

Utility of Nonlinear Frequency Compression in Children with Severe to Profound Hearing Loss

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Abstract

A major difficulty faced by children with severe to profound hearing loss is the limited benefit from conventional amplification, particularly, at high frequencies. This puts them at a disadvantage of not perceiving high frequency information which is essential for speech and language development. The present study aimed to investigate the utility of nonlinear frequency compression (NLFC) in children with severe to profound hearing loss who have limited or no benefit from high frequency amplification. Two groups who differed in their 4 kHz aided threshold were considered. Group 1 had 12 participants whose aided threshold at 4 kHz with their own hearing aid was 60 to 80 dBHL. Group 2 had ten participants whose aided threshold at 4 kHz with their own hearing aid was >80 dBHL. Detection thresholds for tones and for Ling's six sounds, identification of Ling's six sounds, and speech identification scores in quiet and in noise were obtained with and without NLFC. Results indicated a benefit from NLFC for aided detection thresholds at 500 Hz, 2 kHz and 4 kHz for Group1, whereas Group 2 improved significantly only for 2 kHz. NLFC proved beneficial for improving aided awareness thresholds and identification of high frequency speech sounds for both groups, with Group 1 obtaining more benefit compared to Group 2. It can be concluded that NLFC can be beneficial for children with severe to profound loss and that it can be a viable amplification option in this population as in children with sloping hearing loss.

Key words: Nonlinear frequency compression, High frequency sounds, Severe-profound hearing loss

Introduction

In order to make high frequency speech cues available for persons with hearing loss, the concept of lowering the high frequency information into low frequency regions was invented (Turner & Hurtig, 1999). Frequency transposition and frequency compression technology are the two main types of frequency-lowering technology commonly available today.

Nonlinear frequency compression (NLFC) is a recent frequency lowering method, where signal components above a cut-off are compressed in frequency in addition to providing amplification. Signal components below a cut-off frequency are amplified with appropriate frequency shaping and amplitude compression, but without frequency shifting.

Consequently, a wide range of high-frequency input signals results in a narrower range of output signals. A possible advantage of the scheme is that there is no spectral overlap between the shifted and un-shifted signals. A disadvantage of this scheme is that it does not preserve frequency ratios for those high frequencies that are compressed. It is a possibility that, with NLFC the perception of certain sounds, such as music, may be affected adversely (Simpson, Hersbach & McDermott, 2006).

Several studies have shown benefits of NLFC in adults (Simpson et al., 2005; Boretzki & Kegel, 2009; Simpson et al., 2006) and comparable results have been found even in children. Research with NLFC in children focuses on varying degrees of sloping hearing losses ranging from mild to moderately severe and moderately severe to profound (Glista et al., 2009; Glista, Scollie, Polonenko & Sulkers, 2009). The results have been found to be favourable for these children in terms of improvement in speech recognition measures and detection thresholds of high frequency tones and fricatives.

Further, NLFC has been found to be beneficial for speech identification in the presence of noise in adults with sloping as well as severe to profound hearing loss (Simpson, Hersbach & McDermott 2006; Bohnert, Nyfeller & Keilmann, 2010). In children, studies investigating benefit of NLFC in noise have found mixed results. Wolfe, John, Schafer, Nyfeller, Boretzki & Caraway (2010) evaluated NLFC in the presence of noise in 15 children with a mild to moderately severe sloping loss after a period of acclimatization of 6 weeks. The speech sound recognition improved with NLFC. However, the speech perception in noise did not show any significant benefit with NLFC. It was suggested that the high frequency noise components might have been lowered along with the speech signal and thus led to no improvement with NLFC.

A follow-up study by Wolfe et al., (2011) investigated the same measures used in the previous study in

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children after a period of six months of NLFC use showed an improvement in speech perception in noise. This finding was discussed with respect to acclimatization effects whereby children may have required prolonged time to derive optimal benefits from NLFC. However, a study by Helm (2010) did not show improvement in noise in all the children who were tested.

Though the use of NLFC has been evaluated in children with varying degrees of sloping hearing losses (Glista et al., 2009a, b), children having severe to profound hearing loss across speech frequencies have not been evaluated with NLFC. Many a times, children with severe to profound hearing loss show only limited or no benefit from high frequency amplification even with maximum gain available (Hogan & Turner, 1998). Further, increasing gain at higher frequencies would bring about feedback issues. As a result, they often miss out on high-frequency components of speech, such as consonant sounds, and have difficulties understanding speech especially in background noise. In addition, high frequency information is especially essential for children as it is necessary to use these cues to learn articulation of sounds (Simpson, 2009). Hence, it is needed to find if NLFC would benefit the children with severe to profound hearing loss who have limited or no benefit from amplification at high frequencies, like the children with sloping hearing losses.

