Critical Review: Based on its effect on speech and phoneme recognition in children, should frequency lowering be used in pediatric amplification?

Irene Nicholaou
M.Cl.Sc AUD Candidate
University of Western Ontario: School of Communication Sciences and Disorders

Abstract: The purpose of this critical review is to evaluate the effect of frequency lowering (FL) technology on speech recognition in the pediatric population. One of each of the following study designs were included: a within groups, repeated measure design; a nonrandomized clinical trial, cohort study design; a within subject, crossover design; a counterbalanced, within group repeated measure, modified withdrawal design; and a case series pre-post test design. Overall, the current literature provides suggestive evidence which demonstrates that FL improves speech recognition of high frequency sounds, as improvements were observed in a majority of subjects, however many of the subjects did just as well, or improved with the use of conventional processing (CP). As sample sizes in each study were small, a larger group analysis would be needed to generalize results to a larger population.

Introduction

Consonants are found in high frequency (HF) regions of the speech spectrum. While vowels provide much of the intensity of the speech signal and are lower pitched, consonants are softer in intensity and are responsible for providing the majority of our speech understanding and comprehension. Individuals tend to have higher thresholds, or more severe hearing loss (HL) at higher frequencies, and report hearing speech, but perceive it as sounding muffled or unclear (Glista, D., Scollie, S., Bagatto, M., et al., 2009). This is due to the loss of hair cells in the basal region of the cochlea. Hearing aids can help an individual by adding increased gain in regions of reduced sensitivity, and by applying different methods of digital signal processing to the acoustic signal which can change based on environmental cues. Frequency lowering (FL) is a relatively new technological advancement being incorporated in hearing devices, and was designed to specifically assist with reduced HF hearing sensitivity. FL shifts HF information of an incoming signal that would otherwise be inaudible to a hearing aid user, and places it in a lower-frequency region (Glista, D., 2011). Two types of FL technologies will be discussed in this review, non-linear frequency compression (NLFC), and linear frequency transposition (LFT). Both methods of FL work to bring HF information into the users' residual auditory area, and this is accomplished by compressing HF information non-linearly to a lower frequency band (NLFC) or by transposing the HF acoustic information linearly into lower frequency regions. This technology will inevitably add some distortion to the incoming signal, and could potentially affect the clarity and understanding of speech. While adults acquire HL much later life, the altered signal may have less of an effect on them as they are able to use contextual cues to identify what is being said. However, children with HL have not mastered their native language, thus this added distortion could have a greater impact on their speech understanding. Studies have shown that children are worse, overall at identifying HF consonants when compared to adults, when hearing thresholds are matched, and that speech identification results from an adult population are not predictive of a child's performance (Allen, P. 2011, Stemalchowicz, P., Pitmann, A., Hoover, B., 2004). An alternative that has been suggested for the pediatric population are hearing aids with extended bandwidth. Results from Stemalchowicz (2004) and her colleagues show that even these devices precipitously slope off at about 5000 Hz, which is consistent with the difficulties children with higher-frequency impairments exhibit in phoneme identification tasks that involve HF consonants, or fricatives (Stemalchowicz, et al., 2004). Therefore, the problem arises in children whose HL is so severe, that even with extended bandwidth technology; HF cues continue to remain outside of the child's auditory range. In these situations, FL could be a viable option. Thus the question remains; *does frequency lowering improve phoneme identification of high-frequency sounds in children therefore improving speech recognition?*

Objectives

The main objective of this critical review is to identify whether speech discrimination in children was improved by using FL in the digital signal processing (DSP) technology found in hearing aids as compared to conventional devices.

Methods

<u>Search Strategy:</u> Online databases included Medline Ovid, Pubmed, Google Scholar and Web of Knowledge. They were searched using the following strategy: ((frequency compression or transposition or lowering) and hearing aids).mp. The preceding strategy was limited to the English language, and for ages 0-18 years.

<u>Selection Criteria:</u> Only peer reviewed journals pertinent to the subject at hand were selected. Only articles that reviewed the effects on frequency lowering on children were selected.

