Effect of Spectro-Temporal Enhancement on Speech Perception in Individuals with AD

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Abstract

Auditory dys-synchrony (AD) is a unique disorder which presents itself with impaired speech understanding ability in the presence of relatively spared audibility. The management options for individuals with AD are hearing aids and/or a cochlear implant. Although the listening devices helps these individuals to communicate, the improvements observed are not consistent across individuals. There is a need to see if there are other management options like speech enhancement that can improve speech perception in individuals with AD. Thus in the present study, two types of enhancement strategies (companding and consonant enhancement) were taken to see if they bring about any change in speech intelligibility. To analyse the same, consonant identification scores were obtained from two groups of individuals (10 individuals with AD and 10 individuals with normal hearing sensitivity) in different signal to noise ratio. Individuals with AD showed a significant improvement with companding when compared to unprocessed condition only in quiet situation. However with consonant enhancement, the improvement noticed was not statistically significant. In contrast, normals did not show any advantage with processed stimuli when compared to unprocessed condition across different signal to noise ratios. Sequential Information Transfer Analysis for AD revealed that the information transmitted was most for manner feature followed by place and voicing features. The improvement following enhancement are probably due to the increase in the spectral contrast of thespeech stimuli. The improvement in the contrast might have helped the individuals with AD to extract the acoustical cues available and aided speech perception.

Key words: *Speech perception, companding, consonant enhancement, auditory dys-synchrony*

Introduction

Hearing forms an integral part of effective communication. The physical process of hearing is the ability of the auditory system to detect/perceive a sound by sensing the vibrations in the environment. Interference in this process due to any abnormality along the auditory pathway lead to loss of audibility and perception of sounds. One such interference in the auditory system is auditory dys-synchrony which is recognised as a discrete disorder triggered mainly by disruption in the interpretation of timing information by the auditory nerve.

Auditory dys-synchrony (AD) usually presents itself with unique features and impact of the same, perceptually is more severe. The typical characteristic of AD is the presence of normal outer hair cell functioning; and dysfunction of the auditory nerve making it a retro-outer hair cell disorder (Starr, Picton, Sininger, Hood & Berlin, 1996). The underlying pathophysiology that has been reported in literature varies from being at the level of the inner hair cells, synapse between inner hair cells and the auditory nerve or the discharges at the level of auditory nerve or the brainstem (Kraus et al, 2000). As a consequence of this desynchronised firing, the conduction of timing information is disturbed. The hearing sensitivity in individuals with AD with respect to pure tone detection threshold can range from normal hearing sensitivity to profound hearing loss. However almost 60-70% of them reported to have disproportionate speech identification scores which cannot be predicted from their pure tone thresholds (Zeng, Kong, Michalewski& Starr, 2005). Thus, speech identification ability and therefore communication stands out as a major problem faced by these individuals which aggravates in the presence of noise (Rance, Barker, Mok, Dowell, Ricton& Garratt., 2007). These discrepancies between speech identification and tone identification ability in individuals with AD is attributed to distorted temporal cues at suprathreshold level (Kumar &Jayaram, 2006). There are various management options that have been attempted in order to rehabilitate individuals with AD. The most conventional rehabilitation strategy of hearing aids are usually tried to improve the hearing ability. A person with sensory hearing loss obtains a good benefit in terms of audibility and speech perception from hearing aid which incorporates a non-linear compression. However, many studies conclude that the advantage of a hearing aid to a person with auditory dys-synchrony is minimal as their primary complaint would be difficult to understand speech rather than hearing it (Berlin, Hood, Morlet, Rose, &Brashears, 2003). Due to limited success with hearing aids, cochlear implants are emerging as the choice of treatment for AD. Along with cochlear implants (CI), FM systems, speech reading and cued speech have also been tried to rehabilitate individuals with auditory dys-synchrony (Kraus, 2001). Literature suggests that this population can be benefitted from cochlear implantation (Sininger & Trautwein, 2002 & Budenz, et al., 2013).

However, the recent studies indicate that not all children with auditory dys-synchrony show benefit from CI (Range- Samuelson, Drake, &Wackym, 2008). To begin with, the cost and affordability of CI makes it a difficult option. In addition, the candidacy criteria for CI also

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specifies the degree of hearing loss to be severe to profound level, whereas, individuals with AD can have the pure tone threshold indicating normal to mild-moderate loss whichcontradicts the consideration of CI as an efficient option. These limitations create a need to explore alternative strategies that may help to perceive speech by individuals with auditory dys-synchrony.

A variety of psychophysical techniques have also been tried to check for improvement in speech perception. Kraus et al. (2000) demonstrated that the individuals with auditory dys-synchrony fail to utilize a fast rate of spectro-temporal changes. This is one of the important acoustic cue for perception of speech, especially the stop consonants. Thus, it makes it difficult to perceive the stop consonants in individuals with AD.Baer, Moore and Gatehouse (1993) suggest that processing of signal to enhance spectral contrasts increases the prominences of the peaks. They observed that a moderate enhancement of speech contrasts improves intelligibility and quality rating of speech and obtained better scores in enhanced condition than the unprocessed condition. This was designed considering the fact that the individuals with sensorineural hearing loss has reduced frequency resolution which causes an inability to resolve the spectral shape. This basis can also be generalised for individuals with AD as they exhibit a similar problem of frequency processing. A study in the similar line (Narne & Vanaja, 2008a) has shown an improvement in speech perception when envelop was enhanced in individuals with AD.

