Critical Review: Effects of multi-channel, nonlinear frequency compression on speech perception in hearing impaired listeners with high frequency hearing loss

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The purpose of this critical review is to evaluate the effect(s) of multi-channel, nonlinear frequency compression (NFC) on the speech perception of individuals with high frequency hearing impairment. Study designs include one single group modified withdrawal with repeated measures and four single groups with repeated measures. Overall, the current literature provides evidence to demonstrate that NFC improves speech perception when used with fitting and verification measures that align with best practice standards as well as individualized patient settings. Future research needs to be completed and include greater sample sizes, the inclusion of full methodologies, and increased use of hearing instrument verification.

Introduction

Currently, individuals with high frequency hearing loss are at a significant disadvantage due to current limits of hearing instrument technology. The majority of hearing instruments currently available on the market do not provide sufficient high frequency gain to ensure audibility of high frequency consonants, specifically fricatives such as /s/ and /sh/. These speech sounds are important markers of plurality and are also less intense in comparison to other consonants due to having less energy. These sounds are particularly important for children who have not yet learned grammatical rules and articulation of sounds (Simpson, 2009).

Providing amplification to individuals with significant high frequency hearing loss continues to be controversial. Studies have found limited or reduced speech recognition benefit when providing high frequency audibility to individuals with severe hearing impairments, possibly due to the limitations of the functional abilities of the auditory system (Ching et al, 1998, 2001; Hogan & Turner, 1998). Recent studies have found that providing high frequency audibility to these listeners works to significantly improve speech understanding, even in noisy listening environments (Plyler & Fleck, 2006; Turner & Henry, 2002). Therefore, while providing high frequency gain through the use of conventional amplification to these listeners remains controversial, there is a significant need for processing strategies that shift/lower/compress these inaudible high frequency regions into more audible regions with greater residual hearing of the individual with the hearing impairment.

NFC is one such strategy that has been recently introduced by Phonak. NFC reduces the bandwidth of the speech signal by applying increasing amounts of frequency lowering to relatively high input frequencies (Sekimoto & Saito, 1980). Multi-channel refers to NFC occurring in a hearing instrument with two or more channels in the frequency domain. This allows for the channels to be manipulated separately, with current technology implementing NFC in the high frequency channel, allowing higher frequencies to be compressed in greater amounts while lower frequencies remain unchanged. This preserves a more natural sound quality, vowel intelligibility and no overlap in frequency information provided to the listener (Simpson, 2009). The frequency below where the compression is applied is referred to as the cut-off frequency, and the amount of compression applied to the signal, or how much the signal is squeezed into a smaller bandwidth, is defined as the compression ratio.

Due to the recent application of this processing, limited research exists regarding its efficacy as it relates to speech perception outcomes of individuals or appropriate fitting strategies regarding this technology. Therefore, a critical review of the literature will provide clinicians with an improved understanding of the technology, its appropriate applications, and its effect(s) on speech perception of hearing impaired individuals.

Objectives

The primary objective of this literature review is to critically evaluate the current literature on NFC and determine its effect(s) on speech perception of hearing impaired individuals with high frequency hearing loss. A secondary objective is to determine an evidence-based approach to the prescription and fitting of this type of technology.

Methods

<ins>Search Strategy</ins>

Computerized databases including CINAHL, SCOPUS, MedLine, PubMed, PsychINFO, Sociological Abstracts, and Google Scholar were searched using the following search strategy: [(frequency comp*) OR (frequency transp*) OR (hearing loss, high frequency)] AND [(speech recognition) OR (speech perception) OR (speech detection) OR (speech reception)] AND [(amplification) OR (hearing instrument) OR (hearing aid)]. The search was limited to the English language and human subjects. Reference lists in the obtained journals were also searched for any additional relevant articles.

Selection Criteria

Studies included in this critical review were required to investigate the effects of current NFC technology on the speech perception outcomes of individuals with high frequency hearing loss. No limits were set on the type of speech perception outcome or on the demographics of the research participants (age, gender, race, or socioeconomic status).

Data Collection

A review of the literature yielded five articles consistent with the selection criteria: one single group modified withdrawal with repeated measures design and four single groups with repeated measures design, all of which provide a grade III level of evidence (Dollaghan, 2007). The intent of this critical review was to evaluate all current literature available regarding NFC and its effect(s) on speech perception, resulting in the need to include non-peer reviewed articles at this time.

Results and Discussion

Single Group Modified Withdrawal with Repeated Measures: Glista, Scollie, Bagatto, Seewald, Parsa and Johnson (2009) evaluated the efficacy of NFC in children and adults with high frequency hearing loss by using both tested laboratory outcomes (speech recognition) and real world outcomes (functional performance and preference). They looked at 24 hearing impaired adults and children with sloping high frequency hearing losses ranging from moderately severe to profound in the better ear.

