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

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Abstract

Purpose—Two clinical questions were developed: one addressing the comparison of linear amplification with compression limiting to linear amplification with peak clipping, and the second comparing wide dynamic range compression with linear amplification for outcomes of audibility, speech recognition, speech and language, and self- or parent report in children with hearing loss.

Method—Twenty-six databases were systematically searched for studies addressing a clinical question and meeting all inclusion criteria. Studies were evaluated for methodological quality, and effect sizes were reported or calculated when possible.

Results—The literature search resulted in the inclusion of 8 studies. All 8 studies included comparisons of wide dynamic range compression to linear amplification, and 2 of the 8 studies provided comparisons of compression limiting versus peak clipping.

Conclusions—Moderate evidence from the included studies demonstrated that audibility was improved and speech recognition was either maintained or improved with wide dynamic range compression as compared with linear amplification. No significant differences were observed between compression limiting and peak clipping on outcomes (i.e., speech recognition and self-/parent report) reported across the 2 studies. Preference ratings appear to be influenced by participant characteristics and environmental factors. Further research is needed before conclusions can confidently be drawn.

Keywords

children; evidence-based systematic review; amplitude compression; wide dynamic range compression; compression limiting; amplification

Listeners with cochlear hearing loss experience reduced audibility as well as an abnormal growth of loudness perception, known as *loudness recruitment* (Steinberg & Gardner, 1937; see also Moore, 2007, pp. 97–101, for a review). The combination of decreased hearing sensitivity and increased likelihood of loudness discomfort creates formidable challenges for

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improving audibility using amplification. Loudness discomfort or distortion could result in decreased speech understanding (Moore, Glasberg, & Vickers, 1995) and decreased hearing aid (HA) use or even rejection of amplification. This is particularly concerning for children with hearing loss because early identification and subsequent effective implementation of amplification has been found to positively affect language development (Yoshinaga-Itano, 2003), a fundamental factor in academic achievement. In order to maximize speech understanding and communication development, children with mild to severe cochlear hearing loss require HAs that optimize the audibility of the speech signal over a large range of input levels, while reducing the likelihood of loudness discomfort and distortion for loud sounds. Multiple signal-processing strategies, known collectively as *amplitude compression,* have been developed to alter the amount of gain provided by the HA as a function of input level in order to improve audibility, enhance speech intelligibility, and/or minimize loudness discomfort. Amplitude compression includes strategies that reduce gain only at high input levels to avoid distortion and discomfort, referred to as *compression limiting,* as well as those that prevent loudness recruitment by gradually reducing gain as a function of input level in order to maximize the audibility of signals over a wide range of inputs, known as *wide dynamic range compression* (WDRC). Amplitude compression is often defined by the input level where compression starts, known as the *compression kneepoint,* and the amount of gain reduction in the output signal compared with the input signal, known as the *compression ratio*. As such, a HA may be linear or increase gain (expansion) up to the level of the compression kneepoint and provide compressed gain after that point. In the case of WDRC, the amount of gain is decreased as the input level increases above the compression kneepoint.

In the earliest attempts to limit the maximum output in conventional HAs, peak clipping was implemented to prevent amplification of any sounds above the saturation point of the amplifier. Although peak clipping can successfully reduce loudness discomfort by keeping the output of the HA under the listener's loudness discomfort level, distortion of the signal occurs. Compression limiting is an alternative to peak clipping that reduces gain rapidly at high input levels by applying significant amplitude compression at a specified level just below the saturation point of the amplifier. Because HAs with peak clipping or compression limiting provide linear amplification except at the highest input levels, they are typically classified as linear HAs. Due to wide variability in loudness levels in many real listening environments, linear HA wearers may have to make frequent adjustments to the volume control to maintain comfort across acoustical environments with varied intensity levels (Leijon, 1990). WDRC was developed, in part, to reduce the need for frequent volume control changes by the user when the acoustic environment changes, which has been substantiated in studies of volume control use in adults who use HAs (Banerjee, 2011). Limiting the need for volume control changes is achieved by maintaining gain for low input levels, comfortably preserving gain at average input levels, and reducing gain at high input levels. HAs with WDRC reduce the differences in intensity between the softest and loudest syllables and should increase the proportion of the speech signal that is at an optimal loudness level for listeners, thus theoretically reducing the need to manually adjust the volume control.

Most modern HAs use both WDRC at low and average input levels and compression limiting at high input levels in order to provide audibility of a range of inputs while preventing peak clipping of the signal. However, the specific parameters of amplitude compression, including the number of independent channels, compression kneepoint, compression ratio, and time constants vary across manufacturers and devices. Generic prescriptive approaches to amplification for children, such as the Desired Sensation Level (DSL; Scollie et al., 2005), have been developed and validated to maximize audibility of speech signals across a wide range of input levels. DSL recommends varying amounts of gain for different input levels in order to promote audibility and listener comfort over a range of input levels. Optimizing gain across input levels requires the use of amplitude compression to ensure that soft sounds are audible, while preventing loudness discomfort at higher input levels. Although many manufacturers have implemented DSL into their HA-fitting software, the implementation of DSL and resulting gain and maximum output settings are not consistent or predictable (Seewald, Mills, Bagatto, Scollie, & Moodie, 2008), leaving clinicians to evaluate the adequacy of amplitude compression through verification. Given the variability of the signal-processing strategies described above and the steps undertaken by clinicians to determine the appropriate implementation of such technology, a literature review on the impact of amplitude compression strategies for children is necessary.

Palmer and Grimes (2005) reported on the effectiveness of signal-processing strategies in the pediatric population in a systematic review. Specifically, they addressed whether evidence existed to recommend optimal signal processing for pediatric hearing patients. One aim of the review was to document the evidence comparing linear and WDRC signal processing. The authors concluded that children with mild to moderately severe sensorineural hearing loss (SNHL) should be fit with WDRC signal processing that uses a low-compression threshold, moderate compression ratio, fast attack time, and compression limiting to control maximum output. A separate focus of Palmer and Grimes' review was to compare output-limiting strategies. In the two studies included in their review, neither peak clipping nor compression limiting was shown to be superior to the other in terms of speech recognition or loudness perception outcomes. Palmer and Grimes concluded that evidence existed that could be used to support recommendations for signal-processing strategies for children; however, they stopped short of delineating them further into categories, such as hearing, speech, and language outcomes; quality ratings; and compression settings, which could enhance their clinical application. In addition, the search was completed prior to 2006. Considering recent and rapid innovations in HA signal-processing strategies and the potential impact of delineating findings into the aforementioned categories, a more current systematic review of the literature pertaining to the effectiveness of signal processing in pediatric populations is needed. Research on the effectiveness of HAs on hearing, speech, and language outcomes with adults is more prevalent than with children. Although effectiveness and satisfaction with amplitude compression are likely to differ between the two populations, a brief review of research findings from the adult population may provide some insight into what outcomes can be expected in the pediatric population.

The influence of amplitude compression on speech understanding and listener ratings of sound quality has been widely studied with adult listeners with hearing loss. Outcomes for amplitude compression depend on the type of amplitude compression, as well as the input level where the outcome is measured. For example, differences between linear amplification with peak clipping and linear with compression limiting would only be expected at high-input levels (typically > 85 dB SPL) because the difference between the two processing types occurs only at input levels near the maximum output of the HA. At high-input levels, compression limiting would be expected to provide superior sound quality over peak clipping due to decreased signal distortion, which has been observed in such comparisons with adults (Dillon, 1996; Hickson, 1994). Sound quality comparisons between peak clipping and compression limiting at high-input levels would be anticipated to follow a similar pattern in school-age children as has been observed with adults: Higher ratings of satisfaction with sound quality were noted for linear with compression limiting than for linear with peak clipping.

For comparisons between linear amplification and WDRC, the largest differences would be expected to be at input levels equivalent to soft speech (< 55 dB SPL), where WDRC would provide more gain and audibility for an equivalent signal than linear processing. For conditions in which the input level is either equivalent to average speech (> 60 dB SPL) or higher, differences in audibility between WDRC and linear amplification would be anticipated to be small and would depend on the degree to which audibility of the softest components of the speech signal are enhanced by WDRC, which would provide more gain for less intense speech sounds than linear amplification. For measures of comfort and sound quality in adults, WDRC is preferred over linear amplification with compression limiting (Boike & Souza, 2000; Davies-Venn, Souza, & Fabry, 2007; Souza, 2002; Walden, Surr, Cord, Edwards, & Olson, 2000). Whereas WDRC improves the audibility of soft speech (Souza, 2002; Souza & Turner, 1998), an advantage for WDRC over compression limiting on speech recognition with adult listeners is less consistently observed (Moore, Peters, & Stone, 1999; Souza, Jenstad, & Folino, 2005). Variables such as the participant's degree of hearing loss (Davies-Venn, Souza, Brennan, & Stecker, 2009; Kam & Wong, 1999), presentation level where speech recognition is compared (Barker, Dillon, & Newall, 2001), and the method used to amplify stimuli (Souza et al., 2005) could influence whether or not a difference was observed.

Whereas linear amplification with compression limiting changes the output only at high-input levels, WDRC occurs over a broad range of input levels. Therefore, WDRC may be more likely to introduce spectral and/or temporal distortion to the speech signal than linear processing (Bor, Souza, & Wright, 2008). As a result, improvements in speech recognition with WDRC compared with linear processing are only expected in conditions in which WDRC increases the audibility of the speech signal relative to linear amplification. For school-age children, the pattern of results is more difficult to predict. Children may experience greater benefit from increased audibility of soft speech cues, which would be expected to occur with WDRC. However, children are also more likely than adults to experience degradation in speech recognition due to distortion (Eisenburg, Shannon, Martinez, Wygonski, & Boothroyd, 2000). If improvements in the audibility of soft sounds occur at the expense of greater signal distortion, the net effect of WDRC for children would be expected to be null or even negative in cases of significant distortion.

The purpose of the present review was to examine a selection of literature, specifying a range of hearing, speech, and language outcomes associated with the use of amplitude compression in school-age children with permanent hearing loss, in an effort to quantify the impact of amplitude compression on aided audibility with children. Beginning in 2010, the American Speech-Language-Hearing Association's (ASHA) National Center for Evidence-Based Practice in Communication Disorders conducted a systematic literature search of several types of HA signal-processing features for children. The results of that search are discussed in a series of three evidence-based systematic reviews (EBSRs). The present review pertains to the effect of amplitude compression on outcomes related to hearing and communication outcomes for school-age children with hearing loss, whereas the two other reviews in this series address directional microphone response/digital noise reduction and frequency-lowering HAs.

This series of reviews considers four categories of outcome measures: audibility, speech recognition, speech and language, and self-/parent report measures. The importance of measuring these outcomes in HA research was discussed in an article by Hogan (2007). *Audibility* is defined as the ability to hear sounds directly and includes measures such as sound-field testing, real ear measures, real-ear-to-coupler difference, Articulation Index (AI; American National Standards Institute [ANSI], 1969) scores, and Speech Intelligibility Index (SII; ANSI, 1997) scores. Speech recognition measures are objective measures of speech stimuli identification, which include phoneme, nonword, word, and sentence materials. Speech and language outcomes are measured by formal or informal tests of receptive and expressive speech and language, such as the Goldman–Fristoe Test of

Articulation—Second Edition (GFT–2; Goldman & Fristoe, 2000) or mean length of utterance. Finally, self- and parent report measures are typically obtained through satisfaction surveys and listening questionnaires.

