Relationship between Envelop Difference Index (EDI) and Speech Perception with Noise Reduction Strategies in Hearing Aids

Principal Investigator: Geetha. C, Lecturer in Audiology, AIISH
Co- Investigator: Hemanth. N, Lecturer in Audiology, AIISH
Research Officer: Vinodhini. P
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Abstract

Individuals with sensorineural hearing loss depend more on the temporal cues for speech perception. Hearing aids are fitted for these individuals to overcome their speech perception difficulties. Hearing aids use digital signal processing (DSP) algorithms such as wide dynamic range compression (WDRC), digital noise reduction (DNR) and directionality tend to modify the envelope of the signal to cut down noise. Hence, it is important to understand the effect of these algorithms in terms of perception and also to quantify these changes objectively using envelope difference index (EDI). The study included two groups of individuals: twenty adults and twenty older adults. Sentences and VCVs were presented through 0^0 azimuth and noise was presented through 180^0 azimuth at low-, mid- and high presentation levels. Speech perception testing and EDI calculation for both sentences and VCVs were carried out with different combinations of different DSP algorithms. The results revealed that the combined activation of the noise reduction algorithms along with WDRC significantly improves speech recognition scores when compared to independent activation of the algorithms at all the presentation levels in both younger and older individuals with hearing impairment. The temporal changes induced by these algorithms are only minimal and these changes can be considered as positive as the speech recognition scores are higher.

Keywords: *Speech perception, EDI, DSP algorithms, sentence, VCV.*

Introduction

Hearing mechanism is an important link in the speech chain for proper communication. Impairment in hearing sensitivity leads to communication breakdown. Individuals with sensorineural hearing impairment have broadened auditory filters and have difficulty in perceiving fine structures (Moore, Glasberg, & Simpson, 1992). Understanding speech in the presence of background noise also remains to be difficult.

In realistic environment, noise most often accompanies speech and alters the spectral component of speech and partly the temporal content of speech. It is well established that temporal envelope cues have been reported to contribute for speech recognition (Dorman, Marton, & Hannley, 1985; Gordon-Salant & Fitzgibbons, 1993; Healy & Warren, 2003; Price & Simon, 1984; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995) and quality (Anderson, 2011). Additionally, depending on the amount of modification in the envelope of the signal, the quality of the signal is also degraded (Anderson, 2011). Hence, when there is a modification of envelope cues, perception of speech is reported to be affected (Anderson, Arehart, & Kates, 2013). Thus, temporal envelope is an important aspect of speech signal.

Hearing aid users require a signal-to-noise ratio (SNR) of about 4 - 10 dB more than that required by normal hearing individuals for equal amount of speech understanding (Dillon, 2001; Hamacher et al., 2005). In order to overcome the difficulties of perceiving speech in the presence of noise, digital signal processing (DSP) algorithms like digital noise reduction (DNR) and directionality are used in hearing aid technology (Dillon, 2001). Nevertheless, the digital signal processing algorithms have been reported to alter the temporal cues and affect the speech perception in the process of cutting down noise and enhancing speech. There are a few studies available to explain the effects of these algorithms on the temporal envelope of the speech signal.

Several studies have reported a negative effect of WDRC on speech intelligibility and quality, and the extent of the influence has been reported to be depended on the settings of WDRC parameters (Gatehouse, Naylor & Elberling, 2006; Hansen, 2002; Moore, Stainsby, Alcántara, & Kühnel, 2004; Neuman, Bakke, Mackersie, Hellman, & Levitt, 1998). DNR used for improving the speech perception in the presence of noise has also been reported to alter the temporal envelope of the incoming speech signal (Levitt, 2001) and to affect the speech perception in individuals with sensorineural hearing loss (Alcantara, Moore, Kuhnel, & Launer, 2003; Boymans & Dreschler, 2000; Levitt, Bakke, & Kates, 1993). Further, activation of directionality in hearing aid improves speech perception in noise when the source of the noise and the signal are spatially separated (Luts, Jean, & Wouters, 2004; Valente, Fabry, & Potts, 1995). Though the primary aim of these algorithms is to improve speech perception, due to the alteration of the temporal envelope of the signal, the intelligibility of the signal could be affected.

Thus, it is important to note the temporal envelope changes if at all exists in the speech signal after it is processed through hearing aid using subjective and objective measures. There are different objective measures that are available to quantify the changes in the temporal envelope. The Envelope Difference Index (EDI) is one of them. This was originally developed by Fortune, Woodruff and Preves (1994).

Envelope Difference Index. EDI quantifies the temporal changes between two signals. This metrics quantifies the changes between the two signals and provides a value ranging from 0 to 1 where ‘0’ means no difference and ‘1’ means maximum difference (Fortune et al., 1994).

Researchers have attempted to correlate the output of the hearing aids in terms of temporal deviations with that of speech recognition scores. The effect of attack time, release time (Arpitha & Manjula, 2012; Souza, 2012) and combination of WDRC and DNR (Hickson & Thyer, 2003; Muller, Weber, & Hornsby, 2006; Souza, 2002) algorithms on EDI have been studied.

Relationship between EDI and speech perception with different digital signal processing algorithms. Jenstad and Souza (2005, 2007) have reported that an increase in EDI resulted in a decrease in speech recognition scores for various compression ratios and release times of a WDRC hearing aid. Souza et al. (2012) have reported that the EDI value increases with increase in audibility, though it is more useful for describing the general distortion rather than comparing EDI syllable by syllable. Hence, the authors concluded that, the temporal changes caused by amplitude compression of hearing aids can be quantified using EDI.

Souza et al. (2012) studied the effect of combination of compression ratios and release times on processing consonant prefixed and suffixed to a vowel (VCV syllable). Higher the value of EDI, more was the voicing errors and manner errors for plosives and fricatives. In case of fricatives, instead of amplification, the hearing aid compresses it, thereby resulting in distortion of the speech signal.

In the study done by Jenstad and Souza (2005), the relationship between EDI and speech recognition scores were obtained for VC nonsense syllables. Higher EDI has been reported for shorter release time and lower EDI has been reported for longer release time constants. The reason for this has been attributed to the fact that, due to longer release time, the burst portion of stop consonant also gets compressed. Whereas, for a shorter release time, the amplitude of the burst has been reported to increase due to amplification. They also reported that EDI was well correlated with the phoneme errors.

The acoustic changes were quantified using EDI and correlated with the quality rating to quantify the independent and interactive effects of compression, DNR and directionality by Geetha and Manjula (2014). The authors have recorded the output of the hearing aid and processed it for obtaining EDI. They also obtained quality rating in normal hearing individuals for the recorded outputs and tried relating the perceptual and the acoustical measure. The authors concluded that the temporal changes observed in the output of the hearing aid were irrespective of the number of algorithms used in combined and independent manner. The results of the quality analysis revealed no significant difference in clarity rating across the aided conditions. Correlation was not done as the acoustical measures were done only once.

EDI with sentences and VCV stimuli. Pols and Schouten (1985) studied the plosive consonant identification in ambiguous sentences. They reported that the transition cues are more accessible for speech perception in sentence level than in VCV level even when the sentences were ambiguous. Sentences contain more redundant cues like segmentals and suprasegmental. Suprasegmentals like stress, rhythm and intonation are lacking in VCVs. The syntax and the semantic cues present in the segmental might also aid in the perception of sentences easier when compared to VCVs. Although the EDI was originally proposed for short speech segments, such as syllables, its application is expanded to sentences. The EDI obtained for syllables and sentences were reported to be similar for similar hearing aid compression conditions (Jenstad & Souza., 2005). However, this aspect has not been studied extensively and hence, strong evidences on the use of sentences s. VVCs for computing EDI is not available.

Need for the study. Many research studies have been carried out to evaluate the effect of different algorithms used in hearing aids on speech perception (Hickson & Thyer, 2003; Muller et al., 2006; Souza, 2002). The effects of the algorithms, like compression, DNR and directionality have been found to depend on the settings of the hearing aid and the noise conditions tested.

Temporal envelope cues have been reported to be important for speech recognition (Dorman et al., 1985; Gordon- Salant & Fitzgibbons, 1993; Healy & Warren, 2003; Price & Simon, 1984; Shannon et al., 1995). The advanced signal processing algorithms have been reported to alter these temporal envelope cues (Venn, Souza, Brennan, & Stecker, 2009). EDI has been used to quantify the distortions induced by the WDRC on the temporal envelope of the signal. While Jenstad and Souza (2005) reported a good correlation reported between the EDI and the speech recognition, Souza et al. (2012) stated that though it is not clear if EDI can be adapted as a clinical tool, EDI can be a useful tool to measure the temporal envelope changes induced by different compression settings. However, changes induced by DNR and directionality algorithms have not been quantified. As these algorithms are present in almost all advanced digital hearing aids at present, it is important to quantify the changes and correlate it with subjective measures.

Further, most of these studies have studied the independent effects of these algorithms. In real life, these algorithms may work simultaneously, depending on the environment. Hence, it is important to quantify the alterations in the temporal envelope when all of these algorithms work together and its effects on speech recognition.

It is known that the hearing aid’s behavior for a sentence can be different from that of syllables. All the above mentioned studies on EDI have used syllables and have found good correlation between EDI and speech recognition. However, Vinodhini (2015) found no correlation between EDI and sentence recognition.

Thus, in the present study, two kinds of target stimuli, sentences and VCV syllables were included. For VCV stimuli, consonants combined with vowel in /i/ in the initial and final position was used as /i/ covers the entire frequency bandwidth of hearing aid.

Aim of the study. The present study aimed-

- To find the effect of activation of different hearing aid algorithms on temporal changes and its influence on speech perception in adults and elderly individuals with hearing impairment, and
- To find the importance of the type of stimulus to judge the temporal changes by different hearing aid algorithms on speech perception in adults and elderly individuals with hearing impairment.

Objectives of the study. The objectives of the studies were-

1. To obtain speech recognition scores for sentences at 55, 65 & 80 dB SPL in noise at +5 dB SNR in both the age groups,
2. To obtain recognition scores of VCV syllables at 55, 65 & 80 dB SPL in noise at +5 dB SNR in both the age groups,
3. To record the output of the hearing aid at 55, 65 & 80 dB SPL in noise at +5 dB SNR using sentence and syllables for finding out EDI in both the age groups,
4. To correlate the EDI and the subjective measurements across different aided conditions within each age group, and
5. To compare the sentences recognition scores, VCV recognition scores and EDI across different algorithms within each age group.

The above were done in the unaided and in the aided conditions given below:

- Only DNR on
- Only directionality on
- Both DNR and directionality on
- Both DNR and directionality off.

METHODS

The current study aimed to evaluate the effect of different hearing aid algorithms on temporal envelope of speech stimuli using EDI, and its influence on speech perception in younger and older groups of individuals. The study also aimed to find out the effect of these algorithms on temporal envelopes of different lengths of stimuli. The method consisted of the following steps:

Step 1: Selection of participants

Step 2: Routine evaluation

Step 3: Hearing aid programming

Step 4: Experiment for subjective measurements

Step 5: Experiment for objective measurements

Step 1. Selection of participants

Two groups of participants with different age range were selected in the study. The younger group (Group I) had 20 participants (age range: 18 - 45 years) and the older group (Group II) had 20 participants (age range: 50 - 65 years). Participants fulfilling the following criteria were selected for the study.

Inclusion criteria.