Further, studies on perception in noise with NLFC in children with sloping losses of varying degrees have given mixed results (Helm, 2010; Wolfe et al., 2010; Wolfe et al., 2011). In addition, no studies to our knowledge have investigated benefit of NLFC for perception in noise in children with severe to profound losses. It would be beneficial to know the effects of NLFC in quiet as well as in the presence of noise in children with severe to profound hearing loss, many of whom, generally as observed in the clinic have limited or no benefit with amplification at high frequencies.

In addition, NLFC was found to have different effects depending on the high frequency thresholds and slope of audiogram (Simpson, Hersbach, & McDermott, 2006; Glista et al., 2009). Hence, we were interested to study if NLFC has varied effects depending on the aided thresholds at 4 kHz within the severe to profound hearing loss group.

The aim of the study was to compare the performance with and without NLFC in two groups of children who differed in their aided threshold at 4 kHz, for the following Task-Detection thresholds of frequencies from 500 to 4 kHz in quiet, Awareness thresholds of Ling's six sounds, Identification of Ling's six sounds

and Identification of words in quiet and in presence of noise at +5 dB SNR.

Method

Selection of participants: Routine audiological tests were conducted including puretone audiometry, speech audiometry, immittance evaluation and aided audiogram to select participants for the current study. Puretone audiometry was carried-out to track air conduction thresholds from 250 Hz till 8 kHz and bone conduction thresholds from 500 Hz till 4 kHz at octave frequencies. This was carried out with a calibrated Madsen Orbiter 922 diagnostic audiometer with TDH 39P supra aural headphones and B-71 bone vibrator. Speech detection threshold and Uncomfortable loudness level for speech were also determined.

Tympanometry and acoustic reflex assessment using standard procedures were carried-out. A calibrated GSI-Tymp Star Middle Ear Analyzer (Version 2) was used for this purpose.

Sound field aided audiogram was obtained for individual ears with participant's own hearing aid, using a calibrated Orbiter 922 diagnostic audiometer with two Martin Audio C115 loudspeakers. Aided audiogram was obtained using conditioned responses at octave frequencies of 500 Hz, 1 kHz, 2 kHz and 4 kHz. Along with this, awareness thresholds and identification of Ling's six sounds were also obtained.

Children selected for the present study had bilateral severe to profound sensori-neural pre-lingual hearing loss with aided threshold out of speech spectrum, at audiometric frequency of 4 kHz. It had to be above 60 dBHL. They could not identify /s/ and /ʃ/ sounds at 40 dBHL. All the participants had the ability to perform auditory identification task (closed set). The participants were either Kannada or Malayalam speakers. Selected participants were between 4 and 11 years of age. All of them had atleast two years of experience of hearing aid (Digital BTE) usage.

Participants with or a history of neurological, middle ear disorders or mental retardation were excluded. Children who did not have adequate skills to perform the closed set identification task for the experiment were also excluded. The participants were grouped into two groups based on the aided detection threshold at 4 kHz. Though they were grouped based on the aided threshold at 4 kHz, all the children in Group 2 had poorer thresholds at all frequencies than the children in the Group 1. Group 1 had participants whose aided threshold at 4 kHz with their own hearing aid was 60 to 80 dBHL. 12 ears satisfying these criteria were

included in Group 1. The participants' age ranged from 5 to 11 years. Group 2 on the other hand had participants whose aided threshold at 4 kHz with their own hearing aid was >80dBHL. Ten ears satisfying these criteria were included in Group 2. The participants' age ranged from 4 to 9 years. *Stimulus Material:* The speech identification test for Kannada speaking children developed by Vandana (1998) and Picture Test of Speech Perception in Malayalam developed by Mathew (1996) were used to assess speech identification ability of the children. The tests have two lists of 25 bisyllabic words each and also, have two more lists which consist of the same words as the first list but in a randomized order. It was administered as a closed set test. For each stimulus word the picture book had four choices.

Procedure: After grouping the selected participants into the appropriate group, actual experiment was carried out. For this, a digital BTE hearing aid which had the feature of NLFC was used. This could be manipulated by means of a slider which changes the strength parameter of frequency compression. The strength parameter includes cut-off frequency and compression ratio. The cut off frequency ranges from 1.5 to 6.0 kHz and compression ratio varies from 1.5:1 to 4:1. Increasing the strength parameter leads to decrease in the cut off frequency and an increase in the compression ratio and vice-versa.

