Comparison of Channel Free^{TM} and Multi Channel Hearing Aids on Performance in Indviduals with Sensorineural Hearing Loss

Shamantha M[1]. & P. Manjula[2]

Abstract

Individuals with sensorineural hearing loss with flat and sloping configuration, face major problems such as reduced audibility, reduced dynamic range, reduced frequency selectivity and impaired temporal resolution giving rise to poor speech perception and listening discomfort, in quiet as well as in adverse listening situations. Multichannel hearing aids with wide dynamic range compression made their way in order to resolve some of these issues. The ChannelFreeTM hearing aids were developed claiming to improve speech intelligibility and listening comfort. To see the effect of channels on speech perception, a comparison of three-channel, five-channel and ChannelFreeTM hearing aids, in ears with flat and sloping SNHL, was done by collecting data on SIS in quiet using phonemically balanced words from eleven participants having flat SNHL and high frequency words for ten participants having sloping SNHL group. In addition, data on SNR-50 and quality rating from eleven ears of participants with flat SNHL and ten ears of participantswith sloping SNHL. The results revealed more benefit from ChannelFreeTM hearing aid processing in flat and sloping SNHL groups compared to three-channel and five-channel hearing aids in the presence of noise (SNR-50) and parameters of quality was perceived better in all parameters of quality except for loudness with ChannelFreeTM processing. The speech was perceived as softer with ChannelFreeTM compared to three-channel and five-channel hearing aids. Non-parametric tests revealed more benefit from ChannelFreeTM hearing aid processing in flat SNHL group of population compared to sloping SNHL group of population. Hence, the present study finds ChannelFreeTM hearing aid processing as a better amplification method for individuals with flat and sloping configuration of sensorineural hearing loss, as it provides better speech perception in the presence of noise and better quality of speech.

Key words: *Multichannel, ChannelFreeTM, Speech identification, SNR-50, Quality.*

Introduction

The major problems faced by individuals with sensorineural hearing loss (SNHL) is reduced audibility, reduced dynamic range, reduced frequency selectivity (Moore &Glasberg, 1997) and impaired temporal resolution (Nelson et al., 1997) giving rise to poor speech intelligibility and listening discomfort, in quiet as well as in adverse listening situations. In SNHL, the damage to outer hair cells (OHC) produces cochlear amplifier dysfunction (Dallos, 1973) and wider auditory filters (Glasberg& Moore, 1986).

To compensate for reduced audibility and reduced dynamic range, hearing aids have incorporated amplification and compression in order to improve speech audibility and comfort. The main goal of hearing aids is to amplify sounds such that it is audible and comfortable. The compression reduces gain for high level signals and amplification increases gain for low level signals (Johnson, 1993; Killion, 1996). The main rationale for splitting the audible frequency range into independent channels was to apply processing schemes such as amplitude compression in specific frequency region, also known as Wide Dynamic Range Compression (WDRC) (Bor et al., 2008).

According to Moore (2008), fast systems have attack and release times between 5 and 200 ms, whereas slow systems have attack and release times exceeding 500 ms. Consequently, the time constants used in a WDRC system can have a significant effect on the intelligibility and comfort of the speech signal (Dillon, 2001)

Yund and Buckles (1995) reported that fewer channels bands in hearing aids help individuals with sloping sensorineural hearing loss to perceive speech as clear. They evidenced at least eight channels to be incorporated in hearing aids which are sufficient to provide information across frequency bands since there was no performance difference between eight channel and twelve channel hearing aids while speech scores improved from four channels to eight channels. They stated the drawbacks of multichannel amplification as formant disruption, timbre disruption and co-articulation which interferes with sound quality and speech intelligibility (Dillon, 2001).

In order to overcome limitations of eight channel or multichannel hearing aids, ChannelFreeTM hearing aids were developed claiming to improve speech intelligibility and listening comfort (Schaub, 2010). The manufacturer claims that the ChannelFreeTM digital signal processing assesses the incoming signals at phonemic speed; even the shortest speech unit (the phoneme) is amplified precisely according to its particular intensity. According to them, the main goal of ChannelFreeTM processing is to amplify the low-level portions of speech without over amplifying high level sounds which is usually seen in fast acting compression. Further, the typical characteristic of ChannelFreeTM hearing aid is that it detects and

1 Shama15aiish@gmail.com &
2 manjulap21@hotmail.com

operates on wideband signal while still providing variable compression ratios across frequency and adjusts the gain 20,000 times per second without dividing the signal into fixed channels or bands (Schaub, 2008). Each phoneme is analyzed and adjusted 2000 times. These advanced features in ChannelFreeTM hearing aids help to recognize even the shortest as well as the weakest speech segments. This allows applying instantaneous and accurate gain with less distortion (Kodiyath, Mohan,&Bellur, 2017). It is claimed that the ChannelFreeTM processing provides clear and natural sound quality, as the ChannelFreeTM processing has the highest temporal resolution of any hearing system by providing correct amplification of the smallest parts of speech. According to Dillon et al. (2003), ChannelFreeTM processing has been shown to have the highest rated sound quality for speech and music when compared to multi-channel hearing aids. It has been reported that channelFreeTM processing retains the spectral contrast and also facilitate temporal cues from the amplified speech in noise (Kodiyath, Mohan, & Bellur, 2017).

Schaub (2008) reported that the working principle of ChannelFreeTM hearing aids closely resembles cochlear non-linearity by providing a higher gain to low level signal and compressing a high level signal. One distinctive feature of channelFreeTM processing as reported by the manufacturer is an extremely short reaction time of 10 ms, such short reaction time can cause distortion problem in conventional compression systems (Schaub, 2010). Thus, ChannelFree™ processing analyses and adjusts 20,000 times, the spectral and temporal resolution is better to provide clear and natural sound. The present study aims at comparing the speech perception, in quiet and noise, with multichannel and ChannelFreeTM hearing aids for persons with different configurations of sensorineural hearing loss.

Need for the study

It has been documented in literature that ChannelFree hearing aids are better when compared with regular multichannel hearing aids on speech identification performance (Hemanth et al., 2016) for individuals with sloping sensorineural hearing loss. ChannelFree hearing aids are reported to provide listening comfort and better speech intelligibility (Schaub, 2010). Plyer et al., (2013) has reported better speech scores in individuals with mild to moderately severe sloping sensorineural hearing loss (SNHL) using open fit receiver in the canal (RIC) hearing aids (Kumar (2007) showed that individuals with sloping SNHL performed better with ChannelFree hearing aids in quiet and in noise with constant SNRs (i.e., +10 dB & 0 dB SNR) when compared to single channel and multichannel (4 and 8) hearing aids. In his study, the hearing aids chosen were from different companies. It would be interesting to study the effect of ChannelFree and multichannel hearing aids from the same company to ensure the similar technology.

ChannelFreeTM processing was designed to address the limitations of fast-acting multichannel WDRC in order to solve the trade-off between speech intelligibility and listener comfort (Schaub, 2008). Since the routine hearing aid evaluations are generally carried out in quiet condition, the outcome of the hearing aids cannot be ideally generalised to day-to-day natural situations, where the hearing aid wearer will be in noisy background. Evidence shows that individuals with hearing impairment demonstrate marked reduction in speech recognition scores in the presence of noise compared to individuals having normal hearing (Cohen & Keith, 1976; Leshowitz, 1977). To address this situation, aided SNR-50 evaluation for both multichannel hearing aids and ChannelFreeTM hearing aids are carried out for the two groups, those with flat and those with sloping SNHL, to determine the speech recognition ability in quiet and in the presence of background noise.

Since the ChannelFreeTM hearing aid processes the signal 20,000 times, and does not split frequency band, the gain or amplification provided in such processors, should not compromise for the comfort in hearing aid users.

Aim of the study

To compare the effect of ChannelFreeTM processing in hearing aids for individuals with different configurations of SNHL, in quiet and noise, with multichannel hearing aids.

