Music Processed by Hearing Aids

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ALL INDIA INSTITUTE OF SPEECH & HEARING,

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DEDICATED TO

SANTOSH

Met you as a stranger,

Loved you as a friend.

Hope we meet in Heavens,

Where friendship never ends...

CERTIFICATE

This is to certify that this dissertation entitled **"Music Processed by Hearing Aids"** is a bonafide work in part fulfillment for the degree of Master of Science (Audiology) of the student Registration No. 05AUD018. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any diploma or degree.

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Mysore
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CERTIFICATE

This is to certify that this dissertation entitled **"Music Processed by Hearing Aids"** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.

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DECLARATION

This is to certify that this master's dissertation entitled **"Music Processed by Hearing Aids"** is the result of my own study and has not been submitted earlier to any other university for that award of any degree or diploma.

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Chapter I

INTRODUCTION

Speech is the most vital sound we hear in our lives. None the less, our life is also enriched by various other sounds and this especially is true for music. Music is an important and enjoyable part of life of people of all ages. It has been found to release tension, raise spirits and promote a feeling a well-being. There are just a few people who do not enjoy listening to music, but there are many people who regard music as one of their chief pleasures. Music is an important ingredient of every culture throughout the world as a form of entertainment and as a form of an art.

Following the perception of speech, the appreciation of music is the next commonly expressed requirement by the users of cochlear implants (Stainsby, McDermott, McKay & Clark 1997). This may well be said for the individuals who use hearing aids also. When the individuals who enjoy listening to music become hearing impaired one might expect a significant effect on music perception and the pleasure derived from music. Although there may be some restoration of hearing through the use of hearing aids, it is questionable whether most hearing aids process music in such a way as to enable the user to hear and enjoy music to the same degree as prior to acquiring hearing loss.

The reason that persons with hearing impairment fail to perceive or appreciate the sound quality of music is because the hearing loss has differential effects on frequency selectivity, temporal resolution, loudness perception/intensity discrimination and suprathreshold performance. These contribute to the difficulty of the individuals with hearing impairment to perceive or appreciate music (Chasin, 1996).

There is a dearth of research in the field of music and hearing impairment. This is also because the musicians and the scientists often use different terminologies in describing the characteristic of a tone. For example, a researcher may say 440 Hz tone and a western musician may denote it by A. The musicians are particularly interested for the tones below C, i.e. 262 Hz. But most audiologists would ignore the sound energy below 250 Hz because of the poor signal-to-noise ratio and because of hearing assessment problems. But for musicians this low frequency information can significantly contribute to the quality judgment (Chasin, 2003).

Speech tends to be a well controlled spectrum with well established and predictable perceptual characteristics. In contrast, music spectra are highly variable and the perceptual requirement can vary based upon the musicians, type of music and the type of instrument being played. There are five major differences between speech and music stimuli as reported by Chasin (2003, 2004 & 2006). They are (i) The long-term average spectrum of music vs. speech (ii) Differing overall intensities (iii) Crest factors (iv) Phonetic vs. phonemic perceptual requirements and (v) Difference in loudness summation and loudness intensity.

Unlike the long-term average spectrum of speech, music is highly variable and a goal of a long-term average music spectrum is poorly conceived. The potential intensity range for speech is quite restricted, approximately 30 to 35 dB. But the dynamic range of music is of the order of 100 dB. A typical crest factor with speech is about 12 dB. Crest factors of 18 to 20 dB are not uncommon for many musical instruments. The perceptual need for speech is quite clear. But for music the perceptual need is quite varied and depends upon the instrument being played. The vocal cords function as half wave resonators, whereas, the musical instrument can be half wave resonator or quarter wave resonator depending upon the instrument which is played. These differences make it difficult for a hearing aid user to enjoy music with a hearing aid that is mainly designed for speech.

Need for the Study

Historically, the primary concern for the hearing aid design and fitting is the optimization for speech input (Chasin & Russo, 2004). Musicians with hearing loss have often complained about the poor sound quality while they are playing or listening to the music through their hearing aid (Chasin, 2003). Not only the technology for music input in hearing aids is in its infancy, but the research and clinical knowledge of what the musicians, and those who like to listen to music, need to hear is also in the early stage of understanding (Chasin & Russo, 2004).