The BTE was connected by means of a Hipro to the personal computer in which the iPFG 2.5a software was installed. Client details were entered in the software. DSL i/o prescriptive formula was used to calculate the target gain and initial fit was applied to match the gain of the hearing aid to target gain curve. Adequacy of gain was ensured by routine hearing aid evaluation.

In order to evaluate NLFC, in the first program (P1) of the hearing aid, NLFC settings were disabled and in the second program (P2), NLFC settings were enabled. Both the programs had the same gain and frequency response settings. To determine the strength of frequency compression, child's detection thresholds of speech sounds /s/ and /j/ were established. The strength of frequency compression was changed till best detection thresholds for /s/ and /j/ were achieved. All other special features like noise reduction strategies, directional microphone settings in the hearing aid were disabled. The volume control was disabled and Tac tronic switch for selecting program was enabled.

Testing for each participant was conducted with these two programs of the hearing aid, using a calibrated

Orbiter 922 diagnostic audiometer with two Martin Audio C115 loudspeakers at 45° angles at 1m distance. Aided detection thresholds for warble tones at frequencies from 500 Hz to 4 kHz, with and without NLFC was estimated using the modified Hughson-Westlake method. Awareness threshold of Ling's six sounds (/a/, /i/, /u/, /s/, /j/, /m/) with and without NLFC was also obtained. Identification of Ling's six sounds with and without NLFC was done at 40 dBHL. The child was asked to indicate the correct sound by pointing to the written script.

Speech identification scores in quiet and noise with and without NLFC was measured by closed set task of picture pointing, using the standardized word lists and the picture book. This was done in quiet by presenting speech at 40 dBHL from a loud speaker on the aided side. For obtaining speech identification score in noise, the speech and the speech noise were presented from two different loudspeakers (kept at 45° angle) at +5 dB SNR. The child was instructed to point to the picture depicting the word said by tester. Each correctly identified word was given a score of one. The order of testing with the two programs was randomized across the participants, such that half of the children were tested with P1 first and other half with P2 first.

Results

Comparison of detection thresholds for tones with and without NLFC

Comparison of detection thresholds at 500 Hz, 1 kHz, 2 kHz, and 4 kHz with and without NLFC in Group 1:

It was found that the mean thresholds at all frequencies are better with NLFC compared to No NLFC condition in Group 1. From Table 1 it can be observed that with NLFC, the improvement in threshold is greater at 4 kHz. The results of Paired t-test also revealed a significant difference for thresholds at 500 Hz, 2 kHz ($p < 0.05$) and 4 kHz ($p < 0.01$) between NLFC and no NLFC conditions. However, there was no statistically significant difference for thresholds at 1 kHz ($p > 0.05$) between the two conditions.

Comparison of detection thresholds at 500 Hz, 1 kHz, 2 kHz, and 4 kHz with and without NLFC in Group 2:

The detection threshold for 4 kHz was analysed separately in Group 2, as seven ears out of the total 10 ears, had no measurable thresholds at 4 kHz even at maximum limits of the audiometer in the no NLFC condition. The thresholds at 500 Hz, 1 kHz and 2 kHz were analysed using Paired t-test, while the threshold at 4 kHz was analysed using Wilcoxon Signed Rank Test.

Table 1: Results of Paired t- test for comparison of aided detection thresholds at 500 Hz, 1 KHz, 2 KHz and 4 KHz with and without NLFC in Group 1

Frequency	Condition	Mean (dB HL)	S.D.	t
500 Hz	No NLFC	35.41	4.98	2.345*
	NLFC	33.75	4.33	
1 kHz	No NLFC	35.83	7.33	1.149
	NLFC	34.58	7.52	
2 kHz	No NLFC	45.41	7.21	2.691*
	NLFC	41.66	5.36	
4 kHz	No NLFC	69.58	8.10	8.69**
	NLFC	53.75	7.11	

Note: * - p <0.05, **-p <0.01

Table 2: Results of Paired t-test for comparison of aided detection thresholds at 500 Hz, 1 kHz, and 2 kHz with and without NLFC in Group 2

Frequency	Condition	Mean (dB HL)	S.D.	t
500 Hz	No NLFC	37.50	7.16	1.17
	NLFC	35.50	7.24	
1 kHz	No NLFC	40.50	8.64	1.76
	NLFC	37.50	5.89	
2 kHz	No NLFC	49.50	6.43	4.12*
	NLFC	43.50	7.47	

Note *-p <0.01

It is evident from Table 2, that the detection thresholds are slightly better in all frequencies with NLFC than without NLFC, even in Group 2. However, results of Paired t-test, revealed a significant difference only for 2 kHz (p<0.01) between NLFC and no NLFC conditions. However, there were no significant improvements in thresholds for 500 Hz and 1 kHz (p>0.05).