Objectives:

The major objectives taken up in the present study were:

1. To evaluate the effect of ChannelFreeTM hearing aids on speech identification in quiet, in individuals with flat SNHL and sloping SNHL.
2. To evaluate the effect of multichannel hearing aids on speech identification in quiet, in individuals with flat SNHL and sloping SNHL.
3. To evaluate the effect of ChannelFreeTM hearing aids on speech identification in noise, in individuals with flat SNHL and sloping SNHL.
4. To evaluate the effect of multi channel hearing aids on speech identification in noise, in individuals with flat SNHL and sloping SNHL.
5. To compare the speech identification in quiet with ChannelFreeTM and multi channel hearing aids in flat SNHL and sloping SNHL.
6. To compare the speech identification in noise with ChannelFreeTM and multi channel hearing aids in flat SNHL and sloping SNHL.

7. To evaluate the effect of ChannelFreeTM and multi channel hearing aids on quality of speech, in individuals with flat SNHL and sloping SNHL.

Method

The details of the method in order to realize the objectives of the study are given below. The research design adopted was within and between group design.

Participants

The age range of the participants was from 36 to 59 years for male participants and from 37 to 60 years for female participants, with the mean age being as follows: 50.6years of 5 male participants in flat SNHL group, 53 years of 5 female participants in flat SNHL group, 56 years of 7 male participants in sloping SNHL group and 48 years of 3 female participants in sloping SNHL group. The participants had post-lingually acquired hearing loss and were native speakers of Kannada language, a Dravidian language spoken in the state of Karnataka, India. The data were collected from 11ears with flat sensorineural hearing loss (Group I) and 10 ears with sloping sensorineural hearing loss (Group II).

Inclusion criteria:

Group I comprised of 11 ears with flat configuration of audiogram. Flat configuration is operationally defined as audiometric thresholds across frequencies not varying by more than 20 dB from each other (Pittman &Stelmachowicz, 2003). Group II comprised of 10 ears with sloping audiogram configuration, with audiometric thresholds at equal or successively higher levels from 250 to 8000 Hz. The difference between thresholds at 250 and 8000 Hz was always >20 dB (Pittman & Stelmachowicz, 2003). Individuals with speech identification scores (SIS) greater than 60% in quiet in the test ear were considered. Individuals with bilateral SIS of >60% or the SIS in the better ear of >60% in case of asymmetrical hearing loss on routine audiological evaluations, were considered. In case of asymmetrical hearing loss, the better ear was considered as the test ear. Test ears having 'A' type tympanogram either with acoustic reflexes present or absent.

Exclusion criteria:

Individuals with any outer and middle ear infections, complaint of any cognitive related disorders, retro cochlear pathologies, tinnitus and / or vestibular problems were not included.

Procedure:

The following procedure was followed in order to achieve the objectives of the study. The testing was done in three phases:

Phase I: Routine audiological evaluation to ensure participant selection criteria

Phase II: Aided speech identification in quiet

Phase III: Aided signal to noise ratios required for 50% performance (SNR-50)

Phase I: Routine audiological evaluation: In order to ensure the audiological inclusion criteria of the participants, audiometric air-conduction hearing thresholds were obtained at octave frequencies from 250 Hz to 8000 Hz for) and the bone-conduction thresholds were established at octave frequencies from 250 to 4000 Hz. Thresholds were established using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959

The speech recognition threshold (SRT), using the paired words in Kannada, was established by using a starting presentation level of 20 dB SL (re: pure tone average, PTA) (Tillman & Olsen, 1973). The speech identification score (SIS) was obtained at 40 dB SL (re: SRT) using the PB word list in Kannada (Yathiraj & Vijayalakshmi, 2005). The uncomfortable level (UCL) for speech in the test ear of the individual was also noted. The test stimuli were routed through the auxiliary input of the audiometer through headphones to the participant. Based on the audiometric results, the test ears were grouped as moderate flat SNHL or sloping configuration of SNHL. Immittance evaluation was done to rule out any middle ear pathology in the test ear.

Phase II: Aided speech identification in quiet: Selected hearing aids, viz., one ChannelFreeTM and two multichannel hearing aids (3-channel & 5-channel) were programmed. In quiet condition, one of the three hearing aids was selected to determine speech identification in quiet, using phonemically balanced word list in Kannada and presented to the participant. The participant was instructed to repeat the words heard. The aided SIS scores were obtained in each of the three aided conditions. The speech identification scores (SIS) were obtained at 45 dB HL using the PB word list in Kannada (Manjula et al., 2014). The SIS were retained as raw scores (Maximum score being 25) and not converted to percentage. The order of testing with the three hearing aids was randomized for each test ear.

Phase III: Aided response in noise (SNR-50): The level of speech, through audiometric loudspeaker was kept constant at 45 dB HL. The initial level of Kannada four-speaker multi talker babble through the same loud speaker was kept 15 dB HL below that of the speech i.e., at 30 dB HL. The level of the babble was increased in 5 dB steps, until the participant repeated at least two out of four (i.e., 50 %) words being presented. From this level, the speech babble was varied in 2 dB steps in order to obtain a more precise level of multi talker babble at which 50 % of the words were correctly repeated. At this instance, the difference in level of speech and multi talker babble was noted as SNR-50. This method was carried out for all three hearing aids selected.

Quality judgment

As a qualitative measure, a quality rating scale (Sruthy & Manjula, 2009) was used by presenting three different recorded paragraphs to each of the test hearing aids. The quality rating was based on five parameters on a 10-point rating scale. It was administered to do the quality judgements of the recorded speech paragraphs chosen while listening through each of the three hearing aids for the participant.

The parameters for quality rating and their rating scale were 0 to 10 for each of quality parameters, i.e., loudness, clearness, fullness, naturalness, and overall impression. For each parameter, the rating varied from very poor to excellent, with 0 being 'Very poor'; 0-2 being 'Poor'; 2-4 being 'Fair'; 4-6 being 'Good'; 6-8 being 'Very good'; and 8-10 being 'Excellent'.

Reliability check

In order to do the test-retest reliability check, 60% of the test ears each from flat SNHL and sloping SNHL groups were tested again within two weeks of the first evaluation. This was done following the same procedure used for Phase II and Phase III,.

Results

The data on SIS in quiet, SNR-50, and rating on quality parameters (loudness, clearness, fullness, naturalness, overall impression) from eleven ears with flat moderate sensorineural hearing loss and ten ears with sloping sensorineural hearing loss were tabulated and subjected to statistical analyses. The data were analyzed using Statistical Package for the Social Sciences (SPSS for Windows, version 17) software.

Effect of hearing aid processing on speech identification in quiet within and between flat and sloping SNHL groups:

The mean, median, and standard deviation (SD) for SIS with three different hearing aid are given in Table 1. In order to know if the slight differences in SIS with different hearing aids were significantly different, Friedman's test was performed between hearing aids, separately in flat SNHL and sloping SNHL groups providing mean, median and standard deviation in Table 2.

Table 1 Significance value (p) for SIS in quiet and SNR-50 for two groups of ears using Shapiro-Wilk's normality test.

S. No.	Parameters	Hearing aid processing	Group	df	p
1.	SIS	with 3-channel	Flat	11	0.001*
			Sloping	10	0.698
		with 5-channel	Flat	11	0.003*
			Sloping	10	0.021*
		with channelFree	Flat	11	0.205
			Sloping	10	0.111
2.	SNR-50	with 3-channel	Flat	11	0.409
			Sloping	10	0.596
		with 5-channel	Flat	11	0.449
			Sloping	10	0.881
		with ChannelFree	Flat	11	0.238
			Sloping	10	0.022*

Note: * indicates p = <0.05

Table 2: Mean, Median and standard deviation (SD) of SIS in quiet with three types of hearing aid processing in ears with flat and sloping SNHL.

