Effectiveness of Signal Processing Strategies for the Pediatric Population: A Systematic Review of the Evidence

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Abstract
A systematic review of literature addressing the question “Is there evidence pointing to optimal signal processing for pediatric hearing aid patients?” was conducted. Key words and authors were used as search terms in five databases, and one textbook appendix was reviewed for related references. The levels of evidence that were accepted comprised randomized controlled trials, nonrandomized controlled trials, cohort, and before/after designs with or without control groups. Two hundred twenty-six articles were identified during the preliminary search with 183 of these eliminated by review of abstracts because they did not meet the search criteria. Forty-three manuscripts were reviewed, with eight meeting the evidence levels and search criteria. The strengths and weaknesses of these studies are highlighted, and the systematic review question is answered in light of these studies. There is evidence to recommend wide dynamic range compression signal processing for pediatric hearing aid users with mild, moderate, and moderately severe sensorineural hearing loss when full-time and consistent audibility is the goal of the hearing aid fitting. Further, there is evidence that audibility across a wide frequency bandwidth as well as across a large range of input levels is essential for pediatric hearing aid users to recognize critical components of the spoken language.

Key Words: Audibility, comfort, linear, pediatric, signal processing, verification, wide dynamic range

Abbreviations: A = audibility; CL = compression limiting; DSL = Desired Sensation Level; MCL = most comfortable loudness level; PC = peak clipping; RCT = random controlled trial; WDRC = wide dynamic range compression

Sumario
Se realizó una revisión de la literatura planteando la pregunta: “¿Existe evidencia que apunte al procesamiento óptimo de la señal para pacientes pediátricos con auxiliar auditivo?” Se utilizaron palabras clave y autores como términos de búsqueda en cinco bases de datos, y el apéndice de un libro de texto fue revisado buscando referencias relacionadas. Los niveles de evidencia que fueron aceptados incluyeron estudios aleatorios controlados, estudios controlados no aleatorios, diseños de cohorte y de antes/después, con y sin grupos control. Se identificaron doscientos veintiséis artículos durante la búsqueda preliminar y 183 de éstos fueron eliminados con la revisión de los sumarios, pues éstos no cumplían los criterios escogidos. Se revisaron

The protocol states that “although certain signal processing schemes require digital processing, the discussion here is only relevant to the strategies. That is, the appropriate signal processing question is not whether we should select digital or analog hearing aids, but rather, what signal processing schemes are appropriate. In some cases the desired signal-processing scheme may require digital signal processing, in other cases it may not. The choice of appropriate features for each individual will be paramount” (American Academy of Audiology, 2004). The protocol goes on to list the “Basic Requirements” for pediatric amplification that are self-evident and include low distortion, audibility across a wide range of inputs, comfort, and flexibility in programming to meet the changing needs of a pediatric patient.

The following is a systematic review of signal processing as it relates to the pediatric population. The goal was to examine whether there is evidence in the literature to support the recommendations of the Pediatric Amplification Protocol related to signal processing or whether we must continue to depend largely on expert opinion. Specifically, is there evidence to recommend optimal signal processing for pediatric hearing aid patients?

METHODS

Inclusion and Exclusion Criteria

The level of evidence accepted included randomized controlled trials, nonrandomized controlled trials, cohort, and before/after (repeated measures) design with or without a control group. In a randomized controlled trial (RCT), a set of subjects are identified and then randomly assigned to two or more treatment groups. One group serves as a control group and receives no treatment or standard care. It often is difficult to produce randomized controlled trials in a pediatric population because researchers and parents are uncomfortable withholding treatment in this population. Nonrandomized controlled trials indicate that the subjects are not randomly assigned to treatment groups. One group serves as a control group and receives no treatment or standard care. It often is difficult to produce randomized controlled trials in a pediatric population because researchers and parents are uncomfortable withholding treatment in this population. Nonrandomized controlled trials indicate that the subjects are not randomly assigned to treatment groups. For instance, the subjects may be entered into groups in order to match the groups on certain characteristics (e.g., age, hearing loss, etc.). Cohort studies are more feasible than
randomized controlled trials and involve a prospective study in which one group has been exposed to a particular treatment and another group has not. Unlike RCT, the assignment of subjects to groups is not under the control of the investigators. Unfortunately, this can result in the two groups being compared having inherent differences, making the results difficult if not impossible to interpret. In before/after designs, the outcomes of interest are assessed before and after a treatment. A control group generally is not included because the investigator does not wish to withhold treatment. Without a control group, it is impossible to identify whether the treatment alone was responsible for any change. For example, in pediatric studies, maturation may be a cause for change, and without a control group of subjects who also are maturing, the researcher would have difficulty sorting out this variable. If a study was not of one of the above described designs, it was excluded from the systematic review.

