Effect of Hearing-Aid-Processed Speech on Brainstem Responses

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Abstract

An ideal hearing aid is expected to have an output that is an exact replica of the input signal in terms of its spectral and temporal parameters. However, all of the commercially available hearing aids produce distortions in terms of spectral and temporal parameters of the signal. Such distortions of stimulus may affect the neuro-physiological processing and in turn the perception. In order to experimentally investigate this, the present study was taken up. Twenty nine adults with normal hearing and 22 adults with sensori-neural hearing loss participated in this study. A synthesized stimulus /da/ was processed through analog and digital hearing aids. Brainstem responses were recorded for the hearing aid processed /da/ as well as for unprocessed /da/ in normal and hearing impaired adults. Findings of this study suggest that hearing-aid-induced distortions affect amplitude and latency of the brainstem responses. Due to reduced temporal and spectral resolution in individuals with hearing impairment, auditory brainstem responses elicited from them were poorer compared to normal hearing individuals.

Key words: *Hearing aid, FFR, processing*

Introduction

Based on the technology, hearing aids can be classified into analog and digital hearing aids (Sandlin, 2000). Although both types of hearing aids (analog & digital) enhance speech perception in individuals with conductive hearing loss, their ability to enhance speech perception in individuals with sensori-neural hearing loss has not been satisfactory (Dillon, 2001). This is because of the fact that individuals with sensori-neural hearing loss, in addition to their reduced sensitivity, present deficits in temporal resolution (Rawool, 2006), spectral resolution (Turner, Chi, Ling & Flock, 1999), speech perception in noise (Dubno, Dirks & Morgan, 1984; Helfer & Wilber, 1990) reduced ability to perceive high frequency formant as well as a reduced phase locking (Miller, Schilling, Franck, & Young, 1997). Any device that is provided to enhance speech perception must address these issues for a successful hearing aid fitting. An ideal hearing aid is expected to have an output that is an exact replica of the input speech in terms of its spectral and temporal parameters. On the contrary, electro-acoustic measures of hearing aids show a permissible percentage of distortion up to 10% (Nielsen, Nielsen & Parving, 1990).

The difference between the output and input speech signals, termed as distortion, could be either in terms of spectral parameters like formant frequencies, formant transition, spectrum of the onset burst etc., or in terms of temporal parameters like VOT, burst duration, transition duration, vowel duration etc. Although the percentage of distortion is correlated well with the extent of reduction in speech perception (Dempsey, 1997), the type of distortion (spectral and temporal) should also be a primary determining factor in the reduction of speech perception. Characterization of distortions introduced by the hearing aid hence becomes necessary. Digital hearing aids have been reported to approximate natural signal more compared to analog hearing aids (Wood & Lutman, 2004), which support a lesser signal distortion in digital hearing aids. Hence, it is also necessary to characterize the distortion separately for analog and digital hearing aids.

The primary purpose of the study is to characterize the distortion induced in analog and digital hearing aids in terms of their spectral and temporal parameters. The secondary purpose is to investigate the effects of such distortion on the signal processing in the auditory brainstem of subjects with normal hearing sensitivity and those with sensori-neural hearing loss. Because brainstem responses elicited by speech are reported to evidence even the subtle changes in the signals (Tremblay, Billings, Friesen & Souza, 2003), the present study adopted auditory brainstem responses to speech as a tool to study the effects of signal processing of speech on the neurophysiology.

It is well established that a hearing aid introduces distortions into the speech output (Licklider, 1946). However, the percentage of distortion introduced by the 2 types of hearing aids (analog and digital) is not similar (Dillon, 2001). Hence, it is warranted to examine the acoustic properties of the output, from both the types of hearing aids, before it is used for any further investigations.

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Individuals with sensori-neural hearing loss are known to have inherent deficit in spectral and temporal processing due to the damage of sensory hairs cells. In such situation, the negative influence of hearing aid induced distortions is expected to be more. However, none of the earlier studies documented such effects.

Further it is also important to know as to what kind of influence such distortions are going to have on the brainstem signal processing. The majority of studies that have tried to measure the hearing aid benefit using the electro-physiological measures have used long latency response (cortical auditory evoked potential) and revealed confounding findings. Billings, Tremblay, Souza and Binns (2007) recorded cortical evoked potentials in normals and found that there was no significant effect of amplification on latencies or amplitudes. Korczak, Kurtzberg and Stapells (2005) also studied the benefits of personal hearing aids on subjects with sensori-neural hearing loss through cortical ERPs. They found that cortical ERPs were dependent on the degree of sensori-neural loss, the intensity of the stimuli, and the level of cortical auditory processing that the response measure is assessing.

The primary objective of the present study was to examine the effect of hearing-aid induced distortion on brainstem responses. The secondary objective was to characterize the hearing-aid-induced distortions. The tertiary objective was to study the effect of cochlear hearing loss on the brainstem processing of hearing-aid processed signal.

Method

The present study hypothesized that there is no difference in the brain stem responses recorded for hearing aid processed speech compared that to that elicited by original unprocessed stimulus. The study used a true experimental design, standard group comparison design and the following method to test the null hypothesis.

Subjects

Fifty one subjects participated in the study. They were divided into two groups; a control group having 29 adults with normal hearing sensitivity and clinical group having 22 adults with mild to moderate degree of sensori-neural hearing loss. They were in the age range of 18 to 45 years. Subjects in the Group-1 were required to have three important qualifications. First, they had to have normal hearing (hearing acuity within 15 dBHL) at octave frequencies between 250 Hz and 8000 Hz for air conduction and, between 250 Hz and 4000 Hz for bone conduction. Puretone audiometry was done using a calibrated diagnostic audiometer (Grason Stadler, Inc. SI-61) with TDH 39 supra aural earphones and Radio ear B-71 BC vibrator as transducers. Second, they had normal middle ear function as assessed on Immittance audiometry using calibrated middle ear analyzer (GSI Tympstar). Only those with type 'A'- tympanogram with normal ipsilateral and contralateral reflexes were considered for the study. There was no history of relevant otological or neurological dysfunction, and all of them were screened for auditory processing disorder by administrating speech perception in noise test at 0dB SNR. A score of more than 60% was the third qualifying criteria.