Parameter	Hearing aid processing	Mean		Median		SD	
		Flat	Sloping	Flat	Sloping	Flat	Sloping
SIS (Max.=25)	with 3-channel	22.2	20.4	23	21	0.9	2.5
	with 5-channel	22.8	20.9	24	21.5	1.6	2.7
	with Channel Free	22.5	20.9	23	21.5	1.03	2.02

The type of processing in hearing aids did not make a significant difference (p>0.05) in each of the two groups as given in the Table 3.

Table 3 Significant difference (? 2& p) between SIS with three hearing aid processing in flat and sloping SNHL groups.

Parameter	χ^2		Significance (p value)	
	Flat	Sloping	Flat	Sloping
SIS with 3-channel, 5-channel and ChannelFree^{TM}	1.05	1.60	0.592	0.449

Table 4 shows the results for Mann Whitney U test that revealed significant difference between the flat and sloping sensorineural hearing loss groups, with higher SIS scores in flat SNHL compared to sloping SNHL groups, with all the three types of hearing aid processing. The same results has been depicted in box plot representation in figure 1.

Table 4 Significant difference (Z & p) in SIS with three hearing aid processing between flat SNHL and sloping SNHL.

Parameter	/Z/	Significance (p)
SIS with 3-channel	-1.99	0.046*
SIS with 5-channel	-1.99	0.047*
SIS with channelFree	-2.062	0.039*

Note: * $p<0.05$

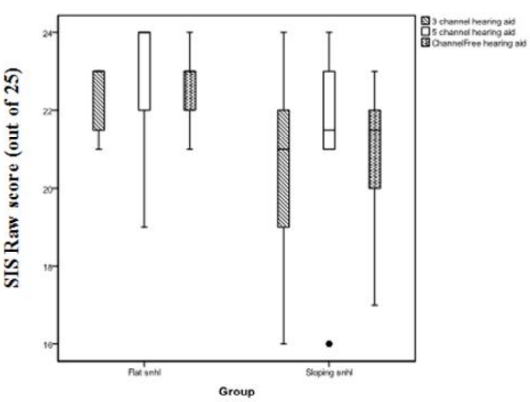

Figure 1 Box plot depicting the 95% CI of SIS scores (Max. 25) in two groups of participants

Table 5 reveals the mean, median, and, SD of SNR-50 with 3-channel, 5-channel, and ChannelFreeTM hearing aids within flat SNHL group. The results revealed that the mean and median SNR-50 was lower with ChannelFreeTM hearing aid compared to 3-channel and 3-channel hearing aids. That is, the performance is better with ChannelFreeTM hearing aid compared to the other two hearing aids. Friedman's test was performed in order to find out if there was any difference in SNR-50 between hearing aids in flat SNHL group. Table 6 depicts chi-square (?2) values and 'p' values for flat SNHL and sloping SNHL groups. The results showed that the difference was significant between the hearing aids in flat SNHL group [? 2 =10.585, p =0.005] as well as in sloping SNHL group [? 2 =8.909, p =0.012].

Since there was a significant difference between hearing aids in SNR-50 in flat SNHL group, Wilcoxon signed ranks test was performed to check the processing that was significantly different. The results revealed that there was no significant difference between 3-channel and 5-channel hearing aids in flat and sloping SNHL groups; and also between 5-channel and ChannelFreeTM in sloping SNHL group. In all the other aided conditions, there was a significant difference in SNR-50.

The table shows that ChannelFreeTM hearing aid had lower mean and median values for SNR-50 compared to 3-channel and 3-channel hearing aids.

Friedman's test was performed in order to check for the significant difference in SNR-50 between hearing aids in sloping SNHL group. Table 6 depicts chi-square (? 2) values and 'p' value for SNR-50 between hearing aid processing types within sloping SNHL group. The results showed that there is a significant difference between the hearing aids in SNR-50 parameter [? 2 =8.909, p =0.012]. Since there was a significant difference observed between hearing aids in SNR-50 in sloping SNHL group, Wilcoxon signed ranks test was performed in order to know the hearing aid processing that was bring about significantly different SNR-50. Figure 7 depicts Z score and 'p' value for difference in SNR-50 between three different hearing aids. The results revealed that in sloping SNHL group, the ChannelFreeTM hearing aid was significantly better than the 3-channel hearing aid ($Z = -2.124$, $p = 0.034$). There was no significant difference between the other hearing aid processing conditions.

Mann Whitney-U test was performed to find out if there was any difference in SNR-50 between flat SNHL and sloping SNHL groups. Table 8 shows Z score and 'p' value for SNR-50 with each hearing aid processing. The results revealed that there was no significant difference in SNR-50 between groups in three hearing aid processing conditions ($p > 0.05$) with same results being depicted in box plot manner in figure 2.

Table 8 Significant difference (Z & p) in SNR-50 between flat SNHL and sloping SNHL with three different hearing aid processing.

SNR-50	/Z/	Significance (p)
with 3-channel	0.42	0.670
with 5-channel	1.78	0.074
with channelFree	1.73	0.083

Table 5 Mean, median, and standard deviation (SD) of SNR-50 with three types of hearing aid processing in ears with flat and sloping SNHL

Parameter	**Mean**		**Median**		**SD**	
	Flat	Sloping	Flat	Sloping	Flat	Sloping
SNR-50 with 3-channel	5.45	6.4	5	6	1.43	3.5
SNR-50 with 5-channel	4.81	6.5	5	6.5	1.16	2.27
SNR-50 with channelFree	3.45	5.4	3	4.5	1.29	2.5

Table 6 Significant difference ($\chi 2$ & p)on Friedman test for SNR-50 between three hearing aid processing for flat SNHL and sloping SNHL groups

Parameter	χ^2		Significance (p)	
	Flat	Sloping	Flat	Sloping
SNR-50 with 3- channel SNR-50 with 5- channel SNR-50 withchannelFree	10.585	8.909	0.005**	0.012*

Table 7 Significant difference (Z & p)on Wilcoxon's test in SNR-50 between three hearing aid processing in flat SNHL and sloping SNHL

SNR-50	/Z/		Significance (p)	
	Flat	Sloping	Flat	Sloping
Between 3-channel and 5-channel	1.30	0.96	0.191	0.339
Between 3-channel and channelFree	2.74	2.12	0.006**	0.034*
Between 5-channel and channelFree)	2.40	1.93	0.016*	0.054

Note: * p <0.05; **:p<0.01

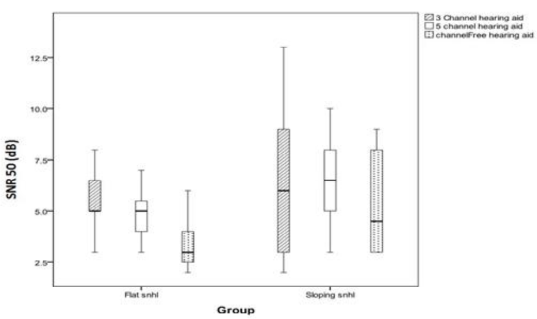

Figure 2: Box plot depicting the 95% CI of SNR-50 in flat and sloping SNHL groups.

From Table 9, it can be noted that the ChannelFreeTM processing was rated to be better than the 3-channel and 5-channel processing in terms of clearness, fullness, naturalness, and overall impression. This was true for flat and sloping SNHL groups. However, the loudness was rated to be higher with 5-channel hearing aid followed by 3-channel and ChannelFreeTM hearing aids. In order to see if the hearing aid processing had a significant effect on each parameter of quality judgement in flat SNHL population, Friedman's test was performed.

In order to see the effect of hearing aid processing on each of the five parameters of quality judgement in flat SNHL and sloping SNHL population, Friedman's test was performed. Table 10 shows the chi-square value and 'p' value for all five parameters of quality between the hearing aid processing, in flat SNHL and sloping SNHL groups. The result shows significant difference between hearing aids in all the parameters in flat SNHL group. In case of sloping SNHL group, except for loudness parameter, all other four parameters showed a significant difference between hearing aid processing.

