Exploring the Possibility of Using Spectral Tilt to Judge the Quality of Hearing Aid Output Speech

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Abstract

This study explored the possibility of using spectral tilt to judge the quality of hearing aid output speech. Thirty normally-hearing persons in the age range of 20 to 40 years participated in the study. Four digital hearing aids with different specifications and processing strategies selected were from different manufacturers and with different technical features were used in the study. Natural CV syllables with stop consonants were used as speech material in the study. Spectral tilt measurement and acoustic analysis were done on the input and output speech samples. Slope of least squares linear fit to the log power spectrum of the speech stimuli was considered as spectral tilt. Speech identification scores were tested for each of the input and output syllables and each syllable was presented four times. The present study revealed that there is a change in spectral tilt when speech is processed through the hearing aid. Subjective evaluation established that the speech identification scores correlated well with changes in the spectral tilt. Thus the results of the present study indicated the possibility of using spectral tilt as an index towards the quality of output sound of the hearing aid.

Key words: - Spectral tilt, measuring spectral tilt, index of hearing aid output quality, hearing aid signal processing.

A) Background

Advent of advanced technology in hearing aids has led to an overall improvement in the usage of hearing aids (Kochkin, 2010). Kochkin (2012) reported on the significant factors that would motivate the non-user to purchase hearing aids. Availability of hearing aids with better sound quality was reported to be one of the factors that encouraged non-users to go for hearing aids. Kochkin (2010) found that six of the top ten correlates of overall customer satisfaction were related to signal processing and sound quality. One of the most common reasons people report that they stop wearing or return their hearing aids is poor sound quality (Abrams & Kihm, 2015).

The output quality of a hearing aid gets affected because of the unfavourable temporal behaviour of the Wide Dynamic Range Compression system (WDRC). Many studies have shown that intelligibility and sound quality reduces when speech is processed through a WDRC system (Souza, 2002). The undesirable side effects of WDRC systems include loss of spectral contrast, signal overshoot, alteration of temporal envelope and acoustic feedback, among others (Schaub, 2008).

Several indicators have been experimented to represent the sound quality at the output of hearing aids. Kates and Arehart (2010) developed an index named Hearing Aid Speech Quality Index (HASQI) to judge the quality of sound output of a simulated hearing aid. This index was arrived at as a combination of two sub-indices, one of which was related to distortion. However this measure was arrived through complex procedures.

Harmonic distortion, an indirect indicator of the output quality of the hearing aid, is measured using a pure tone input signal with a frequency 'f'. Its harmonic frequencies then are 'nf,' where 'n' is an integer. Total harmonic distortion, or harmonic distortion of the nth order, is

defined as the ratio of the output sound pressure of the harmonics to the output sound pressure of the total signal. Total harmonic distortion is typically expressed as a percentage. Harmonic distortion is an incomplete measure because of the limitations of hearing aid receiver. While total harmonic distortion can be measured for an input frequency of 800 Hz, it is not possible for an input frequency of 1600 or 2500 Hz because of the limitations of the hearing aid receiver. The output of the hearing aid at integral multiples of input frequency (1600 Hz or 2500 Hz) will fall outside the receiver frequency range (Vonlanthen, 2007).

Several researchers (Fortune, Woodruff and Perves, 1994; Hoover, Souza, and Gallun, 2012) have employed EDI for quantifying temporal distortion in hearing aid processed speech and then to relate temporal distortion to speech recognition or speech intelligibility. EDI is limited in its utility particularly when used with reference to vowel-consonant-vowel (VCV) syllables.

A short review of the factors that contribute to non-adoption of hearing aids as well as dissatisfaction with hearing aid performance suggests that issues related to quality of output speech in hearing aids is crucial. Review of the measures currently used to express this crucial factor revealed that they are inadequate in providing a clear indication to the user or the professional, about the output speech quality. This raises the need for exploring the possibility of using other measures.