Presently, the digital technology is replacing the analog technology used in the hearing aid industry. The digital technology has the advantage of employing various algorithms such as adaptive noise-reduction systems, adaptive directionality, adaptive feedback suppression, and highly flexible control of numerous amplification characteristics, including complex forms of compression. Digital technology is also enabling the processing of sounds in different channels having different compression settings. Chasin (2003, 2006) recommended a set of parameters being ideal for the perception of music through the hearing aids. Thus, through controlled study design, the parameters in a hearing aid ideal for music perception need to be evaluated.

Aims of the Study

The present study is an attempt to evaluate the hearing aid processed music, while changing different parameters of the hearing aid. Thus the aims were as follows:

1. To compare the processing of music by using a six- channeled and a fifteen-channeled hearing aid, where, all the other parameters of signal processing of the hearing aid are kept the same.
2. To compare the music processed in a six-channeled hearing aid by setting
    - the compression knee-point being set high than that optimized for speech for a particular a hearing loss
    - by enabling and disabling the noise reduction system
    - by enabling and disabling the feedback management system.

Chapter II

REVIEW OF LITERATURE

The following section provides a brief, yet comprehensive and most pertinent review of the literature in music acoustics related to hearing loss. For easier conceptualization, the review has been given under different headings, such as, historical perspective, properties of music, perceptual parameter contributing to music perception, perceptual studies in music and hearing aids, studies on perceptual judgment and objective analysis in music and hearing aid, and, studies on noise reduction system and feedback management system in hearing aids.

2.1. Historical Perceptive

Music acoustics is both young and old as a science. Sunderberg (1991) outlined the history of research in music acoustics where he summarized as follows. Early contributions were made back in the Greece antiquity when Pythagoras wondered why certain musical interval emerged from certain string length ratio. In 1862, Helmholtz published a thick book with a thought provoking title "The science of tone perception as physiological basis for music theory". The gospel implied by this title is that music theory ultimately goes back on how our sense of hearing perceives the tone. Helmholtz dealt not only with the sense of hearing, but also developed theories for several music instruments that explained how they worked (i.e., how the tone is generated in the instrument). Many of his theories have not been greatly challenged by later research.

In 1930, the use of electronic technology was started in music instrument research. Seashore used a tonometer and he examined in detail the musical sound from an acoustical point of view. He performed studies on intonation, tone duration and other tone properties. Seashore published his results in a classical book titled "Psychology of Music".

Another page in the history of music acoustics was turned with the use of digital computers leading to more sophistication in research. This nutshell historical survey may perhaps give an idea as to what kind of problems music acoustics used to work with and is working with at the present.

2.2. Properties of Music

The subject of properties of music and musical instrument is extremely complex. Olson (1967) discussed both the physical and psychological properties of music. From the standpoint of music, sound waves may be defined in terms of six parameters namely, frequency, intensity, waveform duration, vibrato, tremolo, and growth and decay. *Frequency* is defined as the number of repetitions of a complete sequence of values of a periodic function per unit variation of an independent variable in a physical sense. The audible frequency ranges from 20 to 20,000 Hz. The frequency range essential for music ranges from 30 to 4000 Hz. Most relevant musical harmonics appear below 1000 Hz, but many instruments like harpsichord and some percussion instruments contain significant components up to 10,000 Hz or 20,000 Hz. The *intensity* (or energy flow) of a sound wave is the power (in energy/sec) transmitted through a unit area oriented perpendicular to (normal to) the propagation direction of the wave. For musical sounds the intensity can range from 20 to 30 dB and can reach up to 130 dB. The *waveform* of a musical tone complex sound wave is made up of the fundamental frequency and its harmonics often referred to as overtones. The harmonic structure in music is more aptly termed as the fine structures of the waveform. Fine structures of a waveform are essential for the perception in subtle pitch change in the musical tone. *Duration* is the length of the time that a tone persists or lasts. Duration of the tone has differential effect on judging the intensity and frequency of the tone. Hence, it is essential for music perception. *Vibrato* is the term used for a frequency modulation of musical tone. It is accompanied by an amplitude modulation as well as pulsating change in timbre. The average rate of frequency modulation in vibrato is seven cycles per second. *Tremolo* is an amplitude modulation. It is produced mechanically by modulating air supply to pipe. Violin makes use of pitch vibrato. Most of the *growth and decay* characteristics exhibited by musical instrument are in exponential function. Growth of tone involves the time required for the tone to build up some arbitrary fraction of its intensity. The decay of tone involves the time required for the tone to fall to some arbitrary fraction of the reference intensity. In piano, the growth is shorter, decay is long and in pipe both are long. The growth decay affects pitch, loudness and timber of a tone.