Participants were familiarized with the study aid programmed with conventional processing (CP) and NFC. They were also familiarized with the outcome test battery. Counterbalancing of the allocated NFC program across participants with single and double blind outcome measures occurred. The devices (similar to a Phonak Savia 311 or 411) were fitted using the DSL v5.0 prescriptive methodology and age-dependent prescriptive targets. Real-ear to coupler difference measures were obtained and electroacoustic characteristics were verified using the Audioscan Verifit. Individual cut-off frequencies and compression ratios were determined based on individual preference and verified to ensure comfort, audibility and no confusion of speech sounds due to overlapping signals from frequency compression.

The test battery was composed of four objective tests: aided speech sound detection using an adaptive version of the Ling six-sound test, consonant recognition using a modified version of the University of Western Ontario Distinctive Features Differences test, plural recognition, and vowel recognition. All speech tests used recorded stimuli to reduce variability between tests and participants. Presentation level was varied to accommodate individual hearing losses with a minimum testing level of 50 dB SPL used, with increases up to a level of 65 dB SPL for some participants.

Both group-level and individual-level results were analyzed using single subject design methods due to small sample size and variability of testing levels. Contributing factors to individual's test results were explored using multiple regression analysis.

Group Level Analysis

Speech Sound Detection: At the group-level analysis a repeated measures ANOVA was completed with processor type (CP versus NFC) and phoneme (/s/ versus /sh/) as within subject variables, and age group (adult versus children) as a between subjects variable. Significant simple main effects were found for the processor type as well as the phoneme type [$F(1,22)=42.97$, $p<.001$; $F(1,22)=6.84$, $p=.02$]. Aided thresholds were somewhat lower when NFC processing was activated for both the /s/ and /sh/ phonemes, indicating that NFC tended to improve high frequency audibility.

Speech Recognition: A repeated measures ANOVA was completed with processor type (CP versus NFC) and test type (consonant, plural, or vowel recognition) as within subject variables and age group (adults versus child) as a between subjects variable. Results suggest a significant interaction between test and processor type. A Bonferroni correction was employed; analyses indicate that scores were significantly higher with NFC activated for the consonant and plural recognition tasks [$t(23)=3.40$, $p=.002$; $t(23)=5.15$, $p<.001$]. On average, high frequency speech recognition scores increased with the use of NFC, while vowel perception did not change significantly.

Single-subject results: Scores obtained in the treatment versus withdrawal phase were analyzed using confidence limits for performance change. Limits were calculated for levels of significance equivalent to the 90^{th}, 95^{th}, and 99^{th} percentiles.

Speech Sound Detection: Results improved significantly for twelve individuals using NFC (five at 90%; four at 95%; three at 99%) and improved significantly for two individuals using CP (one at 90%; and one at 95%). Results across the group were variable, indicating that NFC may not benefit everyone.

Speech Recognition: Confidence limits for significant change on the consonant recognition task, plural recognition task, and vowel recognition task were calculated. Five adult individuals reached significance for at least one of the three measures; one for consonants at 95%; four for plurals: two at 90% and two at 95%, and one for vowels at 90%. Greater improvement was seen in the children for a greater number of tasks. Seven children had significantly improved scores on at least one of the three measures; all seven had significant improvement on plural recognition for at least the 95% CI and three of the seven also had significantly improved consonant recognition for at least the 95% CI.

Benefit when using NFC processing on plural recognition and detection tasks differed between the participants. Specifically, those with a greater amount of high frequency hearing loss occurring at higher frequencies derived greater NFC benefit. NFC was found, on average, to improve high frequency audibility while not significantly changing vowel sounds. Overall, younger participants were found to derive better overall benefit from NFC and preferred the processing to conventional amplification.

Overall, this study demonstrated improved speech perception of high frequency sounds, more so for children than for adults. Complete methodologies, individual and group level analysis, counterbalancing, single and double blinding, and the use of high frequency specific tasks all contribute substantial support regarding the use of NFC to improve high frequency audibility and speech perception of individuals with high frequency hearing loss.

Single Group with Repeated Measures # 1: Wolfe, Caraway, John, Schafer and Nyffeler (2009) examined the effects of NFC in children with varying degrees of sensorineural hearing loss (from mild to moderately severe). Preliminary study results are available for 12 children between the ages of 5 and 13 years old. At the time of writing, baseline audiological testing had been obtained while using the child's own bilateral digital hearing instruments and included: aided thresholds at 4, 6, and 8 kHz warble tones plus phonemes /sh/ and /s/, and percent correct plurals recognition with the UWO plural test. The use of the child's own hearing instruments introduce a bias as not all participants have the same electroacoustic characteristics in their individual hearing instruments. The researchers also had the children compare their old hearing instruments with the new ones, which likely have superior technology due to advancements.

