hoover, & Stelmachowicz, 2005; Stelmachowicz, Lewis, Choi, & Hoover, 2007) and perception of important fricative sounds, such as /s/, which serve multiple linguistic functions in language (Stelmachowicz et al., 2001). Providing amplification for frequencies above 6 kHz is also supported by studies that showed improved speech recognition (Hornsby, Johnson, & Picou, 2011), listener preference (Ricketts, Dittberner, & Johnson, 2008), and acceptable noise level (Johnson, Ricketts, & Hornsby, 2009) in adult listeners.

The most obvious strategy for providing a broader bandwidth through HAs would be to develop HAs that can provide better high frequency audibility. Killion and Tillman (1982) reported on a HAwith bandwidth that extended up to 16 kHz, demonstrating that extended bandwidth hearings aids were technologically feasible. However, the extended bandwidth in that system had a limited output that would have only been appropriate for listeners with mild hearing losses. Despite this potential, the bandwidth of most digital HAs has been limited to approximately 5 kHz. Evidence of incremental improvements in HA bandwidth has started to surface (Kreisman, Mazevski, Schum, & Sockalingam, 2010), but numerous barriers to extending the bandwidth of amplification up to 10 kHz in digital HAs have prevented more substantial progress. In regard to determining bandwidth, the Nyquist theorem states that in order to adequately capture the signal, the sampling rate must be at least two times higher than the frequency desired in the input signal. Therefore, to capture inputs up to 10 kHz, a 20 kHz minimum sampling rate is needed (Kuk & Baekgaard, 2009). The extension of bandwidth into higher frequencies can also constrain low-frequency amplification and output power as well as increase distortion and acoustic feedback (Boothroyd & Medwetsky, 1992; Kuk & Baekgaard, 2009). The relatively low level of speech energy at high frequencies means that greater gain is required at higher frequencies to achieve consistent audibility. Moore, Stone, Fullgrabe, Glasberg, and Puria (2008) documented that only approximately 40% of adults with mild to moderate high-frequency hearing loss could achieve audibility at 10 kHz due to the limited speech energy at frequencies above 4 kHz and the significant gain requirements for making those soft sounds audible.

An alternative to extending HA bandwidth is to use signal processing to lower the output frequency of the speech spectrum to overcome HA design and speech energy limitations at higher frequencies. Multiple signal processing approaches, collectively known as *frequency lowering*, shift or compress high-frequency sounds into a lower frequency range, thus making previously undetectable high-frequency sounds perceptible to the hearing-impaired listener. Several different approaches to frequency lowering are currently available in wearable HAs such as nonlinear frequency compression (NLFC), frequency transposition (FT), and dynamic speech recoding systems that use a combination of frequency compression (FC) and temporal consonant enhancement, such as dynamic consonant boost (DCB). In NLFC, inputs to the HA above a specified start frequency are lowered in

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frequency by a specific compression ratio, preserving the frequency of signals below the start frequency (Glista et al., 2009). HAs with FT extract a spectral peak above a start frequency down one octave to preserve harmonic relationships in the input signal (Auriemmo et al., 2009). Devices that use FC with DCB compress the entire input spectrum of the HA and also provide additional gain to sounds with the temporal and spectral characteristics of fricative phonemes. Unlike extending the bandwidth of the HA, frequency lowering involves alteration of the distribution of speech energy as a function of frequency, which has raised concerns about potential negative impacts due to distortion of acoustic cues necessary for speech recognition and speech and language learning. Whereas audibility of high-frequency sounds has been demonstrated to be important for supporting speech and language development, novel word learning, and speech perception in children, questions remain about whether those developmental processes can be facilitated with frequency-lowering strategies.

Prior to the advent of cochlear implants, frequency-lowering strategies were developed to be implemented with individuals with severe to profound hearing loss and limited potential for aided audibility (Braida et al., 1979). The resulting frequency-lowering strategies applied significant signal processing to the entire speech spectrum to maximize audible speech energy, often leading to significant distortion of acoustic speech cues. The initial use of frequency lowering across the entire speech spectrum was necessary for these listeners with extremely limited residual hearing to maximize the potential for making the speech spectrum audible. Consequently, early studies of frequency lowering using techniques of vocoding (Lippmann, 1980; Posen, Reed, & Braida, 1993) or slow playback (Beasley, Mosher, & Orchik, 1976; Bennett & Byers, 1967) demonstrated limited improvement and even degradation in speech intelligibility with hearing impaired users. Subsequent expansion of the candidacy recommendations for pediatric cochlear implantation has reduced the number of individuals with profound hearing loss who utilize HAs and has thus resulted in a greater proportion of HA users with mild to severe hearing loss. Consequently, the focus of the implementation of frequency-lowering strategies has shifted to address the audiological and communication goals of these individuals who typically have adequate low- to mid-frequency audibility. More specifically, newer frequency-lowering algorithms, including NLFC (Glista et al., 2009) and FT (Kuk, Keenan, Korhonen, & Lau, 2009), are applied over a more limited frequency range, typically in the high frequencies, with the goal of extending audibility to frequencies greater than the bandwidth of CP HAs. Because these more recent strategies are often applied only at higher frequencies, the significant spectral distortion that occurred with noise vocoders and slow playback systems is likely reduced. As a result, current frequency-lowering strategies, applied in a population of children with lesser degrees of hearing loss, may show more favorable results than previous approaches.

Studies of frequency-lowering devices are becoming more prevalent in both the pediatric and adult populations. Studies of frequency lowering with adults have shown mixed results depending on the subjects' degree of hearing loss and specific outcome measures used to establish benefit (Bohnert, Nyffeler, & Keilmann, 2010; Glista et al., 2009; Simpson, Hersbach, & McDermott, 2005, 2006). The effects of frequency lowering for children have the potential to be different than in adult studies for several important reasons. First, previous studies have demonstrated that children show larger improvements in speech understanding as the bandwidth of HAs is extended to higher frequencies (Stelmachowicz et al., 2004). The extent to which frequency lowering increases the audibility of high-frequency speech cues may result in more consistent improvements in speech understanding in children than have been observed in adults. Alternatively, children's speech understanding is more susceptible to spectral distortion than adults (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000), who are more easily able than children to use their knowledge of phonology and language to support speech understanding under

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conditions of significant distortion. Manufacturer data suggest that frequency lowering may be activated in as much as 80% of one company's pediatric HA fittings (Jones & Launer, 2010), supporting the need for an evidence-based systematic review (EBSR) to help clinicians understand the potential effects of this technology on outcome measures of HA efficacy in school-age children with hearing loss.

The purpose of this EBSR is to document the current, peer-reviewed research evidence pertaining to the use of frequency-lowering HA signal processing features in school-age children with hearing loss. This review is part of a series of three reviews of current HA signal processing approaches for children. Other reviews in this series address directional microphone response/noise reduction and amplitude compression.