The psychological characteristics of music may be classified as tone, dynamic, temporal and qualitative. The *tonal* characteristic involves pitch, timbre, melody, harmony and all form of pitch variants. The *dynamic* characteristic principally depends upon loudness. The *temporal* characteristics involve the time, duration, tempo and rhythm. The *qualitative* characteristic involves timbre or harmonic constituents. In musical performance, all the four psychological characteristics may be employed in a well-balanced rendition or any one may be emphasized. The decision is intangible and a more concrete division is desirable for outlining the psychological characteristics of music. These are as follows: pitch, loudness, timbre, duration, growth, decay, consonance, volume, rhythm, presence and vibrato.

2.3. Perceptual Parameter Contributing to Music Perception

Russo (2006) provided selective overview of the perceptual dimensions contributing to music experience that may have implications for the treatment and research of hearing loss. He discussed his postulation under the following headings: melodic pitch relations, timbre, and amplification; harmonic pitch relations and reduced frequency selectivity; hierarchical pitch structure, intensity variation, and compression; and tonality and inharmonicity.

2.3.1. Melodic Pitch Relations, Timbre and Amplification

Sensitivity to relations between pitches, called relative pitch, is essential to the music experience and is the basis of the concept of a musical interval. Sequential musical intervals form the basis of melody, and simultaneous intervals form the basis of harmony. Most popular music possesses a tonal framework, in which the stability of pitches is specified with reference to the key-note of a piece. Research has shown that, if a rising pitch contour involves a transition from a dull tone to a bright tone, the perceived distance was expanded; if it involves a transition from a bright to dull tone, the perceived pitch distance was contracted. The converse is true for falling pitch contours. It's quite possible that listeners with selective hearing loss experience these sorts of relative pitch distortions when listening to melody regardless of whether or not timbre is actually changing. These relative pitch distortions may have aesthetic consequences. The researcher postulated that the person having high frequency hearing loss can be benefited from transposition of this energy to the lower frequencies if distortion is kept at a minimum.

2.3.2. Harmonic Pitch Relations and Reduced Frequency Selectivity

The presentation of music by headphone will preserve phase relationships, which can contribute to relative pitch perception. Accurate fine-grained temporal relationships may be very important for perceiving music, particularly in the case of a listener with reduced frequency selectivity. With live music, frequency modulated (FM) systems may also be of some benefit. An optimally placed microphone can compensate for numerous problems including sensitivity to noise, high-frequency losses, as well as reduced frequency selectivity.

2.3.3. Hierarchical Pitch Structure, Intensity Variation, and Compression

Periodic variations in intensity create a temporal framework (rhythm) that supports representations of relative pitch in music. Generally speaking, when variations in intensity are weak or non-existent (isochronous), what is left is a relatively shapeless piece of music, without any clear hierarchical structure.

The use of compression in hearing aids is particularly important for the music signal given its inherently wide dynamic range. However, the overuse of compression may have an effect of minimizing intensity differences, leaving important pitch relationships less apparent. Other important issues to be considered with compression include the subjective assessment of a clear rhythm or pulse.

2.3.4 Tonality and In-harmonicity

Tonality refers to the hierarchical organization of pitches around the tonic or key-note of a piece. In Western music, this organization has been described as a four-level hierarchy of stability. Pitches that occupy more stable positions in the hierarchy are more likely to start and end a piece and to occur more often. However, research has shown that minor perturbations in the fine temporal structure of tones (e.g., in-harmonicity or aperiodicity) can lead to a significant loss in ability to recover the tonal hierarchy. These perturbations are introduced naturally in tones produced by stringed instruments due to deviations from ideal elasticity. Similar perturbations may be introduced by a hearing aid, or by an impaired auditory system.