- Participants with post-lingual mild to moderate flat sensorineural hearing loss were considered. The configuration was considered flat if the threshold difference between two adjacent octave frequencies was not more than 10 dB HL in the frequency range of 250 Hz and 8000 Hz (Kennedy, Levitt, Neuman, & Weiss, 1998),
- Speech identification scores in each ear were not less than 70%,
- On immittance evaluation, 'A' or 'As' type of tympanogram with acoustic reflex thresholds appropriate to the degree of hearing loss,
- Score of ≥ 24 in Mini Mental Status Examination (MMSE) as a score lesser than 24 is indicative of cognitive impairment. This was used to rule out cognitive impairment, if any, in older adults,
- Naïve users of amplification devices, and
- Native speakers of Kannada Language.

Exclusion criteria.

Participants with history / presence of middle ear disorders were excluded from the study. In addition, presence of neurological problems and psychological problems were ruled out through detailed case history.

Instrument Used

- A calibrated dual channel diagnostic audiometer was used for obtaining pure-tone thresholds, speech recognition threshold (SRT) and speech identification scores (SIS). The audiometer was connected to the TDH 39 head phones which was housed in MX-41 AR cushion, and a Radio Ear B-71 Bone vibrator.

- GSI-Tympstar middle ear analyzer was used to assess the functioning of the middle ear by carrying out tympanometry and tracing acoustic reflex thresholds.
- A 16-channel digital WDRC hearing aid with the following features were selected with the:
  - Fitting range of mild to moderately-severe degree,
  - Option of disabling/enabling the DNR and directionality algorithms individually,
- A personal computer loaded with NOAH and hearing aid fitting software was used to program the hearing aids. Programming was done through NOAH Link with appropriate cables.
- Bruel and Kjaer sound level meter (model no. 2270) was used with an ½ inch free-field microphone for the calibration of the stimuli.
- For both the experimental tasks, two Genelec 8020B loudspeakers mounted on Iso-Pod™ (Isolation position/decoupler™) vibration insulating stand were located at 0^o and 180^o Azimuth. The loudspeakers were arranged with two meters' radial diameter from the center.
- The stimuli were calibrated and presented using Cubase 6 software and HP work station desktop using Lynx Aurora Sound card and Signal router hardware.

Test environment

A sound treated double room air conditioned set-up was used to administer all the routine audiological tests. The noise level in the testing room was maintained within the permissible limits (ANSI, 1999).

Stimuli

- For obtaining SRT, Kannada paired words developed at the Department of Audiology, All India Institute of Speech and Hearing, Mysuru, was used.
- SIS in the routine hearing evaluation was obtained using the phonemically balanced (PB) word lists in Kannada language developed by Yathiraj and Vijayalakshmi (2005). This test has four equivalent lists with 25 words each.
- Sentence Recognition Scores (SRS) was assessed using the sentence test in Kannada language developed by Geetha, Manjula, Sharath and Pawan (2014). This test has twenty-five equivalent lists with ten sentences each.
- Recorded VCV (21 consonants combined with vowel /i/) syllables were used for obtaining consonant recognition scores.

Step 2. Routine evaluation

Pure-tone thresholds were obtained with the help of a calibrated dual channel diagnostic audiometer using the modified Hughson and Westlake procedure (Carhart & Jerger, 1959). This was done at octave frequencies from 250 Hz to 8000 Hz for obtaining air conduction thresholds and from 250 Hz to 4000 Hz for bone conduction thresholds. Pure-tone average (PTA) was obtained by averaging the air conduction thresholds obtained at 500 Hz, I kHz, 2 kHz and 4 kHz.

SRT was obtained using Kannada paired words and was correlated with PTA. SIS was obtained at 40 dB SL with phonemically balanced words in Kannada developed by Yathiraj and Vijayalakshmi (2005).

Immittance Evaluation was also done on all participants. GSI-Tympstar middle ear analyzer was used for tympanometry and acoustic reflex assessment. Participants satisfying the selection criteria based on the results of the above tests were involved in further evaluations.

Step 3. Hearing aid programming

The participants were fitted with the hearing aid that was connected to a personal computer with NOAH-3 software connected through Noah link with appropriate programming cable. The programming was done based on the NAL-NL1 formula and optimization level set to '2'. The gain was optimized till all the ling’s six sounds were identified correctly. The compression settings were kept at default. Routing hearing aid evaluation was carried out by asking five questions and SIS for words at 40 dB HL. Initially, the programming was done without enabling DNR and directionality. Later, either DNR and directionality or both of them were enabled to constitute different aided conditions for the actual experiment.

Step 4. Experiments for subjective measurements

VCV recognition and sentence recognition were the subjective measurements. Twenty one VCVs (/k/, /g/, /tʃ /, /t/, /d/, /ŋ/, /t/, /d/, /n/, /p/, /b/, /m/, /j/, /r/, /l/, /v/, /ʃ /, /s/, /h/, /l. /, and /dʒ/) which are frequently occurring in Kannada language (Ramakrishna et al., 1961) were spoken by 3 female speakers having Kannada as their mother tongue. These consonants were paired with low short central vowel /i/ in the initial and final position. Vowel /i/ was used as it has high frequency energy extending up to 6 KHz and hence containing a longer transition (Boothroyd & Medwetsky, 1992). The recordings were done by placing the microphone at 10 cm distance from the mouth of the speaker (Winholtz & Titze, 1997) using Adobe Audition version 3.0. The stimuli were digitized using 32 bit processor with a sampling frequency of 44,100Hz. In addition, a goodness test was done to verify the stimuli. 10 normal hearing individuals were asked to rate the naturalness on a 3-point rating scale and the speaker rated to have a natural utterance was selected. The test set up used was as shown in the Figure 1.

The programmed hearing aid was fitted to the participants. Recorded sentences developed by Geetha et al. (2014) were used to obtain the recognition scores for sentences and recorded VCVs were used to obtain VCV scores. The presentation of the stimuli was at 55, 65 and 80 dB SPL routed through Lynx aurora signal router through the loudspeaker placed at 0˚Azimuth, and the speech shaped noise was presented through loud speakers placed at 180˚Azimuth. A pilot study was carried out with 5 participants to trace the SNR at which 50% scores could be obtained. SNR-50 was carried out for the sentence material. The results showed that a range of +4 to +7 dB SNR was required to obtain SNR-50. Hence, the experiment was carried out at +5 dB SNR. The listeners were asked to repeat the words in the sentences. The responses were noted down in a response sheet. The SRS was calculated based on the total number of key words repeated correctly for each list. The maximum number of key words in each list was 40. The same procedure was done in unaided and all aided conditions given below:

- DNR on and directionality off
- Directionality on and DNR off
- Both DNR and directionality on
- Both DNR and directionality off.

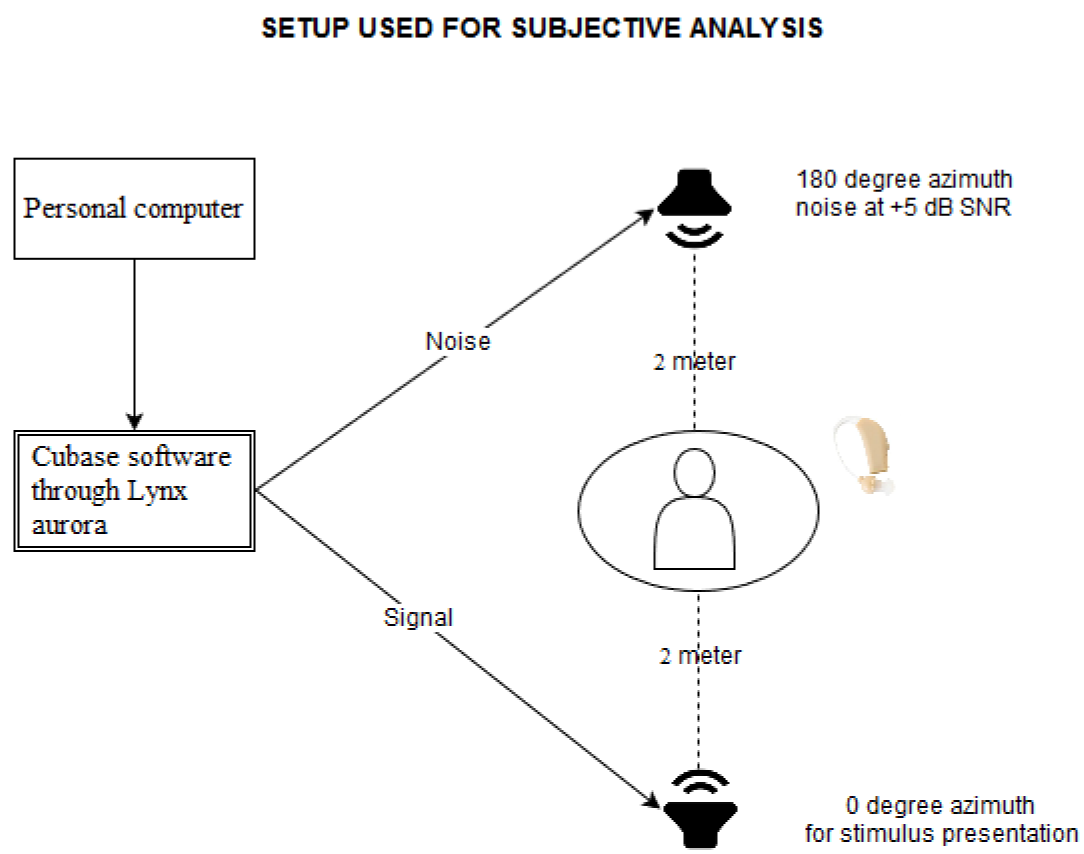

Figure 1: Setup used for subjective analysis.

Step 5. Experiments for objective measurement

For the objective measurement, that is, estimating EDI, the recorded sentences and VCV syllables were presented through Cubase software routed through Lynx aurora signal router to the loudspeaker placed at 0˚ azimuth and the speech shaped noise was presented through loud speakers placed at 180˚azimuths. The recordings were done at 55 dB SPL, 65 dB SPL and 80 dB SPL at +5 dB SNR. The test setup was as shown in Figure 2. As shown in Figure 2, the hearing aid programmed for each participant was fitted to the KEMAR independently. The KEMAR was connected to the SLM to record the output of the hearing aid. The recordings were done in unaided (unprocessed) condition and in the following aided conditions:

- DNR on and directionality off
- Directionality on and DNR off
- Both DNR and directionality on
- Both DNR and directionality off.

Ten unaided and its aided version of sentences that were recorded in each of the experimental conditions were analyzed for temporal content using envelope difference index (EDI). A method of EDI developed by Fortune et al. (1994) was adopted to determine the extent to which the hearing aid altered the natural temporal characteristic of the sentence in each experimental condition. The unaided stimulus and aided version of the stimulus were rectified, filtered with digitally low-pass filtered (Butterworth 6th order filter with a 50 Hz cut-off), and down sampled (sampling frequency of 6 kHz). Further, the mean amplitude was calculated from the down sampled envelope. Each sampled data point in the envelope was scaled to the mean amplitude by dividing every value by the mean amplitude. This provided a common reference for comparing the two envelopes to obtain the EDI. The EDI was calculated using the equation suggested by Fortune et al. (1994). The EDI was computed using the MATLAB code for each of the experimental conditions.