The clinical question was formulated for this review in consideration of the population, intervention, comparison, and outcome. The population under review is school-age children with hearing loss. The intervention is HAs with frequency-lowering signal processing, and the comparison is HAs without frequency lowering. Outcomes of audibility, speech recognition, speech and language, and self- or parent-report (subjective measures) are all important to consider in HA research (Hogan, 2007). There is an inherent relationship between these outcomes such that the level of audibility achieved will impact an individual's ability to recognize speech, an individual's ability to recognize speech will affect his or her expressive and receptive speech and language skills, and the degree to which the HA is able to improve audibility and speech recognition will likely influence the individual's satisfaction with the device. Ideally, one would hope to affect change in all four of these outcome areas, but research may demonstrate that a given HA signal processing strategy impacts one outcome category more or less than another. This research is valuable to understand the strengths and limitations of a hearing device. Audibility outcomes are objective measures of speech audibility (e.g., sound-field testing, real ear measures, articulation index scores [ANSI S3.5–1969], and Speech Intelligibility Index [SII] scores [ANSI S3.5–1997]. Speech recognition outcomes include objective measures of speech stimuli identification at the phoneme, nonword, word, and sentence level. Speech and language outcomes consist of formal and informal measures of receptive and expressive speech and language skills (e.g., Goldman-Fristoe Test of Articulation—Second Edition; Goldman & Fristoe, 2000; mean length of utterance). Finally, self- and parent-report outcomes include subjective measures such as satisfaction surveys and listening questionnaires.

Robey (2004) suggested that clinical research moves through five distinct phases beginning with exploratory research (Phases I and II) and progressing to efficacy (Phase III) and effectiveness research (Phase IV) prior to the investigation of cost-effectiveness (Phase V). Exploratory research typically comprises case studies and discovery-oriented small studies, whereas efficacy research usually includes controlled laboratory trial research. Effectiveness research is often conducted in typical environments to determine the extent to which therapeutic benefit is attainable in realistic situations; cost-effectiveness research typically consists of cost-benefit analysis and is usually targeted to regulators, policy makers, and legislative bodies. In consideration of the known research literature associated with frequency-lowering signal processing and the current availability of this technology, we anticipated that the majority of research would fall into the efficacy phase of research. As such, the following clinical question was formulated for this EBSR: What are the effects of frequency-lowering technology as compared to standard HA bandwidth 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?

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Method

Literature Search

This review is based on a systematic literature search conducted with a combined search strategy of several HA signal processing strategies. In addition to frequency lowering, the search also pulled studies addressing directional microphone response, noise reduction, and amplitude compression. The results of studies addressing these other HA signal processing features are discussed in separate reviews within this series (i.e., directional microphone/ digital noise reduction and amplitude compression). The search strategy was developed by the fourth author, who has experience in conducting systematic literature searches (e.g., Frymark et al., 2010). We initially searched 26 databases (e.g., PubMed, CINAHL, PsycINFO, ERIC) for peer-reviewed literature published from 1980 to April 2010 using key words related to hearing loss and children (e.g., *hearing aid, hearing instrument, amplification, child, frequency compression*). In addition, we searched reference lists of all full-text articles to identify articles for potential inclusion and conducted specific searches based on prolific authors and accepted articles. After an extensive time lapse prior to publication, we updated the literature search in July 2011 to capture the most recently published information. Specific details pertaining to the literature search and update, including a list of databases, key words, and search dates, can be found in McCreery, Venediktov, Coleman, and Leech (2012).

The inclusion criteria required studies to have an experimental or quasi-experimental design, to address the clinical question, and to have been published in English. The sample must have included children between the ages of 5 and 17 years with a documented hearing loss. 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. To be included, study authors must have provided comparative data of outcomes with and without the target HA feature using wearable devices and using signal processing approaches that were currently available in commercial HAs. Operational definitions are included in McCreery et al. (2012). The second and third authors independently read abstracts and full-text articles to determine articles for final inclusion. Interrater reliability was calculated using the kappa statistic () and percent agreement, and disagreements were resolved by consensus or with the advisement of the first author (R.W.M.). Landis and Koch's (1977) labels describing relative strength of agreement were applied to k 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—The second and third authors critically and independently appraised the quality of each accepted article using up to seven appraisal criteria modified from the ASHA levels-of-evidence scheme (Cherney, Patterson, Raymer, Frymark, & Schooling, 2008; Fey et al., 2010; Mullen, 2007). This 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. It was piloted prior to its adoption in 2008. The scheme was adapted for evaluation of within-subject repeated measures designs in consideration of the common threats to internal validity (Portney & Watkins, 2009). The first author provided input regarding the appropriateness of the scheme as it pertained to HA research. The raters both had previous experience (e.g., Gosa, Schooling, & Coleman, 2011; Rousch, Frymark, Venediktov, & Wang, 2011) and training evaluating the methodological quality of scientific literature. The appraisal criteria were as follows: (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

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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). One point was awarded for each appraisal criterion fully met. Interrater reliability was calculated using κ (weighted as appropriate) and percent agreement. Neither rater had an extensive audiological background. As such, the knowledge and experience of the first author was requested in instances of uncertainty to clarify background audiological concepts.

Body of evidence—The strength of the body of evidence available to address the clinical question posed in this review was evaluated using an evidence grading scheme developed by the Cincinnati Children's Hospital Medical Center (2011a). This scheme considers domains of hierarchy, bias, quantity, magnitude of effect, and consistency of evidence, all considered to be important for evaluating bodies of evidence (Coleman, Talati, & White, 2009), and provides an objective and straightforward grading system. The second and third authors independently evaluated the quality of individual studies using the Cincinnati Children's HospitalMedical Center controlled clinical trial appraisal worksheet (Cincinnati Children's Hospital Medical Center, 2011b) to arrive at a quality level for each study. Agreement was calculated using and percent agreement. Next, the two raters independently evaluated the body of evidence for the clinical question using the Cincinnati Children's Hospital Medical Center evidence grading worksheet (Cincinnati Children's Hospital Medical Center, 2011a). Evidence was graded high, medium, low, or grade unassignable. A high grade of evidence was 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. Highly graded bodies of evidence indicate that further research is not likely to change the level of confidence in the answer to the clinical question. A moderate grade is 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 suggests that further research is likely to have an important impact on the answer to the clinical question. Low evidence is based on local or published consensus but not research evidence. The grade was unassignable if there was insufficient evidence and lack of consensus. Questions and interrater disagreements were resolved by consensus or under the advisement of the first author.

Data Extraction and Analysis

The second and third authors summarized the critical features of each study including study design, characteristics of the population, previous HA usage, test HA features, study protocol, outcome measures, findings, and limitations. The first author reviewed summaries for accuracy and completeness. This information is located throughout the tables and text of this review.