2.4. Studies on Perceptual and Objective analysis of Music and Hearing Aid

The processing of music by hearing aids had created interest in researchers in 1980s and these researches were rejuvenated by Chasin throughout 2000 till the present day. A brief yet comprehensive literature review of the researches on sound quality of hearing aids is provided below.

2.4.1. Studies on Perceptual Analysis

Punch (1978) examined the quality judgment of hearing aid processed music by 12 listeners with normal hearing and 12 listeners with hearing impairment. He used a master hearing aid for processing music in different settings of hearing aid's parameters. He found that the hearing aids most preferred by both groups of subjects provided the least frequency cut-off. The second most ranked hearing aid possessed the widest band. Although the highest ranked aid exhibited the second narrowest band width, but preserved the low frequency. It was also noted that for the music stimuli, test-retest variability was greater suggesting that the perceptual criteria appeared to change substantially with time.

Grabrielsson and Sjogren (1979) used multivariant techniques for examining the dimensions of the perceived sound quality of seven body type hearing aids for speech, environmental noise and music. Although specific information on music was lacking in their report, the result indicated a limited number of perceived quality dimensions; i.e., "hardness-softness", "clearness/distinctness", "brightness-darkness", "fullness", "loudness", "feeling space", "nearness" and "disturbing sounds". These investigators also noted that there were interactions between the hearing aids and the type of acoustical material presented. In the only specific statement regarding music, it was pointed out that narrow bandwidth produced more distortion, or bass boost made reproduction "less distinct" for jazz music. However, for one hearing aid system, although the reproduction for music was judged less distinct, the same judgment was not made for speech processed through this system. Such a finding offers some evidence to support the suggestion of the authors that the hearing aid producing the best speech intelligibility may not provide the best quality for music.

Franks (1982) determined the preferences of the subjects using hearing aid compared to subjects with normal hearing for music processed through hearing aids with different frequency response characteristics. The preference judgment of music was evaluated on two different high frequency ranges of the hearing aid and the effect of varied low-frequency cut. For judgment of bass-cut settings of the hearing aids, there was a consistent preference for the inclusion of more low frequency components. The presence of low frequency components were also perceived more readily by the individuals with hearing impairment. In contrast to the subjects with hearing impairment, the subjects with normal hearing showed consistent preference for the extended high frequency components.

The result also indicated that compared to subjects with normal hearing, subjects using extended high frequency response hearing aids did not show greater preference for music with frequency component above 4000 Hz. The results, further, indicated a negative reaction to the presence of high frequency component by the individuals with hearing impairment. These negative reactions were most evident when the hearing aid system excluded a large proportion of the low frequency component. The investigator postulated that the hearing aids failed to compensate adequately for hearing deficiencies involving the high end of the musical spectrum.

Franks and Hall (1985) gave a questionnaire to 325 individuals, out of which 178 responded. The respondents ranged in age from 8 to 91 years with a mean age of 62.3 years. The responses to the questionnaire indicated that prior to hearing impairment, listening to music had been of considerable importance to 88% of the respondents. After hearing loss was acquired, even with the use of hearing aids, there was significant influence on the listening habits and attitudes towards music. For 84% of the respondents, the use of hearing aids has meant a decline in the frequency of listening as well as the degree to which they enjoy it. Moreover, most describe the importance of reduction of enjoyment at least of moderate degree. It was also found that those who wear binaural amplification listen to music more than their monaural counterparts.

Mishra, Kunnathur and Rajalakshmi (2004) compared the perceptual rating obtained from 15 subjects with normal hearing for classical music and hard rock for four commercially available digital hearing aids. Across all the hearing aids and for both the music samples, significantly low scores were obtained for music processed through hearing aids. They further discussed the rationale for good sound quality in digital hearing aids. Once the sound is converted into digital form, it is possible for the sound to be manipulated without the hearing aid adding any significant noise of its own. Unfortunately, by the time hearing aids get to manipulate the sound, it has noise mixed with it, because from the microphone, background noise enters the hearing aid along with the desired sound. So, poor scores were obtained even for the most advanced modern hearing aid.