Clinical research has been suggested to progress through distinct phases beginning with exploratory research and ending with cost-effectiveness research (Robey, 2004). Robey describes these phases as follows: Exploratory research (Phases I & II) typically consists of case studies and discovery-oriented small studies; efficacy research (Phase III) usually includes controlled laboratory trial research; effectiveness research (Phase IV) is often conducted in typical environments to determine the extent to which therapeutic benefit is attainable in realistic situations; and cost-effectiveness research (Phase V) typically consists of a cost–benefit analysis and is usually targeted to regulators, policymakers, and legislative bodies. It was anticipated, given the known evidence base and widespread use of amplitude compression, that the majority of research on this topic would be at the efficacy or effectiveness level of research. As such, the following clinical questions were developed for this review:

> *Clinical Question 1:* What are the effects of compression output limiting as compared with peak clipping output limiting 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?

> *Clinical Question 2:* What are the effects of WDRC as compared with linear amplification 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

The systematic literature search for this review topic as well as those of the two other reviews in this series (i.e., directional microphones/digital noise reduction and frequency-lowering technology) was completed as one combined literature search of HA-processing features and one subsequent update. The search strategy was developed by the fourth author (H.M.L.), who is experienced in conducting comprehensive and systematic literature searches (e.g., Frymark et al., 2010). The literature search covered peer-reviewed research studies indexed in 26 databases (e.g., PubMed, CINAHL, PsycINFO, ERIC) published from 1980 to July 2011 using key words related to hearing loss, amplification, and children (e.g., HA, hearing instrument, amplification, child). Additional specific searches included forward searching of all included studies and prolific author searching. Finally, two authors reviewed the reference lists of all full-text articles to identify potentially relevant studies for inclusion. The original literature search was performed between January and April of 2010. Given the extensive scope of the review, the authors decided to report the findings in three separate systematic reviews. To ensure that the systematic reviews contained the most current information available, an update of the original literature search was performed in July 2011. Specific details pertaining to the literature search, including the full list of databases, key words, and search dates, can be found in Appendix A.

Inclusion criteria required studies to address a specific clinical question within an experimental or quasi-experimental design that compared either WDRC with a form of linear amplification or linear amplification with compression limiting with linear with peak clipping. In studies in which linear amplification with compression limiting is evaluated, this signal-processing strategy may function as either the experimental or the control condition, depending on the clinical question.This processing strategy acts as the experimental condition (compression limiting) in Clinical Question 1 and as the comparison condition (linear amplification) in Clinical Question 2. Also, for studies including more than one comparison condition (i.e., for Clinical Question 2: linear amplification with peak clipping and linear amplification with compression limiting), the results of comparisons between WDRC and both conditions are included. Studies must have included findings based on wearable HAs and signal-processing approaches that are currently available in commercial HAs. Studies must have been published in English, with 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 the data could be split for separate analyses. Operational definitions are included in Appendix B. Two authors independently sifted abstracts and full-text articles to select articles for final inclusion. Interrater reliability was calculated using the kappa statistic (κ) and percent agreement, and interrater disagreements were resolved by consensus or under the advisement of the first author (R.W.M.). Landis and Koch's (1977) labels describing relative strength of agreement were applied to kappa statistics: < 0.00 = *poor,* 0.00–0.20 = *slight,* 0.21–0.40 = *fair,* 0.41–0.60 = *moderate,* 0.61–0.80 = *substantial,* and 0.81–1.00 = *almost perfect.*

Critical Appraisal

Individual studies—The quality of each accepted article was independently appraised by the second (R.A.V.) and third (J.J.C.) authors, both of whom had educational training and previous experience (e.g., Gosa, Schooling, & Coleman, 2011; Roush, Frymark, Venediktov, & Wang, 2011) assessing research quality. An adaptation of ASHA's levels-of-evidence scheme (Cherney, Patterson, Raymer, Frymark, & Schooling, 2008; Fey et al., 2010; Mullen, 2007), consisting of seven appraisal criteria, was used to rate quality. The ASHA 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. It was piloted prior to adoption in 2008. Adaptations to the scheme were made in consideration of the threats to internal validity specifically related to within-subject repeated measures designs (Portney & Watkins, 2009). As the raters did not have an extensive audiologic background, the knowledge and experience of the first author (R.W.M.) was requested as needed to provide audiologic insight to inform the appraisal process. Disagreements were resolved by consensus, and interrater agreement was calculated using kappa (weighted as appropriate) and percent agreement. One point was awarded for each appraisal criterion fully addressed. The appraisal criteria were as follows: (a) an adequate description of study protocol (e.g., sufficient detail provided for replication); (b) assessor blinding; (c) an adequate description of random sampling of participants; (d) randomization to condition; (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—The body of evidence was evaluated for each clinical question using a grading scheme developed by the Cincinnatia Children's Hospital Medical Center (2011a). This scheme 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. Using the Controlled Clinical Trial Appraisal worksheet (Cincinnati Children's Hospital Medical Center, 2011b), the second (R.A.V.) and third (J.J.C.) authors independently assessed individual studies to determine the quality level. Again, the expertise of the first author (R.W.M.) was requested as necessary, and disagreements were resolved by consensus. Interrater reliability was calculated using kappa and percent agreement. The quantity, quality, and consistency of the body of evidence pertaining to each clinical question was then considered by the two raters using the Cincinnati Children's Hospital Medical Center evidence grading worksheet (Cincinnati Children's Hospital Medical Center, 2011a) to arrive at an overall rating of high, moderate, low, or not assignable. 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. A high grade of evidence indicates that further research is unlikely to change our 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. A moderate grade indicates that further research is likely to have an important impact on our confidence in the answer to the clinical question. Low-grade evidence indicates local or published consensus, but no research to answer the clinical question; and if no grade is assignable, there is insufficient evidence and lack of consensus to answer the question.

Data Extraction and Analysis

The second (R.A.V.) and third (J.J.C.) authors reviewed and extracted the critical features from each study, including characteristics of the population, HA features, study protocol, outcome measures, findings, and limitations. The first author (R.W.M.) 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. If raw data were available, the point-biserial correlation coefficient (r_{pb}) 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 (Garbin, n.d.) or from paired t values and degrees of freedom (Rosenthal & DiMatteo, 2001). To calculate the 95% confidence interval (CI) surrounding each effect size, the number of participants and calculated effect size were entered into an online calculator (Garbin, n.d.). Effect sizes favoring the experimental technology investigated in each study were assigned a positive value, whereas effect sizes favoring the control condition (HAs with inactivated or unavailable technology under investigation) were assigned a negative value. The magnitude of the effect sizes was interpreted as follows: rs ranging from .10 to .29 were considered to be small, rs ranging from .30 to .49 were considered to be moderate, and rs above .50 were considered to be large (Cohen, 1992). 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.

The statistical significance of included study findings are discussed throughout the text of this review. A finding was considered to be significant if the CI surrounding the effect size did not include the null value and/or if the p value, as reported by the author or calculated as noted above, was less than or equal to .05. For each clinical question, results were further analyzed to determine whether any data trends were apparent that may suggest an impact of study design or study quality on the results.

Results

Study Selection

—The search resulted in 376 total sifted articles. Of these, 168 were rejected at the abstract level, 171 were rejected after reading the full text, and an additional 14 were rejected after detailed analysis of the full text. Reasons for rejection are included in Figure 1. This process resulted in a total of 23 articles accepted for inclusion in this series of EBSRs, eight of

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which addressed amplitude compression and met the inclusion criteria for the present review. The remaining 15 articles are discussed in one of two other EBSRs (pertaining to directional microphones/digital noise reduction and frequency lowering). Of the eight included studies, two addressed Clinical Question 1, and all eight studies addressed Clinical Question 2.

Interrater Reliability

The interrater reliability and percent agreement for sifting was substantial (κ = .67, 87.9%). Interrater reliability and percent agreement for each of the seven appraisal criteria was high. Perfect interrater reliability (κ = 1, 100%) was obtained for six of the appraisal points, and reliability was substantial for one appraisal point (reporting of effect sizes/CIs; κ = .75, 88%). The interrater reliability and percent agreement for individual study evidence-level ratings generated with the Cincinnati Children's Hospital Medical Center randomized controlled trial/controlled clinical trial intervention appraisal worksheet were substantial (κ = .60, 88%). Individual ratings are included in the supplementary materials associated with this article.

Compression Limiting

> *Clinical Question 1:* What is the effect of compression output limiting as compared with peak clipping output limiting 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?

Two studies (Christensen, 1999; Marriage, Moore, Stone, & Baer, 2005) included a comparison of linear amplification with compression limiting to peak clipping. Both included speech recognition and HA preference measures, and Marriage et al. (2005) also provided audibility outcomes. As noted in Table 1, participants in these studies ranged from 7 to 15 years and were experienced HA users. Participants in Christensen (1999) had mild-to-moderate SNHL, whereas participants in Marriage et al. (2005) demonstrated severe or profound SNHL. As a result of the heterogeneity within the study designs (e.g., differences in specific outcome measures used, severity of hearing loss, compression thresholds, and stimulus input levels) and small number of included studies for each clinical question, effect sizes were not averaged across studies.

Audibility outcomes—Marriage et al. (2005) investigated the effect of WDRC, linear with peak clipping, and linear with compression limiting on AI scores at average speech-level inputs for children with severe or profound hearing loss. Statistical comparisons between the two linear conditions, peak clipping and compression limiting, were not of interest to (and thus were not conducted by) the study authors. However, data presented in the article from each study participant allowed for the calculation of effect sizes and p values (by the authors of this review). This comparison for the severe hearing loss group produced a moderate, although non-significant, effect size and a significant p value, favoring compression output limiting (r_{pb} = .31, 95% CI [−.67, .90], p = .043). Comparisons between the two output-limiting strategies were not significantly different for the profound hearing loss group (r_{pb} = −.02, 95% CI [−.68, .65], p = .833).

Speech recognition outcomes—Both studies (Christensen, 1999; Marriage et al., 2005) presented information to compare HA output limiting by compression or peak clipping (see Table 2). No significant differences in p values were observed across several measures presented in both studies at any inputs, including inputs above 80 dBA/dB SPL. Effect sizes were not presented or calculable for either study.

Self- and parent report outcomes—Both Christensen (1999) and Marriage et al. (2005) investigated HA preferences across WDRC, linear with peak clipping and linear with compression-limiting devices (see Table 3). Over half (56%) the children (*n* = 18, who reported a preference for a study HA over their own HAs) preferred WDRC over linear peak clipping and linear compression-limiting devices. Of the children who preferred linear amplification, three preferred peak clipping output limiting, and five preferred compression limiting.

WDRC

> *Clinical Question 2:* What is the effect of WDRC as compared with linear amplification 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?