The Wilcoxon's signed rank test was done to check the hearing aid processing that significantly differed on all the five quality parameters. Table 10 depicts Z value and 'p' value for quality parameters between hearing aid processing conditions, separately in flat SNHL and sloping SNHL groups. Except for the loudness being significantly higher with 5-channel compared to ChannelFreeTM condition, there was no significant difference between any of the aided conditions in flat SNHL group. In case of sloping SNHL, loudness did not differ between hearing aids.

For clearness parameter, in all the three paired condition, ChannelFreeTM hearing aid processing tended to be much clearer than 3-channel and 5-channel hearing aids in flat SNHL group sloping SNHL.

Except for the fullness being significantly higher with ChannelFreeTM compared to 3-channel hearing aid, there was no significant difference between any of the aided conditions in flat SNHL group. In case of sloping SNHL group, fullness being significantly higher with

Table 9 Mean, median, and standard deviation (SD) of quality parameters with three hearing aid processing types in ears with flat and sloping SNHL.

Quality Parameters	*Hearing aid processing*	*Mean*		*Median*		*SD*	
		Flat	*Sloping*	*Flat*	*Sloping*	*Flat*	*Sloping*
Loudness	3-Channel	6.18	5.6	6	6	0.60	1.26
	5-Channel	7.09	5.4	8	5	1.04	1.64
	ChannelFree	5.81	5.8	6	6	1.07	1.47
Clearness	3-Channel	4.18	4.8	4	4	0.60	1.39
	5-Channel	5.63	6.0	6	6	1.2	1.63
	ChannelFree	7.45	7.6	8	8	1.29	1.57
Fullness	3-Channel	5.45	6.2	6	6	1.2	1.13
	5-Channel	6.72	5.6	6	6	1.34	1.57
	ChannelFree	7.09	7.2	8	8	1.04	1.68
Naturalness	3 Channel	5.27	5.6	6	6	1.34	1.57
	5 Channel	5.81	5.8	6	6	1.07	1.75
	ChannelFree	7.81	7.0	8	7	1.40	1.69
Overall Impression	3 Channel	5.81	6.4	6	6	0.60	1.26
	5 Channel	7.09	6.4	8	6	1.04	1.57
	ChannelFree	8	7.8	8	8	0.00	1.98

Table 10. Significant difference (χ^2 & p) in quality judgement parameters between three hearing aid processing in flat SNHL and sloping SNHL groups.

Parameter	***Hearing aid processing***	χ^2		***Significance (p)***	
		Flat	*Sloping*	*Flat*	*Sloping*
Loudness	With 3-Channel, 5–Channel, & ChannelFree	8.00	0.296	0.018*	0.862
Clearness	With 3-Channel, 5Channel, & ChannelFree	14.098	11.806	0.001**	0.003**
Fullness	With 3-Channel, 5–Channel, & ChannelFree	6.414	6.242	0.040*	0.044*
Naturalness	With 3-Channel, 5–Channel, & ChannelFree	9.75	7.032	0.008**	0.030*
Overall Impression	With 3-Channel, 5–Channel, &ChannelFree	16.545	6.750	0.000**	0.034*

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

ChannelFreeTM compared to 35-channel hearing aid.

For naturalness parameter, perception through ChannelFreeTM hearing aid processing was found to be more natural compared to 3-channel, there was no significant difference between any of the aided conditions in flat SNHL group and sloping SNHL group of population.

The overall impression was better preferred with ChannelFreeTM hearing aid processing when compared to 3- channel and 5-channel hearing aids. Significant difference between 3-channel and 5-channel hearing was not observed in flat SNHL group and sloping SNHL.

Mann-Whitney U test was performed to find out if there was any difference in quality judgement rating between flat SNHL and sloping SNHL groups. Table 4.11 shows Z score and 'p' values for quality ratings in each type of hearing aid processing. The loudness parameter was significantly higher in flat compared to sloping SNHL group [Z = -2.367, p = 0.018].

Table 11. Significant difference (Z & p) in quality judgement parameters between three hearing aid processing in both flat SNHL and sloping SNHL groups.

Quality Parameter	***Hearing aid processing***	***/Z/***		***Significance (p)***	
		Flat	*Sloping*	*Flat*	*Sloping*
Loudness	3-channel & 5-channel	1.89	-	0.06	-
	3-channel &-ChannelFree	0.81	-	0.41	-
	5-channel &ChannelFree	2.33	-	0.02*	-
Clearness	3-channel -5-channel	2.31	1.50	0.02*	0.13
	3-channel & ChannelFree	2.97	2.72	0.00*	0.00*
	5-channel & ChannelFree	2.23	2.07	0.02*	0.03*
Fullness	3-channel -5-channel	1.93	1.00	0.05	0.31
	3-channel ChannelFree	2.16	1.50	0.03*	0.13
	5-channel & ChannelFree	0.70	2.39	0.48	0.02*
Naturalness	3-channel -5-channel	1.13	0.378	0.25	0.70
	3-channel & ChannelFree	2.45	2.33	0.01*	0.02*
	5-channel & ChannelFree	2.37	2.12	0.02*	0.03*
Overall Impression	3-channel -5-channel	2.34	0.00	0.02*	1.00
	3-channel ChannelFree	3.20	2.11	0.00*	0.03*
	5-channel&ChannelFree	2.23	2.11	0.02*	0.03*

Note: * : p <0.05

Table 13 Test-retest reliability for SIS in quiet and SNR-50 in flat SNHL group.

Parameters	*Hearing aid processing*	*Cronbach's α*	
		Flat	*Sloping*
SIS	With 3-channel	0.946	0.969
	With 5-Channel	0.968	0.984
	With channelFree	0.966	0.976
SNR-50	With 3-channel	0.828	0.973
	With 5-Channel	0.981	0.972
	With channelFree	0.906	0.992

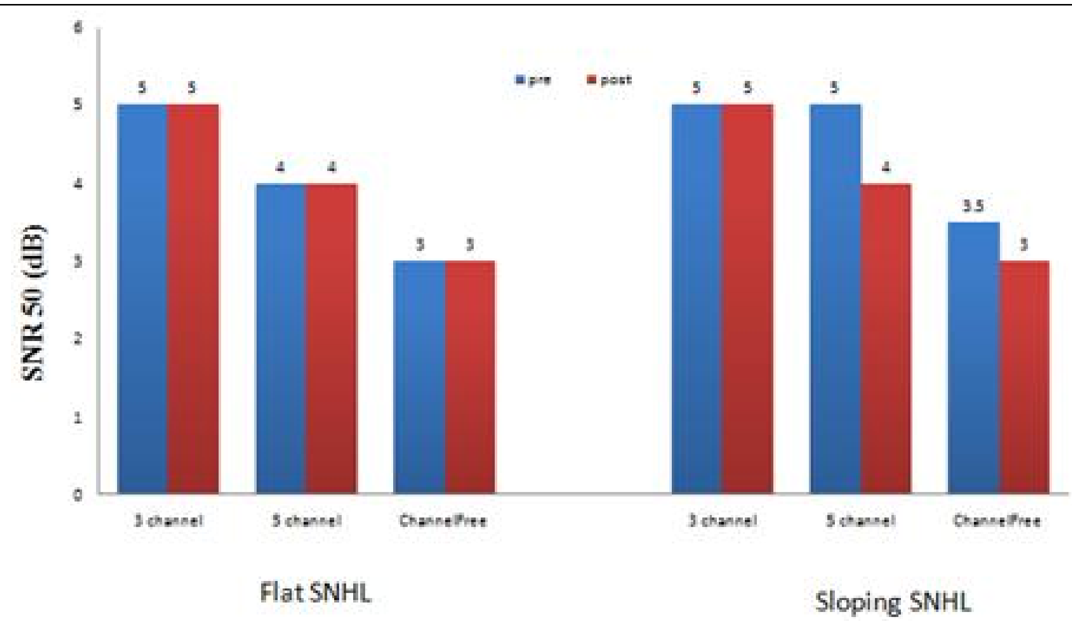

Figure 3 Test and re-test data on SNR-50 with three hearing aid processing types in flat and sloping SNHL groups