Mishra, Kunnathur and Rajalakshmi (2005) in a similar study used a 10 point rating scale and took 3 music samples, two classical and a hard rock to obtain the perceptual ratings by 15 subjects with normal hearing. As in their previous study, they obtained significantly poorer scores for music processed through hearing aids. They emphasized that music programs available in commercial hearing aids cannot improve the fidelity for music, because they operate based on speech acoustics. They further discussed the parameters of hearing aids essential for ideal perception of music based upon the ratings obtained for the four commercially available hearing aids. They recommended a multi-channel hearing aid programmed to function as a single or a double channel hearing aid as speech perception is better in multi-channel hearing aids. Hearing aid systems are liable to confuse music with noise and feedback hence the noise reduction and feedback system should be switched off. In most cases, there is a fairly good signal to noise ratio for the music. Directional system leads to significant loss of low frequency sounds which may remove valuable musical information. Thus, an omni directional microphone is better for good perception of music. Multiple programs in a hearing aid are better with different programs for speech and music. The essential discussion in this study was the comparison between rock music and folk music. They found that the hearing aid processed folk music better than rock music which was evident from the perceptual rating given to the music samples.

2.4.2. Studies on Subjective Judgment and Objective analysis

Singh (1984) undertook a study to judge the quality of hearing aid processed speech stimuli based on the spectrographic analysis. In the second part of the study, the stimuli were presented to eight judges and they were asked to rank the hearing aids based on perceptual judgment. Seven hearing aids from different companies were selected for the study. The receiver of the hearing aid was connected to a 2 cc coupler which in turn was connected to the frequency analyzer. The outputs from the measuring amplifier were recorded on the spool tape recorder. He took the control recording of the speech stimuli without the hearing aids and the coupler. Through the spectrographic analysis and the perceptual analysis it was possible to judge the best and the worst hearing aid and thus the hearing aids were rank ordered. The findings revealed that both perceptually and objectively the hearing aids obtained similar ranking.

Chasin (2003) studied the representation of music filtered in the frequency range of 2 kHz to 3 kHz using 105 or 115 dB SPL and 92 or 96 dB SPL peak clipping. He found that there was no much difference in sound reproduction using 105 and 115 dB SPL peak clipping. However, the sound reproduction was poorer while using 92 and 96 dB peak clipping. In his discussions, he further discussed other parameters ideal for music perceptions. He recommended a single channel hearing aid to be probably the best. In music, unlike speech, the relationship or the balance between the low frequency fundamental energy and the high frequency harmonic energy is crucial for the perception of optimal sound quality. This is especially true for violinist and violists, as well as for the people with hearing impairment who regularly listen to music. Therefore, it is necessary to use a single channel aid that maintains this balance. On the other hand, for woodwinds and the quieter music or for patients with precipitous audiometric configurations, a multi-channel hearing aid may be acceptable since the woodwinds rely perceptively on the lower frequency information in their music. He also recommended setting the knee-point approximately 5 to 8 dB higher for music than for speech due to the difference in crest factors for speech and music. He further recommended a Wide Dynamic Range Compression (WDRC) circuit for musicians considering their hearing loss which is mostly due to noise exposure or due to presbycusis; both the types of hearing loss reflects predominant damage of the outer hair cells.

Dillon, Keidser, O'Brein and Silberstein (2003) took ten normal hearing individuals, nine experienced hearing aid users and one individual with hearing impairment with no experience of hearing aid use. They took five commercially available high end digital hearing aids. The six stimuli that were used were male voice, female voice, piano music, each subject's own voice, a male voice in noise and listening in quiet room. In listening to quiet situation, subjects favored Symbio, a channel-free hearing aid, compared to the other hearing aids in subjective rating. With all other stimuli, the scores obtained by the different hearing aids were not different. On the objective measurement, the researchers found that the coherence decreased when the delay in the devices caused the input and output to appear in two different analysis frames during the coherence measurements. A correlation analysis of the objective measures and the preferences obtained for each of the six stimuli revealed that in normal-hearing subject group, there was a significant correlation between the peak $OSPL_{90}$ and the average preference obtained for the piano music. Although the variation in peak $OSPL_{90}$ is small (within 4 dB), higher preference scores were produced, on average, for devices with higher peak $OSPL_{90}$. The researchers further stated that correlations with the objective measurement implied that the devices with preferred sound quality have low internal noise, high peak $OSPL_{90}$, and low internal delay.

