Effect of compression, digital noise reduction and directionality on envelope difference index, log-likelihood ratio and perceived quality

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Abstract

The aim of the present study was to evaluate the use of the envelope difference index (EDI) and log-likelihood ratio (LLR) to quantify the independent and interactive effects of wide dynamic range compression, digital noise reduction and directionality, and to carry out self-rated quality measures. A recorded sentence embedded in speech spectrum noise at +5 dB signal to noise ratio was presented to a four channel digital hearing aid and the output was recorded with different combinations of algorithms at 30, 45 and 70 dB HL levels of presentation through a 2 cc coupler. EDI and LLR were obtained in comparison with the original signal using MATLAB software. In addition, thirty participants with normal hearing sensitivity rated the output on the loudness and clarity parameters of quality. The results revealed that the temporal changes happening at the output is independent of the number of algorithms activated together in a hearing aid. However, at a higher level of presentation, temporal cues are better preserved if all of these algorithms are deactivated. The spectral components speech tend to get affected by the presentation level. The results also indicate the importance of quality rating as this helps in considering whether the spectral and/or temporal deviations created in the hearing aid are desirable or not.

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Key words: wide dynamic range compression, digital noise reduction, directionality, envelope difference index, log-likelihood ratio.

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Introduction

Individuals with sensorineural hearing loss have difficulties in frequency discrimination and temporal resolution in addition to audibility issues.[1] In order to prevail over these issues, Many recent hearing aids are incorporated with advanced signal processing strategies such as wide dynamic range compression (WDRC), digital noise reduction (DNR) algorithms and directionality. Studies have shown that these algorithms alter the temporal and spectral characteristics of the speech signal.[2-4] It is imperative to quantify these changes for effective optimization of hearing aid characteristics.

There are different acoustic and perceptual measures that could quantify the changes in speech signal induced by these algorithms. There have been many reports in the literature on the independent effect of these algorithms on speech perception.[3-9]

WDRC has been found to modify the acoustic signal to a considerable extent when compared to linear amplification.[2] Dillon[1] reported that WDRC could also cause other unfavorable effects such as amplifying noises occurring during the gaps of speech, distorting the intensity relationship within syllables and reduction of speech along with noise.

Similarly, studies have shown that DNR algorithms have been found to show greater alterations of signal when the amount of noise reduction is greater,[10] though DNR may improve the speech recognition in noise in conditions when the signal and noise spectrum are different and the signal and noise are spatially separated.[11]

The above studies have evaluated the independent effects of WDRC and DNR algorithms. However, in actuality, the algorithms work jointly either in sequence or parallel.[12] In either case, the amount of alterations/distortions induced by these algorithms may be expected to be higher than when tested alone.

Keidser *et al*.[13] studied the effect of compression and noise reduction algorithms on localization of hearing aid users. Wu and Stangl[14] assessed the acceptable noise levels (ANL) in the WDRC hearing aid with DNR and directional algorithms. They found that WDRC alone-created noise in the output. However, the DNR activation improved the signal to noise ratio (SNR). Directionality did make a difference in terms of ANL.

Even the different acoustic measures have shown that the algorithms alter the spectral and temporal resolution. The different acoustic measures that could be used to quantify the changes in acoustic properties of the signal are envelope difference index (EDI) and log-likelihood ratio (LLR). The EDI is an index of alteration in the temporal envelope of the processed signal in comparison with the unprocessed signal. This was originally devised by Fortune *et al*.[15] The

EDI has gained popularity because it can be compared directly with the subjective performance. The EDI can be used to quantify the temporal changes caused by amplitude compression of hearing aids.[16]

On the other hand, LLR is a measure which quantifies the difference in the spectrum between the processed and unprocessed signals. This measure has been found to have applications in measuring the spectral deviations caused by hearing aid.[17,18]

Souza *et al.*[16] have reported that the amplitude compression alters the temporal cues as evidenced by EDI and the EDI varied with the compression ratio and time constants. Arpita and Manjula have reported that LLR measure showed that the shorter release time constants resulted in larger spectral distortion (*Arpita V, Manjula P. Effects of compression release time in hearing aid on acoustic and behavioral measures of speech. Unpublished Master Dissertation; 2012*). Hence, EDI and LLR have been proven to be good measures of indication of changes induced by different settings of compression amplification.