Effect size, r, was calculated for all studies providing sufficient data. For studies providing raw data, the point-biserial correlation coefficient, r_{pb}, was determined using an online calculator (Lowry, 2010). Effect size, r, was also approximated for several studies providing F statistics or paired t values and corresponding degrees of freedom (df; Garbin, n.d. [online calculator]; Rosenthal & DiMatteo 2001, respectively). The confidence interval surrounding each effect was determined from the sample size and effect size estimate using another online calculator (Garbin, n.d.). Effect sizes favoring the experimental technology (i.e., frequency lowering) investigated in each study were assigned a positive value, whereas effect sizes favoring the control condition (i.e., HAs with inactivated or unavailable frequency lowering) were assigned a negative value. Effect size magnitudes were labeled

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small, medium, or large according to the scale suggested by Cohen (1992) such that $r = .10$ is a small effect, $r = .30$ is a medium effect, and $r = .50$ is a large effect. The *p* values were calculated in several studies in which raw data were provided but statistical significance for our sample of interest was not reported. The Wilcoxon signed ranks test was used 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 significant if the confidence interval surrounding the effect size did not include the null value and/or if the *p* value (provided by the author or calculated as indicated above) was less than or equal to .05. For each clinical question, results were further analyzed to determine if any data trends were apparent which may suggest an impact of study design or study quality on the results.

Results

Study Selection

Of the 376 citations retrieved, we rejected 168 after reading the abstract, 171 after reading the full text, and 14 after detailed analysis (see McCreery et al., 2012, for flow chart and reasons for rejection). We fully accepted 23 articles for inclusion in the series of EBSRs; six articles (five studies) pertained to frequency lowering, and the remaining studies addressed either directional microphones/digital noise reduction or amplitude compression and are discussed in separate reviews. The authors of one study (Wolfe et al., 2010) included in this review provided follow-up data in a separate article (Wolfe et al., 2011).

Interrater Reliability

Interrater reliability for sifting articles for inclusion or exclusion was substantial ($\kappa = .67$; percent agreement = 87.9%), and all interrater disagreements were resolved by consensus. Interrater reliability for the critical appraisal of individual studies and the body of evidence was also calculated using the κ statistic (weighted as appropriate) and percent agreement for each of the seven appraisal points based on the raters' agreement across the five studies. These values ranged from substantial agreement ("effect size," $\kappa = .62$; 80%) to perfect agreement ("assessors blinded," "sampling," "allocation," "counterbalancing," $\kappa = 1.00$; 100%) with the exception of two appraisal points related to the adequacy of study protocol description and availability/calculability of *p* values for which interrater reliability was poor ($\kappa = 0$; 80%). For the first appraisal point, raters agreed that there was an adequate description of study protocol for four of the five studies. For the remaining study, the authors disagreed on the adequacy of the protocol description and resolved by consensus that the study provided an inadequate description. For the appraisal point regarding the reporting or calculation of *p* values, the raters agreed that the *p* value was reported or calculable in four of five studies. The one *p* value disagreement was resolved via consensus to have been reported or calculable as well. The raters arrived at full independent agreement ($\kappa = 1.00$; 100%) when identifying the individual study quality levels as the first step in determining the grade of the body of evidence. Individual rater responses are included in the supplementary materials associated with this article.

Study Findings

We obtained five studies that addressed the clinical question posed for this review. Two sets of researchers (Auriemmo et al., 2009; Smith, Dann, & Brown, 2009) studied the use of FT, two (Glista et al., 2009; Wolfe et al., 2010, 2011) investigated NLFC, and one (Miller-Hansen, Nelson, Widen, & Simon, 2003) used FC with DCB. 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

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number of included studies for each clinical question, effect sizes were not averaged across studies.

Frequency Compression With DCB

Miller-Hansen and colleagues (2003) used FC with DCB and collected audibility outcomes for 19 children and speech recognition outcomes for 16 children who had previous outcome data with CP HAs. This study was a repeated measures design with a quality appraisal score of 2/7 (see Table 1 for full list of appraisal criteria and quality scores). As noted in Table 2, children were experienced HA users and had hearing losses ranging from mild-moderate to profound. Outcome measures were obtained 1 month post-fitting of the frequency-lowering device and compared to previous measures with the children's CP HAs. Whereas effect sizes were not calculable for any outcomes in this study, aided thresholds significantly favored the use of the frequency-lowering device over CP at 500, 1000, and 2000 Hz ($p < .0001$); word recognition outcomes also favored the use of frequency lowering ($p = .006$).

Frequency Transposition

Two studies (Auriemmo et al., 2009; Smith et al., 2009) investigated the effect of FT as found in the Widex Inteo 9 and 19 HAs compared to CP in the same or a previously worn device. Both studies were repeated measures design studies with quality appraisal scores of 2/7 (see Table 1). The children in these studies ranged from 6 to 14 years of age with sloping sensorineural hearing losses. They were all experienced HA users (see Table 2). In Auriemmo et al. (2009), speech recognition, speech production, and self-report outcome measures were collected for the study HAs in CP and FT settings at baseline and /or after 3- or 6-week acclimatization and training periods. In the study by Smith and colleagues (2009), speech recognition and speech production outcome measures were obtained after 12 and 24 weeks, respectively, for the study aids in FT mode as compared to the children's previous performance with their own CP HAs.

Speech recognition outcomes—Auriemmo and colleagues (2009) reported no statistically significant differences for a nonsense syllable test presented at 30 dB HL and 50 dB HL between FT and CP at baseline and after 3 weeks of training with each type of processing. There was a significant difference ($p < .05$) between scores after 6 weeks of training in the FT program compared to CP at baseline and after 3 weeks of training at 30 dB HL for consonant recognition and after 3 weeks of training compared to CP at baseline for vowel recognition. Additionally, scores after 6 and 3 weeks of training with the FT settings were significantly better than scores with FT at baseline for consonant and vowel recognition at 30 dB HL (see Table 3). Smith et al. (2009) found statistically significant differences ($p \leq .01$) on tests of word and phoneme perception for participants using frequency lowering after 12 weeks over previous scores with CP HAs.

Speech and language outcomes—Both Auriemmo et al. (2009) and Smith et al. (2009) investigated differences in speech production outcomes after use of FT. Smith et al. noted significant differences ($p = .01$) in the children's scores on the Goldman-Fristoe Test of Articulation—Second Edition (Goldman & Fristoe, 2000) after 24 weeks of HAs with FT as compared to their previous scores without FT. Children in the Auriemmo et al. study also demonstrated significantly better ($p < .05$) production of /s/ and /z/ in reading and conversation after 6 weeks of auditory training with FT as compared to their previous productions after 3 weeks of training without FT.