Chasin and Russo (2004) stated that the physical parameters that contribute to our experience of timbre include the spectrum, temporal envelope, and transient components of a tone. Grey (1977) found that the timbral distinctions are best described along three dimensions: spectral energy distribution (i.e., bandwidth and concentration), synchronicity of the temporal envelope across the partials and onset characteristics (e.g., speed of the attack). The investigators formulated a set of proposals for the effect of distortions by hearing aids on pitch and timbre. As the timbre is influenced by the spectral distribution of energy, an imbalance in amplification of low and high frequency channels will affect timbre. Having a consistent spectral distribution of energy over a series of tones serves to perceptually glue the tones together. If the tones of a melody possess spectra that modulate unpredictably, the coherence of the melody may deteriorate (Bergman A.S., (1990), cited in Chasin, M. and Russo, F.A., 2004). Thus, a balance of amplification in low and high frequency channels should remain consistent over time.

Modulating the amplification in the low frequency and high frequency channels may also lead to problems of musical pitch perception. Warner and Zatorre (2002, cited in Chasin, M. and Russo, F.A., 2004) noted that pitch discrimination threshold increased when a large change occurred in the spectral distribution of energy from one tone to another (Warrier CM., Zatorre R.J., (2002), cited in Chasin, M. and Russo, F.A., 2004). Related to the pitch discrimination is the musical construct known as the interval scale size, which is perceived distance between the two pitches. This ability is broken down substantially when the distribution of spectral energy modulates from tone to tone. Hearing aids have been designed without much consideration to the phase distortion. It is now known that listeners are sensitive to phase relationships, particularly for tones of low frequencies and rich harmonic structure (Galembo, Askenfelt, Cuddy & Russo, 2001). Although the phase distortion introduced by stereo system in the open room was relatively benign, phase distortion introduced by hearing aids enter the ear canal directly and may be quite audible as a result. If the distortion are binaural (varying across the channels), the auditory image may be experienced as being in motion. If these distortion are monaural (consistent across the channels), the experiences of pitch may be altered.

Chasin and Russo (2004) noted that the source of non-linear distortion in hearing aids is mainly attributed to amplitude of the signal which is driven beyond the limits of the receiver. The additions of such harmonics is particularly noticeable in clarinet that produces tones with odd harmonics and instruments like piano that produces inharmonic tones. In case of tones with odd harmonics, the addition of even harmonics will certainly alter the timbre. In case of inharmonic tone, new harmonic of the fundamental energy would lead to beating harmonic and inharmonic partials. This beating would add roughness to the timbre as well as reduce pitch clarity. The beating is less perceivable in harmonic tones as the distortion products do not introduce neither new partials nor beating but rather a shift in the spectral profiles.

Music is normally composed with metric grid in which prominent pitches occur regularly in time. These primary pitches are indicated by intensity. Too much compression will minimize the differences in intensity from tone to tone and hence may impede perception of relationship between prominent pitches. The clinical experiences of Chasin (2003) suggested that the compression system for most of the music should be set with relatively low compression ratio (e.g., 1.5:1) and with relatively high threshold knee-point settings (e.g., 65 to 75 dB). They emphasized that the peak input level is set to about 85 dB SPL since most engineers have traditionally had speech input in mind. But for inputs typically found in music this input limiting should be increased beyond 85 dBSPL. In addition to the experiment in 2003, Chain and Russo (2004) obtained sound quality measures using five, five-point perceptual scales that are relevant to music. They obtained significantly higher scores as the peak input level increased from 92 dB SPL to 115 dB SPL. They further went to discuss other parameters of the hearing aid and recommended a single-channel hearing aid or multi-channel hearing aid in which the gain parameters in all the channels is set at similar level, setting the knee-point higher by 5 to 8 dB for music than for speech and recommended a WDRC circuit for musicians.