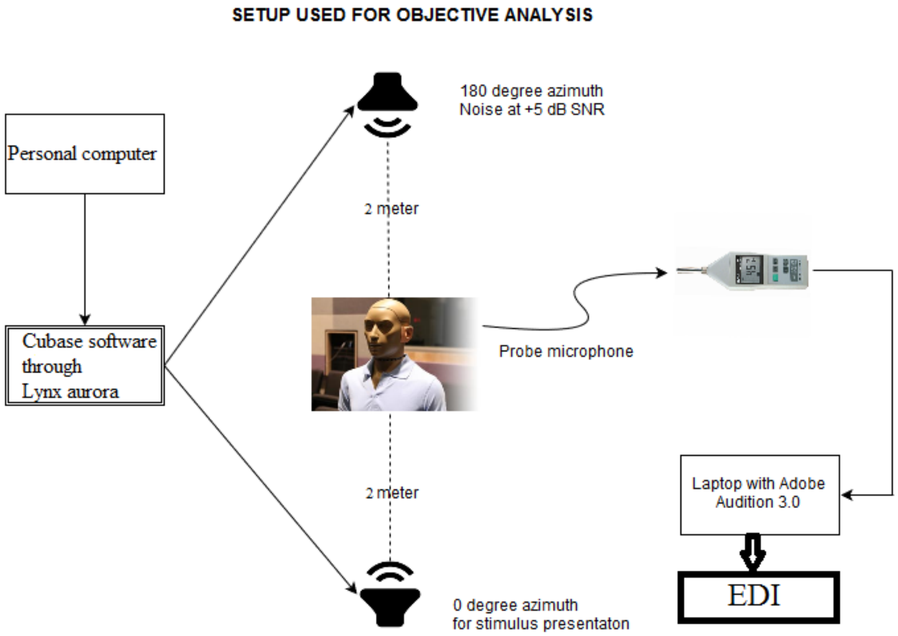

Figure 2: Setup used for objective analysis.

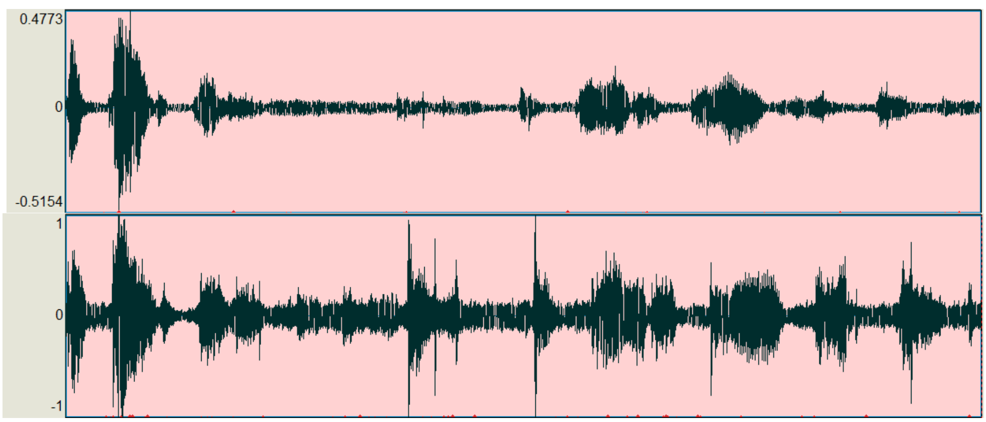

Figure 3: The upper panel shows waveform of a sentence in the unprocessed condition recorded at 65 dB SPL and the lower panel shows waveform of a sentence recorded in the aided condition with both directionality and DNR algorithm activated at 65 dB SPL. The EDI in this condition was measured as 0.297.

Statistical analysis:

Statistical Package for Social Sciences (SPSS, version 17.0) software was used for tabulating and statistically analyzing the data obtained. The obtained data did not follow normal distribution as indicated in Shapiro-Wilks test of normality. Hence, for both Group 1 and Group 2, the comparison across aided conditions were made at each presentation level using Friedman's test followed by Wilcoxon signed rank test for pair-wise analysis. For correlating EDI with speech perception, spearman's correlation was used.

RESULTS

The aim of the present study was to find the changes in the temporal envelope of the signal induced by the activation of different noise reduction algorithms, and to quantify its effect on speech perception in older and younger groups of individuals. Another aim was to find the effect of activation of different noise reduction algorithms on temporal envelope using different lengths of stimuli.

The data were analyzed statistically using SPSS (Statistical package for social science) software version 17. Shapiro-Wilks test of normality was carried out and the results revealed that the data did not follow a normal distribution in any of the conditions in both the groups. Hence, non- parametric tests were used.

Effect of hearing aid algorithms on Sentence Recognition Scores (SRS) in Group I

The descriptive statistics of SRS across aided conditions are given in Table 1. From the Table 1, it is clear that the SRS ranged from 3 to 35. Higher SRS is indicative of good speech perception. SRS was better in the aided conditions when compared to the unaided condition. The scores were similar among the aided conditions. However, there was an increase in SRS with increase in the presentation level. In order to verify these observations statistically, Friedman's test was carried out. The results showed a significant difference across aided conditions at 55 dB SPL (χ^2 (4) = 67.311, p = 0.000), 65 dB SPL (χ^2 (4) = 52.041, p = 0.000) and 80 dB SPL (χ^2 (4) = 54.187, p = 0.000) presentation level.

Table 1

Median and Standard deviation (SD) of SRS obtained across aided conditions in Group I (N = 20)

Aided condition	Presentation level	SRS		
		Mean	Median	SD
Unaided	55 dB SPL	04.55	03.00	5.06
	65 dB SPL	14.50	12.50	5.95
	80 dB SPL	23.00	24.50	5.69
DNR only	55 dB SPL	15.95	16.50	3.69
	65 dB SPL	32.35	33.00	3.57
	80 dB SPL	33.90	35.00	3.55
Directionality only	55 dB SPL	13.40	13.00	3.33
	65 dB SPL	30.40	30.50	2.82
	80 dB SPL	30.80	31.00	1.74
Both DNR and Directionality on	55 dB SPL	20.40	21.00	3.25
	65 dB SPL	33.10	32.50	2.63
	80 dB SPL	34.50	35.00	2.70
Both DNR and Directionality off	55 dB SPL	14.95	14.00	2.56
	65 dB SPL	29.30	30.00	3.01
	80 dB SPL	31.00	31.00	1.62

Note. SRS- Sentence Recognition Scores (Maximum possible score = 40); DNR- Digital Noise Reduction.

Further, Wilcoxon signed rank test was carried out to verify pair-wise differences. The results of this are given in the Table 2. The results revealed that, at all the presentation levels, the SRS obtained in the unaided condition was significantly lesser when compared to all the aided conditions.

Table 2

Comparison of SRS across different aided conditions using Wilcoxon signed rank test in Group I

Presentation Level	Conditions	|Z|	Significance
55 dB SPL	Unaided vs. DNR only	3.937	0.000***
	Unaided vs. Directionality only	3.942	0.000***
	Unaided vs. Both DNR and Directionality on	3.936	0.000***
	Unaided vs. Both DNR and Directionality off	3.925	0.000***
	DNR only vs. Directionality only	3.194	0.001**
	DNR only vs. Both DNR and Directionality on	3.947	0.000***
	DNR only vs. Both DNR and Directionality off	1.370	0.171
	Directionality only vs. Both DNR and Directionality on	3.948	0.000***
	Directionality only vs. Both DNR and Directionality off	2.145	0.032*
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.943	0.000***
65 dB SPL	Unaided vs. DNR only	3.936	0.000***
	Unaided vs. Directionality only	3.925	0.000***
	Unaided vs. Both DNR and Directionality on	3.936	0.000***
	Unaided vs. Both DNR and Directionality off	3.930	0.000***
	DNR only vs. Directionality only	2.002	0.045*
	DNR only vs. Both DNR and Directionality on	0.986	0.324
	DNR only vs. Both DNR and Directionality off	3.561	0.000***
	Directionality only vs. Both DNR and Directionality on	3.026	0.002**
	Directionality only vs. Both DNR and Directionality off	0.965	0.334
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.414	0.001**
80 dB SPL	Unaided vs. DNR only	3.944	0.000***
	Unaided vs. Directionality only	3.931	0.000***
	Unaided vs. Both DNR and Directionality on	3.927	0.000***
	Unaided vs. Both DNR and Directionality off	3.732	0.000***
	DNR only vs. Directionality only	3.266	0.001**
	DNR only vs. Both DNR and Directionality on	0.646	0.519
	DNR only vs. Both DNR and Directionality off	2.738	0.006**
	Directionality only vs. Both DNR and Directionality on	3.595	0.000***
	Directionality only vs. Both DNR and Directionality off	0.418	0.676
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.619	0.000***

Note. *$p < 0.05$, **$p < 0.01$; ***$p < 0.001$; DNR- Digital Noise Reduction.

The results also revealed that, among the aided conditions, the combined activation of the algorithms resulted in significantly higher SRS when compared to independent activation of the algorithms at all the presentation levels. Further, the SRS obtained for ‘DNR only’ condition was significantly greater when compared to 'Directionality only' condition. SRS obtained at 'both on' (i.e., DNR + Directionality) condition yielded a greater SRS when compared to 'DNR only' condition and 'Directionality only' condition.

Effect of hearing aid algorithms on Envelope Difference Index (EDI) obtained for sentences in Group I

The descriptive statistics across presentation levels for different aided conditions are as shown in Table 3. From the Table 3, it is clear that the EDI ranged from 0.243 to 0.341. A higher EDI value is indicative of a greater change in the temporal envelope of the processed signal when compared to the unprocessed signal. The EDI, as shown in the Table 3, is similar across different aided conditions except at 55 dB SPL wherein the EDI is slightly lesser.

Table 3

Median and Standard deviation (SD) of EDI obtained for sentences across aided conditions in Group I (N = 20)

Aided condition	Presentation level	EDI		
		Mean	Median	SD
DNR only	55 dB SPL	0.25	0.25	0.02
	65 dB SPL	0.32	0.32	0.02
	80 dB SPL	0.33	0.33	0.03
Directionality only	55 dB SPL	0.25	0.25	0.02
	65 dB SPL	0.33	0.33	0.03
	80 dB SPL	0.31	0.32	0.04
Both DNR and Directionality on	55 dB SPL	0.27	0.26	0.05
	65 dB SPL	0.34	0.34	0.03
	80 dB SPL	0.35	0.33	0.05
Both DNR and Directionality off	55 dB SPL	0.25	0.24	0.04
	65 dB SPL	0.31	0.31	0.03
	80 dB SPL	0.34	0.33	0.02

Note. DNR- Digital Noise Reduction.

Friedman's test was carried out for statistical comparison of EDI for sentences across aided conditions. The results showed that the EDI was significantly different across aided conditions only at 65 dB SPL (χ^2 (3) = 22.061, p = 0.000) and 80 dB SPL (χ^2 (3) = 9.091, p = 0.000) and was not significantly different at 55 dB SPL. Hence, pair-wise analysis was carried out using Wilcoxon signed rank test across different aided conditions at 65 and 85 dB SPL.

Table 4

Comparison of EDI obtained across different aided conditions and presentation levels using Wilcoxon signed rank test in Group I

		Conditions	|Z|	Significance
Across aided conditions	65 dB SPL	DNR only vs. Directionality only	1.918	0.050*
		DNR only vs. Both DNR and Directionality on	2.933	0.003**
		DNR only vs. Both DNR and Directionality off	1.046	0.295
		Directionality only vs. Both DNR and Directionality on	1.346	0.178
		Directionality only vs. Both DNR and Directionality off	3.175	0.001**
		Both DNR and Directionality on vs. Both DNR and Directionality off	2.765	0.006**
	80 dB SPL	DNR only vs. Directionality only	2.580	0.010*
		DNR only vs. Both DNR and Directionality on	1.830	0.067
		DNR only vs. Both DNR and Directionality off	0.149	0.881
		Directionality only vs. Both DNR and Directionality on	2.839	0.005**
		Directionality only vs. Both DNR and Directionality off	2.724	0.006**
		Both DNR and Directionality on vs. Both DNR and Directionality off	1.868	0.062

Note. *p < 0.05, **p < 0.01; DNR- Digital Noise Reduction.