However, the temporal and spectral cue alterations caused by directionality and the DNR have not been quantified using these objective measures. Further, the temporal and spectral alterations caused by the combination of all the DSP algorithms have also not been evaluated. It is essential to study the combined effect as, in actuality, they all work together either parallel or sequentially, and the different combinations of these algorithms that cause the maximum deviation in the input should be known for better optimization of hearing aid settings.

Further, the quality measurement is yet another important outcome measurement tool. Few studies[17-19] have indicated the importance of the rating on the quality. These studies have shown quality preferences for a specific compression setting in the absence of differences in speech intelligibility scores across the compression settings. Hence, carrying out a quality rating in addition with an objective measurement would throw light on the subjective perception. The aim of the present study was to evaluate the use of EDI and LLR to quantify the independent and interactive effects of compression, DNR and directionality on the temporal and spectral aspects of sentence in noise, and to assess the perceived quality.

Materials and Methods

Programming the hearing aid

A four-channel WDRC digital hearing aid with DNR algorithms and directionality was selected. The hearing aid had the option to turn *on* or *off* each of these algorithms. The selected hearing aid was programmed using NOAH platform, for a moderate flat sensorineural hearing loss, *i.e.*, thresholds ranging from 40 to 50 dB HL at the audiometric frequencies. The gain settings were kept at default settings as prescribed by the NAL-NL1 formula. The compression threshold was 55 dB and the compression ratio was 1.33. After the basic programming, different permutation and combinations of the three algorithms-WDRC, DNR and directionality algorithms were formed. This led to a total of eight aided conditions. The conditions were as follows: i) Compression alone; ii) DNR alone; iii) Directionality alone; iv) Compression+Directionality; v) Compression+DNR; vi) Compression+DNR+Directionality; vii) Directionality+DNR; and viii) in the all algorithms deactivated (with all three algorithms deactivated) conditions. The measurements were also made ix) with the original signal.

Recording the output of the hearing aid

After programming, the hearing aid was coupled to a 2 CC coupler connected to Larson-Davis Sound Level Meter. The hearing aid along with the sound level meter was mounted on a tripod kept at the height of 1 meter from the ground level. A recorded sentence in Kannada language, from the standardized sentence test developed by Geetha and Manjula[19] spoken by a female speaker, embedded in speech spectrum noise at +5 dB SNR was routed to loud speakers through a calibrated diagnostic audiometer. The speakers were kept at a 45° angle at a distance of 1 meter from the hearing aid.

The signal from the speaker was picked up by the hearing aid and the output of this was routed to a laptop with i5 core processor through the sound level meter. Praat software was used to record the output as .wav files. A sampling rate of 44,100 was used. All the measurements were done at the presentation level of 30, 45 and 70 dB HL. Recorded stimuli were then edited with reference to the common reference point shared by them.

Spectral and temporal distance measurement

For the temporal and spectral comparisons of the output recorded in the previous section, EDI and LLR were used respectively. MATLAB software (Version R2009b) was loaded with the algorithms for EDI and LLR.

The method given by Fortune *et al*.[15] was used to calculate EDI. The edited stimuli were loaded into the MATLAB software. The difference between the temporal envelopes of each of the above mentioned eight aided conditions and the original signal were obtained using the software. The EDI ranges from 0 to 1. The value of *0* indicates perfectly similar envelopes and the value of *1* indicates completely dissimilar envelopes.

COLEA software developed by Loizou[20] was used for computing LLR. In the present study, the procedure adopted to compute LLR was same as used by Jeon and Lee.[17] The formant mismatch between the unaided and aided conditions was computed. As the weightage of enhancement increases, LLR values are also said to increase.