Alternative means ofimproving speech intelligibility is ‘clear speech’(Picheny, Durlach, &Braida, 1985, 1986, 1989). This means that when a speaker is asked to speak clearly, he/she usuallyproduce more intelligible speech than they would whenthey are casually conversing. The clear speech emphasises onreduced speaking rate, increased energy in the1000–3000Hz range, enhanced temporal modulations,expanded voice pitch range and vowel space resulting in the higher intelligibility (Liu,Del Rio, Bradlow, & Zeng, 2004).Clear speech is found to be advantageous in various population like individuals with auditory neuropathy, and individuals with cochlear implants (Kraus et al., 2000).A higher advantage of clear speech is observed when given through electric stimulation compared to acoustic stimulation. Another such technology is burst enhancement which incorporates enhancement of burst portion of the consonant, thus modifying the consonant to vowel ratio. This would bring about an amplification of the spectral contrast. Guelke (1987) suggested that, increasing the amplitude of the burst of a stop consonant up to the level of the vowel in normal speech could result in increased intelligibility by perceiving information that would otherwise be inaudible to a person with hearing impairment.Summerfield, Foster, Tyler and Bailey (1985) examined spectral enhancement by narrowing bandwidths and digital signal processing and showed a slight improvement in intelligibility of speech.

Companding is one of the novel ideas which is a combination of the process “compressing” and “expanding” od acoustic signal.It is a technique which is developed based on relatively broadband compression followed by more frequency selective expansion of complex acoustic signal. Turicchia and Sarpeshkar (2005) proposed this strategy for time domain spectral enhancement. This approach tries to mimic certain properties shared by the peripheral auditory system. This technique enhances the spectral peaks in a stimulus, relative to nearby spectral valleys. It is observed that the spectral enhancement techniques mainly modify the regions of the signal that contain acoustic cues for consonant identification to aid the perception. This retains the consonant cues makes it more resistant to further degradation of the stimuli. Bhattacharya and Zeng (2007) demonstrated some improvement in speech intelligibility for cochlear implant users and for normal-hearing subjects.

Speech perception with lengthened transition duration was studied by Kumar and Jayaram (2011) in individuals with AD. The CVs with enhanced transition duration, have shown an improvement in speech perception both with respect to placement and voicing feature. However the mechanism underlying this improvement remains unclear.

Due to lack of benefit with the conventional amplification system, some alternate management options like enhancement of the signals are tried to evaluate the usefulness in perception of speech in individuals with auditory dys-synchrony. There is still scope for fine tuning these strategies as many techniques that have been developed, either improve the signal-to noise ratio (SNR) without any improvement in intelligibility, or have added artifacts by introducing spurious sounds and enhancing random spectral peaks. Thus, the aim should be to choose an appropriate technology that would increase the intelligibility of speech in favourable and unfavourable listening environments in individuals with auditory dys-synchrony which the current hearing aids do not do efficiently.

Need for the study

Multiple studies are carried out concerning the issue of management of AD which poses a huge challenge. Each study which incorporates the application of psychophysical techniques have seen a considerable improvement in speech perception (Bhattacharya &Zeng, 2007; Guelke, 1987; Narne&Vanaja, 2008a). The companding technology was used to study the speech perception in individuals with AD (Narne, Barman, Deepthi&Shachi, 2014). They considered 10 participants with AD to check the perception of consonants and sentences in quiet and at different SNRs (0, 5, 10 and 15 dB). There was a significant improvement observed in terms of increment in consonant identification scores in individuals with AD especially in quiet and 15dB SNR.

Consonant enhancement for AD individuals are tried in various studies (Narne&Vanaja, 2008a, Kumar &Jayaram, 2011). They have either considered enhancement with respect to bandwidth or duration of burst or transition. These are done owing to the perceptual consequence of the pathophysiology of AD where temporal perception is the severely affected. However, there is a need to see if a spectrally enhanced stimuli (amplitude of consonant enhanced) can bring about any change in the perception.

Also, to see whether there are subgroup of AD who gets benefit more with spectral or temporal enhancement. There are no comparison made across strategies in the same study which helps to compare the improvement with each strategy. Also, the studies of speech perception have either taken words or sentences as the stimuli which possess some redundancy within them. This makes it difficult to attribute the differences in perception to the different techniques. To overcome the same the present study considered consonant vowel combinations which has very less inherent redundancy.

It is established that speech perception has greater detrimental effects especially in the presence of noise in AD when compared to normal hearing counterparts. Hence, this poses a need to test the robustness of the improvement provided by the companding and consonant enhancement algorithms and compare the same across different levels of noise. Furthermore, there are no controlled studies which report of comparison between the strategies to compare the improvement across different signal to noise ratios. It is also required to identify the spectral or spectro-temporal cues that are critical in providing the improvement in speech intelligibility that can help us further rehabilitation procedure required for individuals with auditory dys-synchrony.

Aim of the study

To evaluate the effect of companded and consonant enhanced speech on speech perception in quiet and in noise among normal hearing individuals and individuals with auditory dys-synchrony.

Objective of the study

Thus the present study has been taken up with the following objectives.

1. To evaluate the effect of spectral-temporal enhancement using companding and consonant enhancement strategy on speech perception in quiet and noise among individuals with normal hearing sensitivity and auditory dys-synchrony.
2. To compare the speech perception scores obtained using companding and consonant enhancement within the group.
3. To compare the relative benefit of processed signal at each listening condition across the two groups.
4. To analyse the consonantal error patters in terms of voicing, manner and place of articulation cues perceived by the AD individuals.

Method

Participants

Two groups of participants, the control and the clinical group participated in the study. Both the groups had 10 native Kannada speakers in the age range of 14 to 40 years (mean age: 21.6years). This age range was taken as there is literature evidence that the psycho- acoustic abilities reach a plateau in normal hearing individuals by 12 years of age (Werner& Gray, 1998). The control group had participants with hearing sensitivity within normal limits and the clinical group included participants having auditory dys-synchrony.