On the other hand, subjects in Group 2 had mild or moderate degree of sensori-neural hearing loss which was either flat or gradually sloping in configuration. They had type-A tympanogram and absent oto-acoustic emissions indicative of dysfunction of outer hair cells.

Procedure

The experiment involved 3 phases, phase-1 (Generation of the test stimuli), phase-2 (perceptual and acoustic analysis of the generated stimuli) and phase-3 (recording of the auditory brainstem responses).

Phase-1 involved stimulus generation. Auditory brainstem responses were recorded by using speech syllable /da/ borrowed from Professor Kraus, Principal Investigator, Auditory neuroscience lab, Northwestern University, Chicogo. The stimulus was 40 ms in duration (generated using Klatt synthesizer) (Klatt, 1980). It comprised of an initial noise burst and formant transition between the consonant and the vowel. It included an onset burst frication at F3, F4, and F5 during the first 10ms, followed by 30 ms F1 and F2 transitions ceasing immediately before the steady state portion of the vowel. The F0 and the first three formants (F1, F2, & F3) changed over the duration of the stimulus: F0 from 103 to 125 Hz; F1 from 220 to 720 Hz; F2 from 1700 to 1240 Hz; and F3 from 2580 to 2500 Hz. F4 and F5 were constant at 3600 and 4500 Hz respectively. Figure 1 shows the waveform and spectrogram of the stimulus /da/.

Syllable /da/ was used because of 2 reasons. One, being a stop consonant it consists of evident onset burst and formant transition which could elicit better electro-physiological responses. Second, because of its complex spectral structure, any subtle distortions in the spectrum secondary to signal processing throughhearing aid would be evident. A short duration

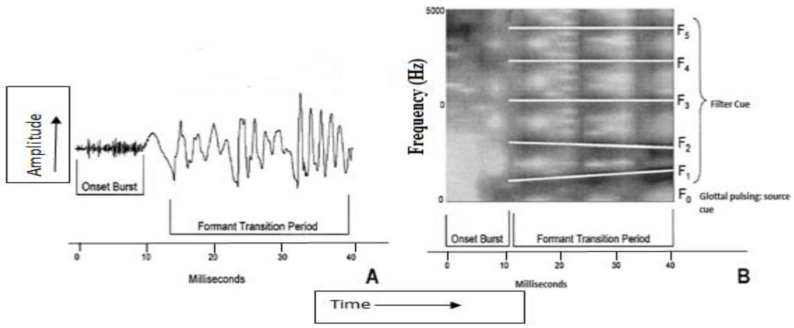

Figure1: (A) Time-amplitude waveform and (B) Spectrogram of Synthetic Syllable /da/.

Table1: Electro-acoustic Characteristics of two hearing aids

Measurement Parameter	Hearing Aid	
	Alps N (analog hearing aid)	Alps DH+ (Digital Hearing aid)
OSPL90	1kHz - 119.34 dB HFA Level - 116.4 dB	1 kHz- 119.5 dB HFA Level-116.9 dB
Full on gain	HFA level - 44.2d B	HFA Level-44.3 dB
Frequency response	200 Hz to 4477 Hz	200 Hz to 5000 Hz
Equivalent input noise	17.9 dB	9 dB
Battery current drain	1.5 mA	0.9 mA
Harmonic distortion	2.48%	1.89%

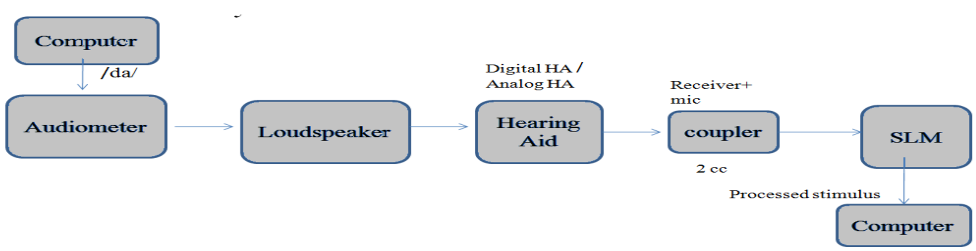

Figure 2: Block diagram of instrumentation and setup used for recording the processed stimuli.

syllable was preferred, as a longer analysis Window (that is - necessary to record responses elicited by longer duration stimulus) restricts the repetition rate which in turn prolongs the duration of testing.

To compare the processed and the natural stimulus in phase 2 and phase 3, stimulus /da/ was processed through a digital (DH+Alps) and an analog (Alps N) hearing aid. Two hearing aids were of same company (Alps international limited). The characteristics of the hearing aids were matched to maintain the uniformity. Both were moderate gain hearing aids. Analog hearing aid was with a trimmer control while the digital hearing aid was multi channel with WDRC (wide dynamic range compression) and noise reduction algorithm features. However, WDRC and Noise reduction algorithm were switched off to rule out the influence of those features. The EAC (Electro-acoustic characteristic) of the 2 hearing aids as measured by Fonix 7000 are as given in Table1.