Subjects were fitted bilaterally using the DSL v5.0 prescriptive methodology with test hearing aids (Phonak Nios micro). Audibility was checked informally to verify children could identify /sh/ and /s/ from 12 feet away at an average conversational level of speech. Verbal feedback from children was used to determine the NFC starting parameters that yielded acceptable sound quality. 15 minutes after hearing instruments were fitted, a subset of the participants that had NFC enabled were given the UWO Plural Test to get insight into initial benefits of NFC compared to the child's baseline measures with their own digital hearing instruments.

Initial results were positive according to subjective comments and average recognition of plural words. Many children reported better speech understanding, with an initial average improvement of approximately 30% on UWO Plural Test scores. A paired t-test indicated the difference in average performance between children's own aids and test devices with NFC enabled was statistically significant ($p=.002$). Individual performance varied, with some individuals demonstrating greater improvement than others.

While this study is still preliminary in its findings, it does demonstrate evidence to support NFC benefit. However, the chosen statistical analyses provide a low level of evidence; conclusions made from findings are therefore limited. Small sample size, lack of information regarding electroacoustic characteristics of own hearing instruments, comparisons to own hearing instruments, incomplete explanation of methodologies, no discussion of testing levels and the variability of hearing losses across subjects combine to reduce the claims of improved high frequency audibility at this time. Confounds of this study make it difficult to interpret the results and NFC cannot be attributed as the sole cause for improved speech perception.

Single Group with Repeated Measures # 2: Nyffeler (2008) examined the effects of multi-channel NFC and its ability to boost speech intelligibility in individuals with high frequency hearing loss. This study looked at eleven participants with moderately severe to profound sensorineural hearing loss. Subjects were fitted binaurally with prototype Naida Ultra-power hearing aids with NFC turned on. Subjective comparisons of participants' own hearing instruments versus newly fitted conventional hearing instruments are provided.

A non-significant improvement in speech reception threshold was found. However when combined with subjective findings the author felt a significant benefit from the Naida with NFC was found over the children's own hearing instruments. Subjective measures also found an acclimatization effect over a short period of time. Fricatives were reported to sound different to the participants, with sound quality ratings improving over time. Participants also rated their own voice sound quality as more pleasant with NFC on.

This article demonstrates support for NFC benefit, however due to confounds within the study, the results should be interpreted with caution. No statistical analysis results were reported throughout the article, which in itself does not provide any evidence for the use of NFC. Comparison of own devices, along with lack of electroacoustic characteristics of the subjects own devices, poor and incomplete explanation of methodologies, along with a lack of sensitive testing materials are all contributing confounds which reduce the evidence of this study to provide support for NFC benefit.

Single Group Pre-Posttest # 3: Simpson, Hersbach and McDermott (2005) evaluated the performance of a multi-channel NFC device by comparing speech understanding abilities of 17 hearing impaired listeners with NFC enabled and disabled. This study looked at 17 hearing impaired adults with moderately severe sensorineural hearing losses. A counterbalanced sequence of testing was applied to minimize acclimatization over time.

Hearing instruments (Phonak Supero 412) were fitted using equal loudness level measurements and the Phonak fitting software to derive an initial fitting suggestion. This was modified when necessary based on subject's feedback. Cut-off frequencies were employed based on the subject's audiogram and fine-tuned according to preference. A compression ratio of 2:1 was applied to all participants. A trial period of 4-6 weeks was allowed for the new devices. Consonant-vowel nucleus-consonant monosyllabic recorded word lists were presented to subjects wearing the instruments with both the CP and NFC schemes enabled at an average level of 55-60 dBA.

Across the subjects, speech recognition scores were compared with the two hearing aid processing schemes by means of a two-factor ANOVA. A statistically significant improvement was found for NFC over CP ($p<.001$) for phoneme, consonant, fricative, and vowel scores. A significant interaction term was found, indicating that individual subjects performed with the different schemes in different ways. Therefore, individual subject's data was analyzed separately through pair-wise comparisons using the Holm-Sidak test for each subject, and for each type of score (phonemes, consonants, fricatives, and vowels). Of the 17 subjects, eight obtained a significant ($p<.05$) phoneme score increase with the experimental NFC scheme, eight subjects showed no significant change in scores, and one showed a significant decrease in score with NFC. On average, the group showed a statistically significant improvement of 6% for phoneme scores.

The NFC scheme provided superior perceptual performance, on average, to the performance of the CP program for words presented at a moderate level in quiet conditions. There is also evidence to demonstrate that the positive outcome of this group did not come from high frequency audibility alone as a subset of participants completed the test battery with a high frequency gain program. These results are encouraging regarding those hearing impairments where conventional hearing instruments are limited in their ability to provide adequate audibility in the high frequencies. Reported improvement in fricative sounds suggests that the experimental scheme provided additional high frequency speech cues. NFC provided some beneficial speech cues for identifying this group of consonants.