Self- or parent-report outcomes—Investigators of both studies (Auriemmo et al., 2009; Smith et al., 2009) addressed HA self-report, teacher-report, or family-report outcomes for children using frequency-lowering devices. No measures of effect size were reported or

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calculable for either study. In Auriemmo et al. (2009), significant differences on subjective questionnaires favoring FT were reported after 6 weeks of training ($p < .05$) compared to 3 weeks of training with CP. Also, the majority of children reported a preference for the FT setting over the default HA setting when listening to bird songs, music, and female discourse. Smith .et al. (2009) investigated family perceptions of HA benefit. Only four of the six families responded to the researcher-generated questionnaire. Of those who responded, all reported increased responses to specific high-frequency sounds, observed some degree of change in their child's speech production, and noted that their child heard better during one-on-one conversations. Some families also noted that their child requested repetition less frequently.

Frequency Compression

Outcomes using NLFC were reported in two studies (Glista et al., 2009; Wolfe et al., 2010, 2011). Glista et al. (2009) used a repeated measures design and received a quality appraisal score of 2/7. Wolfe et al. (2010, 2011) randomized and counterbalanced study conditions and was therefore classified as a crossover design with a quality appraisal score of 5/7 (see Table 1). Children in these studies were between the ages of 6 and 17 years and demonstrated sloping sensorineural hearing loss that was either moderately severe to profound (Glista et al., 2009) or mild-moderate to moderately severe (Wolfe et al., 2010, 2011; see Table 2). The acclimatization period ranged from 3 weeks to 1.3 years in Glista et al. and 6 weeks in each condition in Wolfe et al. Both studies provided audibility and speech recognition outcomes, and Glista et al. also provided self- or parent-report outcome measures.

Audibility outcomes—Glista et al. (2009) and Wolfe et al. (2010, 2011) provided audibility outcomes consisting of aided thresholds using tones and/or high frequency speech sounds (i.e., /s/ and /sh/) for both NLFC and CP conditions. Effect sizes were calculable for Wolfe et al.; all were large and significant (they ranged from $r = .60$, 95% CI [.13, .85] to $r = .82$, 95% CI [.53, .94]; see Table 4). These findings favored the use of NLFC over CP conditions. Wolfe et al. (2011) also provided follow-up data at 6 months which revealed no significant change from audibility measures after 6 weeks of use. Although effect sizes were not available for the study by Glista et al., aided thresholds for at least one phoneme, /s/ or /sh/, were significantly ($p < .05$) better for 2 of 10 participants with NLFC as compared to CP. Group level statistical analysis was not completed for the child data in isolation from the adult data; results of a repeated measures analysis of variance (**ANOVA**) completed with combined adult and child data revealed a significant main effect of processor type, favoring **NLFC** over CP. Glista et al. included age group as a between-subjects variable and did not indicate a main effect of age. Further, results from the multiple linear regression analysis indicate that age group was not significantly correlated to the results.

Speech recognition outcomes—Both studies provided efficacy data pertaining to speech recognition outcomes; however, effect sizes were available only in Wolfe et al. (2010, 2011). Wolfe et al. measured discrimination of plurals and several phonemes in tokens, that is, /asa/, /ada/, /afa/, /aka/, /asha/, and /ata/, as well as performance on a speech-in-noise test. A large and statistically significant effect was noted on the University of Western Ontario Plurals Test (Glista & Scollie, 2012), favoring NLFC ($r = .81$, 95% CI [.51, .93]). Two tokens, /asa/ and /ada/, revealed large and statistically better outcomes for NLFC over CP ($r = .57$, 95% CI [.03, .85], $p < .05$; $r = .56$, 95% CI [.07, .83], $p < .05$, respectively). Effect sizes were not calculable for tokens /ada/, /afa/, /aka/, or /asha/, and effect sizes were not significant for tokens /ata/ and /asa/ at 6000 Hz. None of these tokens were statistically significant. Performance on the Bamford-Kowal-Bench Speech-in-Noise Test (Etymotic Research, 2005) was neither clinically nor statistically significant. There

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were no statistically significant differences on any speech recognition outcomes at 6 month follow-up with the exception of a large and significant improvement in discrimination of tokens /ada/ ($r = .68$, 95% CI [.26, .88], $p < .01$) and /asa/ ($r = .62$, 95% CI [.13, .87], $p < .05$) filtered at 6000 Hz for the frequency-lowering condition compared to results at 6 weeks. Glista and colleagues (2009) measured participants' scores on a speech recognition test using a HA with NLFC activated or deactivated. Group-level analysis was not performed for child data in isolation; a repeated measures **ANOVA** completed with adult and child data combined revealed that speech recognition scores were significantly higher in the NLFC condition as compared to the CP condition for consonant and plural stimuli. However, scores were not significantly different for vowels. Age group was included as a between-subjects variable, and it was not indicated that there was a main effect of age. The authors' results of the multiple linear regression indicated no significant correlation of age group on the results for consonant recognition but a significant correlation for plural recognition. Those findings revealed that the children in the study received greater benefit associated with the **NLFC** condition for the plural recognition task than adults. Visual depiction of the child data support that, on average, children's speech recognition scores were higher in the NLFC condition than the CP condition for consonant and plural stimuli, although the statistical significance and magnitude of this effect are unclear. As noted in Table 4, individual analysis of the child data indicated a statistically significant ($p < .05$) difference in speech recognition scores favoring **NLFC** for consonants and plurals for 4/10 participants and 7/11 participants, respectively. There was not a statistically significant difference between the processing types for any children with the vowel stimuli.

Self- or parent-report outcomes—No effect sizes or p values were reported or calculable in either study; however, Glista et al. (2009) noted that 64% of children preferred the NLFC device over CP, 9% preferred CP over NLFC, and 27% preferred neither of the processing conditions.

Trend Analysis by Study Design and Quality

Table 1 depicts the specific appraisal points met or unmet for each study as well as the total quality score. Repeated measures designs were used in four studies. One study used a crossover design (Wolfe et al., 2010, 2011). In that study, participants were randomly allocated to the sequence of conditions and counterbalanced. Study quality scores ranged from 2/7 (Auriemmo et al., 2009; Glista et al., 2009; Miller-Hansen et al., 2003; Smith et al., 2009) to 5/7 (Wolfe et al., 2010, 2011). Although the majority of these studies did provide an adequate description of study protocol and provided measures of statistical significance (or sufficient data to calculate statistical significance), studies did not collect a random sample of participants and in many instances did not randomize to a sequence of conditions or counterbalance to avoid practice effects or blind assessors. The findings were further analyzed to determine whether there were any apparent effects of study design and study quality on results. Visual inspection does not suggest that differences in study quality were responsible for trends in the results. Auriemmo et al. (2009) explained that counterbalancing was not used due to the ethical implications of providing the children with new technology and subsequently removing it as would be necessary in a crossover design. Glista et al. (2009) used a withdrawal study in order to eliminate uncertainty that significant findings in favor of the experimental treatment were erroneously attributed to practice or acclimatization effects. The methods used to quantify high-frequency audibility varied across studies. For example, Glista and colleagues completed a test for cochlear dead regions in their participants to optimize audibility of frequency-lowering settings, whereas Auriemmo et al. did not attempt to provide amplification above 3000 Hz. These decisions could have resulted in differences in high-frequency audibility between the different frequency-lowering strategies. Another consideration is that confounding variables within a

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study may significantly impact the results. Potential confounds noted in this review included unequal amounts of total training time provided in the frequency lowering and CP conditions in Auriemmo et al. and the use of different HA devices (children's own HAs were used to assess CP) in Miller-Hansen et al. (2003).