Spectral tilt is a parameter which is linked to the glottal excitation produced by vocal folds when they open and close. If the closing is smooth, then a large spectral tilt is observed and if the glottal flow is abrupt it would result in a small spectral tilt (Jokinen and Alku, 2017). Several researchers have analyzed or modified spectral tilt to find its influence on various factors affecting the speech quality or intelligibility. Remes, Takanen, Palomäki, Kurimo, and Alku (2014) proposed a method to improve intelligibility of narrowband telephone speech by adjusting the spectral tilt. Alexander and Kluender (2008) highlighted the contribution of

spectral tilt in perceiving the place of articulation in stop consonants. Summers, Pisoni, Bernacki, Pedlow, and Stokes (1988) while investigating the factors responsible for increase in the intelligibility of Lombard speech found spectral tilt as one. Childers and Lee (1991) observed spectral slope of the source excitation as one of the factors influencing vocal quality. Sluijter and van Heuven (1996) while trying to relate linguistic stress and spectral tilt observed that vowels which are stressed through accent have a smoother negative spectral tilt than vowels which are stressed not through accent. Estimation of the spectral tilt is also done for the glottal flow waveform which is derived from the speech signal through inverse filtering. This estimation will help to map the original tilt to a smaller tilt which will in turn improve the intelligibility of the transmitted speech in noisy situations (Jokinen and Alku, 2017).

Murphy (2001) established spectral tilt as a reliable parameter to estimate the noise embedded in the speech signal and subsequently to judge the voice quality. O'Leidhin & Murphy (2005) used spectral tilt as a noise estimator and suggested its potential use in expressing the voice quality of a speaker. Alexander and Kluender (2008) in their effort to relate hearing impairment and spectral tilt in speech observed that hearing impaired listeners are more likely to use (in comparison with normal listeners) spectral tilt onset when classifying stop consonants. While trying to find out the effect of vowel tilt on consonant vowel (CV) syllable perception, they found that speech identification scores for hearing impaired listeners decrease as spectral tilt of the vowel becomes more. Finally they concluded that hearing impaired listeners use relative spectral tilt as a cue for perception.

Spectral tilt was considered as one of the acoustic measures to find the correlation with the breathiness ratings from the sustained vowels (Hillenbrand and Houde, 1996). A louder voice has a lower spectral tilt, and spectral tilt increases when loudness decreases (Fant and Lin, 1988; Hanson, 1997). According to Kasuya, Yoshida, Ebihara, & Mori (2010) spectral tilt parameter can be one of the important factors in perception of speech signal. Differences in

the spectral tilt of steady-state vowels (Ito, Kojima, & Kawaguchi, 2001; Kiefte and Kluender, 2005) have shown to serve as cues for place of articulation. Kabuta, Taniguchi, Hatoko, Matsui, Fukumoto, & Takeda (2010) analyzed voice quality features of emotional speech in terms of spectral tilt. They conducted spectral tilt analysis for speech samples of anger and joy group. Voice quality changes with spectral tilt are more emphasized as the degrees of joy and anger increases.

All these previous research opens up the possibility of using spectral tilt as a parameter to judge the quality of output sound of a hearing aid. This paper is an attempt to find out whether there is any spectral tilt change in the output of a hearing aid when compared to the input. If present, the change in spectral tilt would probably influence the hearing aid users in speech perception. The above studies make us to believe that spectral tilt would give a better indication of the real life performance of the modern non-linear adaptive types of hearing aids. Hence the present study explored the possibility of using spectral tilt to judge the quality of hearing aid output speech.

The objectives of the study were:-

- To find out the change in spectral tilt of the output speech of the hearing aid, in comparison to the input speech.

- To correlate the spectral tilt changes to the results of subjective evaluation.

- To explore the possibility of using spectral tilt as an indicator of speech quality of the output of hearing aids.

B) Materials and Methods

i. Participants

Thirty normally-hearing persons in the age range of 20 to 40 years participated in the study. It was ensured that all normal participants were literate (minimum 5 years of schooling), native speakers of Kannada, and came from the middle socio-economic strata of the society.

ii. Material

Hearing aids

Four digital hearing aids with different specifications and processing strategies were used in the study. The hearing aids selected were from different manufacturers and with different technical features. All the hearing aids were set to manufacturers' default "first-fit" setting for test purpose. Table 1 shows the comparison of technical features of these hearing aids.