To record the stimulus processed through the hearing aids, stimulus was initially fed into a computer. The audio output of computer was routed into a calibrated diagnostic audiometer. The syllables were then played at 40 dB HL and 45 degree azimuth through the sound field speaker. An analog hearing aid or a programmed digital hearing aid was placed in the subject's position at a 1 meter distance. The receiver of the hearing aid was connected to a 2 cc coupler. The other end of the coupler was attached to a Sound Level Meter (SLM). The SLM in turn was connected to another computer which received the processed stimulus. The so recorded stimulus was then normalized to maintain the overall amplitude constant across stimuli. A block diagram of the set up is shown in Figure 2.

Phase-2 involved acoustic and perceptual analysis of unprocessed and processed /da/ syllables. In the acoustic analysis, spectral and temporal aspects of the unprocessed stimulus and the processed stimuli were studied using PRAAT (Version 4.1.21) software. Comparison was made across unprocessed stimulus, stimulus processed through analog hearing aid and stimulus processed through digital hearing aid. The parameters analyzed included Fundamental frequency, F1, F2, F3, F4, total stimulus duration, burst duration, and formant transition duration. The analysis was carried out by speech pathologists with expertise in acoustic analysis.

In the perceptual analysis, stimuli were perceptually analyzed for the quality. The three syllables were played to 20 sophisticated listeners at comfortable levels through audio deck. The participants were instructed to rate the naturalness on a five-point rating scale wherein '1' is most natural, '2'- near natural, '3'- moderately natural, '4'- almost unnatural and '5'- completely unnatural.

In phase-3, auditory brainstem response (ABR) was recorded for the 3 target stimuli in a sound treated room where the noise levels were as per the guidelines in ANSI S 3.1 (1991). The clients were seated comfortably in a reclining chair. The skin surface at the vertex (Cz), nape of the neck, and forehead (Fz) was cleaned with skin abrasive gel, to obtain the absolute electrode impedance of less than 5 kΩ and inter-electrode impedance of less than 2 kΩ. The electrodes were placed with the help of skin conduction paste and secured tightly in their respective places using surgical plaster. Participants were instructed to relax and refrain from extraneous body movements to minimize artifacts. The testing was done monaurally in both the ears. The stimulus and acquisition parameters used for recording brainstem responses are given in Table 2.

Brainstem responses elicited by speech were visually analyzed independently by two audiologists, experienced in the area of electrophysiology. Only the replicated waves were considered for the analysis. Both transient and sustained elements of the responses were analyzed. Each individual wave was analyzed to record latency and amplitude of wave V, A, C, D, E, F and O.

The sustained portion was further analyzed using Fast Fourier Transformation to record the energy at frequencies corresponding to F0 and F1. The Fast Fourier transformation was performed on the recorded waveforms. Activity occurred in the frequency range of the response corresponding to the fundamental frequency of the speech stimulus (103– 121 Hz), first formant frequencies of the stimulus (454-719 Hz) and for the higher harmonics (721-1155 Hz) were measured for all the subjects. A 2 ms on 2 ms off Hanning ramp was applied to the waveform. Zero-padding was employed to increase the number of frequency points

Table 2: Protocol for recording auditory brainstem responses

Parameters	Target Settings
Stimulus Parameters	
Stimulus	1. /da/- unprocessed 2. Hearing aid processed -/da/-digital hearing aid -/da/ - analog hearing aid
Duration	40 ms
Polarity	Rarefaction
Stimulus Intensity	70 dBnHL
Repetition Rate	7.1 Hz
Acquisition Parameters	
Mode	Ipsilateral
Analysis Time	60 ms
Band Pass Filter	30 to 3000 Hz
Electrode Montage	Vertical - Fpz, Cz, Nape
Sweeps	1500
Transducer	Insert ER-3A
Electrode Impedance	<5 kOhms
No. of Channels	One
No. of Replications	Two

where spectral estimates were obtained. An auditory evoked response from the subjects was required to be above the noise floor in order to be included in the analyses (Russo, Nicol, Musacchia & Kraus, 2004). This calculation was performed by comparing the spectral magnitude of the pre-stimulus period to that of the response. If the quotient of the magnitude of the F0, F1 and higher harmonics frequency component of the FFR divided by that of the prestimulus period was greater than or equal to one, the response was considered to be present. The analysis of F0 and F1was done with the MATLAB software.

Results

The results of the study are discussed under 3 headings; results of acoustic analysis, results of perceptual analysis and results of brainstem responses.

Results of Acoustic Analysis

Acoustic analysis was carried out on the 3 test stimuli to identify the spectral and temporal parameters, which were then compared for any differences. Results of the acoustic analysis revealed that the signal processing influenced spectral as well as temporal parameters of the syllable /da/. For the acoustic analysis, the spectral parameters considered were fundamental frequency and the subsequent higher formants (first, second, third and fourth). Among these parameters, fundamental frequency did not vary between unprocessed /da/ and processed /da/ stimuli, while first, second, third and the fourth formants were different (higher), in processed stimuli compared to that in unprocessed stimulus. The temporal parameters considered in the spectral analyses were burst duration, transition duration and the overall duration of the stimulus. Among these measures (burst duration & transition duration) marginal differences were seen in burst as well as transition durations. Burst duration was increased while the transition duration was decreased in the processed stimuli compared to the original /da/. There was no considerable difference between temporal measures of stimulus processed through analog and digital hearing aids.

Results of Perceptual Analysis

It can be seen in the Figure 3 that most of the listeners rated original unprocessed /da/ as either natural, near natural or moderately natural. None of them perceived it to be almost unnatural or completely unnatural. However, this was not the case with processed stimuli. Neither of the processed stimuli was rated most natural by any of the listener. Within the 2 processed stimuli, output of the analog hearing aid was perceptually rated poorer than the digital hearing aid.