WDRC was compared with linear amplification for pediatric HA users in eight studies. One study (Gou, Valero, & Marcoux, 2002) investigated the use of enhanced dynamic range compression (EDRC), which is a type of WDRC with a very low-compression kneepoint, and one study (Stelmachowicz, Kopun, Mace, Lewis, & Nittrouer, 1995) used a type of WDRC with a full dynamic range K-amp compression circuit. Four studies included audibility outcomes (Gou et al., 2002; Jenstad, Pumford, Seewald, & Cornelisse, 2000; Jenstad, Seewald, Cornelisse, & Shantz, 1999; Marriage et al., 2005), seven included speech recognition outcomes (Boothroyd, Springer, Smith, & Schulman, 1988; Christensen, 1999; Gou et al., 2002; Jenstad et al., 2000, 1999; Marriage & Moore, 2003; Marriage et al., 2005; Stelmachowicz et al., 1995), one (Gou et al., 2002) included speech and language outcomes, and three studies included HA satisfaction outcomes (Christensen, 1999; Gou et al., 2002; Marriage et al., 2005). Participants in these studies ranged from 4 to 27 years of age and had mild to profound hearing losses. Most studies noted participants to be experienced HA users. See Table 1 for participant information by study. Additional information regarding individual study features, such as fitting prescription, duration of each condition, and other HA features, is provided in Appendix C. As with Clinical Question 1, pooled effect size estimates were not computed as a result of heterogeneity and small sample sizes across the included studies.

Audibility Outcomes—The following types of audibility outcomes were included in the four relevant studies: thresholds, loudness measures, dynamic range, and AI (ANSI, 1969; see Table 4). These studies investigated the use of WDRC. One study (Gou et al., 2002) looked at effects of audibility on low input levels (thresholds), one study (Marriage et al., 2005) used average speech input levels (AI), and two studies (Jenstad et al., 2000, 1999) investigated audibility outcomes over a range of input levels. Ten effect sizes, ranging from moderate to large, compared WDRC with linear amplification (with *r*s ranging from .32 to .96); only six were considered significant.

Gou et al. (2002) recorded warbled sinusoid thresholds for children wearing their own linear HAs and compared them with thresholds obtained with an experimental HA featuring WDRC. Although effect sizes were not available or calculable, thresholds were significantly lower ($p < .05$) across all tested frequencies when children used the WDRC HAs. These findings remained stable at 3- and 5-month follow-up testing.

Marriage et al. (2005) provided AI scores of severely and profoundly hearing-impaired participants for three types of amplitude compression: WDRC, linear with peak clipping, and linear with compression limiting. Because the objective of Clinical Question 2 is to compare WDRC with linear amplification (including peak clipping or compression limiting), this study included two comparisons of interest: (a) WDRC versus linear with peak clipping and (b) WDRC versus linear with compression limiting. As noted previously, *p* values and effect sizes were not presented by the study authors; however, they were calculated by the authors of this review from data presented in the article. Although moderate to large in magnitude, no effect sizes were statistically significant. However, comparisons of AI scores with WDRC to both linear amplification with peak clipping and linear amplification with compression-limiting conditions were found to be statistically significant, favoring WDRC, for both severe and profound hearing loss groups ($p < .05$).

Jenstad et al. (1999) reported subjective loudness measures using WDRC HAs and linear amplification; however, effect sizes were not available or calculable. WDRC HAs were rated as significantly louder than linear aids for average speech presented at 4 meters and significantly softer for shouted speech ($p < .05$). No significant differences were noted by participants for compression versus linear amplification for ratings of their own speech, average speech at 1 meter, and classroom speech at 1 meter.

In a later study with the same participants, Jenstad et al. (2000) found large and statistically significant increases in participants' dynamic range, favoring the use of WDRC over linear amplification for tones ($r = .87$, 95% CI [.53, .97], $p = .001$), environmental sounds ($r = .88$, 95% CI [.56, .97], $p = .000$), and speech ($r = .96$, 95% CI [.84, .99], $p = .000$). Furthermore, Jenstad et al. reported that significantly more participants using WDRC HAs achieved a normalized dynamic range than participants using linear HAs for tones ($r = .79$, 95% CI [.32, .95], $p = .004$), environmental sounds ($r = .79$, 95% CI [.32, .95], $p = .004$), and speech ($r = .77$, 95% CI [.27, .94], $p = .005$).

In summary, findings from one study suggest that WDRC significantly increased participants' dynamic range, and other studies suggest a positive impact on hearing thresholds and AI scores. Subjective loudness ratings also were affected by WDRC in some listening situations.

Speech Recognition Outcomes—Seven studies (Boothroyd et al.,1988; Christensen, 1999; Gou et al., 2002; Jenstad et al., 1999; Marriage & Moore, 2003; Marriage et al., 2005; Stelmachowicz et al., 1995) measured speech recognition using open or closed set word recognition tests, sentence recognition, phonemic identification, discrimination of nonsense words, or identification of phonemic contrasts. All of the studies compared outcomes using WDRC with outcomes with linear amplification. As the efficacy of the amplitude compression is directly related to the compression threshold of the device and the input level of the signal, the speech recognition outcomes are discussed in three sections: WDRC compared with linear amplification at low-, average, and high-input levels.

Low input (i.e., less than 55 dB SPL): As shown in Table 5, six studies investigated the use of WDRC with low-input levels ranging from 40 dB SPL to 53 dB SPL. The compression thresholds of these devices were generally between 40 and 50 dB SPL. Effect sizes were calculable for only one study, Marriage and Moore (2003). Of the four large effect sizes from this study, two closed set word recognition tasks with both the moderate and severe/profound hearing loss groups were statistically significant and favored WDRC ($r = .86$, 95% CI [.16, .98], $p = .013$; $r = .78$, 95% CI [.07, .97], $p = .021$, respectively). On open set word tasks, one finding from the moderate hearing loss group was not significant, and the other finding from the severe hearing loss group had a significant *p* value (< .001) favoring WDRC; however, the effect size could not be interpreted because CIs could not be calculated. As noted by the authors, performance on the open-set identification of phonemes in words test (for which the latter two effect sizes were calculated) was more variable across children.

Although effect sizes were not presented or calculable in the remaining studies, *p* values were available. In studies reporting outcomes for either open or closed set word recognition measures, four outcomes in two studies (Gou et al., 2002; Marriage et al., 2005) were statistically significant ($p < .01$; see Table 5), favoring WDRC, and the remaining five word recognition outcomes (in two studies; Christensen, 1999; Marriage et al., 2005) were not statistically significant. Two studies reported nonsense word or nonsense syllable outcomes. Jenstad et al. (1999) reported a statistically significant ($p < .05$) difference favoring WDRC, whereas Stelmachowicz et al. (1995) did not report a significant difference between WDRC and linear conditions using two different devices. Two studies, Christensen (1999) and Jenstad et al. (1999), used passage- or sentence-level stimuli. These findings were not found to be significantly different.

Average input (i.e., 55 to 70 dB SPL): Seven studies measured speech recognition outcomes at average-level inputs. These levels were typically 60–65 dB SPL, and compression thresholds ranged from 40 to 55 dB SPL across studies for WDRC conditions (see Table 6). Effect sizes were calculable for two studies (Boothroyd et al., 1988; Marriage & Moore, 2003). Boothroyd et al. (1988) reported one small overall effect size, favoring linear amplification and eight small, mixed effect sizes for individual phonemic contrasts. None were statistically significant. Overall, there was a statistically significant *p* value ($p < .01$) favoring linear amplification over WDRC, and there was a significant interaction ($p < .01$) of compression by contrast condition, favoring linear amplification for final consonant voice, vowel height, and initial consonant continuance. In contrast, the two large effect sizes reported in Marriage and Moore (2003) both favored WDRC over linear amplification. In a closed set word recognition test presented to individuals with severe and profound hearing loss, a large and statistically significant finding was reported ($r = .78$, 95% CI [.07, .97], $p = .021$). In an open set word identification test presented to children with severe hearing loss, a statistically significant *p* value and large effect size was noted ($r = .999$, $p < .001$). Unfortunately, the statistical significance of this effect size cannot be determined because CIs could not be calculated.

Effect sizes were not available or calculable in the remaining studies, but *p* values were presented. In three studies presenting word recognition outcomes (Christensen, 1999; Gou et al., 2002; Marriage et al., 2005), two of six outcomes were statistically significant ($p < .01$), favoring WDRC. Two studies (Christensen, 1999; Stelmachowicz et al., 1995) provided nonsense word or nonsense syllable outcomes. Both findings were nonsignificant. Christensen (1999), Jenstad et al. (1999), and Marriage et al. (2005) included outcomes based on passage- or sentence-level input. None of these outcomes produced a significant difference.

High input (i.e., greater than 70 dB SPL): Four studies (Christensen, 1999; Jenstad et al., 1999; Marriage et al., 2005; Stelmachowicz et al., 1995) investigated the impact of WDRC on speech recognition outcomes when speech was presented at high-input levels ranging from 72 to 83 dB SPL. Whereas no effect sizes were available for any studies, all studies reported *p* values. Of the 14 total findings reported (measures varied by stimuli type, open/closed set, and presentation level; see Table 7 for additional information), only two were statistically significant. Jenstad et al. (1999) noted *p* values less than .05 favoring WDRC over linear amplification on a closed set nonsense word recognition test and an open set sentence identification test presented at 82 dB SPL.

Speech and Language Outcomes—Gou et al. (2002) also investigated the impact of amplitude compression on speech production, including both voice and articulation outcomes. No significant differences in *p* values were noted between WDRC and linear conditions in the children's fundamental frequency, jitter, and shimmer; these results did not change over time at the 3- or 5-month follow-up sessions. There were, however, statistically significant differences favoring the use of WDRC on word articulation measures ($p < .001$) in addition to a significant decrease ($p < .05$) in the number of production errors at the 5-month follow-up. The magnitude of these findings is unknown, as effect sizes were not available or calculable.

Self- and Parent Report Outcomes—Three studies reported self- or parent report outcomes (Christensen, 1999; Gou et al., 2002; Marriage et al., 2005; see also Table 3). Two studies (Christensen, 1999; Marriage et al., 2005) presented participants' HA preferences, and one reported the results of a listening skills inventory. Of the 21 children across the two studies who reported a preference, 10 (48%) preferred or kept the WDRC HA. Of the remaining children, eight preferred linear aids with peak clipping or compression limiting, and three preferred their previous HAs (various compression settings). Data from a parent-completed questionnaire conducted in Gou et al. (2002) indicated a statistically significant preference ($p < .05$) for the test (WDRC) instrument over the linear instrument in all subcategories.