Overall Quality of Body of Evidence

This body of evidence consists of one low-quality randomized controlled trial (Wolfe et al., 2010, 2011) and four low-quality controlled clinical trials. Findings across these studies were generally consistent and favored the use of frequency lowering over CP amplification for outcomes assessed. This body of evidence is graded moderate, which suggests that further research is likely to have an important impact on conclusions regarding this clinical question.

Discussion

We included five studies in the current review that examined outcome measures for HAs with frequency lowering. Two of the included studies evaluated FT (Auriemmo et al., 2009; Smith et al., 2009), two studies evaluated NLFC (Glista et al., 2009; Wolfe et al., 2010, 2011), and one study evaluated FC with DCB (Miller-Hansen et al., 2003). Overall, studies of frequency lowering reported equivalent or positive results across studies and outcome measures.

Frequency Compression With DCB

Limited evidence from the one study (Miller-Hansen et al., 2003) that reported outcomes for FC with DCB indicated significantly improved audibility and speech recognition outcomes for children using this technology compared to their previous performance with CP HAs. This study suggests that the 1-month acclimatization period was sufficient for children to adapt successfully to these devices. It is unclear whether additional acclimatization would continue to result in significantly improved audibility and speech recognition outcomes. A notable limitation of this study is the use of two different devices (i.e., the experimental frequency compression device and the children's own CP HAs) to assess the two different conditions. We cannot be certain that the study findings were a result of frequency compression and not a result of other uncontrolled differences between the two devices. Also, lack of a control group and lack of counterbalancing reduce the internal validity of the study and ability to control the influence of maturation on speech recognition outcomes. Further, the magnitude of the effect of FC with DCB is unknown because effect sizes were not presented and we were unable to calculate effect sizes from available data. Additional research with FC with DCB is necessary in order to draw meaningful conclusions regarding the impact of this technology for children with hearing loss.

Frequency Transposition

Evidence from two studies (Auriemmo et al., 2009; Smith et al., 2009) addressed the use of FT in the Widex Inteo 9 and 19 HAs. Neither study provided sufficient data comparing audibility outcomes with FT to outcomes with CP amplification for statistical analysis; however, visual analyses of four audiograms in Auriemmo et al. (2009) depicting sound-field thresholds with FT and without FT in the right and left ears clearly suggest lower thresholds for all participants in both ears with FT. Neither study provided speech recognition, speech and language, or self- or parent-report outcomes.

Although no differences in speech recognition were noted in Auriemmo et al. (2009) after 3 weeks of training in each condition, significant differences were noted for consonant recognition after 6 weeks of training in the FT condition compared to outcomes after 3

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weeks in the CP amplification condition. Further, scores after 3 weeks and 6 weeks of training with FT were significantly better than baseline FT scores. Similarly, Smith and colleagues (2009) noted a significant difference between phoneme perception scores in favor of FT following a 12-week acclimatization period in comparison with scores associated with previous use of CP amplification. Findings from Auriemmo et al. and Smith et al. suggest that length of acclimatization may have a significant impact upon speech recognition outcomes and warrants further systematic evaluation. Unfortunately, the lack of a control group and counterbalancing in both of these studies does not allow us to rule out practice, training, or maturational effects. Also, the duration of the training was a confounding variable because unequal amounts of training were provided in each condition. We cannot be certain that study findings reflect differences caused by FT and not additional auditory training. Auriemmo et al. noted that auditory training alone was unlikely to have been responsible for the findings because outcomes on a nonsense syllables test were similar at time of fitting with the default condition and after 3 weeks of training.

Speech and language outcomes are consistent with speech recognition findings from both studies. Smith et al. (2009) noted significantly higher scores on an articulation test after 24 weeks of FT use as compared to previous scores associated with the use of CP amplification. Auriemmo et al. (2009) noted significantly better production of /s/ and /z/ in the study participants after 6 weeks of training with FT as compared to previous scores after 3 weeks of training with CP amplification. As with speech recognition outcomes, practice effects, training, and maturation (i.e., the passage of time between the two speech and language measurement periods in each condition), all threats to internal validity and potential confounding variables, such as differences in the length of training between CP and FT, may account for the significant difference in findings.

Limited evidence from one study (Auriemmo et al., 2009) indicated a child preference for FT after 6 weeks of acclimatization compared to CP amplification. In the study by Smith and colleagues (2009), families noted improvements in children’s auditory functioning with FT. The lack of effect sizes for the majority of these findings limits the characterization of the magnitude of the effect of FT in these studies. Because blinding was not used in these studies, results of subjective preference measures should be viewed with caution. Without blinding children, parents, and teachers to the experimental processing, positive effects may be related to expectations of improvement related to labeling, and negative effects may be moderated by the same expectations. Such effects have been documented in HA outcomes research with adults (Bentler, Niebuhr, Johnson, & Flamme, 2003) and can significantly impact listeners’ perceptions and expectations about benefit.

Frequency Compression

Authors of two studies (Glista et al., 2009; Wolfe et al., 2010, 2011) investigated the use of NLFC on audibility and speech recognition outcomes in children (and adults: Glista et al., 2009) with hearing loss. Although significant findings were reported for audibility outcomes and consonant and plural speech recognition outcomes in Glista et al. (2009), these findings included both adult and child data combined. Additional statistical analyses indicated that there was not significant variability between adult and child findings for /s/ and /sh/ detection and consonant recognition, and that the variation in plural recognition resulted from larger improvement with NLFC for children as compared with adults. However, it is uncertain whether statistical analysis of the child data in isolation would have sufficient power to produce a statistically significant result or a large effect size. Individual audibility and speech recognition data from Glista et al. indicated that some, but not all, participants had significantly better outcomes with the use of NLFC. Wolfe et al. (2010, 2011) reported statistically significant findings favoring the use of NLFC for all tested thresholds (4000–8000 Hz) and phonemes /s/ and /sh/. Additionally, significant speech recognition outcomes

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were noted, favoring NLFC for plurals and some speech tokens (/asa/, /ada/, /ata/), but not for sentences in noise. The magnitudes of these effects were all medium to large. Unlike the previous study designs discussed, Wolfe et al. used a counterbalanced crossover design with equal (6 week) acclimatization periods for each condition, thereby eliminating the concern for practice, order, training, and maturation effects noted in previous studies.