Clinical group: Individuals with Auditory dys-synchrony:

This group consisted of 10 participants diagnosed as having auditory dys-synchrony at the Department of Audiology, All India Institute of Speech and Hearing. All of them reported to have acquired post lingual hearing loss. The hearing loss in terms of pure tone thresholds ranged from near normal hearing to moderate sensorineural hearing loss and the speech identification scores in quiet were disproportionate to the degree of hearing sensitivity. All the participants had no known speech and language deficits or any other associated neurological symptoms as reported. The Audiological details along with the demographic data are given in the Table 1

Table 1: Demographic and Audiological details of participants with auditory dys-synchrony

Subjects (Test ear)	Age/Gender	Pure tone average	SIS in quiet	Tympanometry	Acoustic reflexes	OAE	ABR
S1 (Left)	29y/M	33.75	32%	'A'	Absent	Present	Absent
S2 (Left)	21y/M	53.75	32%	'A'	Absent	Present	Absent
S3 (Right)	14y/F	34.75	68%	'A'	Absent	Present	Absent
S4 (Right)	15y/F	38.75	64%	'A'	Absent	Present	Absent
S5 (Right)	35y/M	27.5	60%	'A'	Absent	Present	Absent
S6 (Right)	18y/F	32.5	68%	'A'	Absent	Present	Absent
S7 (Left)	22y/M	45	52%	'A'	Absent	Present	Absent
S8 (Right)	18y/M	20	64%	'A'	Absent	Present	Absent
S9 (Left)	29y/F	32.5	52%	'A'	Absent	Present	Absent
S10 (Left)	15y/F	34.75	76%	'A'	Absent	Present	Absent

Control group: Individuals with normal hearing sensitivity:

This group consisted of 10 adults who were age and gender matched with the clinical group. Their hearing sensitivity was within normal limits (four frequency average pure tone threshold, 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz) and speech identification scores in noise was 60% or above at 0dB SNR. Transient evoked otoacoustic emissions were present in all the participants. 'A' type tympanogram with middle-ear acoustic reflexes (both ipsilateral & contralateral) and auditory brainstem responses were present in all the participants.

Testing environment:

All the tests were carried out in an air conditioned, double room situation with ambient noise levels within permissible limits (ANSI S-3, 1991).

Stimulus generation:

The consonants (/p/, /b/, /d/, /g/, /tò/, /dz/, /r/, /v/, /n/, /m/, /l/, /l̲/, /j/, /k/, /d̲/, /s/, /ò/, /t/, /d̲/) were recorded in the vowel context /a/. All the recorded syllables were subjected to goodness test using a three point rating scale (3-good, 2-fair, 1-poor). This was done by asking five Kannada speakers with normal hearing sensitivity to listen and rate the quality of syllable. The syllables having maximum score were selected for the study. The selected signal was then mixed with six speaker speech babble developed by Jain, Konadath, Vimal, and Suresh (2014) to achieve signal to noise ratios of 0, +5, +10 and +15 dB. The mixed and the unmixed stimuli were subjected to companding and consonant enhancement processing. Companding and consonant enhancement were done using MATLAB 7.8 and UCL Enhance software respectively.

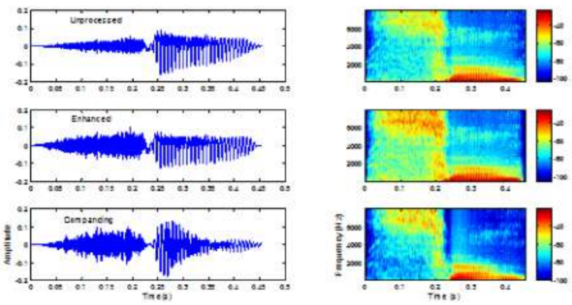

Figure 1: Figure showing the spectrum and spectrogram of the syllable /sa/ in all the three conditions without noise.

Procedure:

To obtain the consonant identification scores, all the participants of both groups were made to undergo the following testing procedure.

- The most comfortable level for speech was obtained for each participant before the commencement of the actual testing. The further testing was carried out at that particular level (MCL).
- The participants were familiarised to the stimuli before the testing phase either by showing the

written syllables or by making them listen to them in quiet condition.

- The stimuli were presented through calibrated headphones attached to the laptop interface whose output was calibrated beforehand. MATLAB- 7.8 software was used for stimulus presentation. Every syllable was presented thrice under each stimulus condition. The processed and unprocessed stimuli were randomly presented. To start with, stimuli in quiet condition was presented and then moved to complex situation consisting of different SNRs.

The participants were asked to identify the syllable heard and that was selected as the response by the examiner on the response screen. The stimulus presentation was randomised by the software for every trial and thus making it blind-folded for the tester to avoid tester bias. The response screen is as shown in the figure 2.

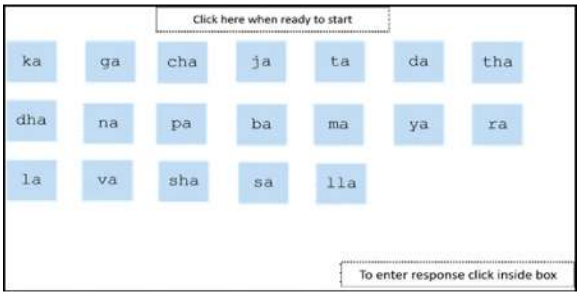

Figure 2: *Response screen showing the arrangement of syllables considered for testing*

- The next stimulus was presented following the response of the prior stimuli. A two minute interval was given after completion of every SNR condition and the testing was carried out in two sessions to avoid fatigue.
- A score of 1 was awarded for the correct response and 0 for incorrect response. No score was awarded for partial correct response to the stimulus. Using the response, a stimulus response matrix was constructed for each stimulus condition separately at each signal to noise ratio. In the matrix, the sum of scores of diagonal axis gave the total correct score for every condition.
- The obtained scores were analysed in every stimulus condition across all the SNRs considered for both the groups of individuals. On visual inspection of the consonant identification scores in clinical population, there was a lot of variability that was noted. Owing to this reason, the clinical group was further subcategorized based on their performance in syllable identification in quiet condition as good and poor performers. The criteria of 8 correct responses was set for this categorization. Out of the 10 individuals with AD, 5 individuals obtained scores greater or equal to 8 who formed the good performers group (ADG) and remaining 5 formed the poor performers group (ADP).
- The consonant identification scores were later compared across different SNRs in each condition separately and also across conditions in order to achieve the objectives of the study.