The results of this are given in Table 4. The results revealed that 'Directionality only' condition resulted in a significantly greater EDI when compared to 'DNR only' condition at 65 dB SPL and it was the other way around at 80 dB SPL. At 65 dB SPL, 'Both on' condition resulted in greater EDI when compared to 'DNR only' condition and 'Both off' condition. In addition, 'Directionality only' condition resulted in greater EDI when compared to 'Both off' condition. Whereas at 80 dB SPL, 'Both on' and 'Both off' condition resulted in greater EDI when compared to 'Directionality only' condition.

Comparison of SRS and EDI for sentences in Group I

In order to study the relationship between EDI and SRS, spearman's correlation was carried out. The results revealed that the SRS was not significantly correlating ($p > 0.05$) with EDI obtained for sentences in any of the aided conditions.

Table 5

Correlation between EDI and SRS using Spearman's correlation in Group I

Aided condition	Presentation level	ρ	Significance
DNR only	55 dB SPL	-0.270	0.250
	65 dB SPL	0.049	0.839
	80 dB SPL	-0.188	0.428
Directionality only	55 dB SPL	-0.220	0.350
	65 dB SPL	-0.126	0.598
	80 dB SPL	0.163	0.492
Both DNR and Directionality on	55 dB SPL	-0.012	0.961
	65 dB SPL	0.038	0.874
	80 dB SPL	-2.000	0.398
Both DNR and Directionality off	55 dB SPL	-0.239	0.309
	65 dB SPL	0.030	0.899
	80 dB SPL	0.307	0.188

Note. DNR- Digital Noise Reduction.

Effect of hearing aid algorithms on VCV perception in Group I

The descriptive statistics of VCV perception for different aided conditions across different presentation levels are given in Table 6. The Table 6 shows that the scores for VCV perception were greater for aided conditions when compared to the unaided condition. Among the aided conditions, the VCV recognition scores were similar across the conditions where DNR was activated.

Table 6

Median and Standard deviation (SD) of VCV recognition scores across different aided conditions in Group I (N = 20)

Aided condition	Presentation level	*VCV recognition scores*		
		Mean	Median	SD
Unaided	55 dB SPL	01.15	1.00	1.03
	65 dB SPL	01.90	2.00	1.54
	80 dB SPL	04.75	4.50	2.08
DNR only	55 dB SPL	04.97	5.00	1.55
	65 dB SPL	11.67	12.00	1.24
	80 dB SPL	12.25	12.50	2.01
Directionality only	55 dB SPL	03.07	3.00	1.61
	65 dB SPL	10.90	10.50	1.47
	80 dB SPL	12.12	12.00	1.76
Both DNR and Directionality on	55 dB SPL	05.65	5.00	2.40
	65 dB SPL	12.02	12.50	2.09
	80 dB SPL	12.17	12.00	1.83
Both DNR and Directionality off	55 dB SPL	04.22	4.00	1.53
	65 dB SPL	11.10	10.50	2.08
	80 dB SPL	11.10	11.00	2.07

Note. DNR- Digital Noise Reduction; Maximum VCV score possible was 21.

The results of Friedman's test showed that the scores for VCV syllables at 55 dB SPL (χ^2 (4) = 48.764, p = 0.000), 65 dB SPL (χ^2 (4) = 47.000, p = 0.000) and 80 dB SPL (χ^2 (4) = 44.699, p = 0.000) presentation levels were significantly different between the aided conditions. Further analysis was done using Wilcoxon signed rank test. The results of this are given in Table 7.

Table 7

Comparison of VCV scores obtained across aided conditions using Wilcoxon signed rank test in Group I

Presentation level	Conditions	|Z|	Significance
55 dB SPL	Unaided vs. DNR only	3.933	0.000**
	Unaided vs. Directionality only	3.345	0.001**
	Unaided vs. Both DNR and Directionality on	3.833	0.000**
	Unaided vs. Both DNR and Directionality off	3.789	0.000**
	DNR only vs. Directionality only	3.280	0.001**
	DNR only vs. Both DNR and Directionality on	1.092	0.275
	DNR only vs. Both DNR and Directionality off	1.761	0.078
	Directionality only vs. Both DNR and Directionality on	3.100	0.002**
	Directionality only vs. Both DNR and Directionality off	3.195	0.001**
	Both DNR and Directionality on vs. Both DNR and Directionality off	1.734	0.083
65 dB SPL	Unaided vs. DNR only	3.942	0.000**
	Unaided vs. Directionality only	3.937	0.000**
	Unaided vs. Both DNR and Directionality on	3.928	0.000**
	Unaided vs. Both DNR and Directionality off	3.926	0.000**
	DNR only vs. Directionality only	2.131	0.033*
	DNR only vs. Both DNR and Directionality on	0.883	0.377
	DNR only vs. Both DNR and Directionality off	1.454	0.146
	Directionality only vs. Both DNR and Directionality on	1.730	0.084
	Directionality only vs. Both DNR and Directionality off	0.339	0.734
	Both DNR and Directionality on vs. Both DNR and Directionality off	1.763	0.078
80 dB SPL	Unaided vs. DNR only	3.933	0.000**
	Unaided vs. Directionality only	3.935	0.000**
	Unaided vs. Both DNR and Directionality on	3.931	0.000**
	Unaided vs. Both DNR and Directionality off	3.733	0.000**
	DNR only vs. Directionality only	0.749	0.454
	DNR only vs. Both DNR and Directionality on	0.357	0.721
	DNR only vs. Both DNR and Directionality off	2.099	0.036
	Directionality only vs. Both DNR and Directionality on	0.546	0.585
	Directionality only vs. Both DNR and Directionality off	2.346	0.019*
	Both on vs. Both DNR and Directionality off	2.477	0.013*

Note. $*p < 0.05$; $**p < 0.01$; DNR- Digital Noise Reduction.

The results revealed that VCV recognition scores were significantly greater in all the aided conditions than that of the unaided condition at all presentation levels. Comparison within the aided conditions revealed that at 55 dB SPL, ‘Directionality only’ condition yielded significantly poor scores when compared to 'DNR only', 'Both on' and 'Both off' conditions. Even at 65 dB SPL, the scores of VCV perception were significantly lesser for 'Directionality only' condition when compared to 'DNR only' condition. At 80 dB SPL, 'Both off' condition resulted in significantly lesser scores for VCV perception when compared to 'Directionality only' and 'Both on' condition. There was no significant difference among any other conditions at any presentation levels.

Effect of hearing aid algorithms on EDI obtained for VCV in Group I:

The EDI obtained for 21 VCVs were obtained for each aided condition and computed for analysis. The descriptive analysis of the same is given in Table 8. From the Table 8, it is clear that the EDI ranged from 0.140 to 0.220, where EDI was observed to be greater for conditions wherein either DNR or directionality was activated alone and the least for conditions where both of these algorithms were activated together. It is also clear that EDI increases with increase in the presentation level.

Table 8

Median and Standard deviation (SD) of EDI for VCV across different aided conditions in Group I (N = 20)

Aided condition	Presentation level	EDI		
		Mean	Median	SD
DNR only	55 dB SPL	0.14	0.14	0.02
	65 dB SPL	0.19	0.20	0.02
	80 dB SPL	0.19	0.20	0.03
Directionality only	55 dB SPL	0.15	0.14	0.02
	65 dB SPL	0.17	0.17	0.03
	80 dB SPL	0.22	0.21	0.01
Both DNR and Directionality on	55 dB SPL	0.14	0.14	0.01
	65 dB SPL	0.17	0.19	0.03
	80 dB SPL	0.18	0.19	0.03
Both DNR and Directionality off	55 dB SPL	0.15	0.14	0.02
	65 dB SPL	0.19	0.19	0.02
	80 dB SPL	0.21	0.22	0.02

Note: DNR- Digital Noise Reduction.

To verify the above observations statistically, Friedman's test was carried out. The results showed that the EDI obtained was significantly different across aided conditions at 65 dB SPL (χ^2 (3) = 14.589, p = 0.002) and 80 dB SPL (χ^2 (3) = 10.706, p = 0.013) presentation levels. Further, pair-wise analysis was carried out with Wilcoxon signed rank test. The results are given in Table 9.

Table 9

Comparison of EDI obtained across aided conditions using Wilcoxon signed rank test in Group I

	Conditions	∣Z∣	Significance
65 dB SPL	DNR only vs. Directionality only	2.879	0.004**
	DNR only vs. Both DNR and Directionality on	2.162	0.031*
	DNR only vs. Both DNR and Directionality off	1.903	0.057
	Directionality only vs. Both DNR and Directionality on	1.244	0.214
	Directionality only vs. Both DNR and Directionality off	2.844	0.004**
	Both DNR and Directionality on vs. Both DNR and Directionality off	1.983	0.047*
80 dB SPL	DNR only vs. Directionality only	2.419	0.016*
	DNR only vs. Both DNR and Directionality on	0.822	0.411
	DNR only vs. Both DNR and Directionality off	0.748	0.455
	Directionality only vs. Both DNR and Directionality on	2.916	0.004**
	Directionality only vs. Both DNR and Directionality off	0.915	0.360
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.181	0.001**

Note. $*p < 0.05$, $**p < 0.01$; DNR- Digital Noise Reduction.

At 65 dB SPL, EDI for VCV in ‘DNR only condition was significantly greater when compared to ‘Directionality only’ and ‘Both on’ condition (as shown in the Table 9). ‘Both off’ condition yielded a significantly greater EDI when compared to ‘Directionality only’ and ‘Both on’ condition. At 80 dB SPL, ‘Directionality only’ conditions yielded significantly greater EDI when compared to ‘DNR only’ and ‘Both on’ condition. ‘Both off’ condition resulted in significantly greater EDI than ‘Both on’ condition.

Comparison of measured VCV scores and EDI in Group I:

To study the relationship between EDI and VCV scores, spearman’s correlation was carried out. The result revealed that the VCV scores did not have a significant correlation ($p > 0.05$) with EDI obtained for VCVs across presentation levels and aided conditions as shown in Table 10.

Table 10

Results of Spearman's correlation between EDI and VCV scores in Group I

Aided condition	Presentation level	ρ	Significance
DNR only	55 dB SPL	-0.078	0.745
	65 dB SPL	0.468	0.067
	80 dB SPL	-0.015	0.948
Directionality only	55 dB SPL	-0.306	0.190
	65 dB SPL	-0.390	0.089
	80 dB SPL	0.154	0.518
Both DNR and Directionality on	55 dB SPL	-0.195	0.410
	65 dB SPL	0.095	0.689
	80 dB SPL	0.047	0.844
Both DNR and Directionality off	55 dB SPL	-0.023	0.922
	65 dB SPL	-0.335	0.148
	80 dB SPL	-4.66	0.074

Note. DNR-Digital Noise Reduction.

Effect of type of stimuli on speech perception in Group I:

The speech recognition scores obtained for sentences and VCV was compared using Wilcoxon signed rank test. The results, as given in Table 11, revealed that the scores obtained for sentence recognition was significantly greater when compared to the scores obtained for VCV perception except unaided condition at 55 dB SPL. This indicates that irrespective of the aided condition, the perception of a longer duration stimuli yielded a better result when compared to a shorter duration stimuli.