Individual Study Design and Quality

Table 8 depicts the degree to which each appraisal point was addressed for each study as well as the total quality score. Study quality scores ranged from 1/7 (Stelmachowicz et al., 1995) to 4/7 (Jenstad et al., 2000; Marriage & Moore, 2003; Marriage et al., 2005). None of the included studies obtained a random sample of participants or blinded assessors to experimental condition; however, all studies provided an adequate description of the protocol, and most reported or provided sufficient information to calculate *p* values. Other areas of weakness included failure to randomize to a sequence of conditions or counterbalance to avoid practice effects. Also, some studies did not have sufficient data to calculate effect sizes and confidence intervals. Although not included in our set of appraisal criteria, the extent to which volume control was adjustable by the participants in each condition and the use of different devices in different experimental conditions could significantly impact and potentially confound study results. On one hand, if listeners are allowed to adjust the volume control either in laboratory or in real-world environments, then audibility will vary on the basis of the listener's preference and may not be equal across participants. On the other hand, if listeners are not allowed to adjust the volume control to their preferred listening level, then such conditions may not reflect what the listener would do in a real-world environment. However, the impact of volume control manipulation on studies in the present review is difficult to assess, as volume control settings or the participant's manipulation of those settings were not reported for many of the studies included in this review. Listeners in two studies (Christensen, 1999; Jenstad et al., 1999) were not permitted to adjust the volume control, and in one study (Gou et al., 2002), the volume control was fixed for the linear condition and not available for the WDRC condition. In two studies (Gou et al., 2002; Stelmachowicz et al., 1995), two different devices were used when assessing WDRC and linear conditions, which could significantly confound experimental findings.

The study design classifications are also included in Table 8. All of the studies included in the review used similar repeated measures study designs. Four of the studies were further classified as crossover designs, a subcategory of repeated measures designs in which the order of experimental conditions was counterbalanced across participants. Study findings do not appear to have been influenced by study design or quality, as no apparent trends were found in the data.

Overall Quality of Bodies of Evidence for Compression Limiting and WDRC

Bodies of evidence to answer the clinical questions regarding the efficacy of compression limiting and WDRC are considered to be of a moderate grade of evidence, indicating that further research is likely to have an important impact on our confidence in the answer to both clinical questions. Two low-quality-controlled clinical trials addressed Clinical Question 1, and results were consistent that there was no significant difference between compression limiting and peak clipping conditions on the speech recognition outcomes evaluated. Two low-quality-randomized controlled trials with consistent findings and six low-quality-controlled clinical trials with mostly consistent findings addressed Clinical Question 2 and suggested that WDRC is significantly more favorable than linear amplification for at least some audibility, speech recognition, and speech and language outcomes.

Discussion

The purpose of the present review was to evaluate the findings of peer-reviewed research regarding amplitude compression with school-age children. Included studies were divided into two clinical questions. The first clinical question compared linear amplification with compression limiting with linear amplification with peak clipping, whereas the second question encompassed studies that compared WDRC with linear amplification. The first clinical question was informed by two studies that met the inclusion criteria for this review. Eight studies were identified that included comparisons of linear processing to amplitude compression; however, the method of amplitude compression, kneepoint, number of compression channels, and compression ratios varied significantly across studies. Additionally, individuals with varying degrees of hearing loss were studied; interpretation of these findings is complicated by the fact that the recommended compression characteristics across these subjects were very different.

Audibility Outcomes

Audibility is a key outcome measure of interest in pediatric amplification, as improvements in speech recognition and speech and language outcomes would not be expected without improvements in audibility. Signal audibility with amplitude compression was assessed using a number of different approaches. Jenstad and colleagues (1999) used loudness ratings over a range of input levels for different stimuli to compare WDRC and linear amplification. Consistent with predictions of WDRC providing greater audibility of soft sounds and comfort with loud sounds, WDRC was rated as louder for average speech at 4 m (48 dB), whereas linear was rated as louder for shouted speech at 1 m (83 dB) with no differences in loudness ratings for stimuli with average levels. Jenstad et al. (2000) examined audibility over the dynamic range from threshold to upper limit of comfort for a range of different stimuli and found that WDRC resulted in a greater range of audibility before loudness discomfort than linear amplification for pure tones, speech, and environmental sounds. An evaluation of aided pure-tone thresholds by Gou et al. (2002) using a type of WDRC with a 40 dB compression kneepoint (referred to as EDRC by the authors) also revealed increased audibility for soft sounds with WDRC compared with linear amplification with the children’s own devices. The use of different devices introduces uncertainty, however, that the increased audibility is truly a result of WDRC and not influenced by other device features. Marriage et al. (2005) used an aided AI to quantify the difference in audibility between WDRC and linear signal processing for children with severe to profound hearing loss. The increase in audibility for soft sounds with WDRC resulted in greater audibility compared with linear amplification. Comparisons of aided audibility between linear with compression limiting and linear with peak clipping conditions were not significantly different for the group of children with profound hearing loss; however, the comparison just reached significance, favoring compression limiting for the group of children with severe hearing loss. Differences in aided audibility between peak clipping and compression limiting would not be anticipated for either group at the 50 dB input level where aided audibility was calculated by Marriage et al. In previous studies using aided AI as an audibility outcome, a distortion factor was applied to the aided AI calculation for peak clipping that was not applied for compression limiting (Stelmachowicz, Lewis, Kalberer, & Creutz, 1994). Marriage et al. did not report whether a distortion factor was applied to account for differences in amplitude compression between conditions. For listeners with severe hearing loss who have greater audibility, the application of a distortion factor could explain the significant difference in aided AI between output-limiting strategies. For listeners with profound loss, this difference may not have been observed because of the fact that audibility was more limited in both conditions, and changes related to the distortion factor would have a less significant impact on the aided AI. Collectively, these studies suggest that audibility of soft sounds is enhanced with WDRC compared with linear processing, whereas the audibility of average and high input level signals is maintained. Regarding output limiting, it is difficult to draw conclusions from one study. Additional research is necessary to determine whether compression limiting offers enhanced audibility or reduced distortion and whether these factors are affected by severity of hearing loss.

Speech Recognition Outcomes

Speech recognition was the most frequently evaluated outcome measure in the studies of amplitude compression with school-age children in the present review. Given that the audibility of the signal with WDRC would only be expected to improve for soft input levels (< 55 dB), differences in speech recognition outcomes were less likely to be observed at average and high input levels unless the audibility of softer speech sounds was enhanced or significant distortion occurred. Many of the studies did not quantify audibility differences between comparisons, which restricts our ability to discuss differences in speech recognition outcomes in relation to audibility outcomes. Nearly all of the included studies revealed either no difference or an improvement in speech recognition with WDRC compared with linear amplification; however, the pattern of results across studies varied depending on the stimulus presentation level, amplitude compression characteristics, and linguistic complexity of the speech stimulus.

For soft input levels (< 55 dB), some studies reported improvements in speech recognition for WDRC over linear processing (nonsense words: Jenstad et al., 1999; phonological contrasts and monosyllabic and bisyllabic words: Gou et al., 2002; open and closed set words: Marriage & Moore, 2003; monosyllabic words in quiet for profound hearing loss: Marriage et al., 2005), whereas other studies reported no significant change in speech recognition for the same comparison (nonsense syllables: Stelmachowicz et al., 1995; bisyllabic words, passages, and sentences: Christensen, 1999; sentences: Jenstad et al., 1999; closed set monosyllabic words in quiet and noise for severe hearing loss and open set words in quiet and noise for severe and profound hearing loss: Marriage et al., 2005). This pattern of findings roughly follows the pattern that would be anticipated for WDRC based on audibility outcomes for the studies in which both speech recognition and audibility outcomes were available (Gou et al., 2002; Jenstad et al., 1999; Marriage et al., 2005). Several specific factors may have limited significant differences in speech recognition between WDRC and linear amplification strategies in other studies. Early studies by Stelmachowicz and colleagues and by Christensen did not specify differences in audibility, so it remains unclear whether an improvement in speech recognition would have been anticipated with WDRC compared with linear processing in those studies. Additionally, Christensen (1999) measured speech recognition in noise, which may have reduced the audibility of low-level speech cues that could provide improved audibility with WDRC in quiet. Differences for sentences in Jenstad et al. (1999) may not have been observed as performance may have already been high for linear processing with stimuli that have significant embedded linguistic context, preventing the observation of additional benefits from the audibility provided by WDRC. For Marriage et al. (2005), improvements with WDRC were observed for children with profound hearing loss but not for those with severe hearing loss, which may have been related to the fact that many children in the severe hearing loss group were near ceiling levels of performance with linear amplification, leaving limited range for improvement with WDRC. Whereas significant differences were observed favoring WDRC in Gou et al. (2002), the researchers used two different devices: one WDRC device and a different linear device (the children's own HAs), which confounds these findings as other differences between the two devices could not be ruled out as contributing to the effect.

Differences in speech recognition between WDRC and linear processing would not be anticipated at average or high input levels, as the amount of gain and audibility is not typically different between the two types of processing at these levels. However, if WDRC increases audibility for the less intense parts of speech presented at an average input level, differences in speech recognition could be observed. Additionally, WDRC may result in improved speech recognition and sound quality over linear processing for high-input levels if WDRC results in less compression limiting for the peaks of the speech signal. Differences in speech recognition between linear with peak clipping and linear with compression limiting may be observed at high input levels where distortion from peak clipping would be expected to degrade speech understanding. WDRC resulted in improved speech recognition over linear processing at average and high input levels for four studies (shouted speech at 1 meter: Jenstad et al., 1999; phonological contrasts: Gou et al., 2002; open and closed set words for severe and profound hearing loss: Marriage & Moore, 2003; monosyllabic words and profound hearing loss: Marriage et al., 2005). No differences were reported between linear processing and WDRC for average- or high-input levels for four studies (bisyllabic words and passages: Christensen, 1999; nonsense words and sentences at average speech, classroom, and voice in ear levels: Jenstad et al., 1999; open set words, common phrases, and sentences: Marriage et al., 2005; nonsense syllables: Stelmachowicz et al., 1995). Boothroyd and colleagues (1988) reported a significant degradation in performance with two-channel amplitude compression compared with linear processing for specific speech contrasts with a group of children with severe to profound hearing loss. Audibility was not documented, and the influence of this variable on the outcome cannot be determined. Importantly, the implementation of amplitude compression used in Boothroyd et al. (1988) differs significantly from the signal processing used in modern HAs. Therefore, differences in results related to the processing may exist; a study that directly compares the parameters used in Boothroyd et al. with modern alternatives would be needed to determine the source of those differences.

As expected, there were no significant differences between peak clipping and compression limiting at low and average input levels within the two studies included in this review. No differences were anticipated at these levels, as these output-limiting devices function in a similar linear fashion with soft and average inputs. Compression limiting and peak clipping do function differently at high input levels; therefore, potential differences may be expected at this level if distortion of the speech signal were significant enough to degrade speech recognition with peak clipping. As there were also no significant differences between these output-limiting strategies across the two studies at high input levels (80–83 dB), it is likely that there was not significant distortion of the signal or the distortion did not significantly impact speech recognition.