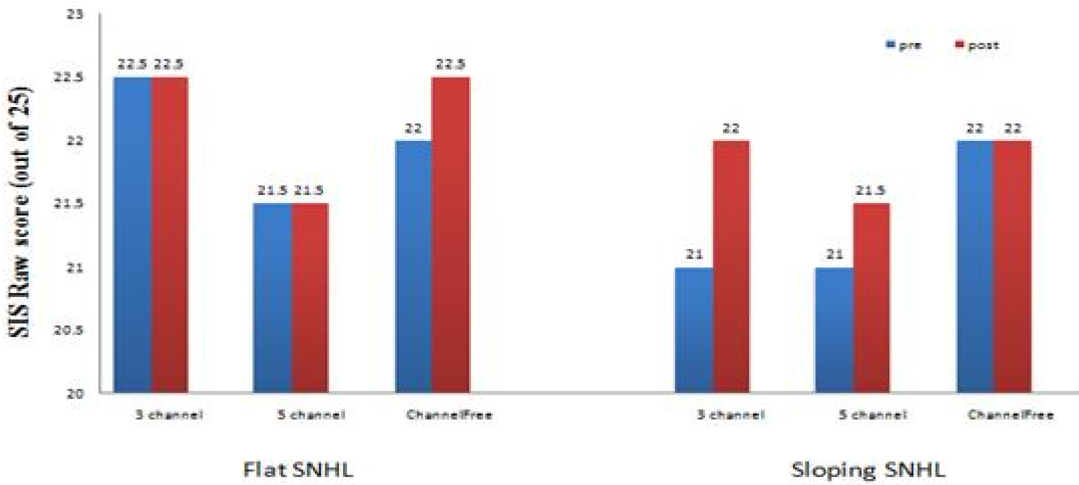

Figure 4 Test and re-test data on SIS with three hearing aid processing types in flat and sloping SNHL groups.

Table 12 Significant difference (Z & p) in quality parameters in three hearing aid processing between flat and sloping SNHL groups.

Quality Parameters	*Hearing aids*	*/Z/*	*Significance (p)*
Loudness	3–channel	-1.370	0.171
	5–channel	-2.367	0.018*
	ChannelFree	0.081	0.935
Clearness	3–channel	-1.236	0.217
	5–channel	0.381	0.703
	ChannelFree	0.081	0.935
Fullness	3-channel	-1.384	0.166
	5–channel	-1.658	0.097
	ChannelFree	0.275	0.783
Naturalness	3–channel	0.461	0.645
	5–channel	0.423	0.672
	ChannelFree	-1.143	0.253
Overall Impression	3–channel	-1.370	0.171
	5-channel	-1.477	0.140
	ChannelFree	0.000	1.000

Test-retest reliability

In order to evaluate the reliability of the data, 60% of the ears of participants were subjected for re-test. The data were subjected to Cronbach's alpha analysis to check for internal consistency for the parameters such as SIS in quiet, SNR-50, and quality judgements for flat SNHL and sloping SNHL. The results of the same has been tabulated in table 13 and graphically represented in figure 3 and figure 4 respectively.

The Cronbach's alpha values (Tables 11 & 12) indicated that the data in all the parameters were reliable (i.e., ? > 0.70), between the first and the second evaluations.

To conclude, among the three hearing aid processing strategies investigated, ChannelFreeTM hearing aid processing was found to be better to perceive in the presence of noise and in terms of quality judgement compared to multichannel hearing aid processing for flat SNHL as well as sloping SNHL groups. Further, ChannelFreeTM hearing aid processing is more beneficial in the presence of noise for flat SNHL group of population.

Figures 5, 6, 7, 8, 9, and 10 are the graphs showing the number of participants, of both flat and sloping SNHL, ratings for different parameters of quality with three hearing aid processing, by both flat and sloping SNHL groups.

For loudness parameter, maximum rating provided out of ten is six with 3- channel and with ChannelFreeTM hearing aid from both the groups. With 5- channel, flat group rated 8 and sloping SNHL group rated 4 out of 10.

The clearness parameter has been rated with the maximum of 4 with 3-channel hearing aid, 6 with 5channel hearing aid, and 8 with ChannelFreeTM hearing aid, from both the groups. The fullness parameter has been rated maximum with 6 with 3-channel and 5-channel hearing aids; and rated maximum with 8 with ChannelFreeTM hearing aid, from both the groups. For naturalness parameter, with 3-channel, 5-channel, and ChannelFreeTM hearing aid, equal rating of 4-6 was given by flat SNHL group. Individuals with sloping SNHL rated maximum of 4 with 3-channel, 6 with 5-channel, and equal rating of 6-8 with

ChannelFreeTM hearing aid processing. The overall impression was rated maximum of 8 with 3-channel, 5-channel, and ChannelFreeTM hearing aid by flat SNHL group; whereas the sloping SNHL group rated maximum of 6 with 3-channel and 5-channel hearing aid, and maximum of 8 with ChannelFreeTM hearing aid processing.

Figure 7 Number. of participants of flat SNHL rated for each quality parameter with ChannelFreeTM hearing aid processing.

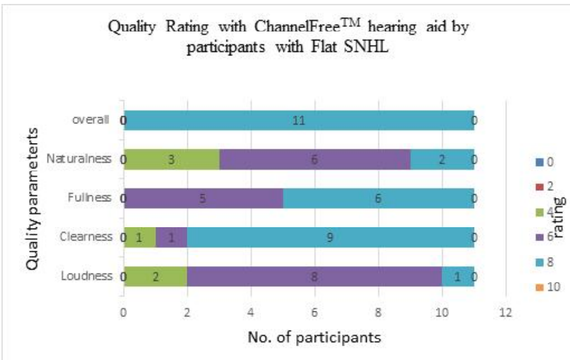

Figure 8 Number of participants of sloping SNHL rated for each quality parameter with three channel hearing aid processing.

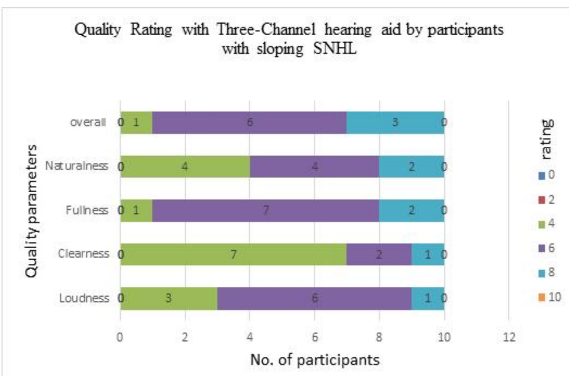

Figure 9 Number of participants of sloping SNHL rated for each quality parameter with five channel hearing aid processing.

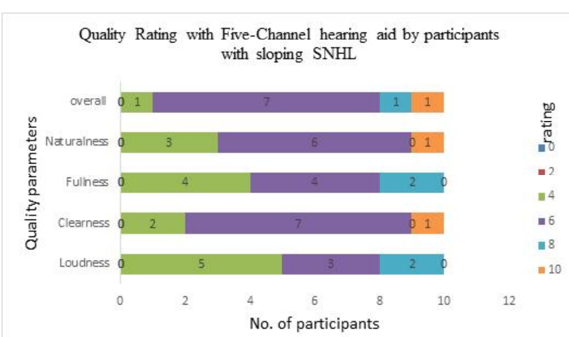

Figure 10 Number of participants of sloping SNHL rated for each quality parameter with ChannelFreeTM hearing aid processing.

Discussion

The SIS in quiet, speech intelligibility in noise (SNR-50), and speech quality judgement were used in order to know the effect of three-channel, five-channel and ChannelFreeTM processing technology in digital Behind-The-Ear hearing aids.