To see whether these observed differences in the perceptual rating were statistically significant, 'Equality of Proportions' was used. In this, the number of listeners who rated the 3 stimuli as natural were compared. Results showed that the number of individuals who rated the unprocessed stimulus as natural were significantly higher [Z=4.50, $p<0.05$] compared to that of processed stimuli. But when they were compared on 'near natural rating', results showed no significant difference [Z=0.38, $p>0.05$] between them.

Results of Brainstem Responses

The latency and amplitude measures of waves V, A, C, D, E, F and O were recorded by 3 different stimuli in 2 groups of subjects. Waves V, A, D, E, and F were present 100% of the time while waves C and O were present in very few individuals in all the conditions. Hence for all further statistical procedures only measures of V, A, D, E and F were considered.

Results of Onset Responses: Brainstem responses were recorded for 3 stimuli and in 2 groups. The statistical results of the latency and amplitude are discussed separately.

Results of Latency of Onset Responses: The data in Table 3 shows that there were mean differences across the responses elicited by 3 stimuli and in 2 groups. Both wave V and A were prolonged when elicited by the processed stimuli compared to the original, unprocessed /da/. Further, onset responses elicited by /da/-digital was more prolonged than /da/-analog. These mean differences were present in both the groups.

The data also showed mean differences between the two groups. Mean latencies were prolonged in the Sensori-neural hearing loss (SNHL) group compared to normal hearing group. This was true for all the 3 stimuli and both the waves.

To verify whether these mean differences were statistically significant, the data was tested on Mixed ANOVA taking stimulus and the group as independent variables. The results of Mixed ANOVA for wave V latency showed an overall significant effect of stimulus [$F(2, 98)=116.27$, $p<0.05$] but not group [$F(1, 49)=1.23$, $p>0.05$]. On the other hand, the results of Mixed ANOVA for wave A showed over all significant effect of stimulus [$F(2, 98)=20.47$, $p<0.05$] as well as group [$F(1, 49)=4.47$, $p<0.05$]. There was no interaction between group and stimulus in either wave V latency [$F(2, 98)=1.43$, $p>0.05$] or wave A latency [$F(2, 98)=2.43$, $p>0.05$].

Because Mixed ANOVA showed overall effect of stimulus, Bonferroni test was used for pair-wise comparison. Results showed that there was significant difference across all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/). Figure 4 (a & b) shows the delayed onset response elicited by processed stimuli in representative normal (a) and SNHL (b) subjects.

Furthermore, MANOVA was done to see the group differences in each stimulus. Results showed no difference between normal group and SNHL group in any of the stimuli; Unprocessed /da/ stimulus - [$F(1, 49)=0.073$, $p>0.05$], Analog hearing aid processed /da/ stimulus- [$F(1, 49)=0.529$, $p>0.05$], Digital hearing aid processed stimulus- [$F(1, 49)=3.06$, $p>0.05$].

As the Mixed ANOVA showed significant difference in wave V and A latencies across the stimulus taking data from both the groups, repeated measure ANOVA was done within group to see which group had significant difference in wave V and A latency across the three stimuli. Repeated measures ANOVA was

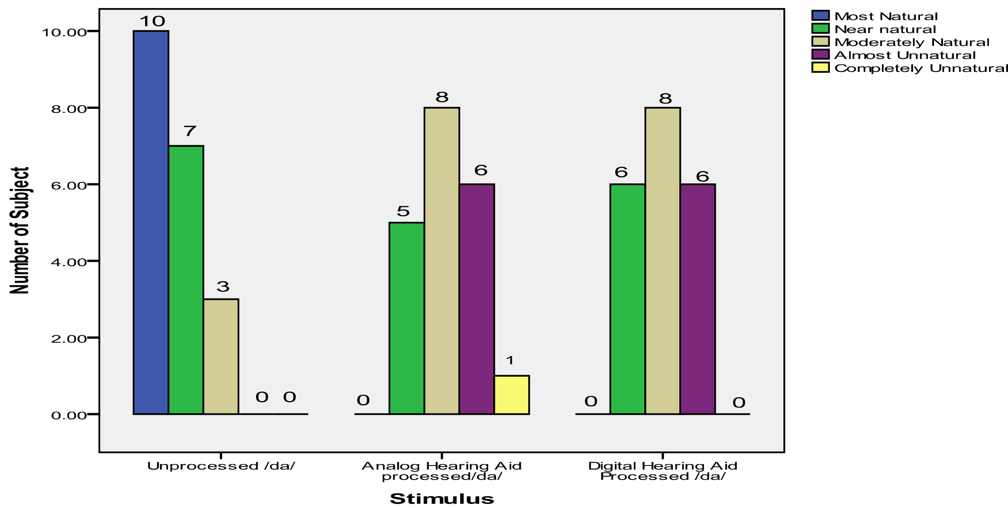

Figure 3: Perceptual judgment of unprocessed /da/, /da/ processed through digital hearing aid and /da/ processed through analog hearing aid on a five point rating scale by 20 sophisticated listeners.

Table 3: Mean and Standard Deviation (SD) of latency and amplitude of wave V and A, recorded for the three test stimuli and in the target groups

Peak	Group	Parameter	Unprocessed stimulus /da/		Analog Hearing aid processed stimulus /da/		Digital Hearing aid processed stimulus/da/	
			Mean	SD	Mean	SD	Mean	SD
Wave 'V'	Normal	Latency (ms)	5.73	0.37	6.26	0.31	6.33	0.36
		Amplitude (µV)	0.25	0.09	0.22	0.09	0.20	0.07
	SNHL	Latency (ms)	5.75	0.35	6.32	0.31	6.55	0.55
		Amplitude (µV)	0.20	0.08	0.16	0.07	0.16	0.08
Wave 'A'	Normal	Latency (ms)	6.60	1.17	7.19	0.35	7.30	0.31
		Amplitude (µV)	0.35	0.09	0.29	0.05	0.26	0.06
	SNHL	Latency (ms)	6.88	0.46	7.37	0.44	7.61	0.61
		Amplitude (µV)	0.32	0.10	0.30	0.14	0.25	0.08

done separately for normal and SNHL groups. Results showed significant difference across stimuli in both normal [$F(2, 56)=83.83$, $p<0.05$], [$F(2, 56)=7.65$, $p<0.05$] and SNHL [$F(2,42)=43.00$, $p<0.05$], [$F(2, 42)=39.98$, $p<0.05$] groups for wave V latency and wave A latency respectively. Pair-wise comparison on Bonferroni test showed significant difference in all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/) in both wave V and A latencies, in both the groups.