Search Strategy and Data Extraction

A systematic review of the literature was conducted in order to produce evidence to support or refute the aforementioned question. The methods of the review followed the guidelines provided by McKibbon et al (1999). The keywords for the search were “child,” “pediatric,” “hearing-impaired,” “hard of hearing,” “hearing loss,” “linear,” “wide dynamic range,” “signal processing,” “microphone,” “language,” “speech understanding,” “speech intelligibility,” “audibility,” “word recognition,” and “discrimination.” In addition, each database was searched using authors’ names identified by the research group as having research programs related to these areas. The databases searched included MEDLINE (1966 to present), Cumulative Index to Nursing and Allied Health Literature (CINAHL, 1982 to present), and EMBASE. Out of this search, the identified authors and institutions producing the research were searched in the MEDLINE In-Process and Other Non-Indexed Citations file. A Web of Science search was used to identify articles that cited target articles that had already been identified as meeting the inclusion criteria. A related author search was conducted in PubMed for all of the authors in appendix A of Lewis’s (2000) chapter entitled “Advanced Signal Processing Hearing Aids with Children.” Linda Hartman, a reference librarian at the University of Pittsburgh Library System, provided expertise in the search process and conducted the searches while consulting with the review team. The review team consisted of the authors, five PhD students, and one research associate in the University of Pittsburgh Auditory Processing Laboratory.

Patricia Stelmachowicz and Richard Seewald were contacted to review the identified articles and to note if they found the list lacking. These two individuals were chosen because they both conduct research programs that investigate the areas under consideration and have an excellent working knowledge of the research in these areas.

Figure 1 provides a flowchart of the search process and results. Two hundred twenty-six studies were identified as potentially relevant to the question. One hundred eighty-three were excluded based on a review of the abstracts. Therefore, 43 studies were reviewed by each reviewer, and thirty-five of these were excluded because they did not meet the inclusion criteria and/or the required level of evidence. Eight studies met the inclusion criteria and are included in this systematic review.

The headings in Table 1 provide some of the categories used for data extraction. All reviewers completed this task, and then the reviews were combined and any discrepancies were resolved through discussions of the investigators. The purpose of the study, the study design, the intervention (independent variable), the outcome measures (dependent variable), and the subject characteristics are described. A summary of the results directly related to the systematic review question and any weaknesses in the study were described. If after data extraction the study met all inclusion criteria, it was accepted into the systematic review and underwent quality assessment.

Quality Assessment

Study quality for the eight selected investigations was assessed by all reviewers and included attention to:

1. Description of the randomization process
if it existed
2. Inclusion of a control group
3. Number of subjects and power analysis
4. Blinding of experimenters and/or subjects
5. Psychometrically sound outcome measures
6. Detailed description of the amplification fitting
7. Verification of the amplification fitting under investigation

Table 2 provides a summary of the quality of the studies that met the inclusion criteria for this systematic review. The first five criteria are standard ways to assess the quality of research investigations. The last two criteria were included specifically because of the present topic of signal processing in pediatric amplification. The hearing aid settings as chosen by the fitting method used in the studies and the subsequent verification could have a large impact on any studies focused on assessing audible signals. It would be ideal if the studies verified audibility objectively prior to obtaining any outcome measures to ensure that the subjects actually heard the stimuli. All seven criteria were considered important in the quality assessment of the studies.