Results and Discussion

Data obtained from both the groups in all three stimulus conditions and 5 different SNRs was subjected to descriptive statistics to obtain the mean, median and standard deviation (SD). The same are tabulated in the Table 1. From visual inspection of the descriptive data from the Table1, it can be said that the individuals with AD had a lower consonant identification scores when compared to normal hearing counterparts. However, in both the population there was a common trend of reduction in scores on an average of almost 50% correct score in quiet to 5.2% correct scores at 0 dB SNR in AD and average correct score of 100% to 73% in normal hearing group across all the stimulus conditions.

Baseline DPOAE Measurement

DPOAEs were analyzed for peaks in the fine structure according to guidelines provided by Abdala, Mishra and Williams (2008). Example of the DPOAE data from a representative participant is shown in Figure 4. 1 and 4. 2. Figure 4. 1 shows original DPOAE recording. In Figure 4. 1 distinct fine structure of the DPOAEs can be seen with peaks and trough. Figure 4. 2 shows the smoothed DPOAE fine structure for the same participant. For smoothing of the data, every three successive data points were averaged to calculate the noise floor and DPOAE amplitude. Data points where signal to noise ratio was less than 6 dB was excluded from the analysis. From this data, peak or the maximum in the fine structure was measured. For the purpose of DPOAE peak identification 1000 Hz to 8000 Hz frequency range was divided to 1/3 octave bands. Maximum or peaks were identified as DPOAE frequencies with maximum amplitude in every 1/3 octave band. Thus, a total of 9 peaks in the DPOAEs were identified for each participant. Figure 4. 3 shows the frequencies and amplitude of DPOAEs at peaks for the participant with a fine structure depicted in Figure 4. 1. Inhibition magnitudes were measured at these peak/maximum frequencies in all subsequent conditions.

Table 2 Mean, standard deviation and median of speech identification scores obtained at 3 conditions, 5 different signal to noise ratio in both the groups

Stimulus condition		Unprocessed (across SNRs in dB)					Companding (across SNRs)					Consonant Enhancement (across SNRs)				
Population		**Quiet**	**15**	**10**	**5**	**0**	**Quiet**	**15**	**10**	**5**	**0**	**Quiet**	**15**	**10**	**5**	**0**
AD	**Mean**	6.7	3.1	3	2.3	1.7	8.6	3.5	2.9	2.1	2	7.5	3	2.4	2.3	2.3
	SD	2.95	1.73	1.56	2.16	2.06	3.27	1.43	1.29	1.2	1.94	2.37	1.41	1.27	1.83	2.58
	Median	7.5	2.5	2.5	1	1	9.5	3	3	2	1.5	7	2.5	2	2	1.5
Normal	**Mean**	18	18.4	18	17.6	13.5	17.5	18.5	18.3	17.2	12.2	17.5	18	18	16.8	14
	SD	2.21	1.27	1.41	1.08	2.55	2.51	0.85	1.16	1.55	2.74	2.17	1.06	1.25	1.03	2.16
	Median	19	19	18.50	17	14	18.5	19	19	17.5	12.5	18	19	18	17	14

Comparison of consonant identification scores obtained across groups (AD v/s Normal)

Shapiro Wilk's test was run which revealed that the distribution of all data did not fullfil the normality criteria. Thus, non-parametric test was chosen to analyse the data. Mann-Whitney U test was carried out to compare the scores obtained across stimulus condition and SNRs between the two groups. The test showed a significant difference between the groups for each stimulus condition and each SNR. However, it did not indicate the effect of stimulus condition on consonant identification scores at each SNR and also effect of SNRs on consonant identification scores at each condition.

To assess the benefit received by each processing condition, the difference between processed and unprocessed consonant identification scores obtained across all the SNRs were calculated that is, consonant identification scores obtained in companding/ consonant enhancement – unprocessed condition.

Results revealed that there is no specific trend obtained for both the groups. However, AD group showed a benefit at 15dB SNR and quiet for companding and a benefit at quiet for consonant enhancement. Mann Whitney test for the difference in scores were carried out which revealed that there was a significant difference between the scores difference of companding and unprocessed in the quiet and 10 dB SNR between the groups. That is, the amount of improvement that AD group utilised was significantly greater than that of normal hearing peers. Also, there was a marginal significant difference for the difference of consonant enhancement and unprocessed condition in quiet condition where the AD group had a greater benefit than normal group.

Comparison of consonant identification scores obtained across SNR within each condition and within group

The non-parametric Friedman's test was carried out under each stimulus condition where the different SNRs acted as the repeated measure in each group. The analysis were done separately for each stimulus condition and each group. The X^2 values were obtained under each condition across different SNRs. Results revealed that SNR affected the consonant identification scores significantly at all the conditions in both the group. Hence, a pairwise comparison was performed to see which pair of SNR is bringing about a significant difference at each condition. This was carried out using Wilcoxon's signed rank test.