The results of Wilcoxon Signed Rank test, given in Table 3, revealed no significant difference in detection thresholds at 4 kHz (p>0.05). This could mainly be due to the limited number of ears which were analyzed.

Table 3: Results of Wilcoxon Signed Rank test for comparison of threshold at 4 kHz with and without NLFC for Group 2

Frequency	Condition	Mean (dB HL)	S.D.	Z	p
4 kHz	No NLFC	85.00	5.00	1.604	0.109
	N= 3				
	NLFC	62.14	12.86		
	N=7				

Subjective analysis of the revealed that out of the total ten ears, seven ears obtained better thresholds at 4 kHz with NLFC, when compared to that of no NLFC condition. Thus, even though there was no statistically significant difference, it could be noted that there is an improvement in threshold for seven ears with NLFC at 4 kHz.

Comparison of thresholds at 500 Hz, 1 kHz, 2 kHz, and 4 kHz between the two groups: The detection threshold at 4 kHz was analyzed separately, using Mann Whitney U test, due to the limited number of ears with measurable thresholds at this frequency in Group 2.

Table 4: Aided detection thresholds (in dBHL) at 4 kHz with and without NLFC in the ten ears of Group 2

Condition	S1	S2	S3	S4	S5	S5	S7	S8	S9	S10
No NLFC	NR	90	NR	80	NR	NR	NR	NR	NR	85
NLFC										
NLFC	80	75	55	45	50	65	NR	NR	NR	65

Note: NR- No response

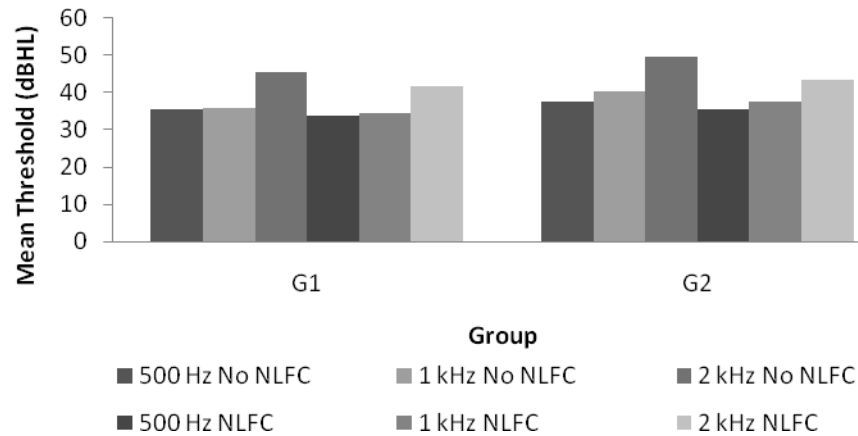


Figure 1: Mean thresholds for 500 Hz, 1 kHz and 2 kHz with and without NLFC across two groups

Table 5: Results of MANOVA comparing Group 1 and Group 2 for detection threshold at 500 Hz, 1 kHz, and 2 kHz with and without NLFC

Statistical parameter	No NLFC			NLFC		
	500 Hz	1 kHz	2 kHz	500 Hz	1 kHz	2 kHz
F (1, 20)	0.644	1.879	1.924	0.492	0.992	0.448
p	0.432	0.186	0.181	0.491	0.331	0.511

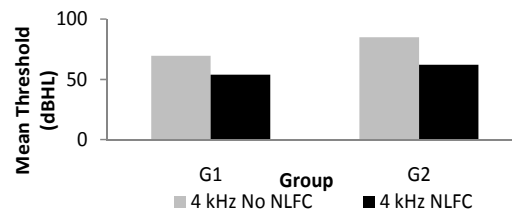


Figure 2: Mean thresholds for 4 kHz with and without NLFC across Group 1 and Group 2.

Table 6: Results of Mann Whitney U test comparing Group 1 and Group 2 for aided detection threshold at 4 kHz with and without NLFC

Statistical parameter	4 kHz No NLFC	4 kHz NLFC
Z	2.421	1.413
p	0.015 *	0.158

Note. *- p < 0.05

MANOVA was done to compare the aided detection thresholds at 500 Hz, 1 kHz and 2 kHz between Group 1 and Group 2. Results given in Table 5 revealed no significant difference between the groups across 500 Hz, 1 kHz and 2 kHz with and without NLFC ($p > 0.05$).