Table 11

Comparison of speech perception scores obtained across stimuli using Wilcoxon signed rank test in Group I

Presentation level	Aided Condition	Z	Significance
55 dB SPL	Unaided	1.334	0.182
	DNR only	3.608	0.000***
	Directionality only	3.628	0.000***
	Both DNR and Directionality on	3.683	0.000***
	Both DNR and Directionality off	3.926	0.000***
65 dB SPL	Unaided	3.926	0.000***
	DNR only	3.854	0.000***
	Directionality only	3.930	0.000***
	Both DNR and Directionality on	3.888	0.000***
	Both DNR and Directionality off	3.683	0.000***
80 dB SPL	Unaided	3.923	0.000***
	DNR only	3.928	0.000***
	Directionality only	3.785	0.000***
	Both DNR and Directionality on	3.832	0.000***
	Both DNR and Directionality off	3.926	0.000***

Note. ****p* < 0.001; DNR- Digital Noise Reduction.

Effect of type of stimuli on EDI at all aided conditions in Group I:

The EDI obtained for sentences and VCV syllables were compared using Wilcoxon signed rank test. The results (given in Table 12) revealed that the scores obtained for sentences were significantly greater when compared to the EDI obtained for VCV syllables in all the conditions. This indicates that irrespective of the aided condition, the changes in the temporal envelope of a longer duration stimuli yielded a greater EDI when compared to a shorter duration stimuli.

Table 12

Comparison of EDI obtained across stimuli using Wilcoxon signed rank test in Group I

Presentation level	Aided Condition	Z	Significance
55 dB SPL	DNR only	3.922	0.000***
	Directionality only	3.890	0.000***
	Both DNR and Directionality on	3.885	0.000***
	Both DNR and Directionality off	3.923	0.000***
65 dB SPL	DNR only	3.922	0.000***
	Directionality only	3.924	0.000***
	Both DNR and Directionality on	3.922	0.000***
	Both DNR and Directionality off	3.933	0.000***
80 dB SPL	DNR only	3.925	0.000***
	Directionality only	3.739	0.000***
	Both DNR and Directionality on	3.923	0.000***
	Both DNR and Directionality off	3.923	0.000***

Note. ***$p < 0.001$; DNR- Digital Noise Reduction.

Effect of hearing aid algorithms on Sentence Recognition Scores (SRS) in Group II:

The descriptive statistics of SRS across different aided conditions for Group II are given in Table 13. From the Table 13, it is clear that the SRS ranged from 0 to 34. A greater score is indicative of good speech perception. SRS was better in the aided conditions when compared to the unaided condition. However, the scores were similar among the aided conditions. There was an increase in SRS with increase in the presentation level.

Table 13

Median and Standard deviation (SD) of SRS obtained across aided conditions in Group II (N=20)

Parameters		SRS		
Aided condition	Presentation level	Mean	Median	SD
Unaided	55 dB SPL	0.55	0.00	0.82
	65 dB SPL	4.65	3.50	4.87
	80 dB SPL	14.70	16.50	6.30
DNR only	55 dB SPL	14.75	15.50	6.29
	65 dB SPL	29.60	30.00	4.15
	80 dB SPL	33.85	34.50	2.96
Directionality only	55 dB SPL	12.35	13.00	4.88
	65 dB SPL	28.45	28.00	3.00
	80 dB SPL	31.60	32.00	1.82
Both DNR and Directionality on	55 dB SPL	16.35	18.50	5.04
	65 dB SPL	31.85	32.00	2.56
	80 dB SPL	34.80	35.00	2.35
Both DNR and Directionality off	55 dB SPL	13.15	14.00	4.96
	65 dB SPL	29.85	29.50	1.72
	80 dB SPL	31.45	31.00	3.34

Note. SRS- Sentence Recognition Scores (Maximum possible score = 40); DNR- Digital Noise Reduction.

In order to verify these observations statistically, Friedman's test was carried out. The results showed a significant difference across aided conditions at 55 dB SPL (χ^2 (4) = 61.344, p = 0.000), 65 dB SPL (χ^2 (4) = 51.099, p = 0.000) and 80 dB SPL (χ^2 (4) = 57.147, p = 0.000) presentation level. Further, Wilcoxon signed rank test was carried out to check for pair-wise differences. The results of this are given in Table 14.

Table 14

Comparison of SRS across aided conditions using Wilcoxon signed rank test in Group II

	Conditions	$\lvert Z \rvert$	Significance
55 dB SPL	Unaided vs. DNR only	3.926	0.000***
	Unaided vs. Directionality only	3.926	0.000***
	Unaided vs. Both DNR and Directionality on	3.925	0.000***
	Unaided vs. Both DNR and Directionality off	3.926	0.000***
	DNR only vs. Directionality only	2.971	0.003**
	DNR only vs. Both DNR and Directionality on	2.142	0.032*
	DNR only vs. Both DNR and Directionality off	1.312	0.190
	Directionality only vs. Both DNR and Directionality on	3.730	0.000***
	Directionality only vs. Both DNR and Directionality off	0.900	0.368
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.685	0.000***
65 dB SPL	Unaided vs. DNR only	3.932	0.000***
	Unaided vs. Directionality only	3.925	0.000***
	Unaided vs. Both DNR and Directionality on	3.923	0.000***
	Unaided vs. Both DNR and Directionality off	3.924	0.000***
	DNR only vs. Directionality only	1.335	0.182
	DNR only vs. Both DNR and Directionality on	2.459	0.014*
	DNR only vs. Both DNR and Directionality off	0.020	0.984
	Directionality only vs. Both DNR and Directionality on	2.978	0.003**
	Directionality only vs. Both DNR and Directionality off	1.612	0.107
	Both DNR and Directionality on vs. Both DNR and Directionality off	2.687	0.007**
80 dB SPL	Unaided vs. DNR only	3.929	0.000***
	Unaided vs. Directionality only	3.922	0.000***
	Unaided vs. Both DNR and Directionality on	3.925	0.000***
	Unaided vs. Both DNR and Directionality off	3.926	0.000***
	DNR only vs. Directionality only	2.332	0.020*
	DNR only vs. Both DNR and Directionality on	1.799	0.050*
	DNR only vs. Both DNR and Directionality off	2.345	0.019*
	Directionality only vs. Both DNR and Directionality on	3.269	0.001**
	Directionality only vs. Both DNR and Directionality off	0.303	0.762
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.412	0.001**

Note. *$p < 0.05$, **$p < 0.01$; ***$p < 0.001$; DNR- Digital Noise Reduction.

The results revealed that, at all the presentation levels, SRS in the unaided condition was significantly lesser than the aided conditions. Among the aided conditions, ‘DNR only’ had significantly better scores than ‘Directionality only’ condition. At all the presentation levels, 'Both on' condition resulted in a higher SRS when compared to 'DNR only', 'Directionality only' and 'Both off' conditions. In addition, 'DNR only' condition gave higher SRS when compared to 'Directionality only' condition at 55 dB SPL and 80 dB SPL presentation levels.

Effect of hearing aid algorithms on Envelope Difference Index (EDI) obtained for sentences in Group II:

The EDI was tabulated in SPSS. The descriptive statistics for the EDI across presentation levels and aided conditions are as shown in Table 15.

Table 15

Median and Standard deviation (SD) of EDI obtained across aided conditions in Group II (N=20)

Aided condition	Presentation level	EDI		
		Mean	Median	SD
DNR only	55 dB SPL	0.19	0.17	0.03
	65 dB SPL	0.22	0.21	0.02
	80 dB SPL	0.23	0.22	0.03
Directionality only	55 dB SPL	0.19	0.17	0.04
	65 dB SPL	0.20	0.20	0.03
	80 dB SPL	0.22	0.21	0.04
Both DNR and Directionality on	55 dB SPL	0.20	0.20	0.04
	65 dB SPL	0.21	0.20	0.04
	80 dB SPL	0.21	0.21	0.05
Both DNR and Directionality off	55 dB SPL	0.19	0.19	0.04
	65 dB SPL	0.20	0.20	0.03
	80 dB SPL	0.21	0.20	0.06

Note. DNR- Digital Noise Reduction.

It is clear from the Table 15 that the EDI ranged from 0.172 to 0.222. A greater EDI score indicates a greater change in the temporal envelope of the processed signal when compared to the unprocessed signal. At most of the presentation levels, 'DNR only' condition exhibited a higher EDI. It is also clear that EDI increases with increase in the presentation level. Friedman's test was carried out in order to check this statistically. The results showed that the EDI was significantly different at across different aided conditions only at 80 dB SPL (χ^2 (4) = 10.200, p = 0.017). Further, pair-wise analysis was carried out with Wilcoxon signed rank test. The results are given in Table 16. The results revealed that, expect between 'DNR only' and 'Directionality only', and between 'Both on' and 'Both off' conditions, all other conditions were significantly different from each other.

Table 16

Comparison of EDI across different aided conditions using Wilcoxon signed rank test in Group II

Parameter		Conditions	|Z|	Significance
Across aided conditions	80 dB SPL	DNR only vs. Directionality only	0.934	0.350
		DNR only vs. Both DNR and Directionality on	2.876	0.004**
		DNR only vs. Both DNR and Directionality off	2.576	0.010**
		Directionality only vs. Both DNR and Directionality on	2.726	0.006**
		Directionality only vs. Both DNR and Directionality off	2.222	0.026*
		Both DNR and Directionality on vs. Both DNR and Directionality off	0.243	0.808

Note. * $p < 0.05$, ** $p < 0.01$; DNR- Digital Noise Reduction.

Comparison of SRS and EDI in Group II:

To study the relationship between EDI and SRS, spearman's correlation was carried out. The result revealed that there was no significant correlation between SRS with EDI obtained for sentences across different aided conditions ($p > 0.05$) as shown in Table 17.

Table 17

Correlation between EDI and SRS in Group II using Spearman's correlation

Aided condition	Presentation level	*ρ*	Significance
DNR only	55 dB SPL	0.147	0.535
	65 dB SPL	-0.207	0.381
	80 dB SPL	-0.095	0.689
Directionality only	55 dB SPL	0.363	0.116
	65 dB SPL	0.232	0.326
	80 dB SPL	0.441	0.552
Both DNR and Directionality on	55 dB SPL	0.064	0.788
	65 dB SPL	0.345	0.136
	80 dB SPL	-0.271	0.248
Both DNR and Directionality off	55 dB SPL	0.225	0.340
	65 dB SPL	0.244	0.300
	80 dB SPL	0.169	0.477

Note. DNR- Digital Noise Reduction.

Effect of hearing aid algorithm on VCV perception in Group II:

The scores of VCV perception were computed and the descriptive statistics across different aided conditions are as shown in Table 18. From the Table 18, it is clear that the scores for VCV perception were greater for aided conditions when compared to the unaided condition. Among the aided conditions, the scores were similar for all the DNR activated conditions and were also similar between all the DNR deactivated conditions.

Table 18

Median and Standard deviation (SD) of VCV recognition scores across different aided conditions in Group II (N=20)

Aided condition	Presentation level	VCV recognition scores		
		Mean	Median	SD
Unaided	55 dB SPL	0.27	0.00	0.37
	65 dB SPL	0.92	0.50	1.04
	80 dB SPL	3.85	3.50	0.90
DNR only	55 dB SPL	2.15	2.50	0.91
	65 dB SPL	9.37	9.50	3.52
	80 dB SPL	11.62	12.25	3.04
Directionality only	55 dB SPL	2.47	2.50	1.29
	65 dB SPL	9.92	9.750	2.94
	80 dB SPL	12.40	12.50	2.69
Both DNR and Directionality on	55 dB SPL	3.42	3.50	0.79
	65 dB SPL	11.25	12.00	3.60
	80 dB SPL	12.62	11.00	3.32
Both DNR and Directionality off	55 dB SPL	2.95	2.50	1.51
	65 dB SPL	11.05	10.25	4.19
	80 dB SPL	10.97	10.50	2.97

Note. DNR- Digital Noise Reduction; Maximum VCV score possible was 21.