Results of Amplitude of Onset Responses: Both V and A amplitude were decreased when elicited by the processed stimuli compared to the original, unprocessed /da/. Within processed stimuli, in most instances, Digit-/da/ elicited lesser amplitude compared to analog-/da/. This was true in both the groups. On comparing the means of 2 groups, in most instances, normal group had higher mean amplitude of wave V and A compared to SNHL group. This was true with all the 3 stimuli.

To verify whether these mean differences were significantly different, mixed ANOVA was done. Results showed significant main effect of stimulus on both wave V [$F(2, 98)=8.54$, $p<0.05$] and wave A [$F(2, 98)=14.76$, $p<0.05$] amplitudes. On the other hand, main effect of group was seen only on wave V amplitude [$F(1, 49)=9.65$, $p<0.05$] and not on wave A amplitude [$F(1, 49)=0.35$, $p>0.05$].

There were no significant interactions either in wave V [$F(2, 98)=2.37$, $p>0.05$] or wave A [$F(2, 98)=0.55$, $p>0.05$]. Consequent to main effect of stimulus seen in Mixed ANOVA, pair-wise comparison was tested on Bonferroni. Results of wave V amplitude showed that there was significant difference between unprocessed

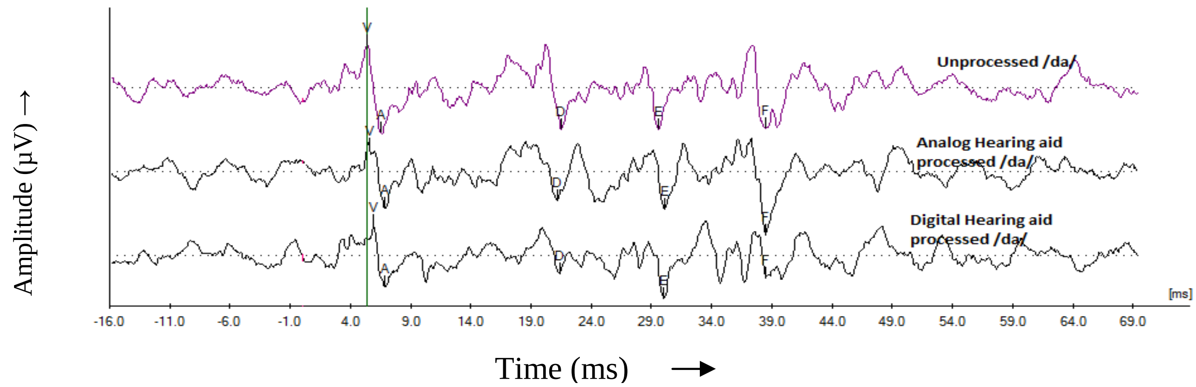

Figure 4(a): Responses recorded in a representative Normal hearing subject.

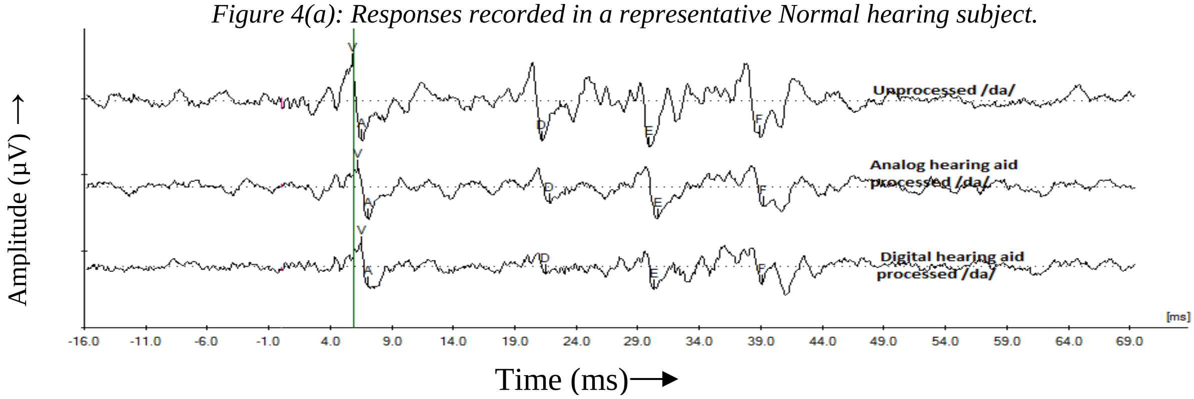

Figure 4(b): Responses recorded in a representative SNHL subject.

stimulus and digital-/da/ only. There were no significant differences in the other 2 pairs. Whereas, results of wave A amplitude showed that all 3 pairs (Unprocessed /da/ - Analog /da/; Unprocessed /da/- Digital /da/; Digital /da/ - Analog /da/) were significantly different.