Table 1: Comparison of technical features of hearing aids used for the study

Features	Hearing Aid Models			
	HA1	HA2	HA3	HA4
Type	Trimmer controlled Digital BTE	Digital BTE	Digital BTE	Digital RIC
Gain (dB)	72	77	84	55
Number of Channels	4	2	3	4
Frequency response (Hz)	100 - 5700	180 - 5040	200 - 6200	100-6700
Compression (Number of Bands)	4	2	4	6
Attack Time (ms)	Variable	2	5	5
Release Time (ms)	Variable	120	70	55

Speech material

Natural CV syllables were used as speech material in the study. Unvoiced - velar /k/ (as in 'king'), retroflex /t/ (as in 'talk'), alveolar /th/ (final sound in 'froth'), and bilabial /p/ (as in 'poem') and their voiced counterparts – velar /g/ (as in 'good'), retroflex /d/ (as in 'dog'), alveolar /dh/ (as in 'this'), and bilabial /b/ (as in 'bed') combined with vowel /a/ formed the

CV syllables. Usage of symbols 'th' and 'dh' to indicate unvoiced alveolar and voiced alveolar consonants should not be interpreted to mean aspirated consonants.

Acquisition and recording of speech stimuli

All the syllables were spoken by a male adult speaker (native speaker of Kannada) aged 35 years, picked up by a condenser microphone (B & K 4189) kept at 15 cm from the speaker's mouth. Recording was done through B & K BZ7226 software attached to B & K 2250, a precision sound level meter. The recorded samples were digitized at a sampling frequency of 22 kHz, rate of 16 bits / sample and stored on a PC. All recordings were carried out in sound treated rooms built according to ANSI standards.

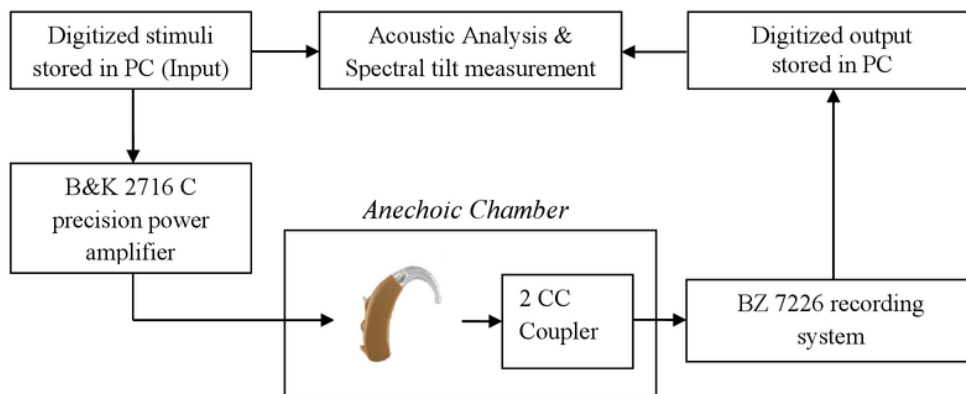## iii. Procedure

Instrumentation

Figure 1: Setup used for spectral tilt measurement and analysis

The setup used for spectral tilt measurement is shown in Figure 1. The digitized speech stimuli stored in the PC were given as input at conversation level to the hearing aid under test through a precision power amplifier. The hearing aid under test was kept inside the anechoic test chamber. The output speech samples from the hearing aid were recorded through the precision sound level meter with sound recording software B & K BZ 7226. The recorded

output syllables were digitized and stored in PC for further analysis. Spectral tilt measurement and acoustic analysis were done on the input and output speech samples.

Measurement of spectral tilt

Spectral tilt is estimated as the slope of least squares linear fit to the log power spectrum of the speech stimuli (Enflo, 2009). It shows the distortion observed in the spectrum when the speech signal is passed through a linear time-invariant filter, like a hearing aid.