Friedman's test was carried out to test the above observations. The results showed that the scores for VCV obtained across different aided conditions at 55 dB SPL (χ^2 (4) = 46.545, p = 0.000), 65 dB SPL (χ^2 (4) = 45.701, p = 0.000) and 80 dB SPL (χ^2 (4) = 46.102, p = 0.000) presentation levels were significantly different. For further analysis, Wilcoxon signed rank test was carried out and the results of the same are given in Table 19. At 55 dB SPL, 'Both on' condition resulted in significantly greater scores than 'DNR only' and 'Directionality only' condition. At 65 dB SPL, the scores obtained for 'Both on' condition were significantly greater when compared to 'DNR only' condition. Whereas at 80 dB SPL, 'Both off' condition resulted in significantly lesser scores when compared to 'Both on' condition and 'Directionality only' condition.

Table 19

Comparison of VCV scores across different aided conditions using Wilcoxon signed rank test in Group II

	Conditions	│Z│	Significance
55 dB SPL	Unaided vs. DNR only	3.850	0.000***
	Unaided vs. Directionality only	3.837	0.000***
	Unaided vs. Both DNR and Directionality on	3.932	0.000***
	Unaided vs. Both DNR and Directionality off	3.828	0.000***
	DNR only vs. Directionality only	0.677	0.498
	DNR only vs. Both DNR and Directionality on	3.389	0.001**
	DNR only vs. Both DNR and Directionality off	1.603	0.109
	Directionality only vs. Both DNR and Directionality on	2.981	0.003**
	Directionality only vs. Both DNR and Directionality off	1.052	0.293
	Both DNR and Directionality on vs. Both DNR and Directionality off	1.175	0.240
65 dB SPL	Unaided vs. DNR only	3.926	0.000***
	Unaided vs. Directionality only	3.928	0.000***
	Unaided vs. Both DNR and Directionality on	3.930	0.000***
	Unaided vs. Both DNR and Directionality off	3.923	0.000***
	DNR only vs. Directionality only	1.245	0.213
	DNR only vs. Both DNR and Directionality on	2.769	0.006**
	DNR only vs. Both DNR and Directionality off	1.788	0.074
	Directionality only vs. Both DNR and Directionality on	1.729	0.084
	Directionality only vs. Both DNR and Directionality off	1.274	0.203
	Both DNR and Directionality on vs. Both DNR and Directionality off	0.121	0.904
80 dB SPL	Unaided vs. DNR only	3.928	0.000***
	Unaided vs. Directionality only	3.925	0.000***
	Unaided vs. Both DNR and Directionality on	3.928	0.000***
	Unaided vs. Both DNR and Directionality off	3.926	0.000***
	DNR only vs. Directionality only	1.371	0.170
	DNR only vs. Both DNR and Directionality on	1.686	0.092
	DNR only vs. Both DNR and Directionality off	0.694	0.488
	Directionality only vs. Both DNR and Directionality on	0.731	0.465
	Directionality only vs. Both DNR and Directionality off	2.635	0.008**
	Both DNR and Directionality on vs. Both DNR and Directionality off	2.209	0.027*

Note. *$p < 0.05$, **$p < 0.01$; ***$p < 0.001$; DNR- Digital Noise Reduction.

Effect of hearing aid algorithm on EDI obtained for VCV syllables in Group II:

The EDI for VCV syllables were averaged for each condition and computed for analysis. The descriptive analysis of the same is given in Table 20. From the table, it can be seen that the EDI ranged from 0.121 to 0.180 where EDI is greater for independent conditions and least for combined conditions. From Table 20, it is clear that the EDI ranged from 0.121 to 0.180. A greater EDI score indicatives a greater change in the temporal envelope of the processed signal when compared to the unprocessed signal. At most of the presentation levels, the Both on condition exhibited a higher EDI. It is also clear that EDI increases with increase in the presentation level.

Table 20

Median and Standard deviation (SD) of EDI for VCV obtained across aided conditions in Group II (N=20)

Aided condition	Presentation level	EDI		
		Mean	Median	SD
DNR only	55 dB SPL	0.11	0.12	0.01
	65 dB SPL	0.16	0.16	0.01
	80 dB SPL	0.16	0.15	0.16
Directionality only	55 dB SPL	0.13	0.13	0.16
	65 dB SPL	0.17	0.17	0.01
	80 dB SPL	0.16	0.16	0.01
Both DNR and Directionality on	55 dB SPL	0.18	0.17	0.02
	65 dB SPL	0.16	0.15	0.02
	80 dB SPL	0.16	0.16	0.02
Both DNR and Directionality off	55 dB SPL	0.16	0.16	0.17
	65 dB SPL	0.18	0.18	0.20
	80 dB SPL	0.18	0.18	0.19

Note. DNR- Digital Noise Reduction.

Friedman's test was carried out to compare EDI statistically across different aided conditions. The results showed that the EDI was significantly different across aided conditions at

55 dB SPL (χ^2 (3) = 51.543, p = 0.000), 65 dB SPL (χ^2 (3) = 25.402, p = 0.000) and 80 dB SPL (χ^2 (3) = 18.857, p = 0.000) presentation levels. Further, pair-wise analysis was carried out with Wilcoxon signed rank test. The results of the same are given in Table 21.

Table 21

Comparison of EDI obtained across aided conditions using Wilcoxon signed rank test in Group II

	Conditions	$\|Z\|$	Significance
55 dB SPL	DNR only vs. Directionality only	3.543	0.000***
	DNR only vs. Both DNR and Directionality on	3.920	0.000***
	DNR only vs. Both DNR and Directionality off	3.920	0.000***
	Directionality only vs. Both DNR and Directionality on	3.920	0.000***
	Directionality only vs. Both DNR and Directionality off	3.548	0.000***
	Both DNR and Directionality on vs. Both DNR and Directionality off	2.558	0.011*
65 dB SPL	DNR only vs. Directionality only	3.747	0.000***
	DNR only vs. Both DNR and Directionality on	0.579	0.563
	DNR only vs. Both DNR and Directionality off	2.633	0.008**
	Directionality only vs. Both DNR and Directionality on	2.838	0.005**
	Directionality only vs. Both DNR and Directionality off	1.027	0.304
	Both DNR and Directionality on vs. Both DNR and Directionality off	3.212	0.001**
80 dB SPL	DNR only vs. Directionality only	2.551	0.11
	DNR only vs. Both DNR and Directionality on	1.154	0.248
	DNR only vs. Both DNR and Directionality off	3.099	0.002**
	Directionality only vs. Both DNR and Directionality on	0.429	0.668
	Directionality only vs. Both DNR and Directionality off	3.305	0.001**
	Both DNR and Directionality on vs. Both DNR and Directionality off	2.203	0.028*

Note. *$p < 0.05$, **$p < 0.01$; ***$p < 0.001$; DNR- Digital Noise Reduction.

The results revealed that ‘DNR only’ and ‘Directionality only’ conditions were significantly different from all the other conditions at most of the presentation levels. Activation of directionality alone or DNR alone did not yield any significant difference.

Comparison of VCV scores and EDI in Group II:

Spearman's correlation was carried out to study the relationship between EDI and VCV scores in Group II. The result revealed that the VCV scores did not significantly correlate ($p>0.05$) with EDI obtained for VCVs in any of the aided conditions as shown in Table 22.

Table 22

Results of Spearman's correlation between EDI and VCV in Group II

Aided condition	Presentation level	ρ	Significance
DNR only	55 dB SPL	0.249	0.290
	65 dB SPL	0.184	0.439
	80 dB SPL	-0.030	0.900
Directionality only	55 dB SPL	-0.022	0.925
	65 dB SPL	-0.181	0.445
	80 dB SPL	-0.360	0.119
Both DNR and Directionality on	55 dB SPL	0.021	0.929
	65 dB SPL	-0.384	0.094
	80 dB SPL	-0.102	0.668
Both DNR and Directionality off	55 dB SPL	-0.146	0.539
	65 dB SPL	0.033	0.892
	80 dB SPL	0.248	0.292

Note. DNR- Digital Noise Reduction.

Effect of type of stimuli on speech perception in Group II:

The scores obtained for SRS and VCV perception was compared using Wilcoxon signed rank test. The results as given in Table 23 revealed that the scores obtained for sentence recognition was significantly greater when compared to the scores obtained for VCV perception except unaided condition at 55 dB SPL. This indicates that irrespective of the aided conditions, the perception of a longer duration stimuli yielded a better result when compared to a shorter duration stimuli.

Table 23

Comparison of speech perception scores obtained across stimuli using Wilcoxon signed rank test in Group II

Presentation level	Aided Condition	Z	Significance
55 dB SPL	Unaided	0.122	0.903
	DNR only	3.924	0.000***
	Directionality only	3.546	0.000***
	Both on	3.924	0.000***
	Both off	3.546	0.000***
65 dB SPL	Unaided	2.553	0.011**
	DNR only	3.786	0.000***
	Directionality only	3.927	0.000***
	Both on	3.786	0.000***
	Both off	3.927	0.003**
80 dB SPL	Unaided	3.533	0.000***
	DNR only	3.923	0.000***
	Directionality only	3.849	0.000***
	Both on	3.923	0.000***
	Both off	3.849	0.000***

Note. $^{**}p < 0.01$, $^{***}p < 0.001$; DNR- Digital Noise Reduction.

Effect of type of stimuli on EDI in Group II:

The EDI obtained for sentences and VCV syllables were compared using Wilcoxon signed rank test. The results (as given in Table 24) revealed that speech recognition scores obtained for sentences were significantly greater when compared to EDI obtained for VCVs. This indicates that irrespective of the aided conditions, the changes in the temporal envelope of a longer duration stimuli yielded a greater EDI when compared to a shorter duration stimuli.

Table 24

Comparison of EDI obtained across different stimuli using Wilcoxon signed rank test in Group II

Presentation level	Aided Condition	Z	Significance
55 dB SPL	DNR only	3.921	0.000***
	Directionality only	3.810	0.000***
	Both DNR and Directionality on	1.924	0.052
	Both DNR and Directionality off	2.801	0.005**
65 dB SPL	DNR only	3.921	0.000***
	Directionality only	3.623	0.000***
	Both DNR and Directionality on	3.472	0.001**
	Both DNR and Directionality off	2.446	0.014*
80 dB SPL	DNR only	3.921	0.000***
	Directionality only	3.921	0.000***
	Both DNR and Directionality on	2.782	0.005**
	Both DNR and Directionality off	1.811	0.070

Note. *$p < 0.05$, **$p < 0.01$; ***$p < 0.01$; DNR- Digital Noise Reduction.

The results across hearing aid algorithm varied for VCV and sentence perception. It also varied for EDI obtained for VCV and sentences. Overall, it can be inferred that activation of noise reduction algorithm has an influence on temporal envelope of the signal reflecting in better speech perception. When directionality is together activated with DNR, there is a negative effect observed on speech perception. The across stimuli analysis also revealed that the perception of sentence was superior when compared to VCVs and the temporal envelope changes induced by these algorithms were also comparatively more for sentences when compared to VCVs.

DISCUSSION

The aim of the present study was to find the changes in the temporal envelope of the signal induced by the activation of different noise reduction algorithms and to quantify the effect of these temporal envelope changes on speech perception in younger and older adults. Another aim was to find the effect of difference in the temporal envelope of the signal induced by different lengths of stimuli. The results are discussed as follows:

Effect of hearing aid algorithms on Sentence Recognition Scores (SRS) in Groups I and II:

The SRS in aided conditions were significantly greater than that of the unaided condition at all the presentation levels in both the younger and older adults. Similar results have been reported in the literature (Arpitha & Manjula, 2012; Aswathi & Geetha, 2013; Jenstad & Souza, 2005). The reason for this could be the improvement in audibility due to amplification from the hearing aid. As audibility increases, it has been reported to increase speech perception scores (Arpitha & Manjula, 2012; Aswathi & Geetha, 2013; Jenstad & Souza, 2005).