To verify whether group differences in the amplitude of wave V and A within each stimulus are significantly different, MANOVA was done. Results of wave V showed significant difference between two groups in analog hearing aid processed stimulus [$F(1, 49)=14.18$, $p<0.05$]. But there was no significant difference between groups in unprocessed stimulus [$F(1, 49)=3.89$, $p>0.05$] and digital hearing aid processed stimulus [$F(1, 49)= 3.00$, $p>0.05$]. On the contrary, results of wave A did not show significant difference between the two groups in any of the three stimuli (unprocessed stimulus [$F(1, 49)=0.79$, $p>0.05$], analog hearing aid processed stimulus [$F(1, 49)=0.03$, $p>0.05$], digital hearing aid processed stimulus [$F(1, 49)=0.57$, $p>0.05$]).

Repeated measure ANOVA was done within each group (normal & SNHL separately) to test the significance of difference in wave V amplitude across the 3 stimuli. In normals, there was significant main effect of stimulus in both wave V [$F(2, 56)=5.88$, $p<0.05$] and wave A [$F(2, 56)=11.17$, $p<0.05$] amplitudes consequent to which Bonferroni test was done. Results of pair-wise comparison of wave V amplitude showed significant difference between unprocessed stimulus and digital hearing aid processed stimulus and, analog hearing aid processed stimulus and digital hearing aid processed stimulus. But wave V amplitude of unprocessed stimulus and analog hearing aid processed stimulus were not different. On the other hand, pair-wise comparison of wave A amplitude showed significant difference between unprocessed stimulus and digital hearing aid processed stimulus, and also between unprocessed stimulus and analog hearing aid processed stimulus. But wave A amplitude of analog hearing aid processed stimulus and digital hearing aid processed stimulus were not different. In SNHL group, there was significant main effect of stimulus on wave V [$F (2,42=6.04$, $p<0.05$) and wave A [$F(2,42)=5.19$, $p<0.05$] amplitudes. On pair-wise comparison it was seen that, for wave V, there was significant difference between unprocessed stimulus and both the processed stimuli. But there was no difference between analog /da/ and digital /da/. On the other hand wave A amplitude was significantly different only between unprocessed stimulus and digital /da/ stimulus. Readers can refer to Figure 4 (a) and (b) for amplitude differences.

Table 4: Mean and standard deviations (S.D) of F0, F1 and higher harmonics (HF) amplitude elicited by three different stimuli cross the group

Peak	Stimulus→	Unprocessed /da/		Analog hearing aid processed /da/		Digital hearing aid processed /da/	
	Group↓	Mean (dB)	S.D	Mean (dB)	S.D	Mean (dB)	S.D
F0	Normal	7.50	3.41	7.11	2.04	6.61	2.29
	SNHL	7.09	3.77	6.05	2.55	5.15	2.4
F1	Normal	1.03	0.42	0.96	0.33	0.87	0.31
	SNHL	0.92	0.38	0.82	0.40	0.77	0.43
HF	Normal	0.39	0.08	0.37	0.12	0.33	0.09
	SNHL	0.31	0.10	0.28	0.06	0.26	0.06

Results of FFR Responses: FFRs (D, E & F) recorded were subjectively analyzed to note down the peak latencies and amplitudes and, objectively analyzed on FFT. The results of subjective analysis of FFR are not mentioned in the article. However, the information is available in the complete dissertation. The interested readers can refer to the dissertation.

Results of FFT: The amplitudes of synchronous neural response at frequencies corresponding to F0, F1, and higher harmonics (HF) were analyzed for the speech evoked ABR for three different stimuli (Unprocessed /da/, analog hearing aid processed /da/, and digital hearing aid processed /da/) and in 2 groups of subjects. The mean and standard deviations (S.D) of amplitude of the F0, F1 and higher harmonics (HF) of speech evoked FFR recorded by the 3 different stimuli, in 2 groups are given in Table 4. Amplitudes of all three frequencies (F0, F1 & F2) were more in normal compared to SNHL group. Also, amplitude was maximum for unprocessed stimuli and minimum for digital hearing aid processed stimulus.

To see the effect of different stimuli on the amplitude of F0, F1 and higher harmonics in both groups, Mixed ANOVA was done. Results of F0 showed that there was neither a stimulus effect [F (2, 98) =1.46, $p>0.05$] nor a group effect [F (1, 49) = 3.96, $p>0.05$] on F0 amplitude. Also, there was no interaction between stimulus and group. For F1 amplitude, the results of Mixed ANOVA showed significant effect of stimulus [$F(2, 98)=7.84$, $p<0.05$) while there was no significant effect of group [$F(1, 49)=1.31$, $p>0.05$]. There was also no interaction between stimulus and group [$F(2, 98)=0.174$, $p>0.05$). Bonferroni test showed significant difference only between unprocessed stimulus and digital hearing aid processed stimulus. There was no significant difference in the other 2 pairs of stimuli. MANOVA was done to see group difference in each stimulus. It did not show significant difference between two groups in any stimulus (Unprocessed [$F(1, 49)=0.78$, $p>0.05$], analog hearing aid processed [$F(1, 49)=1.81$, $p>0.05$], analog hearing aid processed [$F(1,49)=0.84$, $p>0.05$]). Repeated measure ANOVA was done to see the difference between stimuli within a group (normal and SNHL). In normal, there is significant difference across stimuli [$F(2, 56)=14.95$, $p<0.05$]. From Bonferroni test, it was seen that there was significant difference between unprocessed stimuli and digital hearing aid processed stimulus. But there was no significant difference in other 2 pairs of stimuli. In SNHL, there was no significant difference in any of the pairs of the stimuli.