Speech identification in quiet for flat and sloping SNHL groups.

The results for speech identification in quiet for flat SNHL and sloping SNHL groups did not reveal any significant difference among the three hearing aids taken in this study. The performance for speech identification in quiet was similar across 3-channel, 5-channel, and ChannelFreeTM hearing aids. It is noteworthy that the type of processing investigated in the study did not affect the performance in quiet. All these processing types brought about a significant improvement in performance. Probably, since the task of speech identification in quiet is relatively an easy task, the difference in the effect of type of processing was not evident.

In a study by Yund and Buckles (1995), it was reported that there was no difference for speech identification in quiet between 4-, 8- and 12- channel hearing aids. Irrespective of the number of channels, the performance remained similar in both flat and sloping SNHL, as was seen in the present study with 3- and 5- channels.

Speech intelligibility in noise in flat and sloping SNHL groups.

The results for SNR-50 as a measure of speech identification in the presence of noise showed better performance with ChannelFreeTM hearing aid compared to 3-channel and 5-channel hearing aids, in flat and sloping SNHL groups. This improvement could be because the ChannelFreeTM processing adjusts the gain on an average of 20,000 times for each phoneme by measuring its sound pressure level in the level measurement block. This would facilitate the audibility within restricted dynamic range of participants with hearing impairment (DeSilva et al., 2016). In a study by Hemanth et al. (2016), the performance was measured with different SNRs i.e., at +10 dB SNR and 0 dB SNR. They found better speech identification in noise irrespective of SNRs with ChannelFreeTM processing compared to multichannel processing. In addition, the ChannelFreeTM hearing aid rapidly adjusts the gain with respect to the input signal. This scheme in ChannelFreeTM hearing aid could compensate for the mechanism of the cochlea that is damaged i.e., amplification of soft sounds and compressing loud sounds in presence of noise (Stelmachowicz et al., 1995).

The performance in the presence of noise remained similar with 3-channel and 5-channel hearing aids in the present study. Yund, Simon, and Efron (1987) have reported that the performance with multichannel hearing aids is poorer because of the speech distortions that are caused by the type of compression and time constants applied in different channels of a multichannel hearing aid. That is, when the input signal is broken into channels, and applying compression and fast time constants, the spectro temporal features become distorted and important information on speech transition is lost, which has been found to impair speech understanding (Boothroyd et al., 1996). In a later study by Yund and Buckles (1995), it has been reported that there is an improvement in performance in noise with the number of channels increasing up to eight.

The finding of better performance in noise with ChannelFreeTM hearing aids compared to multichannel hearing aids in the present study could be because the ChannelFreeTM hearing aid technology attempts to overcome the adverse effect of multichannel compression on spectral contrasts in speech. The ChannelFreeTM hearing aid does not split the incoming speech signal into different channels, thereby ensuring that the hearing aid output retains the spectral contrasts present in the input speech (Prabhu & Barman, 2017).

For the superior performance by ChannelFreeTM hearing aid, Kodiyath, Mohan, and Bellur (2017) opined that ChannelFreeTM hearing aid strategies with noise reduction are able to process incoming signal faster in order to retain the spectral contrast and also facilitate temporal cues from the amplified speech in noise.

The results comparing between groups revealed that individuals with flat SNHL had better performance in noise compared to sloping SNHL. Researchers have said that high frequency information has a critical role in speech identification in the presence of background noise (Hornsby & Ricketts, 2003; Turner & Henry, 2002). This is in contrast to results from an earlier study using the same paradigm but done in quiet (Hogan & Turner, 1998). The authors suggest that the difference in results obtained in quiet and in noise are due to differences in the relative access to 'easy' i.e., voicing and manner cues and 'more difficult' i.e., place of articulation speech cues when speech is presented in quiet versus noise backgrounds. Baer, Moore, and Kuk (2002) found that, in noise, persons with hearing loss and cochlear dead regions in the high frequencies were less able to make use of amplified high frequency speech information than persons with hearing loss but without dead regions.

Quality judgement in flat SNHL and sloping SNHL groups.

The results of the present study on quality judgements for five different parameters of quality in flat and sloping SNHL yielded similar findings. Out of the five parameters of quality rating, only loudness parameter varied between groups across hearing aids. It was found that the maximum rating obtained for loudness parameter in individuals with flat SNHL was eight through 5-channel hearing aid, followed by 3-channel and ChannelFreeTM hearing aids. Whereas, in individuals with sloping SNHL, loudness parameter was rated comparatively lower through 5-channel hearing aid. Other parameters like clearness, fullness, naturalness, and overall intelligibility impression were rated significantly better through ChannelFreeTM hearing aid compared to 3-channel and 5-channel hearing aids by flat SNHL and sloping SNHL. In contrast with this result, a study has shown that the performance based on quality rating remains similar between ChannelFreeTM and 7-channel hearing aids for individuals with SNHL, in quiet as well as in noisy situations (Plyer et al., 2013).

From the present study, it can be inferred that participants of both groups benefitted from ChannelFreeTM processing and are subjectively satisfied with the quality of amplified speech signal. The reason for better quality transmitted through ChannelFreeTM processing could be lowered distortion.

Conclusions

From the results of the present study, it can be inferred that though the ChannelFreeTM hearing aid does not make a difference in quiet, it improves performance in noise.

Speech identification in quiet

There was no significant difference between the three hearing aids, for the flat as well as sloping SNHL groups. The SIS of the flat SNHL was significantly higher than SIS of the sloping SNHL group. This was true for each of the three types of hearing aids tested.

Speech intelligibility in noise

The performance with ChannelFreeTM processing is higher than 3-channel and 5-channel hearing aid processing, for flat and sloping SNHL groups. In flat SNHL group, the performance was significantly better with ChannelFreeTM compared to 3-channel and 5-channel processing. In sloping SNHL, performance with ChannelFreeTM was significantly better than 3-channel and 5-channel processing. However, the 3-channel and 5-channel were not significantly different in performance. The performance was not significantly different between the flat and SNHL groups in each of the three types of hearing aid processing.

Quality judgement

The results revealed that all the parameters of quality (such as clearness, fullness, naturalness, and overall impression) were rated superior with ChannelFreeTM processing compared to 3-channel and 5-channel processing, except for loudness. The loudness was rated to be higher with 5-channel processing. In flat SNHL, the overall impression was better with ChannelFreeTM and 5-channel processing compared to 3-channel processing. In sloping SNHL, the overall impression was better with ChannelFreeTM compared to 5-chanel and 3-channel processing.

To summarize, the three types of hearing aid processing bring about comparable performance for speech identification in quiet. For speech identification in noise, the performance was better with ChannelFreeTM processing than 3-channel and 5-channel. For majority of parameters of quality, the ChannelFreeTM processing was superior to the 3-channel and 5-channel processing. These findings were true for flat as well as sloping configurations of SNHL.

The ChannelFree processing is found to be better in terms of speech intelligibility as well as in quality. This aspect will contribute to longer durations of hearing aid usage and improved quality of life in individuals with SNHL.

Clinical implications

- ChannelFreeTM hearing aid processing can be recommended to those individuals with SNHL of flat and sloping configurations, as it was documented in the study that the performance was better than the multichannel hearing aids.

Future directions

- The study was conducted in adult population. Further research can be conducted on older adult population to check for the benefit of ChannelFreeTM hearing aid processing in those individuals with neural degeneration.
- The sample size taken was less. To take up more participants to make the test findings more valid.
- The effect of using other types of speech stimuli (viz., monosyllables, sentences) can also be investigated.

References

Baer, T., Moore, B. C., &Kluk, K. (2002). Effects of low pass filtering on the intelligibility of speech in noise for people with and without dead regions at high frequencies. The Journal of the Acoustical Society of America, 112(3), 1133-1144.

Bentler, R. A., & Duve, M. R. (2000). Comparison of hearing aids over the 20th century. Ear and hearing, 21(6), 625-639.