Testing for speech identification

Only CV syllables with stop consonants were used as speech material in this study. Therefore, speech identification score for speech means speech identification scores for these syllables with stop consonants. Speech identification scores were obtained from all the thirty normally hearing participants for each CV syllable. Speech identification scores were tested for each of the syllables and each syllable was presented four times. Presentation of the stimuli and measurement of speech identification scores were automated through software developed specifically for this purpose on PHP platform. Inter stimulus interval was 7 seconds. The software facilitated random presentation of stimuli for each participant as well as across participants. Stimuli were presented to each listener at 40 dB SL (ref. average threshold at 500 Hz, 1kHz and 2 kHz) in a sound treated room constructed as per ANSI standards. Stimuli, stored as wave files in the PC, were routed through the precision power amplifier (B & K 2716 C) and presented to the participants through a 'leveled response' loud speaker. Loudspeaker was positioned at a distance of 1 meter from the listener and at 90° azimuth. The lid of the hearing aid test chamber was open. The stimuli were presented randomly and the participants were asked to repeat as well as write down what they heard. Simultaneously, the tester was entering the response in the software. In addition, the repetitions of listeners were audio-recorded for later analysis by an independent judge. The

test was repeated for all the eight stimuli in one session. Speech identification scores were calculated for each participant, each hearing aid and for each type of stimuli through the software. The test responses entered by the investigator into the software and the identification of the syllables by the participants (as written down by themselves) was compared by an independent judge who was not aware of the purpose of the test. There was 100 percent correlation between the two sets. In all, speech identification scores were measured two times – First, for input speech, and second, for speech processed through hearing aids.

iv. Analyses

The following analyses were carried out:-

a) Measurement and comparison of spectral tilt of hearing aid output speech and input speech to the hearing aid.

b) Measurement and comparison of speech identification score for natural syllables and hearing aid processed syllables.

c) Statistical analyses to find out whether the mean speech identification score (%) for hearing aid output speech was significantly different from that for input speech ($p<0.01$), separately for all the hearing aids.

C) Results

i. Change in spectral tilt of the output speech of hearing aids, in comparison to the input speech
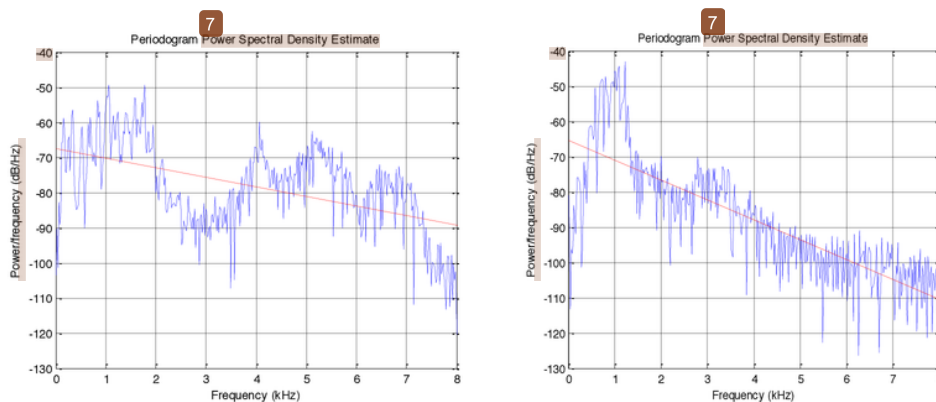
Figure 2: Estimation of spectral tilt a. For input /ba/; b. For output /ba/ from Hearing Aid 1

Spectral tilt is estimated for each of the input stimuli and output stimuli for each hearing aid. The estimation of spectral tilt for the input syllable /ba/ and its output after being processed through hearing aid 1 is shown in Figure 2. The slope of least squares linear fit to the periodogram power spectral density estimate is considered as the spectral tilt.