Pairwise comparison of consonant identification scores between SNRs at each stimulus condition and each group

Group	Conditions	Quiet v/s15	10 v/s quiet	5v/s quiet	0 v/s quiet	15 v/s 10	15 v/s 5	15 v/s 0	10v/s5	10v/s0	5 v/s0
AD	**Unprocessed**	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p<0.05*	*p>0.05*
	Companding	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p>0.05*	*p<0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p>0.05*
	Enhanced	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p>0.05*	*p>0.05*
Normal	**Unprocessed**	*p>0.05*	*p>0.05*	*p>0.05*	*p<0.05*	*p<0.05*	*p>0.05*	*p<0.05*	*p>0.05*	*p<0.05*	*p<0.05*
	Companding	*p>0.05*	*p>0.05*	*p>0.05*	*p<0.05*	*p>0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*
	Enhanced	*p>0.05*	*p>0.05*	*p>0.05*	*p<0.05*	*p>0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*	*p<0.05*

Note: *shaded area in the Table represents a significant difference for the particular pair of SNR under each stimulus condition and group*

The same test was repeated in both clinical and control groups separately. It is observed that there is no significant difference across all pairs of SNRs. The consonant identification scores in quiet condition was higher and was significantly more than the other SNR conditions was observed in AD population. Furthermore, no significant difference was observed between any two SNR conditions in unprocessed condition and 15dB v/s 5dB in companded condition was observed in this population. Importantly scores obtained at 10dB SNR and 15dB SNR did not differ significantly in this group.

In the control group, at all the conditions the consonant identification scores obtained at quiet condition did not differ significantly from the scores obtained at 15dB SNR, 10dB SNR and 5dB SNR. It is significantly different only between 0dB SNR and quiet condition. Additionally, in unprocessed condition, 15dB and 10dB showed significant difference. Whereas in the processed condition (companding and enhanced), 10dB and 5dB and 15dB and 5dB SNR also showed a significant difference.

Comparison of consonant identification scores obtained across stimulus condition at each SNR and within groups

To check for the effect of stimulus conditions on consonant identification scores within each SNR, Friedman's test was performed. It was observed that the conditions were not significantly different at each SNR except for quiet condition which was observed only in AD population. Hence, pairwise comparison was carried out using Wilcoxon's signed rank test only for quiet condition for AD group. Since the control group showed no significant difference across conditions at any SNR, further statistical analysis was not administered.

The Wilcoxon's signed rank test was performed to check for significant difference of the three stimulus conditions by running pairwise comparison for the scores obtained in quiet situation in AD group.It was observed that, there was a significant difference between companding and unprocessed condition. But, no other condition pairs (unprocessed v/s enhancement and enhancement v/s companding) showed any significant difference between them in the quiet situation. This differences in the conditions were obtained only in AD population.

Sub-groups of AD

The data collected from 10 individuals having AD exhibited large variability. This presented a need for further categorization of the clinical group into two subgroups as good and poor performers. For this purpose, a score of 8 in unprocessed quiet condition was set as a criteria for categorization. This made the initial group of 10 divide into 2 subgroups of 5 individuals each. The data obtained in both the subgroups were subjected to descriptive statistics to obtain mean, median and standard deviation. The subgroups are represented as ADG for good performers and ADP for poor performers henceforth.

To compare the subgroups ADP and ADG in the three stimulus conditions in 5 SNRs, Mann-Whitney U test was run. It isnoted that there was a better performance of ADG subgroup when compared to ADP subgroup, which was significantly different only in quiet condition. Also, in the enhancement condition there was a significant difference between the subgroups at 15 dB SNR. The Mann Whitney test showed a significant difference for quiet condition only. As the significant difference was seen only in quiet condition, data was not analysed across SNR at each condition for each subgroup.

Obtaining a significant difference of stimuli conditions in the quiet listening situation necessitated the comparison of conditions to see which conditions are significantly different from each other in both the subgroups separately. For this reason, Friedman's test was performed.

There was no significant difference that was obtained for the ADP subgroup but, there was a marginal significant difference observed in the ADG group. To see which stimulus condition is bringing about a significant change in the consonant identification, pairwise comparison was done using Wilcoxon's signed rank test which revealedthe scores obtained in companding condition was significantly better than unprocessed condition in quiet situation. But, no other condition pairs (unprocessed v/s enhancement and enhancement v/s companding) showed any significant difference between them in the quiet situation. This differences in the conditions were obtained only in ADG population.

Consonant confusion matrices

Nineteen syllables were considered with processed (companding and enhancement) and unprocessed stimulus conditions. The listeners were forced to guess within 19 syllables for every sound presentation. The final response was obtained in the form of matrix. In the matrix the first row indicates the responses and the consonants listed vertically in the first column indicates the stimulus presented. The number in each cell represents the frequency of the particular stimulus-response pair. The number in the cells along the principal diagonal axis would be the correct response. The analysis was started with adding all the response matrices of AD population for the respective stimulus condition in quiet situation. The different SNRs were not considered as the correct scores obtained were less than 50% of total correct scores in most of the participants. An example of the added matrix is provided in Table 2

***Table 2** Example of a stimulus response matrix showing the results obtained for companding condition for 10 participants with correct response highlighted in the diagonal axis*

	b	tʃ	d	d̲	g	k	l	l̲	m	n	p	r	s	ʃ	t	t̲	j	dz	v
b	**5**			1	1						1				1			1	
tʃ		**6**					1											3	
d	1		**4**	1	2										1	1			
d̲	1		3	**3**	1										2				
g			3	1		3			1			1			1				
k			1		1	**6**							1		1				
l					1		**4**		3	1									1
l̲	1						1		1	4					2		1		
m	1						1		**4**	3	1								
n							1		4	**4**							1		
p	2					1	1				**4**				2				
r									2		1	**6**				1			
s													**4**	5				1	
ʃ		1												**9**					
t			1	1							2				**5**	1			
t̲			2	1	1										1	**5**			
j							1		3								**6**		
dz		3															1	**6**	
v							1		1	1	2								**5**

Sequential information transfer analysis (SINFA) (Wang & Bilger, 1973) was performed using the 'Feature Information Xfer (FIX) 'software (developed by University College of London, Department of Linguistics) on the added confusion matrices to assess the amount of information transfer from stimulus to response for place, manner and voicing. SINFA considers the amount of information transmitted in terms of electronic units of 'bits'. To analyse the 19 consonants, a feature matrix was formed using the voicing, place and manner features as a basis for classification. The same is shown in the Table 3.