Implications of Findings

The purpose of frequency-lowering strategies is to increase the audibility of the high frequencies to minimize the negative consequences of limited HA bandwidth. The authors of the studies included in this review evaluated three different frequency-lowering strategies and overall contribute to a moderate body of evidence, suggesting that additional research evidence may have an important impact on conclusions regarding the use of this technology. Across frequency-lowering strategies, audibility, as measured by aided pure-tone thresholds and /s/ and /sh/ detection thresholds, was consistently improved by frequency lowering. Aided detection of pure tones in quiet has limited utility for predicting audibility for speech in realistic listening environments (Stelmachowicz & Lewis, 1988) because thresholds are measured at levels significantly below the average level of speech sounds as processed by hearing aids. Improvements in the detection of fricative sounds would be expected to translate more directly into measurable improvements in speech recognition. Therefore, if clinicians are interested in documenting changes in audibility with frequency lowering, differences in the detection of specific phonemes or phonemic contrasts may be a more valid approach than aided pure tone thresholds in sound field. Specifically, aided pure tone thresholds are likely to be strongly affected by other signal processing systems in the HA, such as amplitude compression or feedback management. Additionally, the researchers who examined NLFC (Glista et al., 2009; Wolfe et al., 2010, 2011) and FC with DCB (Miller-Hansen et al., 2003) used a version of the desired sensation level (DSL; Scollie et al., 2005) prescriptive formulas to verify the gain and maximum output of the HA, which is widely used in pediatric HA fitting. In both of the studies of FT, investigators used the manufacturer's proprietary prescriptive approach (Sensogram). Differences in prescriptive formulae for the types of frequency lowering included in the current review could have resulted in variations in audibility that were related to the prescriptive approach rather than the frequency lowering. Discrepancies in the prescriptive approach make comparisons across studies and types of frequency lowering difficult to attribute to frequency lowering alone. Additionally, generalization to other prescriptive approaches is also not possible.

For studies in the current review, speech recognition outcomes were also generally more favorable with the use of frequency lowering as compared to CP amplification; however, due to methodological weaknesses in the majority of studies, we cannot be sure that the benefit is truly a result of the frequency lowering or that it is clinically significant. The authors of one study (Wolfe et al., 2010, 2011) that was of relatively higher methodological quality did show meaningful and statistically significant benefit of NLFC for some, but not all, speech recognition subtests. These differences across stimuli may have been impacted by varying degrees of sensitivity to the morphosyntactic cues, such as plurality. Specifically, since frequency-lowering strategies are most likely to facilitate detection and understanding of high-frequency speech sounds (such as /s/ and /z/), the largest benefits of these strategies should be realized in tests that are sensitive to morphology at the word level. Speech recognition tests that provide more opportunities to identify plurals, such as the University of Western Ontario Plurals Test (Glista & Scollie, 2012), allow direct assessment of morphology at word level contrasts that are likely to be affected by frequency lowering. Speech recognition tests that include sentence-level syntactic cues, such as the Bamford-Kowal-Bench Speech-in-Noise Test (Etymotic Research, 2005), or do not contain a sufficient number of high-frequency phonemes (Phonetically Balanced Kindergarten words;

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Haskins, 1949) may not accurately reflect the impact of frequency lowering on all aspects of speech understanding. Additionally, sentences may provide listeners with semantic and syntactic cues that support speech recognition even when acoustic cues are limited. Because current frequency-lowering strategies are applied primarily to the high frequencies where speech energy may be limited, standardized estimates of audibility such as the SII (ANSI S3.5–1997) do not predict large improvements in the overall speech recognition score if the audibility of high-frequency bands is enhanced. The limitations of the SII for predicting speech recognition was highlighted in work by Gustafson and Pittman (2010), who reported variability in speech recognition for adults and children with normal hearing between conditions with varying bandwidth but matched for audibility on the SII. Given the significance of high-frequency audibility for the development of phonological (Moeller et al., 2007) and morphosyntactic (Moeller et al., 2010) skills as well as novel word learning (Pittman, 2008), the limitations in enhancing the audibility of high-frequency sounds for speech recognition should not be interpreted as being insignificant to a child's development.

Speech and language outcomes were reported only in the two studies that investigated FT (Auriemmo et al., 2009; Smith et al., 2009). As previously indicated, we cannot conclude that the improvements noted in these outcomes were a result of FT because maturation and practice effects were not addressed by appropriate control conditions. Whereas measures of audibility and speech recognition are more directly linked (i.e., less impacted by factors external to hearing) than speech and language measures to HA signal processing, speech and language measures are also important to investigate because these outcomes have enormous impacts on a child's academic abilities and social well-being.

Measures of user satisfaction are also critical in HA research because the perceptual benefits of amplification do not always correspond to increased listener satisfaction. For example, in studies of digital noise reduction with adult listeners, speech recognition was not altered by the signal processing, but significant improvements in ratings of sound quality were observed (Ricketts & Hornsby, 2005). Limited findings provided in several studies included in this review suggest that many children prefer frequency-lowering devices to CP amplification and that subjective improvements in hearing are noted by many children and their families with the use of frequency lowering.

Directions for Future Research

The current research with frequency-lowering signal processing strategies is in the efficacy phase of research, meaning that the outcomes were primarily measured in controlled laboratory environments. The frequency-lowering strategy of interest in these studies was the independent variable; other signal processing variables generally were controlled for or deactivated. These studies all implemented repeated measure designs to compare children's outcomes related to CP amplification to outcomes associated with frequency-lowering amplification. Although one study (Wolfe et al., 2010, 2011) controlled for potential order effects by counterbalancing amplification conditions, the majority of studies did not. Future efficacy research in this area should carefully control for order effects by randomization and counterbalancing to ensure that all results can be attributed to the use of frequency lowering and not accounted for by practice or, in studies of extended duration, maturation. As the length of the acclimatization period and differences in individual participant characteristics appear to influence outcomes, additional research to determine ideal candidacy and training/acclimatization periods may be warranted. Future research should also include measures of effect size in order to evaluate the magnitude of the impact of frequency-lowering strategies compared to CP amplification.

Once the efficacy of different frequency-lowering strategies is established with additional research, subsequent research may focus on comparative efficacy and effectiveness research.

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Comparative efficacy research will be necessary to determine whether one type of frequency lowering is more beneficial than others, which includes consideration of the influence of the hearing characteristics of the child or other external variables. Also, since most HAs incorporate more than one signal processing strategy into the same device, efficacy and effectiveness research will be needed to investigate how audibility, speech recognition (especially morphosyntax), speech and language, and satisfaction outcomes are affected by the interaction of multiple signal-processing strategies (e.g., directional microphones, wide dynamic range compression, and FT) in real-world environments.