Table 2. Changes in Spectral tilt values of unvoiced plosives

Stimuli	Hearing Aid 1			Hearing Aid 2		
	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)
Velar /k/	-5	-4	1	-3	-7	-4
Retroflex /t/	-4	-5	-1	-3	-6.5	3.5
Alveolar /th/	-6	-4	2	-5	-3	-2
Bilabial /p/	-3	-4	-1	-3	-10	-7
Stimuli	Hearing Aid 3			Hearing Aid 4		
	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)
Velar /k/	-3	-5	-2	-3	-3.5	-0.5
Retroflex /t/	-3.5	-6.5	-3	-2.5	-3.5	-1
Alveolar /th/	-4	-6.5	-2.5	-3	-5	-2
Bilabial /p/	-2.5	-6	-3.5	-3	-2.5	0.5

Table 3. Changes in Spectral tilt values of voiced plosives.

Stimuli	Hearing Aid 1			Hearing Aid 2		
	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)

Stimuli	Hearing Aid 3			Hearing Aid 4		
	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)	Input spectral tilt (dB/kHz)	Output spectral tilt (dB/kHz)	Difference (dB/kHz)
Velar /g/	-4	-9	-5	-3.5	-9.5	-6
Retroflex /d/	-5	-7	-2	-4	-7	-3
Alveolar /dh/	-3	-5	-2	-3	-7	-4
Bilabial /b/	-3	-6	-3	-3	-7	-4
Velar /g/	-3.5	-6	-2.5	-3	-3	0
Retroflex /d/	-3	-2.5	0.5	-3	-2.5	-0.5
Alveolar /dh/	-3.5	-6	-2.5	-4	-2.5	-1.5
Bilabial /b/	-3.5	-7	-3.5	-2	-5	-3

Change in spectral tilt values for the input and output unvoiced syllables for all the four hearing aids are shown in Table 2. Change in spectral tilt values for the input and output voiced syllables for all the four hearing aids are shown in Table 3. The following general observations are made from data in Tables 2 & 3.

a) There is a change in spectral tilt as a result of processing of speech in the hearing aids.

b) Hearing Aid 2 showed the maximum changes and Hearing Aid 4 showed the minimum changes, for both voiced and unvoiced plosives.

However, these are only observations and are outside the scope of any statistical significance.

ii. Results of subjective evaluation

Table 4. Percentage Intelligibility Score of unvoiced CV syllables

Stimuli	Mean	Std. Deviation	N
Unvoiced input	93.70	5.06611	30
HA1 - Output (unvoiced)	72.43	10.39125	30
HA2 - Output (unvoiced)	69.40	9.52890	30
HA3 - Output (unvoiced)	73.60	6.82591	30
HA4 - Output (unvoiced)	80.40	6.71899	30

Table 5. Percentage Intelligibility Score of voiced CV syllables

Stimuli	Mean	Std. Deviation	N
Voiced input	94.97	7.02941	30
HA1 - Output (Voiced)	73.47	6.86688	30
HA2 - Output (Voiced)	67.20	4.54404	30
HA3 - Output (Voiced)	69.20	4.13897	30
HA4 - Output (Voiced)	74.77	7.14714	30

Table 4 shows the Mean and Standard Deviation of speech identification score of syllables perceived by participants when they were presented with 4 repetitions of all 4 unvoiced input & 4 sets of output stimuli from 4 hearing aids. Table 5 shows the Mean and Standard deviation of the intelligibility scores perceived by subjects for the voiced CV syllables.

Two way repeated measure ANOVA was administered to study the main and interaction effect of hearing aid and type of syllables (voiced / unvoiced). Results show a significant main effect of hearing aid ($F(4,116) = 65.379$, $p<0.001$) and significant main effect of type of syllable ($F(1,29) = 133.758$, $p<0.001$) as well as significant interaction between hearing aid and type of syllable ($F(4,116 = 12.971$, $p<0.001$). Bonferroni's multiple comparison was also done pair wise. It was observed that, the interaction was not significant for pairs (HA1, HA2), (HA1, HA4) and (HA2, HA4) at 0.05. Since, significant interaction between hearing aid and type of syllable was observed in two way repeated measure ANOVA, comparison of hearing aid within each syllable type using one way repeated measure ANOVA was done. Results showed that, for unvoiced input there is significant difference between hearing aids ($F(4,116) = 57.995$, $p<0.001$). For voiced input also, there is significant difference between the hearing aids ($F(4,116) = 15.868$, $p<0.001$). This also revealed that, the intelligibility changes are significant at 0.001 level.