Due to the lack of consistency of amplification strategies compared, fitting rationales employed, and outcome measures used, it was not possible to pool results across studies. In fact, the studies were divided into three categories because of their specific aims: investigation of output limiting, investigation of the need for increased audibility for hearing-impaired children, and the comparison between linear and wide dynamic range compression (WDRC) signal processing in the dynamic range. Table 1 provides the detail needed for a qualitative analysis of the investigations. The results as they relate to the question posed in this systematic review are listed in the last column of Table 2 and are summarized as follows.
### Table 1. Key Features of the Studies Reviewed

<table>
<thead>
<tr>
<th>Reference</th>
<th>Design</th>
<th>Intervention</th>
<th>Outcomes</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stelmachowicz et al (1999)</td>
<td>Nonrandomized controlled trial</td>
<td>Peak clipping circuit</td>
<td>Paired comparison for clarity of sentences</td>
<td>Could not differentiate circuits for the hearing-impaired groups</td>
<td>Majority of subjects use peak clipping in their personal hearing aids, small N per group (10), all testing in quiet, speech was the only input signal</td>
</tr>
<tr>
<td>Christensen (1999)</td>
<td>Before/After with Cross Over</td>
<td>Linear with peak clipping</td>
<td>NU-6 CST SIN Diary</td>
<td>No significant performance difference between the three strategies</td>
<td>Diaries were not received from all subjects, all but one subject had experience with linear signal processing, small N (12), testing conducted in noise</td>
</tr>
<tr>
<td>Stelmachowicz et al (2000)</td>
<td>Nonrandomized control trial</td>
<td>Provided more or less audibility and context of test material</td>
<td>SPL and AI to achieve 70% on high and low predictability sentences</td>
<td>Regardless of stimulus context or hearing, children require higher SPL and AI to achieve adult performance. Needed most gain for low inputs, context did not help</td>
<td>Results are in quiet only, no frequency shaping of the signal, 23 hearing-impaired children, 60 normal-hearing children, 20 normal-hearing adults</td>
</tr>
<tr>
<td>Stelmachowicz et al (2002)</td>
<td>Nonrandomized controlled trial</td>
<td>Hearing aids fit to DSL [i/o]</td>
<td>Female and male talker of plural and singular word forms</td>
<td>Significant effect for talker (female worse) and factor (plural words worse). Audibility needed through 8000 Hz for female talker.</td>
<td>All testing in quiet N = 40</td>
</tr>
<tr>
<td>Smith and Levitt (1999)</td>
<td>Before/After</td>
<td>Amount of consonant enhancement</td>
<td>Consonant recognition</td>
<td>Consonant recognition in young children improved significantly by consonant enhancement</td>
<td>Small N (12), no inclusion of a speech (sentence) measure, all testing in quiet</td>
</tr>
<tr>
<td>Jenstad et al (1999)</td>
<td>Before/After</td>
<td>Linear DSL[i/o] WDRC DSL[i/o] Unaided</td>
<td>Speech perception scores under five listening conditions</td>
<td>On average, WDRC performed better than linear gain across 5 listening conditions</td>
<td>Monaural testing, small N (12), no adaptation, previous experience may be a factor, testing with HINT noise</td>
</tr>
<tr>
<td>Marriage and Moore (2003)</td>
<td>Before/After</td>
<td>WDRC Linear with peak clipping</td>
<td>CCT MJWL BKB</td>
<td>CCT revealed significant benefits of WDRC over linear</td>
<td>Small N (14), unknown previous amplification experience, no adaptation, responses matched to current hearing aids, testing in speech shaped noise</td>
</tr>
</tbody>
</table>

**Note:** AI = articulation index; BKB = Bench-Kowall-Bamford (Bench and Bamford, 1979); CCT = Connected Confusion Task (Markides, 1997); CST = Connected Speech Test (Cox et al., 1987); DSL [i/o] = Desired Sensation Level [input/output] (Cornelisse et al., 1995); HINT = Hearing in Noise Test (Nilsson et al., 1994); MJWL = Manchester Junior Word List (Markides, 1997); NU-6 = Northwestern University Test #6 (Tillman and Carhart, 1966); SIN = Speech in Noise (Etymotic Research, 1993); SPL = sound pressure level; UCL = uncomfortable loudness level; WDRC = wide dynamic range compression.
“PC > CL” means that peak clipping was superior to compression limiting on one or more outcome measures.