Among the aided conditions, at 55 dB SPL, activation of DNR resulted in better SRS when compared to Directionality only condition. However, the combined activation of the algorithms resulted in significantly higher SRS when compared to independent activation of the algorithms at all the presentation levels in both the groups. Similar results have also been reported by Nordrum et al. (2006), and Aswathi and Geetha (2013). The reason attributed to this was that the combinations of algorithms nullify the negative effects of independent algorithms. Hence, it is clear that when directionality is used along with DNR, the speech perception improved which was not observed for 'Directionality only' condition. The results obtained at 65 and 80 dB SPL showed that DNR only condition resulted in greater SRS scores when compared to Directionality only and when both the algorithms were deactivated. In addition, activation of both the algorithms resulted in significantly greater SRS when compared to ‘Directionality only and Both off’ conditions. Hence, it is clear that, at mid and high presentation levels, activation of DNR helps in speech perception in the presence of noise. Even though activation of Directionality alone did not result in better speech perception, the combined effects of these algorithms had helped in improving speech perception. Similar results were reported by Jenstad and Souza (2005).

The reason for the above results could be that the noise reduction strategies were studied by keeping compression parameters constant and the WDRC was always activated. It has been reported that WDRC algorithm has been reported to decrease the SNR (Souza, Jenstad, & Boike, 2006), as reflected in the decreased SRS when noise reduction strategies were deactivated. When the noise reduction strategies came into action, it would have helped in improving the SNR thereby improving SRS (Massola de Oliveira, Lopes, & Alves, 2010). Further, the results obtained at 65 dB SPL were similar to that obtained at 80 dB SPL. The reason for this could be the same amount of compression acting at two different presentation levels (Shanks, Wilson, Larson, & Williams, 2002) as the compression knee point was below these levels.

Effect of algorithms on Envelope Difference Index (EDI) obtained for sentences in Groups I and II:

At the lower presentation level, the EDI remained to be similar irrespective of the activation of one or more of these algorithms in Group I. A similar finding has been reported in literature (Geetha & Manjula, 2014). At lower presentation level, the hearing aid tends to amplify noise and speech equally (Dillon, 2001). Hence, the effects of noise reduction strategies were not significant at lower presentation levels across different aided conditions.

At 65 dB SPL, activation of both the algorithms and the Directionality algorithm alone resulted in greater EDI when compared to DNR only condition and deactivation of both the algorithms. Hence, it is clear that the activation of directionality and DNR has increased the temporal envelope changes of the incoming signal when combined with WDRC. This is against the results obtained in the study done by Geetha and Manjula (2014). This difference could be attributed to the difference in the activation of directionality feature in the hearing aid. In the current study, the source of speech and noise were spatially separated. From literature it is clear that, directionality functions effectively when the target signal and noise are spatially separated (Rickets et al., 2005). Whereas, in the earlier study, the presentation of speech and noise were from the same source. This would have contributed to the differences in the results. Group II had similar EDI across all the aided conditions at 55 and 65 dB SPL presentation levels.

Whereas at 80 dB SPL, 'DNR only', 'Both on and Both off' conditions resulted in greater EDI when compared to 'Directionality only' condition in Group I. In group II, there was a significant difference between most conditions only at 80 dB SPL. Activation of DNR resulted in increased temporal envelope change when compared to combined activation in this group as well. At higher presentation level, the compression would have its effect of the temporal envelope of the signal (Souza, 2002). This when combined with directionality, has resulted in a reduced EDI. This shows that the activation of directionality at higher levels has reduced the effect of WDRC on EDI. It is also clear that the EDI induced by DNR is greater when compared to directionality. Hence, it is clear that the noise reduction strategies reduce the effect of WDRC on temporal envelope. Among the noise reduction strategies, directionality reduces the effect of

WDRC more when compared to DNR. A similar nullifying effect of WDRC by DNR and directionality has also been reported earlier (Aswathi & Geetha, 2012; Vinodhini, 2015).

Correlation between SRS and EDI in Groups I and II:

There was no significant correlation between SRS and EDI in any of the conditions in both the groups. In the earlier studies done by Hoover et al. (2012) and Jenstad & Souza (2005), it has been reported that there is a strong negative correlation between EDI and subjective perception. Earlier, studies were only focused on this line by using WDRC (across different compression ratios and compression time constants) alone (Alexander & Masterson, 2015; Hoover & Souza, 2012; Jenstad & Souza, 2005; Jenstad & Souza, 2007). Vinodhini (2015) studied the combined effect of WDRC, DNR and directionality and reported a moderate level positive correlation between EDI and speech perception, which was only restricted to few parameters. However, in the present study, WDRC was kept constant and the effects of noise reduction strategies were measured independently and in a combined manner. The stimuli used in the present study were sentences, which was similar to earlier studies (Alexander & Masterson, 2015; Vinodhini, 2015; Jenstad & Souza, 2007; Walaszek, 2008). There was a difference in terms of the results between the earlier studies and the current study in spite of the similarity in the type of stimuli. Hence, it is clear that the variations in the results are due to the type of algorithm used.

In addition, in the earlier studies, the output of the hearing aids were recorded using a 2 CC coupler (Geetha & Manjula, 2014), ear simulator (Walaszek, 2008) and real ear (Vinodhini, 2015). The use of real ear measurement has been considered to increase the strength of the method and was argued to have more realistic outcomes. In the current study, the programmed hearing aid of each individual was fitted on the KEMAR and the output of the hearing aid was recorded. This could have been an additional factor that had contributed to the variations in the results.

Effect of algorithms on VCV perception in Groups I and II:

The VCV perception was found to be better in the aided conditions than the unaided condition similar to SRS. As mentioned earlier, improvement in the audibility resulted in better aided scores.

Among the aided conditions, at low and mid presentation levels, activation of both directionality and DNR resulted in better VCVs than when both were deactivated. These results were common to both the groups. ‘DNR only’ also resulted in equivalent VCV recognition scores when compared to ‘both on’ condition in group I whereas this was not observed in Group II. At 80 dB SPL, activation of directionality resulted in better VCV perception, and when both the algorithms are activated together it resulted in better speech perception. Across the other aided conditions the results were not similar at all the presentation levels.

The reason for this could be the difference in the functioning of WDRC algorithm. At lower presentation levels, there will be amplification of the signal and at higher presentation level, there would be compression of the signal. In general, vowels have more energy and consonants have lesser energy. Hence, the action of WDRC varies within VCV. This has been clearly reported by Dillon (2001) and Souza et al. (2012). Individuals also rely on the level difference between the consonant and vowel to identify few consonants (Balakrishnan, Freyman, Chiang, Nerbonne, & Shea, 1996; Freyman, Nerbonne, & Cote, 1991; Kennedy, Levitt, Neuman, & Weiss., 1998) especially affecting the place of articulation (Hedrick & Rice, 2000; Hedrick & Younger, 2001, 2003; Ohde & Stevens, 1983). Hence, this could have been a reason for variations in the results.

Effect of hearing aid algorithms on Envelope Difference Index (EDI) obtained for VCV in Groups I and II:

The EDI results for VCVs were similar to EDI for sentences in both the groups. That is, DNR alone resulted in increased variations in the temporal envelope of the stimuli and addition of directionality decreased the changes in the temporal envelope. As seen in EDI for sentences, EDI for VCVs also exhibited differences at each presentation levels. As discussed in earlier studies, it is clear that WDRC has a significant effect on the temporal envelope of the signal (Souza et al., 2012). The addition of noise reduction algorithms have not been reported to vary EDI (Geetha & Manjula, 2014). These variations in the results could be due to the variations in the methodology. In the current study, EDI was calculated separately for each individual. Whereas in the study done by Geetha and Manjula (2014), EDI was calculated only once. Hence, this could have resulted in the varied results. The level difference between a vowel and a voiced consonant is greater when compared to vowel and a voiceless consonant (Ellison, Harris, & Muller, 2003). Temporal envelope has been reported to carry voicing and manner of consonants and it has also been reported that the temporal envelope gets altered greatly by compression algorithm (Van Tasell & Trine, 1996). Hence, when DNR is activated along with WDRC, the envelope changes can be expected to be more pronounced.

Comparison of measured VCV and obtained EDI in Groups I and II:

The scores obtained for VCV perception was correlated with EDI obtained for VCVs. There was no significant correlation observed across any of the conditions similar to that was observed for sentences. It has been reported that EDI has good correlation with speech perception in the earlier studies using VCVs (Jenstad & Souza, 2005; Jenstad & Souza, 2007).

Though the type of stimuli used was same, the variations in the results between the current study and the earlier studies could be due to the type of algorithms activated. In the current study, WDRC was kept constant and the effects of noise reduction algorithms were alone studied. Whereas, in the earlier studies algorithm studied was restricted to WDRC alone.

In the earlier studies, the outputs of the hearing aid were recorded using a 2 cc coupler (Geetha & Manjula, 2014), ear simulator (Walaszek, 2008) and real ear measurement (Vinodhini, 2015). The use of real ear measurement was good and was argued to have more realistic outcomes. In the current study, the programmed hearing aid of each individual was fitted on the KEMAR and the output of the hearing aid was recorded. Hence, the acoustics of ear canal was included but this remained constant across the recordings. Hence, this could have been an additional factor that had contributed to the variations in the results.

Hence, it is clear that even when speech segment is audible and other cues like spectral cues, amplitude modulation are available speech perception might remain unaltered even with variations in the temporal envelope of the signal (Souza & Turner, 1996).

Effect of type of stimuli on speech perception at all aided conditions in Groups I and II:

The perceptual scores obtained for sentences were significantly greater than scores obtained for VCVs at all the tested conditions except at 55 dB SPL for unaided condition. This could be because of the fact that noise reduction algorithm tries to segregate the speech segment from the background noise. In this attempt, some essential parts of speech segments might have been filtered out (Bentler & Chiou, 2006; Levitt, 2001). Hence, more parts of speech would have been altered in a lengthier stimulus than a shorter stimulus. As the duration of the stimuli increases, the syntactic and semantic cues also increase. This in turn facilitates the perception of speech at a complex level. The internal redundancy of the stimuli could be one of the reasons for better perception of sentences. The segmentals and the suprasegmentals could have acted as another cue for better perception of sentences.

Effect of type of stimuli on EDI at all aided conditions in Groups I and II:

The EDI obtained for sentences were significantly greater when compared to EDI obtained for VCVs at most of the conditions aided conditions and presentation levels. The reason for this could be due to the inherent fluctuations within the speech stimuli. As the duration of stimuli increases, the variations in terms of the temporal envelope also increase. This could have led to an increased EDI for sentences. Since WDRC algorithm amplifies the low level sounds and compresses the high level sounds, there is more fluctuation in gain in sentences than VCVs (Dillon, 2001). Hence, the EDI for sentences are higher when compared to VCVs.

CONCLUSIONS:

It can be concluded from the results of the current study that the combined activation of the noise reduction algorithms along with WDRC significantly improves speech recognition scores when compared to independent activation of the algorithms at all the presentation levels in both younger and older individuals with hearing impairment. The temporal changes induced by these algorithms are only minimal and do not cause deterioration in speech recognition scores. In addition, the presentation level of speech and the length of stimuli may influence the working of these algorithms.