Speech and Language Outcomes

The effects of different types of amplitude compression on speech and language outcomes were examined in the study by Gou et al. (2002). No significant differences were observed in several different measures of voice quality between WDRC with an experimental HA and linear amplification with the children's own HAs. Because WDRC and linear amplification result in a similar input-output function except at the level of soft speech (< 55 dB), the finding of no change in voice quality between the two conditions is not surprising, especially because the children in the study would likely have similar audibility of their own speech productions between the two conditions. Children in the study also did not have any reported vocal quality problems, which leaves unresolved questions about the amount of change that would be expected between WDRC and linear amplification for this outcome. Conversely, children did show improvement on measures of speech articulation with WDRC compared with linear amplification. Types of amplitude compression that improve the audibility of soft speech sounds compared with linear amplification would be anticipated to improve articulation problems related to limited or inconsistent audibility. With any developmental outcome measure that is evaluated over time in children, the contribution of developmental factors to the improvement of such measures cannot be ruled out. Therefore, the unique contribution of HA signal processing to the improvements in articulation observed by Gou and colleagues cannot be isolated without experimental elements such as a matched control group or withdrawal phase. Both matched control groups and the use of withdrawal in treatment studies of children with hearing loss have significant barriers to implementation. Despite these methodological challenges, additional experimental control is necessary before changes in speech and language development can be attributed to processing schemes. Additionally, as previously noted, the confound of evaluating WDRC and linear processing with different devices introduces uncertainty that the findings are a result of the WDRC and not any other HA feature that may have been absent in the children's own HAs.

Neither of the studies that addressed differences in output limiting between compression limiting and peak clipping included speech and language outcomes. Because both types of signal processing differ only in the way that the output of the HA is limited at high input levels, audibility for average and soft input levels would likely be equivalent. Any differences in speech and language outcomes between peak clipping and compression limiting would be the result of reduced distortion of the signal at high input levels. Although these differences are subtle, the potential impact of these strategies on speech and language outcomes may be appropriate to consider.

Self- and Parent Report Outcomes

Unlike speech recognition and speech and language outcomes, the relationship between self- and parent report outcomes and audibility is not as straightforward as increased audibility leading to improved outcomes. For example, situations in which the signal is audible but highly distorted or uncomfortably loud could lead to decreased ratings of listener satisfaction or preference, despite having adequate audibility. Listener satisfaction with HA sound quality was evaluated in three studies in which linear amplification was compared with WDRC. Christensen (1999) documented HA preference in six of 12 participants and found that the signal-processing preference differed depending on the environment. Most of the children preferred WDRC over linear amplification for school environments; however, the preference in home environments was divided evenly between linear amplification and WDRC. Given that the range of input levels in a school environment are likely to be higher and more variable than in a home environment, the preference for WDRC in school settings would be anticipated as the processing results in greater listener comfort over a broader range of input levels than linear processing (Jenstad et al., 2000). These results also suggest that improvements in listener preference can be observed even in cases in which speech perception is not significantly improved. Gou and colleagues (2002) documented parent satisfaction using a questionnaire that evaluated 12 different listening situations. Results indicated that parents favored their child's performance with WDRC over linear processing for all 12 conditions. HA preference was also assessed for children in the Marriage et al. (2005) study. For their participants, preference for WDRC over linear amplification was dependent on degree of hearing loss. Whereas five of seven children with profound hearing loss who kept the study HAs preferred WDRC over linear amplification, only two of five children with severe hearing loss shared the same preference. The profound hearing loss group in this study was also more likely to experience improved speech recognition than the severe group, which may have influenced HA preference. Additionally, the lack of blinding may have influenced self- and parent report of potential outcomes with children and parents favoring novel devices or technology that they expected to be superior. However, the inconsistent preferences for WDRC over linear amplification across participants occurred only in specific listening situations, making it difficult to determine the impact of such bias on the results.

Across the two studies (Christensen, 1999; Marriage et al., 2005) that addressed preference outcomes for children using linear devices with compression limiting as compared with linear devices with peak clipping, there were minimal differences in the number of children preferring one type of output limiting over the other.

Implications of Findings

A moderate overall body of evidence consisting of low-quality-controlled clinical trials and randomized controlled trials addresses the efficacy of WDRC. Across all study findings, WDRC at least maintained and, in the majority of findings, improved audibility, compared with linear amplification. Also, the majority of studies documented either improved or maintained speech recognition outcomes. Self-and parent report measures comparing WDRC with linear amplification suggest that the preference for amplitude compression may be related to factors such as the listening environment (Christensen, 1999), degree of hearing loss, and, potentially, the degree of improvement in speech recognition (Marriage et al., 2005). Interestingly, participants in the Christensen study reported preference for WDRC in school environments, despite the fact that improvements in speech perception in noise were not observed.

The findings from this review, overall, are consistent with previous studies with adults (Davies-Venn et al., 2009), as well as those of an earlier systematic review of HA technology for children (Palmer & Grimes, 2005). Given the considerable overlap in study inclusion (Christensen [1999], Jenstad et al. [1999, 2000], and Marriage & Moore [2003], were included in both reviews) between the two reviews, the similarity in findings is not surprising. Previous studies of amplitude compression have suggested that the benefits of amplitude compression for speech recognition may vary as a function of the listener's degree of hearing loss (Souza et al., 2005). Interestingly, the two studies (Christensen, 1999; Stelmachowicz et al., 1995) that demonstrated no difference between linear and WDRC included children with mild to moderate losses, whereas the four studies that demonstrated improved audibility included children with greater degrees of hearing loss. Conclusions about differences between studies of amplitude compression cannot be analyzed because of other methodological differences between the studies; therefore, the interaction between degree of hearing loss and benefit from amplitude compression warrants additional consideration in future studies with school-age children.

A limited number of studies were available providing comparisons between peak clipping and compression limiting for the outcomes identified. Findings were consistent and nonsignificant across the two low-quality-controlled clinical trials addressing these output-limiting strategies; however, we cannot confidently conclude that there is no difference between compression limiting and peak clipping as further research evidence is likely to have a large impact on the answer to this question. The transition from analog to digital HA signal processing and widespread availability of fast-acting output compression limiting has reduced the implementation of peak clipping as an approach to limiting the maximum output of HAs. Despite these developments, children continue to use a wide range of HAs with different amplitude compression strategies, including devices with peak clipping (McCreery, Bentler, & Roush, 2012). Therefore, differences between these approaches to output limiting may continue to be of interest to clinicians, even as signal-processing strategies become more advanced.

The influence of changes in amplitude compression technology over the time period of the studies included in this review should also be noted. HA signal processing has evolved significantly over the past 2 decades, as the vast majority of HAs have moved from analog to digital circuits (Kates, 2008). The availability of digital signal processing has increased the complexity of approaches to amplitude compression in HAs. Although the influence of these developments on outcomes for children are complex and difficult to predict, the first three studies in this review reported either null (Christensen, 1999; Stelmachowicz et al., 1995) or even negative (Boothroyd et al., 1988) outcomes, whereas more recent studies were more likely to show positive effects (Gou et al., 2002; Marriage & Moore, 2003). The trend of improvements in outcomes in more recent studies may be related to differences in HA technology between studies; although a direct comparison of these strategies would be necessary to determine what specific aspects of amplitude compression technology led to a greater likelihood of improved outcomes in later studies.

A version of the DSL was used in most of the studies in the present review (Scollie et al., 2005) as the prescriptive approach, but comparisons based on the National Acoustics Lab–Revised (NAL-R) prescriptive formula were included in one study (Christensen, 1999), and manufacturers' proprietary prescriptions were used in two others. Findings measured with one specific prescriptive approach may be difficult to generalize to different prescriptive approaches that vary in the amount of gain and output prescribed for the same hearing loss.

The stimuli used in each study may have also influenced the outcomes observed in studies of amplitude compression with school-age children. Overall, studies in which stimuli were used with limited linguistic content, such as nonsense syllables or monosyllabic words, were more likely to observe improvements in speech recognition with amplitude compression compared with studies in which stimuli with passages or sentences were used. Because children are able to use linguistic context within the stimulus to support speech recognition (Nittrouer & Boothroyd, 1990), differences in signal processing may only be evident for stimuli where access to these cues is limited, as is the case with nonsense syllables and monosyllabic words. Sentences and passages are more likely to reflect the context and linguistic content of everyday conversations; researchers must select stimuli or a continuum of stimuli that balances ecological validity while controlling for the influences of linguistic ability, particularly on speech recognition tasks.

Directions for Future Research

The majority of studies that met the criteria for inclusion in this review are in the efficacy stage of research; however, some included studies also have components of exploratory (Marriage & Moore, 2003; Stelmachowicz et al., 1995) and effectiveness research (Christensen, 1999). The variability in outcomes and HA settings limits the extent to which findings can be meaningfully compared across studies, and therefore, future research should continue to investigate the efficacy of amplitude compression with attempts to use standard or previously researched HA settings and outcome measures. Studies of longer duration with sufficient follow-up may be necessary to discern meaningful differences with amplitude compression, especially for outcomes of speech and language. To improve cross-study comparisons in future research, investigators should report findings transparently (e.g., report age, gender, severity, thresholds, HA settings, user's ability to control volume, and individual assessment measures for each participant) and provide measures of effect size.

Limitations of the Present Review

Readers should consider several limitations of the present systematic review. The quantity of relevant information included may have been impacted by the restriction that studies be available in English. Also, although intentional, the exclusion of unpublished findings and findings published in non-peer-reviewed journals (which ensures that all included studies were previously vetted in a peer-review process) may increase the likelihood of publication bias (McAuley, Tugwell, & Moher, 2000). Because experimental research studies are continually being conducted and findings are continually published, this EBSR may not include the most recently published literature. Readers are encouraged to consider research that has been published after July 2011 in addition to the research included in this review. It is intended that this review will be periodically updated in response to the evolving research base. Finally, the effect sizes obtained in this EBSR were not pooled as a result of the limited number of studies and heterogeneity of included technologies and outcome measures. As additional research with effect size measures become available, the use of meta-analysis techniques will be feasible, thereby providing more meaningful information.

Conclusion

The present EBSR was intended to describe a pattern of results observed for school-age children with hearing loss for HAs with WDRC compared with linear amplification and/or linear amplification with peak clipping to linear amplification with compression limiting. On the basis of this moderate body of evidence, WDRC results in more favorable results than linear amplification for at least some audibility, speech recognition, and speech and language outcomes. Further research, however, is likely to impact this conclusion. Also, based on a moderate body of evidence consisting of only two studies, compression limiting does not appear to be significantly more favorable than peak clipping as an output-limiting strategy for speech recognition outcomes. The readers are cautioned that, especially given the limited quantity of evidence addressing this question, our confidence in this conclusion is weak and will likely be impacted by additional research. The variable findings regarding child and parent preference for WDRC and linear peak clipping and compression-limiting devices suggest that preference ratings were complex and related to factors such as the specific environment (Christensen, 1999) or degree of hearing loss (Marriage et al., 2005). These findings highlight the importance of considering the needs and desires of the client when considering the most appropriate HA devices and amplification settings. Additionally, clinicians should consider the balance between desirable and undesirable effects of amplitude compression and the cost implications of these signal processing strategies when discussing amplification options with clients.