On the other hand, threshold at 4 kHz between the two groups was found to be different at 95% confidence in

the no NLFC condition ($|z| = 2.421$, $p < 0.05$). However, the groups did not differ for threshold at 4 kHz with NLFC [$|z| = 1.413$, $p > 0.05$]. This indicates that NLFC brought about same improvement at 4 kHz for both groups, even though Group 2 children had poorer aided thresholds. However, from Figure 2 it can be seen that Group 1 has slightly better thresholds for 4 kHz threshold with NLFC than Group 2, though it is not statistically significant.

Table 7: Results of Paired t-test of aided detection thresholds of Ling's six sounds with and without NLFC in Group 1

Ling Sound	Condition	Mean	S.D.	t (11)
/a/	No NLFC	29.58	7.52	1.393
	NLFC	28.33	7.48	
/i/	No NLFC	35.41	9.40	2.548 *
	NLFC	32.50	8.11	
/u/	No NLFC	31.25	6.78	1.483
	NLFC	30.41	7.21	
/s/	No NLFC	49.58	8.90	4.083**
	NLFC	40.83	6.68	
/ʃ/	No NLFC	47.08	9.15	6.092**
	NLFC	39.16	7.33	
/m/	No NLFC	35.41	8.10	1.301
	NLFC	33.75	6.78	

Note: * - p < 0.05, ** - p < 0.01

Aided Detection thresholds of Ling's six sounds

Comparison of aided detection thresholds of Ling's six sounds with and without NLFC in Group 1: From Table 7, it can be seen that the mean of the detection thresholds in Group 1 are better with NLFC than without NLFC for all the six speech sounds. However, from the results of Paired t-test, it can be observed that, the improvement in detection threshold is statistically significant for all the high frequency speech sounds /i/ (t=2.548, p<0.05) at 95% confidence and for the sounds /s/ and /ʃ/ at 99% confidence.

Comparison of aided detection thresholds of Ling's six sounds with and without NLFC condition in Group 2.

Table 8: Results of Paired t-test of aided detection thresholds of Ling's six sounds of Group 2 with and without NLFC

Ling Sound	Condition	Mean	S.D.	t (9)
/a/	No NLFC	35.5	4.97	1.152
	NLFC	34.0	3.94	
/i/	No NLFC	42.5	5.40	3.973 *
	NLFC	37.0	3.49	
/u/	No NLFC	37.5	6.34	0.896
	NLFC	36.0	5.67	
/s/	No NLFC	60.0	7.81	6.500 *
	NLFC	47.0	5.86	
/ʃ/	No NLFC	56.0	9.66	4.607 *
	NLFC	43.5	5.79	
/m/	No NLFC	42.5	4.24	4.000 *
	NLFC	38.5	4.11	

Note. *-p<0.01

From Table 8, it can be seen that for Group 2, the mean scores for detection thresholds of Ling sounds are better

with NLFC than without NLFC. However, Paired t-test results, revealed a significant improvement for the sounds /i/, /s/, /ʃ/ and /m/ with NLFC.

MANOVA was done to compare the aided detection thresholds of Ling's six sounds with and without NLFC between the groups. Results revealed a significant group differences in no NLFC condition for all the six sounds at 95% confidence. From Table 9 it can be seen that, with NLFC significant difference between the groups was present only for /a/ and /s/.

Percentage correct scores for Identification of Ling's six sounds

The percentage correct scores of identification of each of the six speech sounds were calculated for no NLFC and NLFC conditions, for each group separately.

Comparison of aided detection thresholds of Ling's six sounds with and without NLFC between the groups

Comparison of percentage correct scores of Identification of Ling's six sounds with and without NLFC in Group 1: As can be seen from Table 10, Group 1 could identify the high frequency sounds /i/, /s/ and /ʃ/ better with NLFC than without NLFC. Therefore, according to the results obtained in the present study it can be said that NLFC improves the identification of high frequency speech sounds, to some extent, even in children with severe to profound hearing loss.

Comparison of percentage correct scores of Identification of Ling's six sounds in Group 2: Table 11 shows that in Group 2, identification of /i/, /u/ and /ʃ/ improved with NLFC. However, for identification of /s/ there was no improvement seen.