D) Discussion

The first objective of the study was to find out whether there is a change in spectral tilt of the output speech of the hearing aid, in comparison to the input speech. A change in spectral tilt was observed in both the hearing aids for both voiced and unvoiced stimuli. Spectral integrity refers to fine spectral information contained in a speech signal. Multichannel compression systems which provide for differential gains in different channels (depending on the configuration of hearing loss) disturb the spectral integrity of a speech signal leading to continuous spectral distortion (O'Brien, 2002). Boothroyd et al., (1996) described spectral smearing as another form of spectral distortion. Spectral smearing disrupts formant intensity relationships in vowels and vowel to consonant transitions. All the hearing aids used in the present study were having multichannel compression which must have disturbed the spectral integrity of the output speech and must have resulted in spectral smearing. This must have lead to the change in spectral tilt values of the output speech of all hearing aids.

Hearing aid 2 was showing maximum spectral tilt change whereas hearing aid 4 was showing the least change. Hearing Aid 2 is inferior in processing when compared to hearing aid 4. It has only two channels and two compression bands in comparison to four channels and four bands available in hearing aid 4. Moreover, the 16 bit digital signal processor in hearing aid 4 facilitated higher level of processing compared to 8 bit processor in hearing aid 2. This must be the reason for lesser change in the spectral tilt in hearing aid 4. Having multiple channels increases the risk of spectral and temporal smearing. Several studies have shown that spectral smearing increases with number of channels. In contrary, the present study shows lesser change of spectral tilt in a four channel hearing aid (hearing aid 4). This may be because of the anti-smearing algorithm implemented in hearing aid 4 which will cancel the spectral smearing.

Results of subjective evaluation were found to be in close correlation with the extent of spectral tilt changes. Hearing Aid 4 showed best performance and hearing aid 2 the least performance in the speech intelligibility tests. These results are in accordance with the

findings of previous studies conducted by Keidser & Grant (2001); Abhaykumar (2010); Hohmann & Kollmier (1995). These studies reported that speech intelligibility has no relation with the number of channels of hearing aids for inputs with high signal to noise ratio. As all the stimuli used in the study were presented to the listener in a sound proof room, at a good signal to noise ratio, the speech identification scores did not depend on the number of channels. When the speech identification scores were compared with the extent of spectral tilt, it was observed that the scores were lower when there was larger change in spectral tilt. This has lead to the conclusion that the possibility of using spectral tilt as an indicator of speech quality of the output of hearing aids can be explored.

The study was conducted on a limited number of hearing aids and hence the results of the study can't be generalized. Moreover, the extent of spectral tilt change evaluated here is based on only the characteristics of stop consonants, whereas the hearing aid encounters all speech sounds in their daily use. Souza, (2002) is also of the opinion that WDRC can have negative effects on the intelligibility of stop consonants. The sensitive nature of stop consonants for changes in temporal parameters was one of the reasons for their selection as speech material in the present study. Changes in spectral tilt were measured manually by measuring the slope of the line of best fit and therefore, an error cannot be ruled out. If these procedures can be automated, then the evaluation will be more accurate.

Conclusions

The present study revealed that there is a change in spectral tilt when speech is processed through the hearing aid. It was found that the extent of change depends on the features such as anti spectral smearing algorithms incorporated in the hearing aids. Subjective evaluation established speech identification scores correlated well with changes in the spectral tilt. Thus the results of the present study indicated the possibility of using spectral tilt as an index towards the quality of output sound of the hearing aid. Many attempts have been made in the past to have an objective measure to judge the quality of hearing aid processed speech. But,

none of the measures arrived could relate to speech recognition or speech intelligibility. The present study not only measured changes in spectral tilt following processing in hearing aids, but also related them to speech intelligibility. If the procedure of measuring spectral tilt is standardized, then it has the potential to be included in national and international standards relating to hearing aids.

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