“PC < CL” means that peak clipping was inferior to compression limiting on one or more outcome measures.

“PC = CL” means that peak clipping and compression limiting could not be distinguished by the outcome measures.

“A+” means increased audibility produced a significant improvement on one or more outcome measures or was required to match the performance of a control group.

“A−” means that increased audibility did not produce a significant improvement on any outcome measure or was not required to match the performance of a control group.

“WDRC = Linear” means that similar performance on outcome measures were found regardless of signal processing used.

“WDRC > Linear” means that performance on one or more outcome measures was superior when using WDRC signal processing.

“WDRC < Linear” means that performance on one or more outcome measures was superior when using Linear signal processing.

RESULTS

Study Characteristics

The details of the investigations that met the search criteria (Figure 1) are presented in Table 1. The number of subjects per experimental group in the studies varied from approximately 40 to as few as 10. The youngest subjects were five years old while the oldest children were 16 years old. Jenstad et al (1999, 2000) worked with a group of adolescents and young adults (mean age of 16 with a range from 10 to 27 years of age). In two studies, an adult group was included for comparison purposes (Stelmachowicz et al, 1999, 2000). Three studies included young normal-hearing children as a control group (Stelmachowicz et al, 1999, 2000, 2002). A variety of hearing loss was included across the studies as well. One study (Stelmachowicz et al, 2002) purposely included children with a wide variety of degrees of hearing loss, while two studies defined the hearing losses as mild-to-moderate (Christensen, 1999;
Stelmachowicz et al., 1999), and five studies included hearing losses that were moderate-to-severe (Smith and Levitt, 1999; Jenstad et al., 1999, 2000; Stelmachowicz et al., 2000; Marriage and Moore, 2003). All hearing losses were reported as sensorineural.

Four of the eight investigations (Stelmachowicz et al., 1999; Christensen, 1999; Jenstad et al., 1999, 2000; Stelmachowicz et al., 2002) provided a detailed description of the hearing aid fitting using a recognized fitting method and provided a description of the verification procedure. The two methods used included the Desired Sensation Level (DSL i/o; Cornelisse et al., 1995) and the National Acoustic Laboratory-Revised (NAL-R; Byrne and Dillon, 1986). One study described the fitting method, but it consisted of matching the experimental hearing aids to the subject’s personal hearing aid response without any control over how the personal hearing aid was fit and with no verification measures (Marriage and Moore, 2003). Two of the studies did not use a fitting method because listening was conducted through earphones (Smith and Levitt, 1999; Stelmachowicz et al., 2000). Only one of these two studies verified that the test signals were audible through this method (Stelmachowicz et al., 2000). Seven of the eight studies used some type of real speech signal as one of the outcome measures while one of the studies (Smith and Levitt, 1999) used nonsense syllables. Five of the eight studies conducted the outcomes measures in quiet (see Table 1 for a description of noise types used in three studies). It would be of interest to see results of similar studies with noise since that might have a large impact on the results. In two of the studies (Jenstad et al., 1999, 2000), the subjects were tested monaurally while the other six studies used a binaural presentation for outcome measures.

### Study Quality

Study quality parameters are reported in Table 2. Randomized controlled trials offer the highest level of evidence yet are difficult to carry out in a pediatric population where there is concern over withholding treatment. A control group also could consist of a group of children receiving a standard treatment. This design was not found. There is little agreement in the pediatric literature at this time as to what signal processing constitutes a standard treatment. As can be seen in Table 2, none of the studies that met the search criteria were randomized controlled trials. Evidence supporting the use of some type of amplification for children with hearing loss in order to create audibility already exists. The studies reviewed in this paper were focused on refining what that amplification should consist of in terms of signal processing. Four of the eight studies included a control group that consisted of children with normal hearing or normal-hearing adults. Without a control group, it is difficult to attribute improvement on the outcome measures to the treatment alone.