Table 9: Results of MANOVA for detection thresholds of Ling's six sounds with and without NLFC

Condition	df	/a/	/i/	/u/	/s/	/ʃ/	/m/
No NLFC	F(1, 20)	4.51*	4.43*	4.90*	8.31*	4.92*	6.18*
NLFC	F(1, 20)	4.63*	2.64	3.94	5.17*	2.29	3.73

Note. *- p<0.05

Table 10: Percentage correct scores of identification of Ling's six sounds for Group 1 with and without NLFC

Cond.	/a/	/i/	/u/	/s/	/ʃ/	/m/
No NLFC	100%	83%	100%	0%	16%	16%
NLFC	100%	100%	100%	8.3%	25%	16%

Table 11: The percentage correct scores of identification of Ling's six sounds for Group 2 with and without NLFC

Cond.	/a/	/i/	/u/	/s/	/ʃ/	/m/
No NLFC	100%	40%	70%	0%	0%	10%
NLFC	100%	91.6%	100%	0%	30%	10%

Table 12: Results of Paired t-test for SIS in quiet (SIS Q) and SIS in noise (SIS N) with and without NLFC in Group 1

	Condition	Mean	S.D.	t (11)
SIS Q	No NLFC	14.66	3.28	4.34*
Max Score=25	NLFC	18.41	2.46	
SIS N	No NLFC	12.25	3.04	5.00*
Max Score=25	NLFC	14.58	3.60	

Note. *- p<0.01

Table 13: Results of Paired t-test for SIS in quiet (SIS Q) and SIS in noise (SIS N) with and without NLFC in Group 2

	Condition	Mean	S.D.	t (9)
SIS Q	No NLFC	16.80	2.20	10.58*
Max Score=25	NLFC	20.60	1.57	
SIS N	No NLFC	14.70	1.94	2.33**
Max Score=25	NLFC	16.50	2.41	

Note. *-p<0.01, **-p<0.05

Comparison of percentage correct scores of identification of Ling's six sounds between Group 1 and Group 2: The percent scores of identification of Ling's six sounds between Group 1 and Group 2 can be compared by observing Table 10 and Table 11. As mentioned previously Group 2 did not obtain benefit from NLFC for identification of /s/ like Group 1. However, Group 2 had a greater amount of improvement in identification of the high frequency speech sound /ʃ/ (30%) than Group 1 (9%).

Speech identification scores in quiet and in noise with and without NLFC

Comparison of SIS in quiet and in noise with and without NLFC in Group 1: Paired t-test was done to test if mean SIS was better with NLFC in Group 1. The

results of Paired t-test, given in Table 12, shows a statistically significant difference ($|t|(11)=4.34$, $p<0.01$) between no NLFC and NLFC conditions for SIS in quiet. Similar results were also found for SIS obtained in the presence of noise. A statistically significant difference ($|t|(11)=5.00$, $p<0.01$) was found between SIS in noise obtained with NLFC and without NLFC.

Comparison of SIS in quiet and in noise with and without NLFC in Group 2: The results of Paired t-test, given in Table 13, revealed that SIS in quiet significantly improved with NLFC in Group 2 ($p<0.01$). Similarly, even in the presence of noise, there is a significant difference ($p<0.05$).

Comparison of SIS in quiet and in noise with and without NLFC between the two groups.

Table 14: Results of MANOVA comparing Group 1 and Group 2 for SIS Q and SIS N with and without NLFC

	No NLFC		NLFC		
	SIS Q	SIS N	SIS Q	SIS N	
F (1, 20)	3.060	4.802	5.822	2.051	Note. *- p<0.05
p	0.096	0.040 *	0.026 *	0.168	

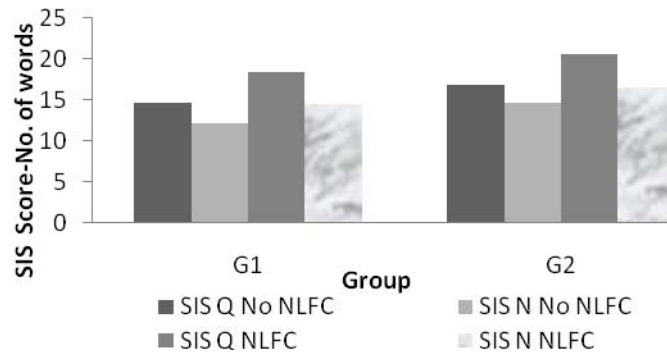


Figure 3: Mean SIS scores in Quiet and Noise with and without NLFC conditions for Group 1 and Group 2

MANOVA was done to compare the SIS between the two groups of subjects. The results given in Table 14, revealed that the groups were found to significantly differ from each other for Speech Identification in Noise (SIS N) in no NLFC condition [$F(1, 20)$, $p < 0.05$] and for Speech Identification in quiet in NLFC enabled condition [$F(1, 20)$, $p < 0.05$].