The outcomes used to evaluate amplitude compression in the present review may provide a framework for clinicians to evaluate these signal-processing strategies for their pediatric patients. The primary goal of pediatric amplification is to maintain the audibility of speech over a wide range of input levels (Bagatto, Scollie, Hyde, & Seewald, 2010). Clinicians can use verification strategies that use speech signals at multiple input levels to assess how amplitude compression influences audibility and select parameters that maximize audibility. Speech recognition testing could provide a clinical tool for comparing the influences of signal-processing strategies on the speech perception abilities of school-age children. The studies in the present review suggest differences in amplitude compression may be dependent on the presentation level, linguistic context of the stimuli, and the child's speech recognition abilities and degree of hearing loss. Careful selection of speech and language measures can also be used to document progress with signal-processing strategies. Self- and parent report outcomes can provide useful information about the child's comfort and acceptance of amplification because this information may not be apparent from audibility, speech recognition, or speech and language outcomes.

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Appendix A. Search strategy

Databases

The following databases were searched during two time periods, 1/20/10–3/11/10 and 7/7/11–7/19/11: PubMed, CINAHL (EBSCO), PsycINFO (EBSCO), Teacher Reference Center (EBSCO), Education Research Complete, Health Source: Nursing/Academic Edition, Psychology and Behavioral Sciences Collection, Communication & Mass Media Complete (EBSCO), ComDisDome, CSA Neurosciences Abstracts, ERIC, CSA Linguistics and Language Behavior Abstracts, PILOTS Database, Social Services Abstracts (CSA), Science Citation Index Expanded (SCI-EXPANDED)—1975 to present, Social Sciences Citation Index (SSCI)—1975 to present, Cochrane Library (Wiley), Centre for Reviews and Dissemination (CRD) Databases, REHABDATA, OTseeker, ScienceDirect, HighWire Press, PsycBITE, SUMSearch, Trip Database

Search Terms

Controlled vocabulary such as Medical Subject Headings (MeSH) were used as available. Search terms used in isolation or in combination in one or more databases included the following: adolescent* (*indicates truncation), amplification, boy*, child*, elementary school, frequency compression, girl*, hearing, hearing aid*, hearing device*, hearing instrument*, hearing loss, hearing system*, high school, junior high, juvenile*, kid*, kindergarten, middle school, paediatric/pediatric*, pediatrician*, preschool, school age, teenage, youngster*, youth

Limits

Limits varied by database and included the following, as available: humans, English, peer reviewed, age 0–18, publication year 1980–2010 (2009–2010 for update)

Forward Search

All accepted articles were forward searched in GoogleScholar during two time periods, 3/22/10–3/24/10 and 7/21/11.

Reference Checking

The reference lists of all relevant articles were checked for other possible studies.

Prolific Author Search

A prolific author search was conducted in EBSCO during two time periods, 3/29/10–4/2/10 and 7/21/11. The searched authors included Marlene Bagatto, John Bamford, Theresa Ching, Harvey Dillon, W.A. Dreschler, Judith/Judy Dubno, Judith/Judy Gravel, Josep Gou, B. M. Hoover, Lorrienne Jenstad, Susan Jerger, Francis Kuk, Dawna Lewis, Josephine Marriage, Ryan W. McCreery, Hugh McDermott, Mary Pat Moeller, Catherine Palmer, Andrea Pittman, Todd Ricketts, Joanna Robinson, Susan Scollie, Richard Seewald, Patricia Stelmachowicz, Anne Marie Tharpe, and Jace Wolfe.

Appendix B. Operational definitions

Digital noise reduction (DNR)

HA signal processing intended to reduce the negative consequences of background noise.

Directional microphone response

HAs with microphone systems that maintain amplification for sound entering the HA from the front/attenuate sound from the rear or sides of the listener.

Omnidirectional response

HAs with microphone systems that amplify sound equally from all directions.

Amplitude compression

Automatic reduction or increase of gain to a predetermined level with the intention of presenting sound at a comfortable listening level; this includes WDRC.

Linear amplification

All sound is amplified by a constant level of gain; peak clipping may be used to prevent loudness discomfort.

Frequency-lowering technology

Technology intended to provide high-frequency sound information to HA users at a lower frequency level; this includes frequency compression or frequency transposition (excludes frequency vocoding).

Audibility outcomes

Objective measures of speech audibility; this includes sound field testing, real-ear measures (gold standard), real-ear–to–coupler difference, Articulation Index (AI; ANSI 3.5-1969), Speech Intelligibility Index (SII; ANSI S3.5-1997), and so forth.

Speech recognition outcomes

Objective measures of speech recognition; this includes materials such as Phonetically Balanced-Kindergarten (PBK) word lists (Haskins, 1949), Word Intelligibility by Picture Identification (WIPI) test (Ross & Lerman, 1970), Speech in Noise Test (SPIN; Kalikow, Stevens, & Elliot, 1977), Hearing in Noise Test—Children (HINT–C; Nilsson, Soli, & Sullivan, 1994), and so forth.

Speech and language outcomes

Objective measures of speech or language abilities; this includes receptive and expressive language abilities, speech intelligibility, articulation, vocabulary, mean length of utterance, and so forth.

HA self-report or parent report outcomes

Subjective measures of the child's quality of life or satisfaction with the HA as reported by the child or parent; this may include Meaningful Auditory Integration Scale (MAIS; Robbins, Renshaw, & Berry, 1991), Listening Inventories for Education (LIFE; Anderson & Smaldino, 1999), Screening Instrument for Targeting Educational Risk (SIFTER; Anderson, 1989), Children's Outcome Worksheet (COW; Williams, 2003), and so forth.

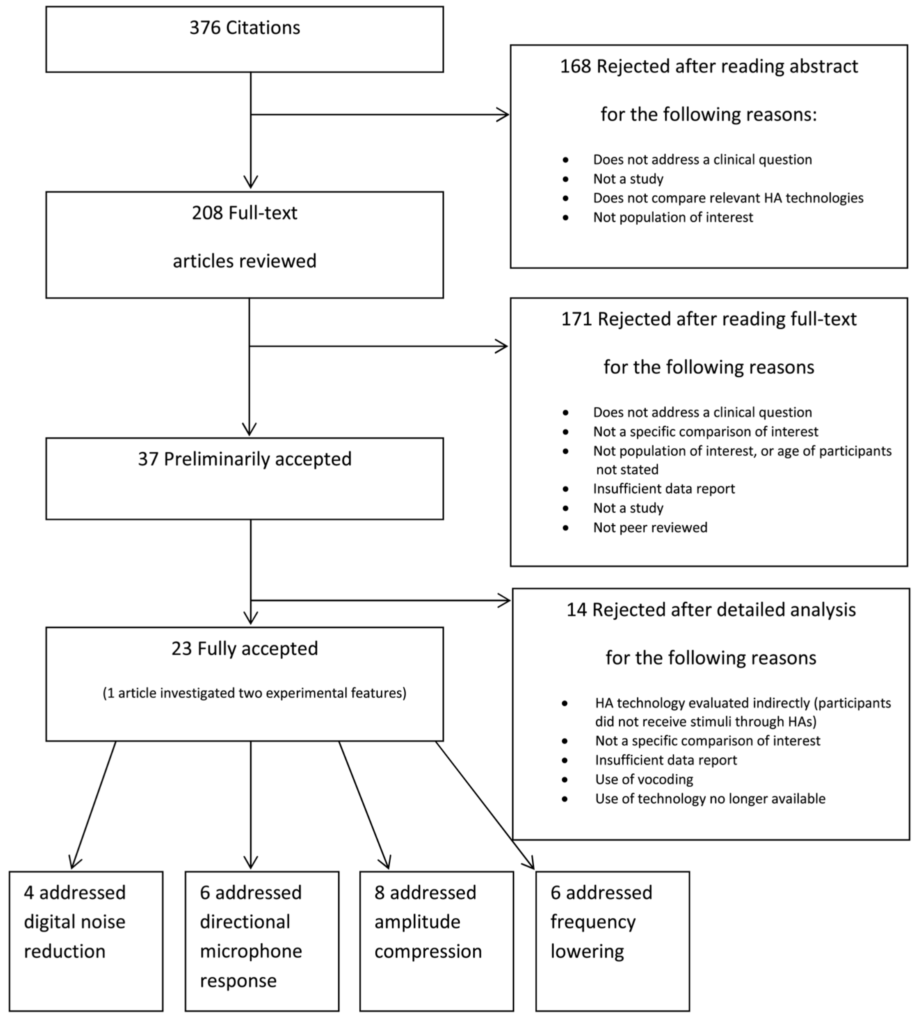

Figure 1.
Flow chart detailing the levels of inclusion and rejection of articles.

Table 1

Participant characteristics.

Citation	Number of participants	Age range (average) in yrs	Gender	HL type and severity	Previous HA use
Boothroyd et al. (1988)	9	11–16 (14.1)	6F/3M	Severe-profound SNHL	NR
Christensen (1999)	12	9–14	NR	Bilateral mild–moderate SNHL	All participants used amplification previously.
Gou et al. (2002)	14	6–13 (8)	NR	Bilateral, mostly symmetrical severe-profound HL	All participants previously used analog, linear HAs on a daily basis for an average of 2.5 yrs.
Jenstad et al. (1999)	12	10–27 (16)	7F/5M	Bilateral moderate-severe SNHL	Full-time HA users for at least 1 yr.
Jenstad et al. (2000)	10	10–27 (16)	6F/4M	Bilateral moderate-severe SNHL	Full-time HA users for at least 1 yr.
Marriage and Moore (2003)	14	4–14 (9.5)	7F/7M	6 with moderate SNHL 4 with severe SNHL 4 with profound SNHL	Full-time HA users for over 2 yrs.
Marriage et al. (2005)	15	7–15 (11.3)	8F/7M	Severe and profound SNHL	Full-time HA users for over 2 yrs.
Stelmachowicz et al. (1995)	3	16–19 (17.3)	3M	Moderate bilateral SNHL	Age at fitting, duration, and compliance of use varied across participants.

Note. yrs = years; HL = hearing loss; HA = hearing aid; F = female; M = male; NR = not reported; SNHL = sensorineural hearing loss.

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Table 2

Clinical Question 1: Comparison of compression limiting versus peak clipping on speech recognition outcomes.

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size	*p*
Christensen (1999)	Linear CL	Threshold: high 75 dB Attack time: 5 ms Release time: adjustable up to 1 s Ratio: 8:1 Volume control: listener unable to adjust during testing	Bisyllabic spondaic words	Open	50, 65, and 80 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Passages	Open	50, 65, and 80 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Sentences	Open	53 and 83 dB SPL (70 dB HL)/ 0, +5, +10, +15 SNR	NR/NC	*ns* across SNRs
	Linear PC	Threshold: none Attack time: instantaneous Release time: instantaneous Ratio: none Volume control: listener unable to adjust during testing					
Marriage et al. (2005)	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR Volume control: NR	Monosyllabic words (profound HL)	Closed	50, 65, and 80 dBA/quiet	NR/NC	*ns*
			Monosyllabic words (severe HL)	Closed	45 dBA quiet/50 dBA noise	NR/NC	*ns*
			Words (profound HL)	Open	50, 65, and 80 dBA/quiet	NR/NC	*ns*
			Words (severe HL)	Open	45 and 80 dBA in quiet 50 dBA noise	NR/NC	*ns*
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR	Sentences SNR (severe HL)	Open	In 60 dB modulated noise	NR/NC	*ns*
			Common phrases (profound HL)	Open	80 dBA/quiet	NR/NC	*ns*

Note. SNR = signal-to-noise ratio; CL = compression limiting; SPL = sound pressure level; NC = not calculable; PC = peak clipping.