<u>Data Collection:</u> The search strategies listed yielded five articles consistent with the selection criteria. One of each of the following designs were represented and measured in terms of their level of evidence: *Within Group, Repeated Measure Design; Nonrandomized Clinical Trial, Cohort Study Design; Within Subject, Crossover Design; and a Counterbalanced, Within Group Repeated Measure, Modified Withdrawal Design;* the former measure as a level 2b in terms

of their level of evidence. The final design was a *Case Series Pre-Post Test Design* which is considered a level 3 with respects to its level of evidence.

Results and Discussion

All studies described adhered to best practice guidelines. Individualized acoustic transforms or real-ear-to-coupler measurements were obtained for all participants and incorporated into the Desired Sensation Level, v.5 algorithm to derive appropriate targets. Audioscan Verifit was used for hearing aid verification in all studies. All child participants were blind to the type of technology being used during the trial and assessment. Only Glista (2009) and her colleagues incorporated a double blind technique. It should be noted that only portions of the study relevant to the research question were discussed in detail.

Nonrandomized Clinical Trial, Cohort Study Design: Miller-Hansen, Nelson, Widen, and Simon (2003) tested the benefit of a frequency transposition technology called Dynamic Speech Recoding (DSR) on children in comparison to devices with conventional processing (CP). 78 children participated in this study; however 16 constituted as part of a *Comparison Subgroup* and participated in speech testing. Data from the children's conventional aids and the DSR devices were compared. The children's own devices were re-fit using best-practice guidelines. Audiometric profiles of the children in the study ranged. Analysis of the data was reported as means, standard deviations, and 95% confidence intervals (CIs). Aided word recognition scores (WRS) were obtained at 35 dB SL relative to the pure tone average when possible. Words from the Phonetically Balanced Kindergarten Test (PBK-50: Haskins, 1949) were presented using monitored live voice. Follow up was conducted 1-month post-fit, and aided recognition scores were re-measured.

Comparison Group Analysis: This subgroup showed a mean improvement of 12.5% *(SD* = 15.7. 95% CI = 4-21,p =.006), with children performing significantly better with the DSR devices when compared to CP. Using a paired t-test, the mild-to-moderate group demonstrated an 8% mean improvement in WRS *(SD* = 13.9); the moderately-severe group demonstrated 4.5% mean improvement *(SD* = 8.7); the severe group demonstrated 23.7% mean improvement *(SD* = 19); and the profound group demonstrated 5.3% mean improvement *(SD* - 6.1). Of these 16 participants, 3 showed 92% improvement with both their own devices and the study aids. Their results were not used in the DSR analysis. Of the remaining 13 participants, 8 showed benefit greater than 10% for the DSR devices (improvement group) and 5 showed benefit between -2% and 8% (no improvement group). Of the 8 which showed improvement, 4 of the children had a flat configuration in their audiogram, 3 had precipitous losses, and one had a sloping audiogram.

This study resulted in suggestive evidence supporting improved speech recognition when using FL technology when compared to CP. An average of 12.5% improvement in WRS with DSR aids when compared to conventional devices would likely result in improved speech understanding, functionally, in daily life. However, 38% (5/13) of the test population showed no improvement from the DSR devices. Ideally the study should have used the same hearing device with DSR in an enabled and disabled condition when drawing comparisons, as technological differences between the two devices could pose a confounding factor in the results. When the HL was in the severe range, a drastic improvement was observed (23.7%), thus it would seem that the degree of hearing loss could be important in predicting benefit based on the results of the study. However due to the small population size, and the mixed results amongst the participants, it would be difficult to generalize the data to a larger population.