In the amplitude of HF, Mixed ANOVA showed significant effect of stimulus [F 2, 98)=8.20, $p<0.05$] as well as group [$F(1, 49)=10.89$, $p<0.05$]. No interaction was seen between stimulus and group [$F(2, 98)=0.34$, $p<0.05$). Bonferroni test revealed significant difference between unprocessed stimulus and digital hearing aid processed stimulus. But no significant difference was seen in other 2 pairs of stimuli. MANOVA was done to see group difference in different stimuli. It showed significant difference between two groups in all three stimuli (Unprocessed [$F(1, 49)=7.33$, $p<0.05$], analog hearing aid processed [$F(1, 49)=7.80$, $p<0.05$], analog hearing aid processed [$F(1, 49)=6.48$, $p<0.05$]). Repeated measure ANOVA was done to see the difference between stimuli within a group (normal and SNHL). There was significant difference across stimuli in both normal [$F(2, 56)=5.11$, $p<0.05$] and SNHL [$F(2, 42)=3.88$, $p<0.05$] groups. From Bonferroni test, it was seen in both the groups that there was significant difference only between unprocessed stimuli and digital hearing aid processed stimulus. There was no significant difference in other 2 pairs.

Discussion

The present study was designed with a null hypothesis that there is no difference in the speech processed through the hearing aids compared to the input signal. It was also hypothesized that there are no differences between the normal and SNHL groups in terms of their brainstem neural processing. However, the results of the study did not support these hypotheses. Brainstem responses elicited in the 2 groups and by the 3 stimuli were different in terms of latency as well as amplitude.

Hearing Aid Induced Distortions

The results of present study showed that processing of synthetically generated /da/ through hearing aids added distortions to the speech stimulus. This was true in both analog as well as digital hearing aids.

Distortions were in terms of both spectral as well as temporal parameters. In terms of spectral measures, there was a difference in absolute frequency as well as ratio of the formants (F3/F2, F2/F1, and F1/F0) after processing the through the hearing aid. The differences in the ratio are given in Table 5.

This finding has important implications in speech perception. Miller (1953) reported that formant frequency ratio acts as a cue for vowel discrimination. It can be seen from Table 5 that there is large difference in the formant ratio between processed and unprocessed /da/ stimuli. Such changes in formant ratio may not influence speech intelligibility significantly as vowel contributes little (only about 5%) to intelligibility (Kent & Read, 1995). However, one should realize that such changes may be detrimental during the development of speech and language in pre-lingually deaf children. It can also be seen from the table that the difference in the ratios were most evident when the F1 was taken into consideration for the calculation of the ratio. This indicates that the major reason for the discrepancy of these ratios is probably the difference in the frequency of F1 between the processed and unprocessed stimuli. Furthermore, even in terms of temporal measures, distortion was added into the speech stimulus while processing through the hearing aids. Major distortion was due to the reduction in the transition duration while the burst duration changed little after processing through hearing aids. A similar distortion was noticed in both the hearing aid processed stimuli. Reduction in duration of transient cues (Transition duration & burst duration), even by few milliseconds is expected to degrade consonant perception (Tallal, Merzenich, Miller & Jerkins, 1998). Also, Voice onset time (VOT) being major cue for the perception of voicing, such temporal distortions if cut down VOT will affect the distinction between voiced and unvoiced speech sounds. Another type of distortion that can be seen in the waveforms of the processed stimuli in comparison to the unprocessed stimulus is the evidence of prolonged ringing within the total duration of the stimuli. This increased ringing, which can be seen to have a relatively higher frequency, has probably led to the frequency of F1 being shifted up to 789.29 and 758.31 (for the analog and digital processed stimuli respectively) from the F1 frequency of 493.45 in the unprocessed stimulus.

Perceptual Changes in Hearing Aid Processed Speech

Perceptually, unprocessed stimulus was found to be more natural than both hearing aid processed stimuli while both the processed stimuli had comparable ratings for the naturalness. This means that although hearing aids are facilitating hearing impaired individuals in terms of audibility, the naturalness of the signal is lost during amplification. However, one is cautioned about the fact that the present study analyzed output of a single syllable and any inferences drawn about naturalness of continuous speech will be premature. Perceptual differences in naturalness observed between unprocessed and hearing aid processed stimuli may have been partly due to changes in formant ratio.

Brainstem Encoding of Hearing Aid Processed Speech

The primary aim of the study was to understand how unprocessed and processed stimuli are coded neuro-physiologically in individuals with normal hearing and sensori-neural hearing loss. Results showed that both onset and sustained responses elicited by the hearing aid processed speech were poorer than that elicited by unprocessed speech syllable. The latencies were prolonged and the amplitudes were reduced. This was true is both the groups. This shows that the distortions produced by the hearing aids are affecting the signal to an extent that the onset and sustained portions of the stimulus will not be coded effectively. Reduced amplitude and prolonged latency indicates poorer synchronization at the level inferior colliculous, which is attributed to the altered rise time of the signal. The responses elicited by /da/-digital were poorer than that of /da/-analog. The exact reason for this is not clear.

The results of the present study are not in agreement with Garvita and Sandeep (2011). Unlike the results of present study, Garvita and Sandeep (2011) reported shorter latency and higher amplitude in the processed stimuli than unprocessed stimulus. The difference in the results could be because of difference in the stimuli and hearing aids used. Garvita and Sandeep (2011) used a natural utterance while the present study used a synthetically generated stimulus and thus ensured better control.