Subjective quality rating

For the quality rating, 30 participants with normal hearing sensitivity were selected, age ranging from 18 years to 38 years (mean age of 24 years). The participants were tested in a sound treated room. Routine clinical audiometry was carried out. MA-53 clinical audiometer was used to carry out pure-tone audiometry, speech audiometry, and the Titan immittance meter was used for immittance evaluation. In pure tone audiometry, pure tone air-conduction thresholds were within 15 dB HL across 250 Hz to 8000 Hz in both ears and bone conduction thresholds were within 15 dB HL across 250 Hz to 4000 Hz.[21] The SRT and SIS were in correlation with the pure-tone audiometry. Further, the participants had *A* type tympanogram and had ipsilateral and contralateral acoustic reflexes within 100 dB HL at the frequencies 500 Hz, 1 kHz and 2 kHz.[22] A laptop with i5 core processor, with MosabaerMB808 headphones, was calibrated using a Larsen-Davis sound Level Meter. The sentences (output of the hearing aid) at three input levels were calibrated to give an equal output of 65 dB SPL in order to avoid the level effect. The stimuli were then presented randomly to avoid the order effect. Along with the processed signals, control (different unprocessed) sentences were also presented. The participants were unaware of the stimulus condition. The participants were presented the sentences and they were instructed to rate the sentences. The parameters for evaluating quality judgment were loudness (of speech with reference to noise in which it is embedded) and clarity (how clear speech sounded with respect to intelligibility, in contrast to distorted or blurred speech). The rating scale used was adopted from Eisenberg and Dirks.[23] The scale ranged from 1 to 5. In the scale, *1* indicated *very poor* and *5* indicated *excellent*. Further, the reliability of the subjective quality ratings was assessed by repeating the same quality rating procedure on thirty percent of the participants. The test procedure and conditions were same as the first trial.

Results

Acoustic analysis

Temporal and spectral differences of different aided conditions in comparison with original signal were analyzed using EDI and LLR respectively. Figures 1 and 2 show the EDI and LLR values for the eight aided conditions at three different input levels.

Acoustic analysis using envelope difference index

From the Figure 1, it is evident that, at 30 dB HL, the EDI ranged from 0.29 to 0.35 indicating that the variation in temporal distortion was not much between aided conditions and the temporal deviation created by the hearing aid algorithms also is only around 30%.

Similar results were obtained for the input levels of 45 and 70 dB HL except for *compression only* condition at 45 dB HL, and for the *all algorithms deactivated* condition at 70 dB HL. In these two conditions, the EDI was 0.58 and 0.50 respectively, signifying larger temporal distortions. These results suggest that compression, DNR and directionality are similar in terms of temporal changes that they introduce.

Acoustic analysis using log-likelihood ratio

Descriptive analysis of LLR revealed that *compression only* condition provided least and comparable spectral changes at all the three input levels. This is evident in the Figure 2.

For all the other conditions, LLR depended on the level of presentation. In general, at lower levels of input, the spectral differences were minimal. As the level increased, the spectral differences increased. However, *Compression+Directionality* and *Compression+DNR* conditions induced maximal spectral changes when compared to the original signal. That is, the results of LLR indicate that the activation of the compression algorithm introduces smaller spectral distortions when compared to DNR and directionality. At the 70 dB level of presentation, activating all the algorithms resulted in lowest spectral changes.

Subjective quality rating

Analysis of subjective quality in terms of the loudness and clarity was done using Friedman Rank order correlation. The results of the rating on loudness and clarity are given separately below.

Analysis of loudness rating

The loudness parameter of quality was rated using a 5-point rating scale, *1* indicated that *speech is not at all intelligible* and *5* indicated that *speech is very distinct from noise*. Figure 3 presents the mean and SD of rating on loudness at three different levels of presentation. Figure 3 reveals that as the level of presentation increased the loudness rating also increased.

Table 1 shows the results of Friedman Rank order correlation. It can be noticed that, at all the three presentation levels, there is a significant difference across conditions. Wilcoxon paired comparison was done to check the conditions that differed at each presentation level.

Loudness rating at 30 dB HL

As it can be viewed in the Figure 3, at 30 dB level presentation, the

Table 1. Results of Friedman test on the measure of loudness and clarity.

Level of presentation	No.	Chi Square		df		Level of significance	
		Loudness	Clarity	Loudness	Clarity	Loudness	Clarity
30 dB HL	30	45.09	60.88	8	8	0.000	0.000
45 dB HL	30	31.47	37.64	8	8	0.000	0.000
70 dB HL	30	32.79	30.73	8	8	0.000	0.000

df, degree of freedom.