Within Groups, Repeated Measure Design: Auriemo, J., Kuk, F., Lau, C., Marshall, S., Thiele, N., Pikora, M., Quick, D., and Stenger, P (2009) examined the effect of using LFT on a group of ten school aged children. Hearing losses ranged from normal to moderate in the low frequencies, and sloped to severe to profound in the high frequencies. Audibility, speech recognition, fricative articulation, and subjective preference was measured in three different conditions 1) using the child's own devices, where baseline measurements were obtained 2) an advanced instrument with LFT capability disabled and 3) the same instrument with LFT enabled. Auditory verbal therapy (AVT) was also incorporated in each condition, with the exception of condition 1. Two experimental models were used in this experiment, the Widex Inteo IN9 and IN19. LFT for soft and conservational speech intelligibility was assessed at 30 and 50 dB HL input levels using non-sense syllables from the *CUNY Nonsense Syllable Test.* The *DIBELS Oral Reading Fluency* passage was used to record accuracy and fluency with connected speech. Pictures for speech testing were obtained from *Spotlight on Articulation /s/*. /S/ and /z/ phonemes were emphasized.

Nonsense Syllable Test Performance at 30 dB HL: on average, participants scored 18% for consonant identification with their own devices, 47% with the study aids, and 69% after 6 weeks of using the LFT activated devices. With the child's own devices, average scores for vowel identification was 56%, and improved to over 90% with the study devices, and after 6 weeks of using the devices with LFT activated, scores improved to 100% for vowel identification. A post-hoc analysis using paired samples t-test with a Bonferonni adjustment for multiple comparisons was performed. For consonant recognition, results showed that for both the default program and with LFT activated, scores were improved when compared to the child's current devices ($p<0.05$). The performance after three weeks of using the LFT devices showed significant improvement over the default program ($p<0.05$) and scores for the LFT trial were significantly improved after six weeks of use ($p<0.05$). For vowel scores, significant differences were observed between the study devices and the child's own devices ($p<0.05$). LFT scores were significantly better than the default setting ($p<0.05$) and significant improvements were observed after six weeks of wearing the LFT enabled devices when compared to the three week trial ($p<0.05$). Results were similar when the *Nonsense Syllable Test* was performed at 50 dB HL, but less dramatic.

Accuracy of /s/ and /z/ Production: speech production data were arcsine transformed and a repeated measure ANOVA was used to test the significance of the two within-subjects effects; speech production (reading or conversation) and aided condition (own aid, default assessment, LFT assessment 1 and LFT assessment 2). Results suggest that the effects of the speech production task ($F(1,9)=6.766$, $p=0.029$, $\eta_p^2=0.43$) and aided condition ($F(3,27)=27.727$, $p<0.001$, $\eta_p^2=0.76$) were significant. Post-hoc analysis using paired-sample t-tests with Bonferonni adjustments showed that both the default setting and the LFT setting on the experimental devices showed significant improvement when compared to the child's own devices for the reading task ($p<0.05$). 6 weeks of hearing aid use with the LFT devices also showed significant improvement when compared to the 3 week trial ($p<0.05$).

Correlation of Default Performance and LFT Benefit: consonant identification scores were plotted with the LFT program on the (y-axis) and default program on the (x-axis). Correlation was significant for both intensity levels (at 30 dB HL, $r=-0.861$; 50 dB HL, $r=-783$; $p<0.01$) where 'r' is the Pearson correlation coefficient. Improvements were greatest for children with the poorest baseline scores. These results suggest that children who perform most poorly with conventional amplification would benefit most from LFT.

According to this study, LFT provided greatest benefit to children who performed the most poorly on speech tasks at baseline. LFT was shown to improve consonant identification, perception of non-speech sounds (results not shown), and improved the articulation of the HF phonemes /s/ and /z/ when compared to CP. AVT was administered in all treatments, with the exception of the baseline where children used their own devices. Thus although there was observed improvement when LFT was enabled versus the disabled condition, it cannot be attributed to the LFT technology alone, as AVT likely played a role in conjunction with the LFT technology in improving speech recognition and production. Scores seemed to improve significantly after six weeks of use, suggesting that these devices may require a period of acclimatization, as they provide novel acoustic cues to the listener. An important finding in this small population study was that all ten of the children continued to use the study aid with LFT enabled upon study completion. Results of this study seem compelling in the promotion of LFT technology and the improvement of speech recognition in children. Appropriate statistical analysis was employed however test statistics and degrees of freedom were missing in some sections. Due to the small number of participants (n=10), it would be difficult to generalize results to a large population.