Delay and reduction in amplitude was also observed in wave E which is a component of FFR. FFR codes for the periodicity and is generated at Brainstem nuclei (Marsh, Brown, & Smith, 1974; Smith, Marsh, & Brown, 1975). The present result indicates that the hearing aid induced distortions affect the encoding of periodicity in signal which in turn is important to

encode pitch of the signal. The additional ringing reported in the acoustic analysis may be contributing for the poor processing of periodicity. Results of FFT further supported this notion. Amplitude at F1 frequency range was significantly less when the response was elicited by /da/-digital compared to that of unprocessed stimulus. These results are contradicting the findings of Garvita and Sandeep (2011) who reported enhanced F0 and F1 when elicited by processed stimuli. The results of FFT of brainstem response showed that energy at F0 was higher compared to F1 and F2 in all condition (in both groups and all the three stimulus conditions) which is in agreement with the study done by Russo, Nicol, Musacchia and Kraus, (2004) where they reported F0 region in the responses showed a greater energy compared to its harmonics.

Effect of Sensori-neural Hearing Loss on Brainstem Encoding of Speech

The secondary aim of the study was to examine the effect of sensori-neural hearing loss on the brainstem encoding of unprocessed and hearing aid processed speech. Results showed that there was group difference only for the brainstem onset responses (wave ‘V’ and ‘A’). Amplitudes of both waves ‘V’ & ‘A’ were found to be significantly reduced in the individuals with hearing impairment compared to the normal hearing group. This could be due to difference in the audibility of the 2 groups. Because of sensori-neural hearing loss, intensity reaching the brainstem will be lesser and in turn leading to lesser amplitude. However, this notion is not supported by the results of latency. If only there was difference in the intensity between the groups, there should have been significant increase in the latency too. Significant difference was absent in the present results.

Lesser amplitude of onset response means that the onset of the stimulus is poorly coded in sensori-neural hearing loss compared to normals. Coding of the onset of responses require synchronous firing of auditory nerve fibers and is important for processing burst of the stop consonants. The reduced amplitude observed in mild to moderate sensori-neural hearing loss individuals could be either because of reduced synchronous firing of nerve fibers or due to reduced number of participating nerve fibers. Goldstein and Srulovicz (1977) reported that there was a reduced temporal processing ability even in individuals with sensory hearing impairment owing to a changed (reduced/altered) traveling wave velocity. Such a change in traveling wave velocity might alter the synchronous firing of the auditory nerve fibres, thus leading to reduced amplitudes of the compound action potential which in turn leads to reduced amplitudes of the wave V. Furthermore, the present finding may be also influenced by the distortions in the stimuli. Introduction of temporal and spectral distortion that are added to the stimuli may be leading to reduced synchronous firing.

In the wave A, there was a clear difference between the two groups in terms of the wave ‘A’ latency. Among the groups, the latency of the wave A in the hearing impaired group was significantly delayed compared to that of the normal hearing group. This effect is possibly due to two reasons. As mentioned before, a cochlear hearing loss also reduces the synchronicity of the neural firing, thus leading to relatively delayed wave A. Another possible reason might be the broadening of the waves because of a relatively more dominant low frequency response from the post synaptic potentials. It is generally agreed that the response spectrum of the post synaptic potential is dominated in the low frequency (Selverston, Kleindienst & Huber., 1985; Schildberger, Milde & Horner, 1988).

There was also significant difference of the wave A between the across stimuli. For the normal hearing group, there was significant difference between the processed stimuli and the unprocessed stimulus whereas, for the hearing impaired group, there was significant difference between all the three stimuli. The difference in the latency for the processed versus the unprocessed might be because of the addition of spectral and temporal distortions into the processed signal. It was observed that the wave A latencies didn’t significantly change for the two processed signal in the normal group, whereas there was significant difference between the two processed signal in the hearing impaired group. This might be possible because, a normal auditory system might compensate for the slight changes in the signal (as seen in the analog Vs digital hearing aid processed stimuli), whereas an impaired auditory system might not be able to off-set these changes in the stimuli, which are also evidenced in the wave A latencies for the analog and digital hearing aid processed stimuli. Acoustical analysis also revealed similar finding where in the burst duration was slightly longer for the digital stimuli compare to analog. And the same is seen in the wave A latency as

Table 5: Ratio of formant frequencies for three stimuli.

Measure	Unprocessed /da/	Analog hearing aid processed /da/	Digital hearing aid processed /da/
F1/F0	4.22	6.79	6.48
F2/F1	2.97	1.96	1.98
F3/F2	1.77	1.62	1.71

well where in latencies of wave A for the digitally processed signal was slightly delayed than compare to that of analog processed signal.

FFT shows decrease in energy of F0, F1 and HF in Hearing aid processed stimuli compared to unprocessed stimuli. In all frequencies (F0, F1 and HF) there is trend of decreasing energy. In F0 and F1 there is no group difference but in HF, significant amplitude difference is present between individuals with normal and SNHL. This may be due the reduced ability to code high frequency formants in SNHL group secondary to reduced phase locking (Miller, Schilling, Franck & Young, 1997). Acoustic analysis shows that in hearing aid processed stimuli, there is increase in frequency of F1 and F2 but F0 remained the same. Decrease in amplitude (energy) may reduce the perception of manner as F2 cues for place of articulation (Kent & Read, 1995).

Thus, it can be inferred that speech cues are likely to be disrupted when processed through hearing aids. Such disruptions are more in individuals with sensori-neural hearing loss as the cochlear pathology acts as an additional degrading factor. The present day hearing aids mainly help in improving the audibility, and improve signal to noise ratio to some an extent. However, there are hearing aid induced distortions which may be detrimental to speech perception. This issue needs to be seriously considered and the respective group must work towards improving the hearing aid technology.

Conclusions

Thus, from the results of the present study it can be concluded that hearing aids create distortion in both spectral and temporal aspects of speech which in turn affects the processing at the level of brainstem. Such distortions are more deleterious in individuals with sensori-neural hearing loss. Individuals with sensori-neural hearing loss need better quality of signal compared to individuals with normal hearing for equivalent perception. So, hearing aid technology should be improved to minimize the distortions which are detrimental to speech perception.

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