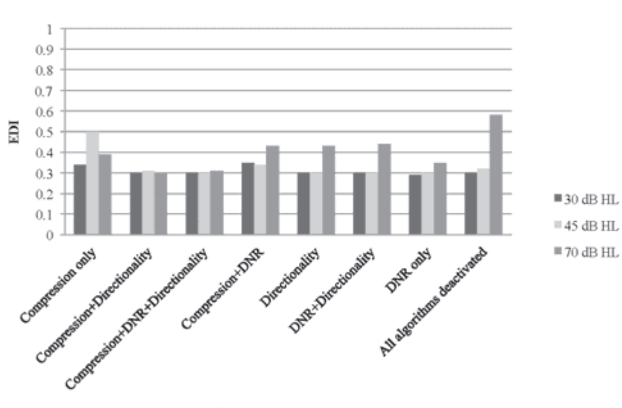

Figure 1. Envelope difference index (EDI) values for different aided conditions at 30 dB, 45 dB and 70 dB HL. DNR, digital noise reduction.

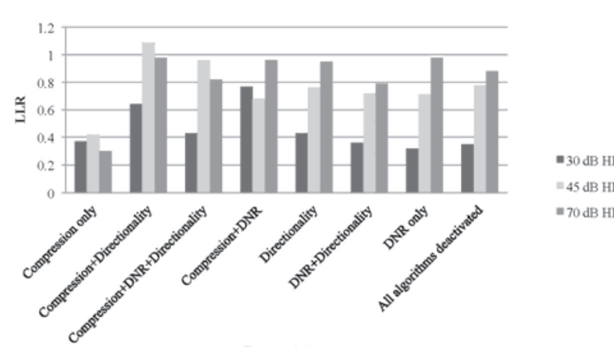

Figure 2. Log-likelihood ratio values for different aided conditions at 30 dB, 45 dB and 70 dB HL. DNR, digital noise reduction.

mean scores revealed that the condition where all the algorithms were deactivated provided better rating followed by *DNR+Directionality* condition. However, activation of all algorithms did not result in the least loudness rating. The least loudness ratings were for the *compression only* condition. Wilcoxon's Sign Rank test was done to see the condition(s) in which there was a difference in loudness rating. Table 2 provides the result of Wilcoxon paired comparison of different conditions at 30 dB HL level. The condition *all algorithms deactivated* resulted in significantly better rating when compared to conditions where compression was activated.

Loudness rating at 45 dB HL

From the Figure 3, it can be seen that, even at 45 dB HL, the *all algorithms deactivated* condition has resulted in a higher loudness rating. However, conditions where compression was activated also received a high loudness rating unlike at 30 dB level of presentation. The condition *DNR+Directionality* received the least rating followed by *DNR only* condition. The result of the Wilcoxon paired comparison revealed that the *DNR+Directionality* condition differed significantly from compression only and the condition where all the algorithms were activated; DNR only differed significantly from *Compression+Directionality.* There was no significant difference across other aided conditions. This can be viewed in the Table 3.

Loudness rating at 70 dB HL

At 70 dB HL, all the aided conditions were rated better in terms of loudness than the unaided as given in Figure 3. However, no significant difference was found among the aided conditions except for the *Compression+DNR* condition which got the least rating on loudness. This condition did not differ significantly only from the *Compression+DNR+Directionality* condition and the *all algorithms deactivated* condition. This can be viewed in the Table 4.

Analysis of clarity rating

Figure 4 presents the mean and SD of quality rating on clarity at three different levels of presentation. It reveals that as the level of presentation increased the rating for clarity also increased. Table 1 shows the results of Friedman Rank order correlation.

The results of this revealed a significant difference. However, Wilcoxon signed rank test revealed no significant difference across the different conditions at all the three presentation levels.