Within Subject, Crossover Design: Wolfe, Shafer, Nyffeler, Boretzki, and Caraway (2010) investigated the effect of speech recognition using NLFC technology when compared to conventional devices, on fifteen school-age children with moderate to moderately severe hearing losses. Phonak Nios BTE devices were used for this study. All participants were assessed following a 6 week trial with NLFC enabled, then following a 6 week trial with NLFC disabled. This was repeated in a two-period crossover-design to alleviate maturation effects. An aided threshold assessment for warble tones (4, 6 and 8 kHz) and phonemes /sh/ and /s/ were measured. Phoneme tokens were developed by researchers at Western University (UWO). An aided speech recognition task in quiet was used to test the child's ability to hear phonemes /s/ and /z/. The UWO Plural Test was used for this measure. Phoneme discrimination using the Phonak Logatome test measured audibility of HF target consonants surrounded by the /a/ vowel phoneme. The BKB-SIN task was used to asses speech recognition in noise, both with the NLFC enabled and disabled. A two-way ANOVA was conducted to test main effect of NLFC (enabled or disabled) and the sound field stimulus item (warble tones vs UWO phonemes). Results showed a significant main effect for the NLFC condition ($F(1, 14)=28.92$, $p<.001$, $\eta^2=.67$) and the item type ($F(4, 56)=18.93$, $p<.001$, $\eta^2=.58$). Post hoc paired testing using a Bonferroni correction was measured to determine the effect of NLFC on each stimulus item. Paired tests demonstrated a significant improvement in the NLFC-enabled condition for all items measured: 4000 Hz ($t(14)=3.48$, $p<.01$), 6000 Hz ($t(14)=4.38$, $p<.01$), 8000 Hz ($t(14)=2.66$, $p<.05$), and UWO phonemes /s/ ($t(14)=6.70$, $p<.001$) and /sh/ ($t(14)=2.81$, $p<.05$). A one-way ANOVA for speech recognition showed that scores were significantly better with NLFC enabled ($F(1,14)=25.86$, $p<0.001$), and that the effect of NLFC was large ($\eta^2=0.65$). All subjects showed some improvements with the NLFC device enabled except for 2 children. Floor effects prevented the calculation of Logatome thresholds for certain tokens when NLFC was disabled, because some participants could not discriminate HF phonemes without NLFC. Therefore tokens were analyzed individually using a one way ANOVA for the main effect of NLFC only. Performance on the Logatome test was significantly better with NLFC enabled for tokens /asa/ ($F(1, 11)=5.44$, $p<.05$, $\eta^2=.33$) and /ada/ ($F(1, 13)=5.41$, $p<.05$, $\eta^2=5.29$). No statistically significant differences were seen for tokens /afa/, /aka/, /asha/, /ata/, or /asa/ filtered at 6000Hz. There was no statistical benefit observed in using NLFC during speech in a noisy environment.

Evidence for improvement in speech test performance for the UWO Plural Test, and for phoneme recognition is suggestive based on the results of this study. Significant improvement was observed only for phonemes /s/ and /d/. Researchers note that other phonemes may not have provided a measurable effect as they were lower in frequency and sufficiently audible without NLFC active. Upon review of the frequency spectrum of these phonemes, this is not entirely accurate (Ferrand, C., 2007). Researchers also suggest that users may have needed a longer time window in order to make appropriate adjustments to the new spectral cues the children were acquiring. A follow up study to investigate acclimatization effects of the NLFC processor after 6 months of use resulted in significant improvement on the Phonak Logatome tests. Researchers in this study concluded that children with moderate to moderately severe HF hearing losses would have excellent audibility for sounds in the 8 kHz region using NLFC, although after closely reviewing the results in this study, this statement seems bold. In addition, due to the small population size, generalizing the results to a large population would require a larger sample size or further study.