Table 3 Feature matrix of the 19 syllables considered

	b	d	g	dz	k	l̲	l	m	n	p	r	s	t̲	v	j	tʃ	t	d̲	ʃ
Voicing	+	+	+	+	-	+	+	+	+	-	+	-	-	+	+	-	-	+	-
Place	b	a	v	p	v	p	a	b	a	b	a	a	a	l	p	p	d	d	p
Manner	p	p	p	a	p	l	l	n	n	p	l	f	p	g	g	a	p	p	f

Note: *Voicing: +=voiced, - =voiceless*
Place: b=bilabial, a=alveolar, v=velar, p=palatal, l=labial, d=dental
Manner: p=plosives, a=affricates, l=laterals, n=nasals, f=fricatives, g=glides

Zero information transmitted indicates no transmission of a particular feature and one indicates complete transmission. In this experiment, the maximum information that can be transmitted for 19 syllables was 4.24.

The total information transmitted is observed to be more in processed conditions (companding and consonant enhancement) when compared to unprocessed condition. Among the two enhancements applied, the information transmitted is greater for the companding when compared to consonant enhancement condition. The information transmitted for different phonetic features and the total information transmitted are represented in the figure 3.

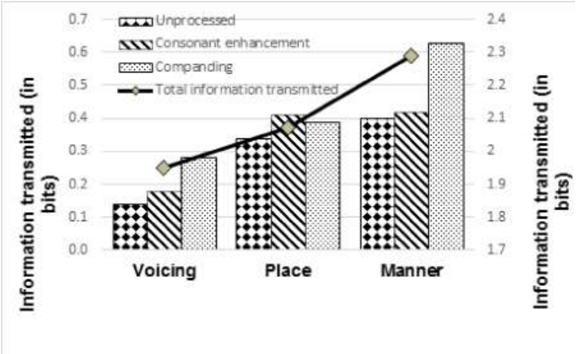

Figure 3 *Relative information transmitted across different stimulus condition*

From the figure 3 it is noted that manner cue is transmitted the maximum in all the stimulus condition, whereas voicing cue is transmitted the least across the three stimulus condition, which is followed by place. Among the stimulus conditions, companding showed maximum improvement for voicing and manner. Whereas, place showed marginal improvement in the consonant enhancement condition.

Discussion

Effect of signal enhancement techniques and SNRs on speech perception between clinical and control group

*Syllable identification was significantly better in normal hearing individuals when compared to individuals with AD. This finding was consistent across all the SNRs and the stimulus conditions considered.*Studies on speech perception in normal hearing individuals show that they utilise both envelop and fine structure cues to understand speech, especially in adverse listening conditions (Dorman, Loizou&Tu, 1998). Whereas, owing to the pathophysiology, individuals with AD are not able to extract the cues available in the speech. Adding noise in the background would exaggerate the speech perception problem due to reduction in modulation depth and addition of spurious waveform (Zeng& Liu, 2006). This reduced accessibility of cues probably is the reason for the reduced scores in AD when compared to normal hearing individuals in the present study. Also, excessive masking can be another reason for the poor performance by AD when compared to normal hearing individuals in the presence of noise (Zeng et al., 2005).

Between group comparisons of amount of improvement obtained from different stimulus techniques:

The findings obtained showed that there was significant benefit from companding over unprocessed condition in individuals with AD as against normal hearing individuals who demonstrated no improvement in quiet situation and also at 10dB SNR. The consonant enhancement showed a marginal improvement when compared to unprocessed condition in quiet situation. The amount of benefit from companding can be attributed to the spectral and temporal enhancement that is provided by the technique which is proven to aid speech perception in AD (Shachi, 2012; Narne et al, 2014). This is especially helpful for AD as they fail to utilize the cues owing to poor temporal perception and the enhancement helped to improve the spectral contrast and probably made the cues more accessible. There was a marginal benefit noted from consonant enhancement in individuals with AD as well. This can be attributed to the increment given to consonant which had improved the spectral contrast and hence increasing the speech perception. However, it did not reach the significance level. This can be because the increment given might not have necessarily increased the spectral contrast sufficiently or the amplification might be insufficient which still could get masked by the following vowels (backward masking effect).

Though there was a significant improvement obtained in AD with processed stimuli when compared to unprocessed stimuli, the benefit obtained for companding or enhanced stimulation was not consistent across SNRs and it did not show any specific trend.

Individuals with AD are very sensitive to the presence of background noise. This can be due to excessive masking which makes it difficult to utilise the enhanced cues, making the consonant identification scores almost similar to that of unprocessed stimuli. Thus, the benefit of processed signal was restricted to quiet condition with no significant difference at other SNRs.

However, benefits were not noted in normals as they could utilise the envelop cues and fine structure cues available in speech in quiet and noisy conditions. Also, in normal hearing individuals there was ceiling effect in unprocessed condition, the amount of improvement could not be appreciated well in them.