This study demonstrates an improvement in subject's speech perception abilities with NFC over CP, and not simply due to improved high frequency gain. However, the use of a Manufacturer specified fitting strategy, no explanation of electroacoustic characteristics of the test aids, and no discussion of blinding are all confounds which detract from the results found in this study.

Single Group with Repeated Measures #4: Simpson, Hersbach and McDermott (2006) examined the performance of an NFC device in quiet and noisy conditions by comparing speech-understanding abilities of seven hearing impaired listeners with steeply sloping hearing losses. Devices (Phonak Supero 412) were fitted by making use of equal loudness level measurements and an initial fitting suggestion based on the NAL-NL1 prescription with fine-tuning as necessitated by the participant. The devices were worn 4-5 weeks prior to the commencement of the study. The cut-off frequency and compression ratios were automatically set for each participant and only adjusted if subject dissatisfaction occurred.

Word recognition in quiet lists were composed of consonant-vowel nucleus-consonant (CNC) monosyllabic word lists. Consonant recognition in quiet tasks were made up of vowel-consonant-vowel (VCV) utterances with some emphasis on higher frequency consonants using a closed set procedure. All of the above stimuli were tested using recorded speech with the volume control on each subject's conventional hearing device set so that speech at a normal conversational level in quiet would be comfortably loud.

Word and consonant recognition in quiet: For the CNC word task, the mean phoneme scores obtained by each subject with their conventional hearing devices and with the NFC device were compared by means of a two-factor ANOVA, with no statistically significant difference found between the schemes. No significant interaction between the scheme and subject factors were reported. Mean percentage correct scores for each subject with both schemes for the consonant test was compared with a two-factor ANOVA. No statistically significant differences were found between the NFC and the CP devices ($p=.186$), although a significant interaction term was present. Therefore, subject data was analyzed separately with pair-wise comparisons using the Holm-Sidak method. This difference was only statistically significant for one subject who performed better with the NFC device over the CP (t=2.736, p=.011), and two subjects who did significantly poorer with the NFC over the CP device (t=3.719, p<.001; t=2.177, p=.038).

The authors concluded that listeners with steeply sloping audiograms received limited benefit from the experimental NFC scheme. Many of the subjects presented with very severe hearing losses, consistent with significant dead regions throughout the cochlea; however, no dead region testing was performed in this study. The use of NAL-NL1 as a fitting strategy for these individuals likely reduced high frequency gain, possibly even with NFC enabled. Cut-off frequencies were not employed based on individual preference, but set to a strong setting and scaled back if subject dissatisfaction occurred. No discussion of verification methods were presented in this article, which reduces clinician knowledge of what the subject is actually hearing. Therefore, while this study does not support the use of NFC for subjects with steeply sloping audiograms, confounds discussed above reduce the ability to draw conclusions from these findings for individuals with steeply sloping audiograms at this time.

Conclusion/Recommendations

Four of the five studies examined in this review suggest NFC benefit in both adults and children with high frequency, sensorineural hearing impairments. In general, reviewed studies included small sample sizes, with some studies presenting incomplete methodologies (i.e., lack of discussion of electroacoustic characteristics of hearing instruments, which could contribute to benefit or lack of benefit derived with NFC). Two of the studies did not provide sufficient statistical analysis. For these reasons, at this time NFC should be used cautiously with individualized settings, the use of speech perception testing and verification of settings in order to guide hearing instrument fittings.

A general trend with this technology is that individuals using NFC have speech perception benefit, especially in regards to plurality and high frequency fricative sounds such as /s/ and /sh/. Finally, there is a large degree of individual variability among users of this technology and therefore, NFC should be fit on an individual basis.

In order to substantiate claims of improved speech perception, future research should address the current limitations in the above studies. By using a greater number of subjects, including full methodologies, using evidence-based fitting protocols/formulas, matching electroacoustic characteristics of hearing instruments, verifying electroacoustic characteristics of the test hearing instruments, and providing more detailed statistical analyses, experimental procedures would be improved and supply greater reliability and validity to the current body of literature.

Clinical Implications

At this time, the pros and cons of implementing NFC should be carefully weighed on a patient-to-patient basis. More current research with appropriate experimental procedures and adequate statistical analysis strongly demonstrates an improvement in speech perception, especially in children, with the use of NFC. However, when looking at the literature as a whole, there are inconclusive results regarding the use of NFC, likely due to inherent confounds found within the studies. This current review promotes the use of NFC when clinicians closely following appropriate fitting protocols, prescribe settings on an individual basis and verify the electroacoustic characteristics of the hearing instrument to guide the fitting.

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