Case Series, Pre-Post Test Design: MacArdle, West, Bradley, Worth, Mackenzie and Bellman (2001) studied the effects of speech recognition when frequency transposition was used as oppose to CP, when using the body worn FT-40 device. Baseline tests were performed with the children's own hearing aids, then after 48 months of use with the FT-40. All participants in the study had profound hearing losses. Children in the study ranged from ages 2.8 and 15.6 years old, and the study was initially comprised of 36 participants. A substantial drop out rate ensued. Reasons for participant dropout included ergonomics (11%); no perceived benefit from the system (11%); cosmetic reasons (17%); and subsequent cochlear implantation (30%). Only 11 children continued to wear the device for the 48 month trial. Threshold measurements were obtained with the child's own hearing aids equipped with CP, as well as with the FT-40 device. Speech perception tests were measured by using the E2L, the *Manchester Picture Test* as well as the *Manchester Junior Word List*. Speech intelligibility was based on assessments of Parker and Irlam (1995) and Dyar (1994). Ling detection and identification tests for vowels and consonants were also used. Aided soundfield thresholds with the FT-40 were significantly better at 500 Hz ($p<0.04$), 1 kHz ($p<0.019$), 2 kHz ($p<0.001$) and 4 kHz ($p <0.001$) compared to thresholds with conventional hearing aids for the participants who remained in the study. With regards to the speech tasks, a small subgroup of participants showed improvement, however maturation effects as well as extraneous factors such as the use of auditory verbal therapy for some of the participants outside the laboratory, were not taken into consideration or controlled for. Results for this study are equivocal in the support of LFT technology. Improvements could have been made in the experimental model, as there was a substantial dropout rate which was not accounted for statistically, and the study failed to control several variables that could have affected the results of the speech testing. It is also difficult to draw comparisons between the FT-40's body worn processor and current frequency transposition technology.

Counterbalanced, Within Group Repeated Measure, Modified Withdrawal Design: Glista, Scollie, Bagatto, Seewald, Parsa and Johnston (2009) evaluated multichannel NLFC using both laboratory outcomes (speech testing) and real world outcomes (the hearing aids functional performance outside the laboratory) with and without the NLFC processor activated. 13 adults and 11 children with sloping hearing losses that ranged from moderately-severe to profound participated in the study. All hearing losses were sensorineural except for one mixed loss. The prototype devices used were BTE hearing instruments similar to Phonak Savia 311 or 411. Participants were familiarized with the test battery as well as with the experimental hearing instrument with NLFC disabled. NLFC allocation to program memories of the hearing instruments was counterbalanced across participants. Data was analyzed using two different methods. Group level analysis results were completed and individual participant results were analyzed using a modified two standard deviation technique.

Group level Analysis

Speech Sound Detection: aided detection threshold for phonemes /s/ and /sh/ were measured in sound field using an adaptive version of the Ling six-sound test. A repeated measure ANOVA was completed using the processor type (CP versus NLFC) and phoneme type (/s/ or /sh/) as the within-subject variables, and the age group (adult versus child) was used as the between-subjects variable. Simple main effects for processor type as well as phoneme type were found to be significant ($F(1,22)=42.97$, $p<0.001$; $F(1,22)=6.84$, $p=0.02$). Results show that speech detection thresholds were lower for the /s/ phoneme, and thresholds were also somewhat lower overall when NLFC was enabled.

Speech Recognition: speech tasks included consonant, plural and vowel recognition. Consonant discrimination was administered using a modified version of Western University's Distinctive Features Differences Test. A repeated measures ANOVA was completed. Within-subject variables included processor type (CP vs. NLFC) and test type (consonant, plural, or vowel recognition). Age (adult vs. child) was used as a between subjects variable. Raw scores were converted to rationalized arcsine values and post-hoc comparisons were computed with a Bonferroni correction. A statistical significance was found when NLFC was used in speech recognition tasks ($t(23)=3.40$, $p=.002$; $t(23)=5.15$, $p<0.001$), as there was a significant improvement in consonant and plural identification when compared to CP with the experimental aid. A significant difference in vowel recognition was not observed.