Effect of SNR onconsonant identification scores obtained for each stimulus condition within the groups

Control group

The consonant identification scores obtained were maximum in quiet situation and was found to deteriorate with decreasing SNR. The number of syllables identified were least at 0dB SNR. The same trend was noted for all the stimulus conditions.

This is a well-established observation that speech identification ability reduces in the presence of noise and makes it an adverse listening condition to communicate (Dorman et al., 1998). However, in normals, the difficulty is not present until the SNR is low. This is credited to the normal auditory physiology which is able to differentiate the wanted signals (speech) form the unwanted signals (background noise). Hence, at higher SNRs, normals can compensate by extracting the fine structure cues along with envelop cues to understand the speech (Wang &Bilger, 1973).

The consonant identification scores showed a significant difference of 0dB SNR with other SNR conditions and quiet situation for all stimulus conditions.

The accessibility to envelop and fine structure cues is not possible at a very low SNR. It is because, the noise reduces the modulation of speech envelop and also distort the temporal fine structure of speech (Houtgast&Steeneken, 1985). Thus, reducing the consonant identification scores in the presence of noise at higher levels (low SNR).

Clinical group

In the present study, it was noted that the consonant identification scores were low and variable in AD individuals. Maximum scores were obtained in quiet condition and a drastic reduction in scores was noticed even at high SNR itself.

This poor performance can be attributed to inability to process the temporal information due to asynchronous neural firing. This variability in performance in speech perception is a common finding across studies (Kumar & Jayaram, 2006; Narne & Vanaja, 2008a). *In the presence of noise, at 15dB SNR, the scores decreased greater than 50% when compared to quiet situation. Further reduction in SNR did not show a significant reduction in consonant identification scores*. There was a significantly poor score obtained at 15dB SNR itself almost reaching the floor effect. Thus, further reduction in SNR did not change the scores significantly. The reason was as explained before which is attributed to excessive masking.

Effect of stimulus condition on consonant identification scores obtained across SNRs within the groups

Control group

There was no significant difference obtained between the processed stimuli and the unprocessed stimuli and also between two processed stimuli across SNRs for normal hearing individuals.

The normal hearing individuals identified almost all consonants in quiet condition for unprocessed stimuli (ceiling effect). They do not face any difficulty in perceiving the envelop or the fine structure cues in quiet or higher SNR conditions. Hence, the role of enhancement or companding contributing to the intelligibility could not be appreciated especially in the quiet situation or at high SNRs.

In the lower SNRs, the consonant identification scores were higher for unprocessed stimuli than the processed stimuli but this was not statistically significant. These findings can be explained on the basis that the normal hearing individuals depend majorly on the spectral characteristics and the format transition to perceive the consonants. This might be because, the normal hearing auditory system can derive sufficient information from amplitude modulation of the speech in quiet situation. But, depends on frequency modulation in the presence of noise as the noise affects the intensity cues first preserving the frequency cues (Zeng et al., 2005). Whereas, application of the techniques changed either the spectro-temporal characteristics or the transition and hence probably acted as a distortion to naturally available cues for normal hearing individuals. This might have led to reduced scores in low SNRs in the processed conditions. However, these differences were not statistically significant and thus it can be said that the techniques did not cause distortions to such an extent that it compromised the intelligibility. These findings are however not in consensus with previous study by Shachi (2012) who found a significantly better consonant identification in VCV condition in the presence of speech shaped noise at 0 dB SNR with companding when compared to unprocessed stimulus in individuals with normal hearing. They also obtained SNR 50 at a significantly lower SNR (better) with companded stimulus for normal hearing individuals. Along with Shachi(2012), other studies by Baer et al, (1993) also support the finding that enhancement provided better speech identification especially in low SNR conditions. These discrepancies in the findings might be due to the stimuli considered, training with the processed stimuli and background noise used across studies.

Clinical group

Companding was proven to be significantly beneficial than consonant enhancement and unprocessed condition only in quiet condition in the current study.However, there was no difference noted between consonant enhancement and unprocessed condition in quiet situation also.

The advantage of companding can be owed to the time domain spectral enhancement which enhances spectral and temporal contrasts of speech making cues more obvious and in turn aiding speech perception. This findings are consistent with other studies where effect of companding was studied on VCV syllables and word identification in AD population with companding (Shachi, 2012; Narne et al, 2014). Thus, the improvement in speech perception observed in the present finding along with previous studies can be acknowledged to the enhancement in the spectral and temporal domain which is brought about by companding.

Between the two modifications, companding condition (average = 9.5) did show a better improvement when compared to the consonant enhancement (average= 7), however was not statistically significant.

The process behind consonant enhancement was that the burst and the transition portion of the syllable were given an additional gain of 6 dB to improve the consonant vowel ratio and aid the speech identification ability. However, in the present study, no improvement was observed following this modification. It can be reasoned that the increment given to the consonant could have masked the transition of the consonant to vowel or there is also a possibility that the enhancement was not sufficient to bring

affected which is aiding them to utilise the enhancement better. This findings is in consensus with the study by Narne and Vanaja (2008a) who also observed an improvement following envelop enhancement in the group of AD. But, AD with severe dys-synchrony exhibited greater variability in the improvement when compared to mild to moderate degree of dys-synchrony who had less variability in the improvement.

Consonant perception and analysis of error pattern:

The information transmitted showed that manner cue is transmitted the information more efficiently when compared to place and voicing across all the stimulus conditions.

Perception of Manner

Information transmission analysis revealed that manner was transmitted more efficiently in both stimulus condition, when compared to the other features. The major cue for manner perception is believed to be the envelop modulation in the speech signal. The errors observed were also within category of substitutions. The perception of continuants (fricatives, nasals) were less affected as they are cued by slow fluctuations of the envelop. The perception of slow fluctuations of the sound are relatively preserved in individuals with AD (Narne & Vanaja, 2008a). The sounds with faster fluctuations like the stops were found to be most affected as the perception of faster about a change in the consonant to vowel ratio. In addition to that, the amplification given probably might not help to overcome the effect of excessive masking effect on consonants by vowels. Also, the scores in enhancement being less than companding can be probably that the spectral contrast that is brought about is not as efficient as the contrast that is obtained due to companding.