Boike, K. T., & Souza, P. E. (2000). Effect of compression ratio on speech recognition and speech-quality ratings with wide dynamic range compression amplification. Journal of Speech, Language, and Hearing Research, 43(2), 456-468.

Boothroyd, A., Mulhearn, B., Gong, J., &Ostroff, J. (1996). Effects of spectral smearing on phoneme and word recognition. The Journal of the Acoustical Society of America, 100(3), 1807-1818.

Bor, S., Souza, P., & Wright, R. (2008). Multichannel compression: Effects of reduced spectral contrast on vowel identification. Journal of Speech, Language, and Hearing Research, 51 (5), 1315-1327.

Braida, L. D., Durlach, N. I., De Gennaro, S. V., Peterson, P. M., Bustamante, D. K., Studebaker, G., & Bess, F. (1982). Review of recent research on multiband amplitude compression for the hearing impaired. The Vanderbilt hearing aid report, 133-140.

Bustamente, D. K., &Braida, L. D. (1987). Multiband compression limiting for severely impaired listeners. J Rehabil Res Dev, 24, 149-160.

Byrne, D., Dillon, H., Ching, T., Katsch, R., &Keidser, G. (2001). NAL-NL1 procedure for fitting nonlinear hearing aids: Characteristics and comparisons with other procedures. Journal-American Academy of Audiology, 12(1), 37-51.

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

Ching, T. Y., Dillon, H., & Byrne, D. (1998). Speech recognition of hearing-impaired listeners: Predictions from audibility and the limited role of high-frequency amplification. The Journal of the Acoustical Society of America, 103(2), 1128-1140.

Cohen, R. L., & Keith, R. W. (1976). Use of low-pass noise in word-recognition testing. Journal of Speech, Language, and Hearing Research,19(1), 48-54.

Crain, T. R., &Yund, E. W. (1995). The effect of multichannel compression on vowel and stop-consonant discrimination in normal-hearing and hearing-impaired subjects. Ear and hearing, 16(5), 529-543.

Dallos P. (1973). The auditory periphery: Biophysics and Physiology. New York: Academic Press

DeSilva, M. D. K., Kooknoor, V., Shetty, H. N., &Thontadarya, S. (2016). Effect of multichannel and Channels Free hearing aid signal processing on phoneme recognition in quiet and noise. International Journal of Health Sciences and Research (IJHSR), 6(3), 248-257.

Dillon H (2001) Compression system in hearing aids. Hearing Aids. New York: Thieme, Boomerang Press; p. 159.

Dillon, H., Keidser, G., O'brien, A., & Silberstein, H. (2003). Sound quality comparisons of advanced hearing aids. The hearing journal, 56(4), 30-32.

Dreschler, W. A. (1988). The effect of specific compression settings on phoneme identification in hearing-impaired subjects. Scandinavian audiology, 17(1), 35-43.

Dreschler, W. A. (1989). Phoneme perception via hearing aids with and without compression and the role of temporal resolution. Audiology, 28(1), 49-60.

Dreschler, W. A. (1992). Fitting multichannel-compression hearing aids. Audiology, 31(3), 121-131.

Dreschler, W. A., Eberhardt, D., & Melk, P. W. (1984). The use of single-channel compression for the improvement of speech intelligibility. Scandinavian Audiology, 13(4), 231-236.

Flynn, M. C., Davis, P. B., &Pogash, R. (2004). Multiple-channel non-linear power hearing instruments for children with severe hearing impairment: Long-term follow-up. International Journal of Audiology, 43(8), 479-485.

Franck, B. A., van Kreveld-Bos, C. S. G., Dreschler, W. A., &Verschuure, H. (1999). Evaluation of spectral enhancement in hearing aids, combined with phonemic compression. The Journal of the Acoustical Society of America, 106(3), 1452-1464.

Glasberg, B. R., & Moore, B. C. (1986). Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments. The Journal of the Acoustical Society of America, 79(4), 1020-1033.

Hickson, L. M. (1994). Compression amplification in hearing aids. American Journal of Audiology, 3(3), 51-65.

Hogan, C. A., & Turner, C. W. (1998). High-frequency audibility: Benefits for hearing-impaired listeners. The Journal of the Acoustical Society of America, 104(1), 432-441.

Hohmann, V., &Kollmeier, B. (1995). The effect of multichannel dynamic compression on speech intelligibility. The Journal of the Acoustical Society of America, 97(2), 1191-1195.

Hornsby, B. W., & Ricketts, T. A. (2003).The effects of hearing loss on the contribution of high-and low-frequency speech information to speech understanding. The Journal of the Acoustical Society of America, 113(3), 1706-1717.

Hornsby, B. W., & Ricketts, T. A. (2003).The effects of hearing loss on the contribution of high-and low-frequency speech information to speech understanding. The Journal of the Acoustical Society of America, 113(3), 1706-1717.

Hornsby, B. W., & Ricketts, T. A. (2006).The effects of hearing loss on the contribution of high-and low-frequency speech information to speech understanding. II. Sloping hearing loss a. The Journal of the Acoustical Society of America, 119(3), 1752-1763.

Hrishikesan&Manjula (2009). Efficacy of Non-linear frequency compression in individuals with and without cochlear dead regions.Unpublished Master's Dissertation submitted to the Univ. of Mysore., Mysore.

Humes, L. E. (1999). Dimensions of hearing aid outcome. Journal of the American Academy of Audiology, 10(1), 26-39.

Johnson, W. A. (1993). Beyond AGC-O and AGC-I: Thoughts on a new default standard amplifier. The Hearing Journal, 46, 37-37.

Kam, A. C., & Wong, L. L. (1999). Comparison of performance with wide dynamic range compression and linear amplification. Journal-American Academy of Audiology, 10, 445-457.

Keidser, G., & Grant, F. (2001). The preferred number of channels (one, two, or four) in NAL-NL1 prescribed wide dynamic range compression (WDRC) devices. Ear and hearing, 22(6), 516-527.

Kent, R. D., Read, C., & Kent, R. D. (1992). The acoustic analysis of speech (Vol. 58). San Diego: Singular Publishing Group.

Killion, M. C. (1996). Compression: Distinctions. The Hearing Review, 3(8), 29.

Kodiyath GK, Mohan KM, Bellur R. (2017). Influence of channel and ChannelFree™ processing technology on the vocal parameters in hearing-impaired individuals. Indian Journal of Otolaryngology; 23, 21-26.

Kumar, R. A., and Krishna, R., (2007). Speech identification with single channel Multichannel and ChannelFree hearing aids. Master's Dissertation, Department of Audiology, AIISH, Mysore.

Kumar, U. A., Ameenudin, S., & Sangamanatha, A. V. (2012). Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. Noise & Health, 14 (58) , 100-105.

Laurence, R. F., Moore, B. C., &Glasberg, B. R. (1983). A comparison of behind-the-ear high-fidelity linear hearing aids and two-channel compression aids, in the laboratory and in everyday life. British Journal of Audiology, 17(1), 31-48.

Leshowitz, B. (1977). Speech intelligibility in noise for listeners with sensorineural hearing damage. IPO Annual Progress Report, 12, 11- 23.

Manjula, P., Geetha, C., Kumar, S.,& Antony, J. (2014). Phonemically balanced (PB) Test Material in Kannada for Adults. Unpublished AIISH Research Fund Project.

Mascarenhas, K. E .&Yathiraj. (2002). High frequency - Kannada Speech Identification test (HF KST). (Master's Dissertation). University of Mysore, All India Institute of Speech and Hearing.

McCandless, G. A., & Miller, D. L. (1972). Loudness discomfort and hearing aids. National Hearing Aid Journal, 25(7), 28.

McDermott, H. J., & Dean, M. R. (2000). Speech perception with steeply sloping hearing loss: effects of frequency transposition. British Journal of Audiology, 34(6), 353-361.