Single Subject Results

Limits for significance were calculated for the 90th, 95th and 99th. Individual scores were obtained in the treatment phase versus the withdrawal phase. Significant change was determined to occur if performance in the treatment condition exceeded the confidence limits.

Speech sound detection: Performance improved significantly for 1 child in the 99th percentile, and for 4 children in the 90th percentile when using the device with the NLFC processor active. 1 child showed improved performance (in the 90th percentile) when using CP.

Speech recognition: With respects to the speech recognition tasks, more children showed improvement in identifying consonants and plurals when the NLFC processor was activated in their hearing device. 7 of the 11 children showed improvement in the 95th and 99th percentile range with respects to plural and consonant identification. Vowel identification was not found to be improved by the NLFC processor in this study.

This experimental design was extensive and thorough in its statistical analysis, and overall results show that children seem to benefit more from NLFC than adults during speech recognition tasks regarding consonant and plural recognition. The study also found that on average, participants performed better at recognizing HF sounds with the NLFC technology, presumably because HF cues were placed in the participant's residual auditory area. Researchers also observed that preference to NLFC, benefit and significant improvement in speech tasks was correlated to increasing HF hearing losses. In other words, individuals with sloping HF hearing losses were likely to benefit more from the NLFC technology. It should be noted that this general trend was not true for all the child participants. A larger sample size would be beneficial to adequately generalize the results of this study.

Conclusions

Aforementioned studies seem to show that FL improves HF phoneme identification during speech recognition tasks when compared to CP. It should be mentioned however, that Wolfe (2010) and his colleagues found no statistically significant differences for phoneme tokens /afa/, /aka/, /asha/, /ata/, or /asa/ filtered at 6000Hz in their phoneme recognition tasks when using FL. Although many participants showed improvements in HF phoneme identification, not all participants exhibited improved benefit. Some participants showed no change with FL active, while others showed improvement from using the experimental aid instead of their own device, which was still only equipped with CP during the measurements. A combination of adhering to best practice guidelines as well as a technological upgrade likely played a role in the improvements exhibited when a child used the study hearing device over their own.

The studies above have generally concluded that benefit from FL technology increased when hearing losses became more severe. All studies, but that conducted by Miller-Hansen (2003) have generally found that children with sloping HF hearing losses show increased benefit from FL technology. Miller-Hansen (2003) and her colleagues found that out of the 7 children who showed benefit, 4 had HL with flat configurations, thus this study does not follow the trend of marked improvement with increased HF loss, or a sloping audiometric configuration. With respects to vowel identification, Glista (2009) and her colleagues did not find improved benefit when using NLFC technology over CP, while Auriemo (2009) and his colleagues found significant improvement in vowel identification with LFT technology.

Overall, the general findings of the studies are suggestive in nature, as although some children showed marked improvement with FL technology, many did not. Above studies also suggest that children who perform poorly with CP, could show improved benefit with FL technology. When patient preference with regards to the sound of FL technology was questioned, many of the participants reported preferring the FL technology, or liking the sound quality equally to CP. This is an important finding as these devices inevitably add distortion to the acoustic signal, and sound quality is important in the acceptance of hearing aid technology.

Future research on FL should work to include larger population studies, as results from these small populations do not show compelling evidence to support the use of this technology on the general population, and should be used on a patient-to-patient basis.

Clinical Implications

Evidence seems to suggest that FL technology can improve recognition of HF phoneme identification and other environmental cues when compared to CP. As conventional hearing devices often do not provide adequate HF gain past 5kHz (Stemalchowicz, P., et al., 2004), FL is a viable alternative for those who may not be receiving important HF acoustic cues. Overall, the evidence to support this technology is suggestive, in that some children show no benefit from FL technology. The marked improvement exhibited in others should not be overlooked clinically. Children who perform worse with CP might show more benefit with FL, and this information should be considered in the clinic. FL should be allocated on a patient-to-patient to basis with caution from the audiologist; and should be fit, and verified, based on best practice guidelines.

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