None of the studies included a power calculation that would indicate the number of subjects needed to identify a clinically significant change on the outcome measures at a particular power level. Three of the studies included large N’s (over 20) while five of the studies had N’s of 12 or less. All eight of the studies included validated outcome measures. Validated outcome measures include tests that have published psychometric data related to reliability and validity. All of the studies indicated that the conditions under test were either counterbalanced or randomized to avoid order effects and to keep the subjects blind to the treatment conditions. All eight of the studies blinded the subjects to the treatment or test conditions, but only one study reported blinding the researchers (Stelmachowicz et al., 2000).

### Findings

A review of Table 1 reveals that the studies used seven classes of outcome measures including (1) connected speech, (2) sentences in noise, (3) sentences in quiet, (4) single words, (5) nonsense words, (6) nonsense syllables, and (7) environmental sounds. In the two investigations that examined output limiting (Christensen, 1999; Stelmachowicz et al., 1999), a significant difference between compression output limiting and peak...
clipping was not observed on judgment measures (paired comparison and self-report) or performance measures (percent correct and signal-to-noise ratio required for 50% correct). This may be interpreted to mean that there is no difference between signal processing strategies, and therefore application of either signal processing strategy is appropriate, or one might conclude that since no difference was found, the strategy that is superior through other measures (e.g., distortion analysis) should be used. Interpretation of these data also must be qualified by the fact that the majority of subjects in both studies had full-time experience with linear, peak-clipping hearing aids prior to the study. Based on this information, one could interpret the results of the study in light of the fact that, although the majority of the subjects were experienced peak-clipping users, they did not perceive compression output limiting as any worse, and it may have other benefits not revealed in these investigations (e.g., low physical distortion). In addition, one must interpret these data cautiously due to the small number of subjects per group (10–12).

The three studies that focused on the impact of audibility on speech understanding outcomes all found increased audibility as compared with desired audibility for adults to have a positive impact on their respective outcome measures. Stelmachowicz et al (2000) concluded that hearing-impaired children needed approximately 13.5 dB more audibility than adults to achieve 85% performance. Children reached 100% performance at 24–28 dB SL. Further, the most critical need for increased audibility as compared with what is considered adequate for adults was for low-level inputs where context did not assist in identification of words in sentences for the hearing-impaired children. Interest in audibility for low-level inputs resurfaces in the next set of studies. Smith and Levitt's (1999) data indicate that increased audibility over most comfortable listening level (MCL) produced better consonant recognition in their subjects. An increase of 5–10 dB over MCL produced the best consonant recognition. These authors make a point of not exceeding the children's loudness discomfort levels, reminding the reader that audibility must always be tempered by comfort in a hearing aid fitting. Stelmachowicz et al (2002) took this work a step farther and focused on the bandwidth of audible sound needed for pediatric amplification users to perceive /s/. The results indicated that audibility was needed through 8000 Hz for correct perception of /s/ for female speakers. In fact, bandwidth of audibility predicted performance more than hearing level, sensation level, or age. These three studies illustrate that increased audibility as compared to what is considered adequate for adults for low-level inputs across a wide bandwidth is essential for adult-like performance for hearing-impaired children. In addition, for hearing-impaired children, the use of context does not replace audibility for low-level inputs.

The third category of investigation related to signal processing compared linear with WDRC processing. These are strategies for processing the signal within the dynamic range as opposed to at the point of limiting. As Byrne tells us, “wide dynamic range compression theoretically reduces the long-term level variations of speech thereby maintaining audibility for soft speech, together with comfort for loud sounds, without the need for volume control adjustment” (1996, p. 288). This definition of WDRC fits nicely with the goals of the Pediatric Working Group (1996), which indicated that the “main goal of providing amplification for children is to ensure that they will receive full-time and consistent audibility of the speech signal at safe and comfortable listening levels." The three studies designed to compare WDRC with linear signal processing found that WDRC produced significantly superior results on the various outcome measures used in the investigations. It was the goal of the first two studies (Jenstad et al, 1999, 2000) to test the theoretical advantages of single-channel WDRC over a linear gain circuit for speech intelligibility, loudness comfort, and increased dynamic range. As would be expected, subjects performed similarly for average speech, but the understanding of softer speech and shouted speech was significantly improved with WDRC signal processing. This speaks to the goal of “full-time and consistent audibility.” The pediatric population presents special issues related to the need for any type of volume control or other manual manipulation, and the WDRC signal processing best met the goals without the need for volume control adjustments.
Children cannot be expected to adequately adjust a volume control in response to their changing listening environment. Although Marriage and Moore’s (2003) study actually was designed to compare outcome measures to identify the most sensitive and reliable measure when comparing technology, their results also related to the comparison of linear and WDRC signal processing. On average, their subjects showed significant improvement on outcome measures when using WDRC as opposed to linear signal processing.