Moore, B. C. (2008). The choice of compression speed in hearing aids: Theoretical and practical considerations and the role of individual differences. Trends in Amplification, 12(2), 103-112.

Moore, B. C. J., &Glasberg, B. R. (1997). A model of loudness perception applied to cochlear hearing loss. Auditory Neuroscience, 3(3), 289-311.

Moore, B. C. J., Alcántara, J. I., Stone, M. A., &Glasberg, B. R. (1999). Use of a loudness model for hearing aid fitting: II. Hearing aids with multi-channel compression. British journal of audiology, 33(3), 157-170.

Moore, B. C., &Glasberg, B. R. (1986). A Comparison of

Two-Channel and Single-Channel Compression Hearing Aids: Comparaison de prothèsesacoustiques avec compression à un et deuxcanaux. Audiology, 25(4-5), 210-226.

Moore, B. C., Glasberg, B. R., & Baer, T. (1997). A model for the prediction of thresholds, loudness, and partial loudness. Journal of the Audio Engineering Society, 45(4), 224-240.

Moore, B. C., Laurence, R. F., & Wright, D. (1985). Improvements in speech intelligibility in quiet and in noise produced by two-channel compression hearing aids. British journal of audiology, 19(3), 175-187.

Nábělek, I. V. (1983). Performance of hearing?impaired listeners under various types of amplitude compression. The Journal of the Acoustical Society of America, 74(3), 776-791.

Nelson, P. B., & Thomas, S. D. (1997). Gap detection as a function of stimulus loudness for listeners with and without hearing loss. Journal of Speech, Language, and Hearing Research, 40(6), 1387-1394.

Pittman, A. L., &Stelmachowicz, P. G. (2003). Hearing loss in children and adults: audiometric configuration, asymmetry, and progression. Ear and hearing, 24(3), 198.

Plomp, R. (1988). The negative effect of amplitude compression in multichannel hearing aids in the light of the modulation-transfer function. The Journal of the Acoustical Society of America, 83(6), 2322-2327.

Plyler, P. N., Reber, M. B., Kovach, A., Galloway, E., & Humphrey, E. (2013).Comparison of multichannel wide dynamic range compression and ChannelFree processing in open canal hearing instruments. Journal of the American Academy of Audiology, 24(2), 126-137.

Prabhu, P & Barman, A. (2017). Effectiveness of low cut modified amplification strategy and channel free hearing aid in individuals with auditory neuropathy spectrum disorder. International Journal of Audiology (In press)

Rankovic, C. M. (2002).Articulation index predictions for hearingimpaired listeners with and without cochlear dead regions.The Journal of the Acoustical Society of America, 111, 2545-2548.

Ricketts, T. A. (2001). Directional hearing aids. Trends in Amplification, 5(4), 139-176.

Sairam, V.V.S. (2002). Long-term average speech apectrum in Kannada. Unpublished Independent Projectsubmitted to the Univ. of Mysore., Mysore.

Schaub, A. (2008). Digital hearing aids. New York: Thieme.

Schaub, A. (2010). Solving the trade-off between speech understanding and listening comfort. The Hearing Journal, 63(7), 26-28.

Shapiro, I. (1975). Prediction of most comfortable loudness levels in hearing aid evaluation. Journal of Speech and Hearing Disorders, 40(4), 434-438.

Shapiro, I. (1976). Hearing aid fitting by prescription. Audiology, 15(2), 163-173.

Souza, P. E., &Boike, K. T. (2006). Combining temporal-envelope cues across channels: Effects of age and hearing loss. Journal of Speech, Language, and Hearing Research, 49(1), 138-149.

Souza, P. E., & Turner, C. W. (1999). Quantifying the contribution of audibility to recognition of compression-amplified speech. Ear and Hearing, 20(1), 12-20.

Stelmachowicz, P. G., Kopun, J., Mace, A., Lewis, D. E., & Nittrouer, S. (1995). The perception of amplified speech by listeners with hearing loss: acoustic correlates. The Journal of the Acoustical Society of America, 98(3), 1388-1399.

Stone, M. A., Moore, B. C., Alcántara, J. I., &Glasberg, B. R. (1999). Comparison of different forms of compression using wearable digital hearing aids. The Journal of the Acoustical Society of America, 106(6), 3603-3619.

Stone, M. A., Moore, B. C., Meisenbacher, K., &Derleth, R. P. (2008).Tolerable hearing aid delays. V. Estimation of limits for open canal fittings. Ear and hearing, 29(4), 601-617.

Stone, M. A., Moore, B. C., Wojtczak, M., &Gudgin, E. (1997). Effects of fast-acting high-frequency compression on the intelligibility of speech in steady and fluctuating background sounds. British journal of audiology, 31(4), 257-273.

Tillman, T. W., & Olsen, W. O. (1973). Speech Audiometry. In J. Jerger, Modern developments in audiology (pp. 37- 74). New York: Academic Press.

Tremblay, K. L. (2005, August). Beyond the ear: physiological perspectives on auditory rehabilitation. In Seminars in Hearing (Vol. 26, No. 03, pp. 127-136).

Turner CW, Cummings KJ. (1999) . Speech audibility for listeners with high-frequency hearing loss .American Journal of Audiology, 8, 1-11.

Turner, C. W., & Henry, B. A. (2002).Benefits of amplification for speech recognition in background noise. The Journal of the Acoustical Society of America, 112(4), 1675-1680.

Valente, M., Sweetow, R., Potts, L. G., &Bingea, B. (1999). Digital versus analog signal processing: effect of directional microphone. Journal of the American Academy of Audiology, 10(10).

vanBuuren, R. A., Festen, J. M., &Houtgast, T. (1999). Compression and expansion of the temporal envelope: Evaluation of speech intelligibility and sound quality. The Journal of the Acoustical Society of America, 105(5), 2903-2913.

vanHarten-de Bruijn, H. E., van Kreveld-Bos, C. S. G., Dreschler, W. A., &Verschuure, H. (1997). Design of two syllabic nonlinear multichannel signal processors and the results of speech tests in noise. Ear and Hearing, 18(1), 26-33.

vanSchijndel, N. H., Houtgast, T., &Festen, J. M. (2001). Effects of degradation of intensity, time, or frequency content on speech intelligibility for normal-hearing and hearing-impaired listeners. The Journal of the Acoustical Society of America, 110(1), 529-542.

Verschuure, J., Benning, F. J., Cappellen, M. V., Dreschler, W. A., &Boeremans, P. P. (1998). Speech intelligibility in noise with fast compression hearing aids. Audiology, 37(3), 127-150.

Verschuure, J., Maas, A. J. J., Stikvoort, E., De Jong, R. M., Goedegebure, A., &Dreschler, W. A. (1996). Compression and its effect on the speech signal. Ear and Hearing, 17(2), 162-175.

Vickers, D. A., Moore, B. C., & Baer, T. (2001).Effects of low-pass filtering on the intelligibility of speech in quiet for people with and without dead regions at high frequencies. The Journal of the Acoustical Society of America, 110(2), 1164-1175.

Yathiraj, A. &Vijayalakshmi, C.S. (2005). Phonemically Balanced word list in Kannada. Developed in Department of Audiology, AIISH, Mysore.

Yueh, B., Souza, P. E., McDowell, J. A., Collins, M. P., Loovis, C. F., Hedrick, S. C., ... &Deyo, R. A. (2001). Randomized trial of amplification strategies. Archives of Otolaryngology-Head & Neck Surgery, 127(10), 1197-1204.

Yund, E. W., & Buckles, K. M. (1995). Multichannel compression hearing aids: Effect of number of channels on speech discrimination in noise. The Journal of the Acoustical Society of America, 97(2), 1206-1223.

Yund, E. W., Simon, H. J., &Efron, R. O. B. E. R. T. (1987). Speech discrimination with an 8-channel compression hearing aid and conventional aids in background of speech-band noise. J Rehabil Res Dev, 24(4), 160-180.