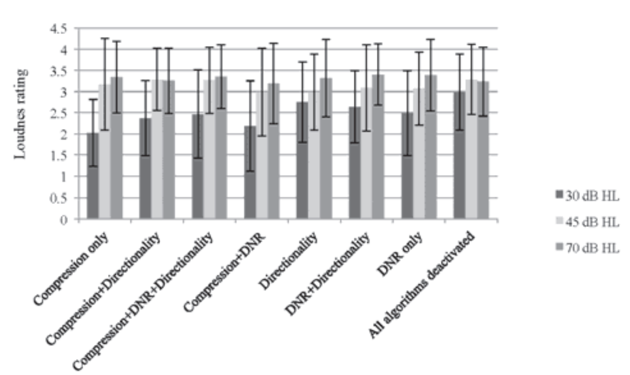

Figure 3. Mean and standard deviation of rating on loudness for different aided conditions at 30 dB, 45 dB and 70 dB HL. DNR, digital noise reduction.

Table 2. Results of Wilcoxon paired comparison for 30 dB HL for loudness.

Test conditions	Z
Compression only *vs* Compression+DNR+Directionality	-2.94*
Compression only *vs*Directionality	-2.28*
Compression only *vs* DNR+Directionality	-2.72**
Compression only *vs* All algorithms deactivated	-3.21**
Compression+DNR *vs* Compression+DNR+Directionality	-2.64**
Compression+DNR *vs* Directionality	-2.67**
Compression+DNR *vs* DNR+Directionality	-3.27**
Compression+DNR *vs* All algorithms deactivated	-3.40**
All algorithms deactivated *vs* Compression+Directionality	-3.11**
All algorithms deactivated *vs* Directionality	-2.35*
All algorithms deactivated *vs* Compression+DNR+Directionality	-2.50*
All algorithms deactivated *vs* Original signal	-3.140**
Original signal *vs* Directionality	-2.13*
Original signal *vs* DNR+Directionality	-2.58**

*P<0.05; **P<0.01. DNR, digital noise reduction.

Table 3. Results of Wilcoxon for 45 dB HL for loudness.

Test conditions	Z
Original signal *vs* Compression+Directionality	-3.06**
Original signal *vs* Compression only	-2.56**
Original signal *vs* Compression+DNR+Directionality	-3.26**
Original signal *vs* Compression+DNR	-2.07*
Original signal *vs* Directionality	-2.39*
Original signal *vs* DNR only	-2.14*
Original signal *vs* All algorithms deactivated	-3.26**
Compression only *vs* DNR+Directionality	-2.44*
Compression+Directionality *vs* DNR only	-2.17*
All algorithms deactivated *vs* DNR+Directionality	-2.00*

*P<0.05; **P<0.01. DNR, digital noise reduction.

Table 4. Results of Wilcoxon for 70 dB HL for loudness.

Test conditions	Z
Original signal *vs* Compression+Directionality	-2.86**
Original signal *vs* Compression only	-2.72*
Original signal *vs* Compression+DNR+Directionality	-2.62**
Original signal *vs* Directionality	-2.96**
Original signal *vs* DNR+Directionality	-2.53*
Original signal *vs* DNR only	-3.05**
Original signal *vs* All algorithms deactivated	-2.43*
Compression+DNR *vs* Compression only	-2.10*
Compression+DNR *vs* Compression+Directionality	-2.29*
Compression+DNR *vs* Directionality	-2.39*
Compression+DNR *vs* DNR+Directionality	-2.23*
Compression+DNR *vs* DNR only	-2.13*

*P<0.05; **P<0.01. DNR, digital noise reduction.

Cronbach's α model was used to assess the reliability of subjective quality rating. All the conditions and levels were combined for this. The ratings between two trials were compared. The results showed that there was moderate level of consistency in the rating for both the loudness (Cronbach's α=0.603) and clarity (Cronbach's α=0.573).

Discussion

The results of the EDI of the present study are similar to that obtained by Fortune *et al*.[15] for the syllable /ITH/ with the non-linear circuit (EDI=0.33). However, the linear circuit had resulted in almost no temporal alteration (EDI=0.04) in the earlier study. In the present study, temporal envelope variations induced by the hearing aid in the *all algorithms deactivated* condition was similar to that of nonlinear conditions except at the presentation level of 70 dB HL. This difference could be that, in the present study, the same non-linear digital hearing aid circuit was used in the *all algorithms deactivated* condition by switching off the non-linear algorithms. At 70 dB HL level of presentation, the *all algorithms deactivated* condition had resulted in higher temporal envelope alterations. This shows that activation of DSP algorithms has preserved the temporal envelope at higher levels, which is a positive trend. This is evident in the quality rating. In the *all algorithms deactivated* condition, the subjective rating revealed a slight decline in the loudness and clarity rating at 70 dB HL which was not observed in any other aided conditions or levels. Among the other aided conditions, EDI revealed higher temporal alterations only in *compression alone* condition at 45 dB HL.