At 15dB SNR, there was a difference in the performance between companding (average = 4), enhancement (average = 2.5) and unprocessed condition (average = 2.5), but was not significant statistically.

This lack of significance suggests that the individuals with AD could not benefit from the enhancement provided in the presence of noise. However, the same effect was not observed across other lower SNRs that is, the performance did not vary significantly with different spectro-temporal enhancement and the unprocessed condition. This is attributed to the inability of the individuals with AD to perceive the temporal fine structure information of the speech which helps in speech perception especially in the presence of noise which is a documented result (Zeng & Liu, 2006; Kumar & Jayaram, 2011).

Effect of stimulus condition and SNR on speech perception in subgroups of AD

The application of the stimulus modification did not bring about a significant difference between the two sub-groups across different SNRs. But, a better improvement for auditory dys-synchrony good performers (ADG) group was observed in quiet situation with companding when compared to auditory dys-synchrony poor performers (ADP) group. This can be reasoned out as the individuals with AD who had a better speech perception scores in quiet situation were able to utilise the enhancement provided better than ADP group. The individuals in ADG group probably had a less severe form of dys-synchrony when compared to ADP group. Hence, their temporal processing ability is not severely fluctuations of the envelop are compromised in AD (Kumar & Jayaram, 2006 and Narne & Vanaja, 2008a)

With companding, the spectrum of the speech sound is enhanced across all the frequencies. It also would result in increase in contrast of the sound. This would make the modulations or the fluctuations of the envelop more robust leading to improvement in perception of manner. This probably would have led to the greater increase in the transmission of the manner feature in this experiment.

With consonant enhancement, the consonant burst portion were enhanced. However, this resulted only in marginal improvement in transmission of manner cue. This can be attributed to the amplification given (6dB) which probably was not sufficient to bring a change in the fluctuations so much to improve manner perception.

Perception of Place

Perception of place feature mainly depends on the burst and formant transition (<50ms). Individuals with AD have difficulty in processing the short duration cues and hence there is less information transmission of the place feature. *The number of errors were also high with respect to place of articulation especially of stop consonants.* This also is a consistent finding across studies (Kraus et al, 2000; Kumar &Jayaram, 2011).

With processed stimuli, there was a marginal increase in information transfer that was observed for place.

Individuals with AD require more depth of modulation to process faster envelopes in the speech signal. This would have hampered the perception of major acoustic cues to identify place of articulation (formant transition, burst amplitude) (Ohde & Stevens, 1983). In this study, the consonant enhancement technique mainly amplified the burst and the transition portions of the consonant. The studies where enhancement on speech perception was considered are in consensus with the result of the current experiment. Guelke (1987) also found improved discrimination ability of place of articulation especially of stop consonants following enhancement of the burst portion of the syllables in sensorineural hearing loss individuals. Hence, enhancement of the transition and burst portion could probably be the reason for greater transmission of place feature.

Perception of Voicing

Voicing feature information was transmitted least when compared to other phonetic features in all the stimulus conditions.

Perception of voicing cues mainly depends on voice onset time (VOT) and first formant onset and transition. This can be attributed to altered temporal processing which affects the perception of short duration cues like VOT. In addition to that, voicing is predominantly a low frequency cue and perception of low frequency is noted to be poor due to dys-synchronous firing in AD (Rance, McKay, & Grayden, 2004). These factors might be the reason for voicing to be transmitted least in the present study.

However, with companding, there was an improvement in the transmission of the voicing feature. This can be attributed to the spectral enhancement that is applied across all the frequencies in companding. The enhancement given may have probably made the VOT and the F1 onset and the transition more robust which would have increased the perception of voicing in AD.

When consonant enhancement was applied, there was a marginal improvement observed with respect to transmission of voicing. This can probably be due to the enhancement of the transition of the consonant stimuli (Kumar &Jayaram, 2011 &Narne&Vanaja, 2008a).

Thus, there was an improvement in consonant identification scores in processed condition when compared to unprocessed stimulus condition. The spectro-temporal enhancement also improves the spectral contrast of the speech stimulus (Turicchia & Sarpeshkar, 2005). This makes the cues more prominent for individuals with AD to utilise. Hence, the total information transmitted was greater in processed than the unprocessed condition. Out of the two processed conditions, companding was found to be more efficient in transmitting the information when compared to consonant enhancement.

Summary and Conclusion

There are various enhancement strategies which has revealed improvement in speech perception but, it has not yet implemented clinically. This study is another attempt to show the behavioural improvement with spectro-temporal enhancement which can benefit the individuals with AD. Out of the different techniques considered, companding showed a significantly better improvement in consonant identification. Consonant enhancement showed a marginal improvement when compared to unprocessed stimulus condition.

It is also an indirect approach of showing that if hearing aids can implement the companding or consonant enhancement strategy, the failure of hearing aids for management of AD can be overcome. But, all the benefit noted for stimulus condition are significant and less variable in the group where the temporal processing is relatively spared. Thus, conclusion from the study should be cautiously made before generalisation.

Implication

1. This study has highlighted the understanding of the speech perception ability of individuals with AD.
2. It helps to understand the consequence of temporal processing on speech perception (pathophysiological basis for speech understanding).
3. This study gives an insight about comparison of spectral enhancement and burst enhancement. On the basis of the outcome of this study, signal processing strategies can be designed for better speech perception.

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