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REFERENCES

Alcantara, J. I., Moore, B. C. J., Kuhnel, V., & Launer, S. (2003). Evaluation of noise reduction system in a commercial digital hearing aid. *International Journal of Audiology, 42,* 34-42.

Alexander, J. M., & Masterson, K. (2015). Effects of WDRC release time and number of channels on output SNR and speech recognition. *Ear and Hearing, 36*, e35- e49.

Anderson, M. C. (2011). The role of temporal fine structure in sound quality perception. Unpublished thesis. University of Colorado, Boulder.

Anderson, M. C., Arehart, K. H., & Kates, J. M. (2013). The effects of noise vocoding on speech quality perception. *Hearing Research, 309,* 75- 83.

Arpita, V., & Manjula, P. (2012). Effects of compression release time in hearing aid on acoustic and behavioral measures of speech. *Unpublished Masteral Dissertation*, University of Mysore, Mysore.

Aswathi, S., & Geetha, C. (2013). The combined effect of compression and digital noise reduction algorithms on speech perception and speech quality. *Unpublished Masteral Dissertation*. University of Mysore, Mysore.

Balakrishnan, U., Freyman, R. L., Chiang, Y. C., Nerbonne, G. P., & Shea, K. J. (1996). Consonant recognition for spectrally degraded speech as a function of consonant-vowel intensity ratio. *Journal of the Acoustical Society of America, 99*, 3758–3769.

Bentler, R., & Chiou, L. (2006). Digital noise reduction: An overview. *Trends in Amplification, 10*, 67–82.

Boothroyd, A., & Medwetsky, L. (1992). Spectral distribution of /s/ and the frequency response of hearing aids. *Ear and Hearing, 13*, 150–157.

Boymans, M., & Dreschler, W. A. (2000). Field trials using a digital hearing aid with active noise reduction and dual- microphone directionality. *Audiology, 39*, 260- 268.

Carhart, R., & Jerger, J. (1959). Preferred method for clinical discrimination of pure tone thresholds. *Journal of Speech and Hearing Disorders, 24 (4)*, 330- 345.

Dillon, H. (2001). Binaural and bilateral considerations in hearing aid fitting. *Hearing aids.* New York, 370-403.

Dorman, M., Marton, K., & Hannley, M. (1985).Phonetic identification by elderly normal and hearing-impaired listeners. *Journal of the Acoustical Society of America, 77*, 664–670.

Ellison, J. C., Harris, F. P., Muller, T. (2003). Interactions of hearing aid compression release time and fitting formula: effects on speech acoustics. *Journal of American Academy of Audiology, 14*(2), 59-71.

Freyman, R. L., Nerbonne, G. P., & Cote, H. A. (1991).Effect of consonant-vowel ratio modification on amplitude envelope cues for consonant recognition. *Journal of Speech and Hearing Research, 34,* 415–426.

Fortune, T. W., Woodruff, B. D., & Preves, D. A. (1994). A new technique for quantifying temporal envelope contrasts. *Ear and Hearing, 15*, 93–99.

Gatehouse, S., Naylor, G., & Elberling, C. (2006). Linear and nonlinear hearing aid fittings: 1. Patterns of benefit. *International Journal of Audiology*, *45(3),* 130- 152.

Geetha, C., & Manjula, P. (2014). Effect of compression, digital noise reduction and directionality on envelope difference index, log- likelihood ratio and perceived quality. *Audiology Research, 4(1*), 46- 51.

Geetha, C., Kumar, K. S. S., Manjula, P., & Pavan, M. (2014). Development and standardization of sentence identification test in Kannada language. *The Journal of Hearing Science. 4(1),* 18- 26.

Gordon-Salant, S., & Fitzgibbons, P. J. (1993).Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech, Language and Hearing Research, 36*, 1276–1285.

Hansen, M. (2002). Effects of multi-channel compression time: Constants on subjectively perceived sound quality and speech intelligibility. *Ear and Hearing; 23(4),* 369-380.

Hamacher, V., Chalupper, J., Eggers, J., Fischer, E., Kornagel, U., Puder, H., &Rass, U. (2005). Signal processing in high-end hearing aids: State of the art, challenges, and future trends. *Journal of Application of Signal Process*, 2915–2929.

Healy, E. W., & Warren, R. M. (2003). The role of contrasting temporal amplitude patterns in the perception of speech. *Journal of the Acoustical Society of America, 113,* 1676–1688.

Hedrick, M. S., & Rice, T. (2000). Effect of a single-channel wide dynamic range compression circuit on perception of stop consonant place of articulation. *Journal of Speech, Language, and Hearing Research, 43*, 1174–1184.

Hedrick, M. S., & Younger, M. S. (2001). Perceptual weighting of relative amplitude and formant transition cues in aided CV syllables. *Journal of Speech, Language, and Hearing Research, 44*, 964–974.

Hedrick, M. S., & Younger, M. S. (2003). Labeling of /s / and /X/ by listeners with normal and impaired hearing, revisited. *Journal of Speech, Language, and Hearing Research, 46*, 636–648.

Hickson, L., & Thyer, N. (2003). Acoustic analysis of speech through a hearing aid: perceptual effects of changes with two channel hearing aids. *Journal of American Academy of Audiology, 14(8),* 414-426.

Hoover, E. C., Souza, P. E., & Gallun, F. (2012). The consonant- weighted Envelope Difference Index (cEDI): a proposed technique for quantifying envelope distortion. *Journal Speech Language and Hearing Research, 55 (6),* 1802- 1806.

Jenstad, L. M., & Souza, P. E. (2005).Quantifying the effect of compression hearing aid release time on speech acoustics and intelligibility. *Journal of Speech, Language, and Hearing Research, 48,* 651–667.

Jenstad, L. M., & Souza, P. E. (2007). Temporal envelope changes of compression and speech rate: Combined effects on recognition for older adults. *Journal of Speech, Language, and Hearing Research, 50*, 1123–1138.

Kennedy, E., Levitt, H., Neuman, A. C., & Weiss, M. (1998).Consonant-vowel intensity ratios for maximizing consonant recognition by hearing-impaired listeners. *Journal of the Acoustical Society of America, 103*, 1098–1114.

Levitt, H. (2001). Noise reduction in hearing aids: a review. *Journal of Rehabilitation Research and Development, 38,* 7- 19.

Levitt, H., Bakke, M., & Kates, J. (1993). Signal processing for hearing impairment. *Scandinavian Audiology Supplement, 38,* 7- 19.

Luts, H., Maj, J. B., Soede, W., & Wouters, J. (2004). Better speech perception in noise with an assistive multimicrophone array for hearing aids. *Ear and Hearing, 25 (5),* 411- 420.

Massola de Oliveira, J. R., Lopes, E. S., & Alves, A. F. (2010). Speech perception of hearing impaired people using a hearing aid with noise suppression algorithms. *Brazilian Journal of Otolaryngology, 76*(1), 14-17.

Moore, B. C. J., Glasberg, B. R., & Simpson, A. (1992). Evaluation of a method of simulating reduced frequency selectivity. *Journal of Acoustic Society of America, 91,* 3402–3423.

Moore, B. C. J., Stainsby, T. H., Alcántara, J. I., & Kühnel, V. (2004). The effect on speech intelligibility of varrying compression time constants in a digital hearing aid. *International Journal of Audiology, 43 (7),* 339- 409.

Muller, G., Weber, J., & Hornsby, B. (2006).The effect of digital noise reduction on the acceptance of background noise.*Trends in Amplification, 10(2),* 83- 93.

Neuman, A. C., Bakke, M.H., Mackersie, C., Hellman, S., & Levitt, H. (1998). the effect of compression ratio and release time on the categorical rating of sound quality. *Journal of the Acoustical Society of America, 103*(5), 2273- 2281.

Nordrum, S., Erler, S., Garstecki, D., &Dhar, S. (2006). Comparison if performance on the hearing in noise test using directional microphones and digital noise reduction algorithms. *American Journal of Audiology.15*: 81- 91.

Ohde, R. N., & Stevens, K. N. (1983). Effect of burst amplitude on the perception of stop consonant place of articulation. *Journal of the Acoustical Society of America, 74*, 706–714.

Pols, L. C. W., & Schouten, M. E. H. (1985).Plosive consonant identification in ambiguous sentences.*Journal of Acoustic Society of America*, *78 (1)*, 33- 39.

Price, P. J., & Simon, H. J. (1984).perception of temporal differences in speech by ‘‘normal-hearing’’ adults: effects of age and intensity. *Journal of the Acoustical Society of America*, *76*, 405–410.

Shannon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., &Ekelid, M. (1995).Speech recognition with primarily temporal cues. *Science*, *270*, 303–304.

Shanks, J. E., Wilson, R. H., Larson, V., & Williams, D. (2002). Speech recognition performance of patients with sensorineural hearing loss under unaided and aided conditions using linear and compression hearing aids. *Ear and Hearing*, *23,* 280- 290.

Souza, P. E. (2002). Effect of compression on speech acoustics, intelligibility, and sound quality. *Trends in Amplification*, *6*, 131- 165.

Souza, P. E., Hoover, H., & Gallun, F. (2012).Application of envelope difference index to spectrally sparse speech. *Journal of Speech, Language and Hearing Research*, *50*, 824-837.

Souza, P. E., & Turner, C. W. (1996).Effect of single channel compression on temporal speech information. *Journal of Speech and Hearing Research, 39,* 901–911.

Valente, M., Fabry, D.A. & Potts, L.G. (1995). Recognition of speech in noise with hearing aids using dual microphones. *Journal of the American Academy of Audiology, 6,* 440-449.

Van Tasell, D. J., & Trine, T. D. (1996). Effects of single-band syllabic amplitude compression on temporal speech information in nonsense syllables and in sentences. *Journal of Speech and Hearing Research, 39*, 912–922.

Venn, E., Souza, P., Brennan, M., Stecker, C. (2009).Effects of audibility and multichannel wide dynamic range compression on consonant recognition for listeners with severe hearing loss. *Ear and Hearing, 30(5),* 494-504.

Vinodhini, P. (2015). Relationship Between Envelope Difference Index (EDI) and Sentence Recognition & Speech Quality in Individuals with Hearing Impairment. *Unpublished Masteral Dissertation*, University of Mysore, Mysore.

Walaszek, J. (2008). Effect of compression in hearing aids on the envelope of the speech signal: Signal based measures of the side- effects of the compression and their relation to speech intelligibility. *Unpublished Masteral Thesis*. Technical University of Denmark, Lingby.

Winholtz, W. S., Titze, I. R. (1997). Conversion of a head-mounted microphone signal into calibrated SPL units. *Journal of Voice. 11*: 417-21.

Yathiraj, A., & Vijayalakshmi, C. S. (2005). *Phonetically balanced words list in Kannada.* Departmental project, Developed at the Department of Audiology, AIISH, Mysore.

Presentation of papers related to the ARF project titled 'Relationship between Envelop Difference Index (EDI) and Speech Perception with Noise Reduction Strategies in Hearing Aids

1. **Geetha C.,** Vinodhini P., & Hemanth N. (2016). 'Effect of number and type of algorithms in a hearing aid on temporal cues and speech perception'. Paper presented in 9th KSB ISHACON 2016 at Palakkad, Kerala on 23.010.2016. Received *Best Paper in Audiology –-II prize*
2. **Geetha C.,** Ms. Vinodhini P, Mr. Hemanth N. (2016). Does the length of stimuli affect the amount of temporal deviation of speech in a hearing aid?'. A scientific paper presented at 6th ISHA TN Conference 2016 at Puducherry from 19-20th Nov 16. Received *Audiology Best Poster Award –Ist Prize for the Paper*