These results suggest that compression, DNR and directionality are similar in terms of temporal changes in the given settings and stimulus conditions. In addition, the EDI did not depend on the number of algorithms activated at a time. According to Chung,[24] introduction of noise reduction algorithm in the WDRC hearing aid resulted in the better speech transmission index and they attributed this to the enhancement in the temporal envelope caused by the DNR algorithm. If this was the case, then the EDI in all the conditions with DNR *on* should have been higher. However, in the present study, that was not observed. In addition, in the present study, there was no difference in EDI in the conditions with directionality *on*. This could be because the speech and noise were presented from the same loud speaker without any spatial separation. The directionality algorithm in the hearing aid worked on the principle of spatial separation of speech and noise. The spatial separation of speech and noise was not present in the present study, and thus limiting the function of directionality algorithm.

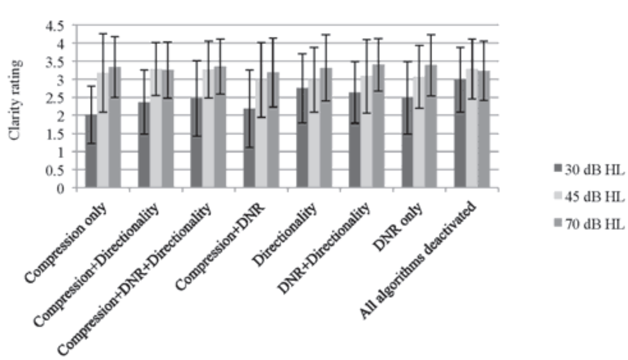

Figure 4. Mean and standard deviation of rating for clarity for different aided conditions at 30 dB, 45 dB and 70 dB HL. DNR, digital noise reduction.

Analysis of LLR revealed that compression alone condition provided least and comparable spectral changes at all the three input levels. This result does not support the results reported by Arpita and Manjula.[17] In the latter study, at higher presentation level, the spectral distortions were higher for compression circuit. The difference in results between the studies could be because of the difference in the compression settings. In the present study, the compression threshold was within 55 dB and the compression ratio used was 1.33; whereas the earlier study used higher compression ratio and shorter compression time constants. Further, Kuk[7] has reported that the spectral smearing in WDRC depends on the time constants and number of channels.

For all the other conditions, LLR depended on the level of presentation. In general, at lower levels of input, the spectral differences were minimal indicating lesser enhancement. As the level increased, the spectral differences also increased. This spectral difference could be considered as spectral enhancement as the results of quality rating improved when the level of presentation increased.

Nevertheless, this effect does not seem to hold good for *Compression+DNR* condition, as in this condition, the spectral alterations are high and loudness rating is poor compared to the majority of the aided conditions. Hence, it can be said that the results of subjective quality measures differ from that of acoustic-spectral and temporal measures. This finding is in accordance with the results of Warner and Bentler[25] who also found that the spectral and temporal measures cannot always predict the subjective perception of quality.

The results of LLR also indicate that activation of compression algorithm introduces smaller spectral distortions when compared to DNR and directionality. Further, activation of all the algorithms does not lead to higher spectral distortions/enhancements. The possible reason for this could be that the WDRC algorithm which preserves the spectral cues in the present hearing aid might have offset the negative effects of DNR and directionality algorithms.

The results of quality rating did not show any specific trend with reference to different aided conditions. However, all the aided conditions yielded better quality rating at higher presentation level. This trend is similar to that of LLR. Further, clarity rating was not significantly different between any aided conditions across the three levels. The reason for this could be that the participants in the present study had normal hearing sensitivity and hence, clarity with respect to speech intelligibility was not an issue for them. Further, reliability of ratings on these quality measures showed a moderate level of consistency between the two trials. This provides authenticity of the results of the present study.