Table 3

Clinical Questions 1 and 2: Comparison of WDRC, compression limiting, and peak clipping on HA self- and parent report outcomes.

Citation	Condition	Compression settings	HA preference
Christensen (1999)	WDRC	Threshold: Low: 45–50 dB SPL Attack time: 5 ms Release time: 50 ms Ratio: Variable: 1.1:1–7.8:1 Volume control: listener unable to adjust during testing	6 of 12 participants returned diary Participants preference for overall best processing strategy (for all environments): linear PC 1/6; linear CL 2/6; WDRC 3/6 Participant preference for school: WDRC 6/6 Participant preference for home: linear PC 2/6; linear CL 2/6; WDRC 2/6 Willing to switch memories for different listening conditions? yes 6/6
	Linear CL	Threshold: high 75 dB Attack time: 5 ms Release time: adjustable up to 1 s Ratio: 8:1 Volume control: listener unable to adjust during testing	
	Linear PC	Threshold: none Attack time: instantaneous Release time: instantaneous Ratio: none Volume control: listener unable to adjust during testing	
Gou et al. (2002)	WDRC	Threshold: 40 dB Attack time: NR Release time: NR Ratio: NR Volume control: NR	Listening Skills Inventory-Child: significance testing not completed Listening Skills Inventory-Parent: $p < .05$ (favors WDRC) in all 12 categories
	Own linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: fixed	
Marriage et al. (2005)	WDRC	Threshold: 40 dB at 200 Hz; 25 dB at 4400 Hz Attack time: 5 ms Release time: 30 ms Ratio: 1.2:1 to 3.0:1 Volume control: NR	Profound: 7/9 children kept study HAs; of the 7: 5/7 preferred WDRC 1/7 preferred linear CL 1/7 preferred linear PC Severe: 5/6 children kept study HAs; of the 5: 2/5 preferred WDRC 2/5 preferred linear CL 1/5 preferred linear PC
	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR Volume control: NR	
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR	

Note. WDRC = wide dynamic range compression.

Table 4

Clinical Question 2: Comparison of WDRC versus linear amplification on audibility outcomes.

Citation	Condition	Compression settings	Stimuli/outcome measure	Effect size [95% CI][a]	*p*
Gou et al. (2002)	WDRC	Threshold: 40 dB Attack time: NR Release time: NR Ratio: NR Volume control: AGC	Warbled sinusoid threshold at 250 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
			Warbled sinusoid threshold at 500 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
	Own linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: fixed	Warbled sinusoid threshold at 1000 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
			Warbled sinusoid threshold at 2000 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
			Warbled sinusoid threshold at 4000 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
			Warbled sinusoid threshold at 6000 Hz	NR/NC	$p < .05$ (favors WDRC) *ns* change at 3- and 5-mo. follow-up
Jenstad et al. (1999)	WDRC	Threshold: 45 dB Attack time: 10 ms Release time: 200 ms Ratio: varied by DSL prescription Volume control: listener unable to adjust	Loudness rating of shouted speech at 1 m (83 dB SPL)	NR/NC	$p < .05$ louder with linear than WDRC by 5/12 participants
			Loudness rating of own voice at ear level (72 dB SPL)	NR/NC	*ns*
			Loudness rating of classroom at 1 m (73 dB SPL)	NR/NC	*ns*
	Linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: listener unable to adjust	Loudness rating of average speech at 1 m (60 dB SPL)	NR/NC	*ns*
			Loudness rating of average speech at 4 m (48 dB SPL)	NR/NC	$p < .05$ softer with linear than WDRC by 9/12 participants
Jenstad et al. (2000)	WDRC	Threshold: 45 dB Attack time: 10 ms Release time: 200 ms Ratio: varied by DSL prescription Volume control: NR	Dynamic range—FM tones	$r = .87$ [.53, .97][b]	$p = .001$ (favors WDRC)
			Dynamic range—environmental sounds	$r = .88$ [.56, .97][b]	$p = .000$ (favors WDRC)
			Dynamic range—speech	$r = .96$ [.84, .99][b]	$p = .000$ (favors WDRC)
	Linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: NR	Number of participants with a normalized dynamic range—FM tones	$r = .79$ [.32, .95][b]	$p = .004$ (favors WDRC)
			Number of participants with a normalized dynamic range—environmental sounds	$r = .79$ [.32, .95][b]	$p = .004$ (favors WDRC)
			Number of participants with a normalized dynamic range—speech	$r = .77$ [.27, .94][b]	$p = .005$ (favors WDRC)

Citation	Condition	Compression settings	Stimuli/outcome measure	Effect size [95% CI][a]	p
Marriage et al. (2005)	WDRC	Threshold: 40 dB at 200 Hz; 25 dB at 4400 Hz Attack time: 5 ms Release time: 30 ms Ratio: 1.2:1 to 3.0:1 Volume control: NR	Articulation Index (profound)	WDRC vs. linear CL r_{pb} = .33 [−.43, .82][c]	p = .011 (WDRC > linear CL)[d]
				WDRC vs. linear PC r_{pb} = .32 [−.44, .81][c]	p = .011 (WDRC > linear PC)[d]
	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR Volume control: NR	Articulation Index (severe)	WDRC vs. linear CL r_{pb} = .32 [−.66, .90][c]	p = .043 (WDRC > linear CL)[d]
				WDRC vs. linear PC r_{pb} = .54 [−.48, .94][c]	p = .043 (WDRC > linear PC)[d]
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR			

Note. CI = confidence interval; AGC = automatic gain control; mo. = month; DSL = desired sensation level.

[a]Positive effect sizes indicate that the direction of the effect favors WDRC; negative effect sizes indicate that the direction of the effect favors linear amplification.

[b]Effect size r calculated using F statistic and degrees of freedom provided in the study.

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

[d]p values were calculated using the Wilcoxon signed-ranks test from individual participant data provided in the study.

Table 5

Clinical Question 2: Comparison of WDRC versus linear amplification on speech recognition outcomes at low input levels (i.e., < 55 dB).

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size [95% CI][a]	*p*
Christensen (1999)	WDRC	Threshold: low: 45–50 dB SPL Attack time: 5 ms Release time: 50 ms Ratio: variable 1.1:1 to 7.8:1 Volume control: listener unable to adjust during testing	Bisyllabic spondaic words	Open	50 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Passages	Open	50 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Sentences	Open	53 dB SPL (40 dB HL)/0, +5, +10, +15 SNR	NR/NC	*ns* across SNRs
	Linear CL	Threshold: high 75 dB Attack time: 5 ms Release time: adjustable up to 1 s Ratio: 8:1 Volume control: listener unable to adjust during testing					
	Linear PC	Threshold: none Attack time: instantaneous Release time: instantaneous Ratio: none Volume control: listener unable to adjust during testing					
Gou et al. (2002)	WDRC	Threshold: 40 dB Attack time: NR Release time: NR Ratio: NR Volume control: AGC	Words (discrimination of phonological oppositions)	Closed	40 dB SPL/quiet	NR/NC	$p < .001$ (favors WDRC)
			Monosyllabic words	Closed	40 dB SPL/quiet	NR/NC	$p < .001$ (favors WDRC)
			Bisyllabic words	Closed	40 dB SPL/quiet	NR/NC	$p < .0001$ (favors WDRC)
	Own linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: fixed					
Jenstad et al. (1999)	WDRC	Threshold: 45 dB Attack time: 10 ms Release time: 200 ms Ratio: varied by DSL prescription Volume control: listener unable to adjust	Nonsense words	Closed	48 dB SPL/quiet (avg. speech at 4 m)	NR/NC	$p < .05$ (favors WDRC)
			Sentences	Open	48 dB SPL/quiet (avg. speech at 4 m)	NR/NC	*ns*
	Linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: listener unable to adjust					

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size [95% CI][a]	*p*
Marriage & Moore (2003)	WDRC	Threshold: 50–55 dB SPL Attack time: 5 ms Release time: 30 ms Ratio: varied between 1.7:1 to 2.7:1 Volume control: NR NR	Words (consonant confusion task) (severe and profound HL)	Closed	60, 50 dBA/quiet, +10 SNR	$r = .78$ [.07, .97][b]	$p = .021$ (favors WDRC)
			Words (consonant confusion task) (moderate HL)	Closed			Compression × Presentation Level: *ns*
			Monosyllabic words (severe HL)	Open	55, 45 dBA/quiet, +5 SNR	$r = .86$ [.16, .98][b]	$p = .013$ (favors WDRC)
			Monosyllabic words (moderate HL)	Open			Compression × Presentation Level: *ns*
	Linear				60, 50 dBA/quiet, +10 SNR	$r = .999$[b,c]	$p < .001$ (favors WDRC) Compression × Presentation Level: *ns*
					55, 45 dBA/quiet, +5 SNR	$r = .75$ [−.16, .97][b]	*ns* Compression × Presentation Level: *ns*
Marriage et al. (2005)	WDRC	Threshold: 40 dB at 200 Hz; 25 dB at 4400 Hz Attack time: 5 ms Release time: 30 ms Ratio: 1.2:1 to 3.0:1 Volume control: NR	Monosyllabic words (profound HL)	Closed	50 dBA/quiet	NR/NC	$p < .01$ (WDRC > linear PC) $p < .01$ (WDRC > linear CL)
			Monosyllabic words (severe HL)	Closed	45 dBA/quiet	NR/NC	*ns*
			Monosyllabic words (severe HL)	Closed	50 dBA/0 SNR	NR/NC	*ns*
	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR Volume control: NR	Words (profound HL)	Open	50 dBA	NR/NC	*ns*
			Words (severe HL)	Open	45 dBA/quiet; 50 dBA/0 SNR	NR/NC	*ns*
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR					
Stelmachowicz et al. (1995)	WDRC	NR	Nonsense syllables	Closed	50 dB SPL	NR/NC	*ns*
	Linear	NR (conditions assessed using 2 different devices)					

Note. avg. = average.

[a]Positive effect sizes indicate that the direction of the effect favors WDRC; negative effect sizes indicate that the direction of the effect favors linear amplification.

[b]Effect size *r* calculated using *F* statistic and degrees of freedom provided in the study.

[c]Confidence intervals were not calculable.

Table 6

Clincial Question 2: Comparison of amplitude compression WDRC versus linear amplification on speech recognition outcomes at average input levels (55–70 dB).