Figure 3 indicates that with no NLFC, Group 2 scored better than Group 1 in the presence of noise. Further, with NLFC in quiet, scores for Group 2 were better than Group 1.

Discussion

Results suggest that NLFC does help in improving the audibility of tones, in both the groups. The results of improvement in 4 kHz threshold with NLFC is supported by results of the study by Wolfe et al., (2010), which was done on children with mild to moderately severe sloping hearing loss. The results suggest that NLFC is beneficial in improving aided detection threshold at 4 kHz even for children with severe to profound hearing loss. The improvement seen in 2 kHz threshold can be attributed to the fact that most of the cut off frequencies chosen for frequency compression were close to 2 kHz. However, the cause of improvement of 500 Hz threshold with NLFC is not known, as NLFC processes low frequencies conventionally with no frequency compression. Hence, it can be said that children with severe to profound hearing loss could also benefit with NLFC for detecting

high frequency tones, like children with lesser degrees of sloping losses in the study of Wolfe et al., (2010).

For the task of detection of Ling's six sounds, results showed significant improvement in detection threshold for the high frequency sounds /i/, /s/ and /j/ for Group 1 and Group 2. These results are in agreement with other studies (Glista et al., 2009a, b; Wolfe et al., 2010) done on children with sloping hearing loss.

NLFC is found to be helpful in detecting high frequency vowel /i/ which has a higher second formant, and fricatives /s/ and /j/ which have more high frequency energy (Kent & Read, 2002). Hence, it can be concluded that the participants of both the groups received high frequency cues with NLFC. This enabled them to obtain better detection thresholds for high frequency speech sounds.

However, when the two groups were compared, for the detection thresholds of Ling's six sounds, results revealed that Group 1 obtained significantly better detection thresholds than Group 2, for all the Ling's six sounds without NLFC. However, with NLFC, it revealed significant group difference only for detection thresholds of /s/. This finding could be because NLFC enabled Group 1 to perceive better high frequency cues for the detection of /s/ which has spectrum mainly above 5 kHz (Manrique & Massonne, 1981). Since the unaided and aided thresholds at 4 kHz and above this frequency for Group 2 were poorer, they could not perform similar to Group 1 for detection of /s/.

It was found that percent correct scores of identification of high frequency sound /i/, /s/ and /ʃ/ increased with NLFC than without NLFC in Group 1. This is because enabling NLFC provided better high frequency cues and helped them to perceive the higher second formant of the /i/ vowel. In addition, NLFC also enabled the identification of the fricatives /s/ and /ʃ/. This finding of improved identification of high frequency consonants is consistent with previous studies done using NLFC on children and adults with moderately severe to profound sloping hearing loss who obtained improved recognition for high frequency consonants (including /s/ and /ʃ/) and for plural recognition scores (ranging from 70-100%) (Glista et al., 2009a, b).

However in Group 2, improvement was only seen for identification of /i/, /u/ and /ʃ/ and there was no improvement of identification of /s/ with NLFC. There can be two reasons for this. One is that in the present study there was no acclimatization period or training given with the NLFC device. The second reason may be that the children in Group 2 had poorer threshold when compared to Group 1 at higher frequencies. Because of this, the fricative /s/ which has energy concentration from 5 kHz and above (Manrique & Massonne, 1981) could not be perceived as well as children in Group 1. Assessment of aided thresholds at 8 kHz with NLFC would have been helpful. Therefore, according to the results obtained in the present study, it can be said that NLFC improves the identification of high frequency speech sounds, even in children with severe to profound hearing loss. However, within severe to profound hearing loss group children with better thresholds would benefit better with NLFC. Further, training might help these children receive better benefit with NLFC.

Results comparing identification of words showed a significant benefit from NLFC when assessed in quiet as well as in noise in both the groups of children. When the two groups were compared for SIS in quiet and in noise, Group 2 showed better results in quiet with NLFC and in noise without NLFC. In other conditions both performed equally. However, in the present study, this difference cannot be attributed only to NLFC as Group 1 obtained better benefit in the task of detection and identification of high frequency speech sounds.