Considering the theoretical underpinnings of properly fit WDRC, it is not surprising to find WDRC outperforming linear signal processing when a variety of input levels are used. The three studies investigating the need for audibility (regardless of signal processing; Stelmachowicz et al, 2000, 2002; Smith and Levitt, 1999) all predict that whatever signal processing produces an audible signal over a wide range of inputs will be superior to signal processing that does not achieve this goal. Therefore, all six studies (last six studies of Table 2) are in agreement and indicate that, for lower input levels, the pediatric population requires a signal at least 13.5 dB more audible across a wider bandwidth of frequencies than an adult population and that this may be achieved through WDRC signal processing consisting of a low-compression threshold (45–55 dB), a moderate compression ratio (1.7 to 2.3) and a fast (10 msec) attack time.

DISCUSSION AND CONCLUSIONS

In terms of output limiting, adult data (Hawkins and Naidoo, 1993; Preves and Newton, 1989) reveal a preference for output compression limiting over peak clipping. In Stelmachowicz et al (1999), the adult normal-hearing group provided data in agreement with these findings. The group with impaired hearing (children and adults) did not reveal a preference between strategies, and this was true for the children in Christensen’s (1999) investigation as well. Since output compression limiting was not perceived to be worse than peak clipping, output compression limiting may be chosen based on other characteristics of the signal (e.g., lower distortion than peak clipping).

The second two groups of papers reviewed dealt with the overall subject of audibility and the specific topic of what signal processing will produce consistent, full-time audibility to the pediatric population, a population of persons who cannot be expected to manipulate volume controls in order to control audibility. The evidence suggests that increased audibility over what is considered adequate for adults for low-input levels is critical for this population to perform similarly to adult listeners (Smith and Levitt, 1999; Stelmachowicz et al, 2000, 2002). Stelmachowicz et al (2002) provided a compelling argument for audibility through 8000 Hz for children learning the important elements of the English language such as the sound /s/ that marks plurals, possessives, and tense.

Jenstad et al (1999, 2000) and Marriage and Moore (2003) provided evidence that the ability to correctly recognize speech in quiet and in noise is enhanced through the use of WDRC as compared with linear gain signal processing for a pediatric population with moderate to severe sensorineural hearing loss. WDRC can vary widely depending on how it is configured in terms of compression threshold, compression ratio, attack time, release time, and how all of these characteristics are varied across frequency channels and input levels. These studies used single-channel instruments with a low-compression threshold (45–55 dB), a moderate compression threshold (1.7 to 2.3), and a fast (10 msec) attack time. Although other WDRC parameters may be effective as well, these are the parameters currently supported in the pediatric amplification literature. The release times in the studies ranged from 30 msec (Marriage and Moore, 2003) to 200 msec (Jenstad et al, 1999, 2000), so it is not possible to recommend a specific release time.

Considering the results of this systematic review, it is reasonable to state that pediatric hearing aid candidates with mild, moderate, and moderately severe sensorineural hearing loss should be fit with amplification that employs WDRC signal processing with a low-compression threshold, moderate compression ratio, and fast attack time and provides increased compression in order to limit signals at the maximum output of the hearing aid. Evidence was found to support the need for increased audibility (13.5 dB) for low-level inputs over what is considered adequate for adults and a wider bandwidth of audibility for the pediatric population as compared to an adult population for speech understanding.
Verification protocols should be predicated on this and future evidence. In other words, if audible signals at low, moderate, and intense input levels across frequencies are essential for speech recognition, then the clinician working with the pediatric population would want to implement a verification protocol that measured audibility as carefully as possible. Development of appropriate verification protocols for pediatric patients should be based on evidence such as that reported in this systematic review.

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REFERENCES