Although several of the studies included in the current review examined the influence of acclimatization on speech recognition outcomes (Auriemmo et al., 2009; Smith et al., 2009; Wolfe et al., 2010, 2011), variations in the time course and degree of improvement over time suggest that factors related to the acclimatization process should be examined. Immediate improvements in audibility are anticipated to support long-term benefits for speech recognition and speech and language outcomes. Therefore, the influence of acclimatization on speech and language outcomes should also be examined, preferably using control groups or other methodological approaches to minimize the influence of maturational and practice effects on outcomes. Two studies that included measurements at two different time intervals (Auriemmo et al., 2009; Wolfe et al., 2010) demonstrated that initial improvements in speech recognition outcomes were either maintained or increased after varying periods of experience (with or without additional auditory training) with the signal processing. Until further research into the time course of improvements related to frequency lowering can be reported, clinicians should anticipate that improvements in outcomes may be observed as listening experience increases over time.

The studies included in the current review also include a heterogeneous sample of hearing impaired children with variations noted in age as well as severity of hearing loss, extent of experience with CP amplification, length of exposure to aided audibility, and other variables that could influence the degree to which frequency-lowering benefits may be observed. These differences across studies are not conducive to developing consistent candidacy for frequency lowering in general or for the three specific implementations of frequency lowering used in different studies. The extent to which these and other variables influence outcomes with frequency lowering should be explored to assist clinicians in making decisions about whether or not frequency lowering is appropriate and, if so, what parameters should be selected to optimize audibility.

Limitations

There are several limitations to the current review. One is the inclusion criterion, which restricted accepted articles to those reporting on a signal processing strategy that is currently implemented in commercial HAs. This restriction eliminated studies that used frequency vocoding and outdated forms of FT, which may have provided a historical background of the earlier outcomes of frequency lowering. In addition, only studies that were published in English were included, which likely reduced the total number of studies that could have been evaluated. Also, the decision was made to accept only studies published in a peer-reviewed journal in order to ensure that all studies received initial vetting and to reduce the likelihood of including biased studies; however, it has been suggested that the exclusion of nonpublished research may introduce publication bias into the systematic review. Because research on this topic continues to be conducted and published, the reader is encouraged to consider all literature published after the systematic search conclusion dates specified in this EBSR. We expect that future updates to this review will capture additional published research. The results of the systematic review were not pooled in a meta-analysis due to the variations across frequency-lowering strategies and the limited number of effect sizes available. Direct comparisons between types of frequency lowering were not possible due to

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multiple methodological differences between studies as well as the fact that studies of FT used the manufacturer's proprietary prescriptive approach, whereas studies of NLFC and FC with DCB used the DSL prescriptive approach to determine HA gain and maximum output levels. Differences in audibility between prescriptive approaches that are unrelated to frequency lowering confound potential comparisons across frequency-lowering strategies for all of the outcomes in the current review.

Conclusion

Based on a moderate body of evidence, current research provides preliminary support for the use of frequency-lowering strategies for school-age children with sloping hearing loss of at least moderate degree in the high frequencies. The majority of research in this area contains methodological limitations that restrict our ability to draw strong conclusions; however, outcomes were generally positive across outcome measures. Additional research is needed in order to draw confident conclusions regarding the use of frequency lowering. For example, individual variation in observed benefit from frequency-lowering strategies, as reported in one study, may reflect differences in audibility. Given the potential heterogeneity of outcomes across school-age children, clinicians should use clinical outcomes to monitor children's auditory development milestones and aided speech recognition to support clinical decisions about the implementation of frequency lowering with their pediatric patients. Future research should attempt to resolve issues surrounding candidacy for frequency-lowering strategies as well as the timeframe and extent of any acclimatization that may occur.

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Table 1

Study characteristics.

Citation	Study design	Critical appraisal points							
		Protocol description	Assessors blinded	Sampling	Allocation	Counterbalancing	*p* values	Effect sizes	Appraisal score
Auriemmo et al. (2009)	Repeated measures	**Adequate**	Not blinded	Conv/HP/ NR	Not random/ NR	Not counterbalanced/ NR	**Rep/calc**	ES/CI not rep/calc	2/7
Glista et al. (2009)	Repeated measures[a]	Inadequate	**Blinded**	Conv/HP/ NR	Not random/ NR	Not counterbalanced/ NR	**Rep/calc**	ES/CI not rep/calc	2/7
Miller-Hansen et al. (2003)	Repeated measures	**Adequate**	Not blinded	Conv/HP NR	Not random/ NR	Not counterbalanced/ NR	**Rep/calc**	ES/CI not rep/calc	2/7
Smith et al. (2009)	Repeated measures	**Adequate**	Not blinded	Conv/HP/ NR	Not random/ NR	Not counterbalanced/ NR	**Rep/Calc**	ES/CI not rep/calc	2/7
Wolfe et al. (2010, 2011)	Crossover	**Adequate**	Not blinded	Conv/HP / NR	**Random**	**Counterbalanced**	**Rep/Calc**	**ES/CI rep/ calc**	5/7

Note. Items in bold 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; HP = hand-picked; NR = not reported; Rep = reported.

[a] The study authors label the study design as a modified withdrawal design.

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Table 2

Participant characteristics.

Citation	Number of participants	Age range (average) in years	Gender NR	Hearing loss type and severity	Previous HA use
Auriemmo et al. (2009)	10	6.3–13.5 (10)	NR	Sloping SNHL with hearing thresholds no worse than 60 dB HL in the low frequencies, but above 70 dB HL above 4000 Hz.	Experienced digital HA users; one participant with frequency compression HA; nine children used FM systems along with their HAs in the classroom.
Glista et al. (2009)	11	6–17 (11)	4F/7M	Sloping, SNHL Moderately severe-profound in better ear 1 participant may have mixed loss.	Nine digital HAs users, one analog HA user; one inexperienced HA user
Miller-Hansen et al. (2003)	19	5.7–21.6 (12.5)	NR	Bilateral SNHL 6 with profound 6 with severe 4 with moderate-severe 3 with mild-moderate	Previous users of CP HAs
Smith et al. (2009)	6	9–14	3F/3M	Sloping high frequency SNHL	Previous HA users
Wolfe et al. (2010, 2011)	15	6–12 (10.4)	NR	Mild to moderate SNHL in low frequencies and moderate to moderately severe loss in high frequencies	All children had previously worn digital HAs. None had experience with frequency-lowering technology.

Note. CP = conventional processing; dB = decibel; F = female; FM = frequency-modulation; HA = hearing aid; HL = hearing level; Hz = Hertz; M = male; SNHL = sensorineural hearing loss.

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Table 3

Frequency transposition.