The reason for the difference in SIS may be because of the stimuli used for speech identification. For the assessment of SIS in the present study, PB word lists were used which included all the speech sounds in the language. Hence, the children might have obtained cues from other lower frequency speech sounds. Further, it was a closed set task. Hence, phoneme error analysis could not be done which could have supported the NLFC in improving SIS in noise. Further, having a test

containing only high frequency sounds is necessary in evaluating NLFC. From the above results, it is clear that children with severe to profound hearing loss can benefit with NLFC for detection of high frequency tones and high frequency speech sounds, and may be, for speech identification in quiet and in noise. However, children with better thresholds at 4 kHz showed better benefit for detection as well as identification of /s/. Hence, aided and unaided thresholds are main factors in determining benefit with NLFC.

Conclusions

It could be concluded that NLFC was beneficial to children with severe to profound loss and that it can be a viable amplification option in this population as in children with sloping loss. Using NLFC facilitates reception of high frequency information which is necessary for adequate development of speech and language. However, the prescription of device with NLFC must be done with caution, as the benefit will depend on the frequency compression parameter settings and also hearing thresholds of the children especially at high frequencies. Further, providing training would have brought about more benefits in speech perception with NLFC.

References

- Bohnert, A., Nyffeler, M., & Keilmann, A. (2010). Advantages of a non-linear frequency compression algorithm in noise. *European Archives of Otorhinolaryngology*, 267(7), 1045-1053.
- Boretzki, M., & Kegel, A. (2009). The benefits of Sound Recover for people with mild hearing loss. Phonak AG: Phonak Field Study News. Retrieved December 10, 2010, from http://www.audiologyonline.com/articles/article_detail.asp?article_id=2317
- Glista, D., Scollie, S., Bagatto, M., Seewald, R., Parsa, V., & Johnson, A. (2009). Evaluation of nonlinear frequency compression: Clinical outcomes, *International Journal of Audiology*, 48(9), 632-644.
- Glista, D., Scollie, S., Polonenko, M., & Sulkers, J. (2009). A Comparison of Performance in Children with Nonlinear Frequency Compression Systems. *Hearing Review*, 16(12), 20-24.
- Helm, K. L. (2010). *The effect of nonlinear frequency compression and linear frequency transposition on speech perception in school-aged children*. (Independent studies and Capstones, Washington University School of Medicine). Retrieved April 21, 2011, from http://digitalcommons.wustl.edu/pacs_capstones/609
- Hogan, C. A., & Turner, C. W. (1998). High-frequency audibility: benefits for hearing-impaired listeners. *Journal of the Acoustical Society of America*, 104(1), 432-41.

- Kent, R. D., & Read, L. (2002). *The Acoustic Analysis of speech*. Singular Publishing Company.
- Manrique, A., & Massone, M. (1981). Acoustic analysis and perception of Spanish fricative consonants. *Journal of Acoustical Society of America*, 69, 1145–1153.
- Mathew, P. (1996). *Picture test of speech perception in Malayalam*. Unpublished Master's Dissertation, University of Mysore, India.
- Nyffeller, M. (2008). Study finds that non linear frequency compression boosts speech intelligibility. *The Hearing Journal*, 61, 12, 22-26.
- Simpson, A., Hersbach, A. A., & McDermott, H. J. (2005). Improvements in speech perception with an experimental nonlinear frequency compression hearing device. *International Journal of Audiology*, 44, 281-292.
- Simpson, A., Hersbach, A. A., & McDermott, H. J. (2006). Frequency-compression outcomes in listeners with steeply sloping audiograms. *International Journal of Audiology*, 45, 619-629.
- Turner, C. W., & Hurtig, R. R. (1999). Proportional frequency compression of speech for listeners with sensori-neural hearing loss. *Journal of Acoustical Society of America*, 106(2), 877-886.
- Vandana, S. (1998). *Speech identification test for Kannada speaking children*. Unpublished Master's Dissertation, University of Mysore, India.
- Wolfe, J., Caraway, T., John, A., Schafer, E. C., & Nyffeler, M. (2009). Non-linear frequency compression for children. *The Hearing Journal*, 62 (9), 32-37.
- Wolfe, J., John, A., Schafer, E., Nyffeller, M., Boretzki, M., & Caraway, T. (2010). Evaluation of Nonlinear Frequency Compression for School-Age Children with Moderate to Moderately Severe Hearing Loss. *Journal of American Academy of Audiology*, 21, 618–628.
- Wolfe, J., John, A., Schafer, E., Nyffeler, M., Boretzki, M., Caraway, T., & Hudson, M. (2011). Long-term effects of non-linear frequency compression for children with moderate hearing loss. *International Journal of Audiology*, 50, 396–404.