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size [95% CI][a]	*p*
Boothroyd et al. (1988)[b]	WDRC	Threshold: NR Attack time: NR Release time: NR Ratio: prelimiting gains increased by the amount by which the participant's dynamic range of hearing fell short of 30 dB Volume control: NR	Nonsense syllables: All contrasts	Closed	NR	$r_{pb} = -.14$ [−.77, .63][c]	$p < .01$ (favors linear)
			Final consonant voice	Closed	NR	$r_{pb} = -.26$ [−.82, .54][c]	$p < .01$ (favors linear)
			Vowel height	Closed	NR	$r_{pb} = -.35$ [−.85, .47][c]	$p < .01$ (favors linear)
			Duration	Closed	NR	$r_{pb} = -.04$ [−.72, .68][c]	*ns*
			Intonation	Closed	NR	$r_{pb} = -.03$ [−.72, .69][c]	*ns*
			Vowel place	Closed	NR	$r_{pb} = -.07$ [−.74, .67][c]	*ns*
			Initial consonant continuance	Closed	NR NR	$r_{pb} = -.28$ [−.82, .53][c]	$p < .01$ (favors linear)
	Linear CL	Threshold: NR Attack time: 2 ms Release time: preamplifier = 1 s; second compression-limiter = 20 ms Ratio: NR Volume control: NR	Initial consonant voice	Closed		$r_{pb} = .11$ [−.64, .76][c]	*ns*
			Initial consonant place	Closed	NR	$r_{pb} = .11$ [−.64, .76][c]	*ns*
Christensen (1999)	WDRC	Threshold: Low: 45–50 dB SPL Attack time: 5 ms Release time: 50 ms Ratio: Variable:1.1:1–7.8:1 Volume control: listener unable to adjust during testing	Bisyllabic spondaic words	Open	65 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Passages	Open	65 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
	Linear CL	Threshold: High: 75 dB Attack time: 5 ms Release time: adjustable up to 1 s Ratio: 8:1 Volume control: listener unable to adjust during testing					
	Linear PC	Threshold: none Attack/release time: instantaneous Ratio: none					

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size [95% CI][a]	p
		Volume control: listener unable to adjust during testing					
Gou et al. (2002)	WDRC	Threshold: 40 dB Attack time: NR Release time: NR Ratio: NR Volume control: AGC	Words (discrimination of phonological oppositions)	Closed	65 dB SPL/quiet	NR/NC	$p < .01$ (favors WDRC)
			Monosyllabic words	Closed	65 dB SPL/quiet	NR/NC	*ns*
			Bisyllabic words	Closed	65 dB SPL/quiet	NR/NC	*ns*
	Own linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: fixed					
Jenstad et al. (1999)	WDRC	Threshold: 45 dB Attack time: 10 ms Release time: 200 ms Ratio: varied by DSL prescription Volume control: listener unable to adjust	Nonsense words	Closed	60 dB SPL/quiet (avg. speech at 1 m)	NR/NC	*ns*
			Sentences	Open	60 dB SPL/quiet (avg. speech at 1 m)	NR/NC	*ns*
	Linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: listener unable to adjust					
Marriage & Moore (2003)	WDRC	Threshold: 50–55 dB SPL Attack time: 5 ms Release time: 30 ms Ratio: varied between 1.7: 1 to 2.7: 1 Volume control: NR	Words (consonant confusion task) (severe and profound HL)	Closed	60, 50 dBA/quiet, +10 SNR	$r = .78$ [.07, .97][d]	$p = .021$ (favors WDRC) Compression × Presentation Level: *ns*
			Monosyllabic words (severe HL)	Open	60, 50 dBA/quiet, +10 SNR	$r = .999$[d,e]	$p < .001$ (favors WDRC) Compression × Presentation Level: *ns*
	Linear	NR					
Marriage et al. (2005)	WDRC	Threshold: 40 dB at 200 Hz; 25 dB at 4400 Hz Attack time: 5 ms Release time: 30 ms Ratio: 1.2:1 to 3.0:1 Volume control: NR	Monosyllabic words (profound HL)	Closed	65 dBA/quiet	NR/NC	$p < .002$ (WDRC > linear CL) *ns* (WDRC vs. linear PC)
			Words (profound HL)	Open	65 dBA/quiet	NR/NC	*ns*
			Common phrases	Open	65 dBA/quiet	NR/NC	*ns*
			Sentences SNR	Open	In 60 dB modulated noise	NR/NC	*ns*
	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR					

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Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size [95% CI][a]	*p*
		Volume control: NR					
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR					
Stelmachowicz et al. (1995)	WDRC	NR	Nonsense syllables	Closed	65 dB SPL	NR/NC	*ns*
	Linear	NR (conditions assessed using 2 different devices)					

[a] Positive effect sizes indicate that the direction of the effect favors WDRC; negative effect sizes indicate that the direction of the effect favors linear amplification.

[b] One outlier removed.

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

[d] Effect size r calculated using F statistic and degrees of freedom provided in the study.

[e] Confidence intervals were not calculable.

Table 7

Clinical Question 2: Comparison of WDRC versus linear gain on speech recognition outcomes at high input levels (> 70 dB).

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size	*p*
Christensen (1999)	WDRC	Threshold: Low: 45–50 dB SPL Attack time: 5 ms Release time: 50 ms Ratio: Variable: 1.1:1 to 7.8:1 Volume control: listener unable to adjust during testing	Bisyllabic spondaic words	Open	80 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Passages	Open	80 dB SPL/quiet, +5, +10 SNR	NR/NC	*ns* across SNRs
			Sentences	Open	83 dB SPL (70 dB HL)/0, +5, +10, +15 SNR	NR/NC	*ns* across SNRs
	Linear CL	Threshold: High: 75 dB Attack time: 5 ms Release time: adjustable up to 1 s Ratio: 8:1 Volume control: listener unable to adjust during testing					
	Linear PC	Threshold: none Attack/release time: instantaneous Ratio: none Volume control: listener unable to adjust during testing					
Jenstad et al. (1999)	WDRC	Threshold: 45 dB Attack time: 10 ms Release time: 200 ms Ratio: varied by DSL prescription Volume control: listener unable to adjust	Nonsense words	Closed	82 dB SPL/quiet (shouted speech at 1 m)	NR/NC	$p < .05$ (favors WDRC)
			Nonsense words	Closed	72 dB SPL/quiet (own voice at ear level)	NR/NC	*ns*
			Nonsense words	Closed	73 dB SPL/quiet (classroom at 1 m)	NR/NC	*ns*
	Linear	Threshold: NR Attack time: NR Release time: NR Ratio: NR Volume control: listener unable to adjust	Sentences	Open	82 dB SPL/quiet (shouted speech at 1 m)	NR/NC	$p < .05$ (favors WDRC)
			Sentences	Open	72 dB SPL/quiet (own voice at ear level)	NR/NC	*ns*
			Sentences	Open	73 dB SPL/quiet (classroom at 1 m)	NR/NC	*ns*
Marriage et al. (2005)	WDRC	Threshold: 40 dB at 200 Hz; 25 dB at 4400 Hz Attack time: 5 ms Release time: 30 ms Ratio: 1.2:1 to 3.0:1 Volume control: NR	Monosyllabic words (profound HL)	Closed	80 dBA/quiet	NR/NC	*ns*
			Words (profound HL)	Open	80 dBA/quiet	NR/NC	*ns*
			Words (severe HL)	Open	80 dBA/quiet	NR/NC	*ns*
			Common phrases (profound HL)	Open	80 dBA/quiet	NR/NC	*ns*
	Linear CL	Threshold: high Attack time: 0.5 ms Release time: 50 ms Ratio: NR					

Citation	Condition	Compression settings	Stimuli	Open/closed set	Presentation level/SNR	Effect size	*p*
		Volume control: NR					
	Linear PC	Threshold: high Attack time: 0.5 ms Release time: 5 ms Ratio: NR Volume control: NR					
Stelmachowicz et al. (1995)	WDRC	NR	Nonsense syllables	Closed	80 dB SPL	NR/NC	*ns*
	Linear	NR (conditions assessed using 2 different devices)					

Table 8

Study characteristics.

Citation	Study design	Critical appraisal points							Appraisal score
		Protocol description	**Assessors blinded**	**Sampling**	**Allocation**	**Counterbalancing**	***p***	**Effect size**	
Boothroyd et al. (1988)	Repeated measures	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	**Rep/calc**	**ES/CI rep/calc**	3/7
Christensen (1999)	Crossover	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	**Counterbalanced**	**Rep/calc**	ES/CI not rep/calc	3/7
Gou et al. (2002)	Crossover	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	**Rep/calc**	ES/CI not rep/calc	2/7
Jenstad et al. (1999)	Repeated measures	**Adequate**	Not blinded	Conv/HP/NR	**Random**	Not counterbalanced/NR	**Rep/calc**	ES/CI not rep/calc	3/7
Jenstad et al. (2000)	Repeated measures	**Adequate**	Not blinded	Conv/HP/NR	**Random**	Not counterbalanced/NR	**Rep/calc**	**ES/CI rep/calc**	4/7
Marriage & Moore (2003)	Crossover	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	**Counterbalanced**	**Rep/calc**	**ES/CI rep/calc**	4/7
Marriage et al. (2005)	Crossover	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	**Counterbalanced**	**Rep/calc**	**ES/CI rep/calc**	4/7
Stelmachowicz et al. (1995)	Repeated measures	**Adequate**	Not blinded	Conv/HP/NR	Not random/NR	Not counterbalanced/NR	Not rep/cal	Only ES or only CI rep/calc	1/7

Note. Conv = Convenience; HR = hand-picked; Rep = reported; calc = calculable; ES = effect size. Bolded items represent the highest quality level for each appraisal point; each is awarded 1 point toward the appraisal score.

Appendix C

HA and procedural details

Citation	HA model	Experimental feature	Other features	Fitting prescription	Monaural/binaural testing	Duration
Boothroyd et al. (1988)	Master HA	WDRC	High-frequency emphasis circuit 2 channels	NR	Tested monaurally	20-min testing sessions over 4–5 weeks
Christensen (1999)	ITE Phonak Dyna P2 Programmable HA	WDRC/linear CL	Equalization 3 programs Multiple memory	DSL (WDRC) NAL-R (linear CL) NAL-R (linear PC)	Binaural	2 mo. in each condition
Gou et al. (2002)	Widex P38/C18+ (WDRC) Unspecified own aids (linear)	WDRC	Digital 3 channel Fully automatic gain control	Based on NAL-R and adjusted to account for device-specific features	Tested binaurally	1 test session with own, linear HA testing after 1, 3, and 5 mo. with test HA
Jenstad et al. (1999)	Siemens Viva Pro 2 BTE	WDRC	Programmable Single channel	DSL v 4.0	Tested monaurally	1 test session
Jenstad et al. (2000)	Siemens Viva 2 Pro BTE	WDRC	Programmable Single channel	DSL v. 4.0 [i/o]	Tested monaurally	1 test session
Marriage & Moore (2003)	Phonak Novoforte E3 or E4	WDRC	Programmable Single channel	Manufacturer software (WDRC) Adjusted to child's previous HA settings (linear)	Binaural	1 test session
Marriage et al. (2005)	Phonak Supero 412	WDRC/linear CL	Digital 5 channel High power	DSL [i/o]	Binaural	1–2 weeks in each condition
Stelmachowicz et al. (1995)	Qualitone, KE (Compression) Unitron UM-60 (linear)	WDRC	NR	DSL	Monaural testing	1 test session

Note. ITE = in the ear; NAL-R = National Acoustic Laboratories–Revised; BTE = behind the ear; [i/o] = input/output.