Citation	Comparison	Acclimatization	Outcome category	Measure	Sub-measure	Effect size [95% CI][a]	*p* value
Auriemmo et al. (2009)	FT (+ training)	FT measures at: Baseline	Speech recognition	Nonsense syllable test	30 dB HL consonants	NR/NC	FT after 6 wks training > CP at baseline, $p < .05$
	CP (+ training)	3 wks					FT after 6 wks training > CP after 3 weeks training, $p < .05$
		6 wks CP measures at: Baseline			30 dB HL vowels	NR/NC	All other comparisons NS FT after 3 wks training > CP at baseline, $p < .05$
		3 wks			50 dB HL consonants	NR/NC	All other comparisons NS All comparisons NS
					50 dB HL vowels	NR/NC	All comparisons NS
		FT: measures at: 3 wks	Speech and language	/s/ and /z/ production	Reading	NR/NC	FT after 6 wks training > CP after 3 wks, $p < .05$
		6 wks					All other comparisons NS
		CP: measures at: 3 wks			Conversation	NR/NC	FT after 6 wks training > CP after 3 wks, $p < .05$
		FT: 6 wks CP: 3 wks	Self- or parent-report	% env HF sounds detect		NR/NC	All other comparisons NS $p < .05$ (favors FT)
Smith et al. (2009)	FT	FT: 12 wks	Speech recognition	Phoneme perception		NR/NC	$p = .003$ (favors FT)
	CP (previous HAs)	CP: Duration of use unknown		Word perception		NR/NC	$p = .01$ (favors FT)
		FT: 24 wks CP: Duration of use unknown	Speech and language	Articulation test		$r_{pb} = .66$ [–.33, .96][b]	$p = .01$ (favors FT)

Note. env = environmental; FT = frequency transposition; HF = high frequency; Hz = Hertz; NC = not calculable; NS = not significant; wks = weeks.

[a] Positive effect sizes indicate that the direction of the effect favors frequency transposition. Negative effect sizes favor conventional processing.

[b] Effect size, r_{pb} (point-biserial correlation coefficient), calculated from individual participant data provided in the study.

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Table 4

Frequency compression.

Citation	Comparison	Acclimatization	Outcome category	Measure	Sub-measure	Effect size [95% CI][a]	*p* value
Glista et al. (2009)	NLFC CP	NLFC: Avg. 10.75 wks (range 3 wks–1.3 yrs) CP: Avg. 4.17 wks (range 2 wks–3 mnths)	Audibility	Aided thresholds	Phonemes /s/ and /sh/	NR/NC	Group analysis: NR[b] Individual analysis: 2/10 participants: $p < .05$ (favors NLFC for at least one phoneme, /s/ or /sh/) 8/10 participants: NS
		User was able to activate/ deactivate NLFC in final phase: Avg. 5.58 wks (range 2 wks to 5 mnths)	Speech recognition	Speech recognition test	Consonants	NR/NC	Group analysis: NR[b] Individual analysis: 4/10 participants $p < .05$ (favors NLFC); 6/10: NS
					Vowels	NR/NC	Group analysis: NR[b] Individual analysis: 11/11 participants: NS
					Plurals	NR/NC	Group analysis: NR[b] Individual analysis: 7/11 participants: $p < .05$ (favors NLFC); 4/11: NS
Wolfe et al. (2010, 2011	NLFC CP	NLFC: 6 wks CP: 6 wks	Audibility	Aided thresholds	Overall	$r = .82$ [.53, .94][c]	$p < .001$ (favors NLFC)
					4000 Hz	$r = .68$ [.26, .88][c]	$p < .01$ (favors NLFC)
					6000 Hz	$r = .76$ [.41, .92][c]	$p < .01$ (favors NLFC)
					8000 Hz	$r = .58$ [.10, .84][c]	$p < .05$ (favors NLFC)
					Phoneme /s/	$r = .87$ [.65, .96][c]	$p < .001$ (favors NLFC)
					Phoneme /sh/	$r = .60$ [.13, .85][c]	$p < .05$ (favors NLFC)
			Speech recognition	Speech recognition test	Plurals	$r = .81$ [.51, .93][c]	$p < .001$ (favors NLFC; ceiling effects for 2 children)
				Phoneme discrimination thresholds:	Token /asa/	$r = .57$ [.03, .85][c]	$p < .05$(favors NLFC)
					Token /ada/	$r = .56$ [.07, .83][c]	$p < .05$ (favors NLFC)
					Token /afa/	NR/NC	NS
					Token /aka/	NR/NC	NS
					Token /asha/	NC	NS
					Token /ata/	NR/NC	NS
					Token /asa/ filtered at 6000 Hz	$r = .52$ [–.04, .83][c]	NS
						$r = .28$ [–.29, .71][c]	
				Sentences in noise test		$r = .35$ [–.20, .73][c]	NS

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Note. Avg = average; CP = conventional processing; CI = confidence interval; Hz = Hertz; mnths = months; NLFC = nonlinear frequency compression; NC = not calculable; NR = not reported; NS = not significant; wks = weeks; yrs = years.

[a] Positive effect sizes indicate that the direction of effect favors frequency compression. Negative effect sizes indicate that the direction of the effect favors conventional processing,

[b] Repeated measures ANOVA completed with combined adult/child data and age group included as between-subjects variable, however results not presented for separate analysis of child data,

[c] Effect size, *r*, calculated using the paired-samples *t* test statistic and df provided in the study.

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Appendix

HA and Procedural Details

Citation	HA model	Experimental feature	Other features	Fitting prescription	Monaural/binaural testing
Auriemmo et al. (2009)	Widex Inteo IN-19 or IN-9	FT	Fully adapted directionally Multiband Active feedback cancellation system Classic noise reduction Slow-acting WDRC 15 channels Active feedback cancellation (CP) Gain limitation feedback mechanism (FT)	Manufacturer proprietary	Monaural soundfield testing
Glista et al. (2009)	Prototype BTE HAs similar to Phonak Savia 311 or 411	NLFC	Omnidirectional Two band Amplitude Compression Multichannel Noise reduction disabled Automatic program selectors disabled	DSL v5.0	Binaural
Miller-Hansen et al. (2003)	AVR ImpaCt HA (FC with DCB) CP HAs, not further specified (CP)	FC with DCB	2 channel (FC with DCB) Not specified (CP)	DSL [i/o]	Binaural
Smith et al. (2009)	Widex Inteo 9 and 19	FT	Amplitude Compression 15 channel Feedback cancellation limits	Manufacturer proprietary	Binaural
Wolfe et al. (2010, 2011)	Phonak Nios	NLFC	Microsized BTE	DSL v5.0	Binaural

Note. BTE = behind the ear; CP = conventional processing; DCB = dynamic consonant boost; DSL = Desired Sensation Level; FC = frequency compression; FT = frequency transposition; HA = hearing aid; [i/o] = input/output; NLFC = nonlinear frequency compression; WDRC = wide dynamic range compression.