Conclusions

The temporal and spectral changes happening at the output is independent of the number of algorithms activated simultaneously in a hearing aid. However, at a higher level of presentation, temporal cues are better preserved if all of these algorithms are deactivated. The results of the present study also indicate the importance of quality rating as this helps in considering whether the spectral and/or temporal deviations created in the hearing are desirable or not.

References

1. Dillon H. Hearing aids. 2nd ed. New South Wales, Thieme: Boomerang Press; 2002.
2. Hickson L, Thyer N. Acoustic analysis of speech through a hearing

aid: perceptual effects of changes with two channel hearing aids. J Am Acad Audiol 2003;14:414-26.
3. Mueller G, Weber J, Hornsby B. The effects of digital noise reduction on the acceptance of background noise. Trends Amplif 2006;10:83-93.
4. Souza PE. Effects of compression on speech acoustics, intelligibility, and sound quality. Trends Amplif 2002;6:157-9.
5. Boike KT, Souza PE. Effect of compression ratio on speech recognition and speech quality ratings with wide dynamic range compression amplification. J Speech Lang Hear Res 2000;43:456-68.
6. Cox RM. Five years later: An update on the IHAFF fitting protocol. Hear J 1999;52:10-8.
7. Kuk FK. Considerations in modern multichannel nonlinear hearing aids. In: Valente M, ed. Hearing aids: standards, options and limitations. 2nd ed. New York: Thieme Medical Publishers; 2002. pp 178-213.
8. Levitt H. A historical perspective on digital hearing aids: how digital technology has changed modern hearing aids. Trends Amplif 2007;11:7-24.
9. Rout A, Hanline LE, Halling DC. New stimuli for evaluation of multichannel noise reduction hearing aids. Proc. 8th EFAS Congress, 6-9 June 2007, Heidelberg, Germany. Oldenburg: European Federation of Audiological Societies; 2008. P35, pp 1-4. Available from: file:///C:/Users/utente/Downloads/Program_EFAS_final.pdf
10. Bray V, Nilsson M. Additive SNR benefits of signal processing in a directional DSP aid. Hear Rev 2001;8:48-5112.
11. Bray V, Sandridge S, Newman C, Kornhass S. Clinical research findings confirm benefits of advanced signal processing, sonic innovations. Audiology Online 2002. Available from: http://www.audiologyonline.com/articles/clinical-research-findings-confirm-benefits-1158
12. Schaub A. Noise reduction. Digital hearing aids. 2nd ed. New York, Thieme: Medical publishers Inc; 2004.
13. Keidser G, Rohrseitz K, Dillon H, Hamacher V,Carter L,Rass U, et al. The effect of multi-channel wide dynamic range compression, noise reduction, and the directional microphone on horizontal localization performance in hearing aid wearers. Int J Audiol 2006;45:563-79.
14. Wu Y, Stangl E. The effect of hearing aid signal-processing schemes on acceptable noise levels: perception and prediction. Ear Hear 2013;34:333-4.
15. Fortune TW, Woodruff BD, Preves DA. A new technique for quantifying temporal envelope contrasts. Ear Hear 1994;15:93-9.
16. Souza PE, Hoover EC, Gallun FJ. Application of the envelope difference index for spectrally sparse speech. J Speech Lang Hear Res 2012;55:824-37.
17. Jeon Y, Lee S. A strategy of contrast enhancement considering acoustic masking effect: 2008; Paper presented at the 2nd Techn. Conf. Rehab. Engine. Aassistive Technol. Society of Korea.
18. Hansen M. Effects of multi-channel compression time: constants on subjectively perceived sound quality and speech intelligibility. Ear Hear 2002;23:369-80.
19. Geetha C, Manjula P. Effect of syllabic and dual compression on speech identification scores. All India Inst Speech Hear 2005;III:57-66.
20. Loizou P. COLEA-A MATLAB software tool for speech analysis: 1998. Available from http://ecs.utdallas.edu/loizou/speech/colea.htm
21. Clark JG. Uses and abuses of hearing loss classification. Am Speech Lang Hear Assoc 1981;23:493-500.
22. Gelfand SA. Hearing: an introduction to psychological and physiological acoustics. New York: Marcel Dekker; 1998.
23. Eisenberg LS, Driks DD. Reliability and sensitivity of paired comparisons and category rating in children. J Speech Hear Res 1995;38:1157-67.