Chasin (2006) examined the differences between speech and music. There are five differences between speech and music stimuli as reported by Chasin (2003, 2006), and Chain and Russo (2004), such as, 1. The long-term spectrum of music vs. speech 2. Differing overall intensities 3. Crest factors 4. Phonetic vs. phonemic perceptual requirements and 5. Difference in loudness summation and loudness intensity

1. *The long-term spectrum of music vs. speech:* It is well documented that speech has a relatively well-defined and uniform long-term spectrum regardless of the

language spoken. Speech tends to have its greatest intensity in the lower frequency ranges, with the higher frequency fricatives being lower in intensity. This is well understood and has been used to set parameters such as gain and compression while programming a hearing aid. Unlike speech, music is highly variable and a goal of a long-term music spectrum is poorly conceived; there is simply no 'music target' as there is for 'speech'.

2. *Differing overall intensities:* There are good estimates of "soft speech", "medium speech", and "loud speech", which are used to set parameters in modern (digital) hearing aids. When considering the physical limitations of vocalization, the potential intensity range is quite restricted, approximately 30 to 35 dB. In contrast, depending on the music played or listened to, various instruments can generate very soft sounds of 20 to 30 dB SPL (e.g.; brushes on a jazz drum) to 120 dB SPL (e.g.; amplified guitar and the brass of Wagner's Ring Cycle). Therefore, the dynamic range of music as an input to a hearing aid is of the order of 100 dB (versus only 30 to 35 dB for speech). Overall, when played at an average or mezzo forte level, classical music at the player's ear can be typically 85 to 100 dB SPL. Rock and roll, on an average, tends to be another 10 to 15 dB more intense, depending on the nature of the band (Chasin, 1996).

3. *Crest factors:* The crest factor is a measure of the difference in decibels between the peaks in a spectrum and the average or RMS (root mean square) value. A typical crest factor with speech is about 12 dB. Crest factors of 18 to 20 dB are not uncommon for many musical instruments.

4. *Phonetic vs. phonemic perceptual requirements:* This refers to the difference between what is actually heard as opposed to the perceptual needs or requirements of the individual or group of individuals. The loudness perception for speech is derived from the energy in the band of frequencies below 1000 Hz, whereas, the parameters essential for speech clarity are derived from frequency bands above 1000 Hz. In contrast to speech, some musicians need to hear the lower frequency sounds more than others regardless of the output (phonetics) of the instrument. The clarinet and the violin both have similar energy spectra (similar phonetics) but dramatically differing uses of the sound (phonemics). The clarinet player was typically satisfied with tones if only the lower frequency inter-resonant is at certain level, whereas, a violin player needs to hear the magnitude of high frequency harmonic before they judge it to be a good sound.

5. *Difference in loudness summation and loudness intensity:* The way the vocal cords are suspended in the larynx, they function as half wave resonators. This means that, not only there is energy at the fundamental frequencies but harmonics are evenly spaced at integer multiples of the fundamental frequencies. The minimal spacing between energy concentrations is 100 Hz in other words no two harmonics fall within the same critical bands. Some musical instruments are speech-like in the sense that they generate mid-frequencies, fundamental frequencies with even spaced harmonics. Oboes, saxophones, guitar and violin are in this category. Some, such as the clarinet are quarter wave generators (odd numbered harmonics) at least for the lower frequencies

notes. Some instrument are half wave resonators, like speech, but tend to be perceived as less loud since one or more of the harmonics fall within one critical bandwidth and do not contribute to loudness. A stringed instrument musician needs to be able to hear the exact relationship between the lower frequency fundamental structure and the higher frequency harmonic structure. In contrast, a wood pipe player such as clarinetist needs to be able to hear the low frequency (e.g. 1500 Hz) and inter-resonant breathiness.

Chasin (2004) further defined a "music program," or a set of optimal electro acoustic parameters for enjoying music to include:

1. A sufficiently high peak input limiting level so that more intense components of music are not distorted at the front end of the hearing aid.
2. Either a single channel or a multichannel system in which all channels are set for similar compression ratios and knee-points.
3. A compression system similar to the speech-based compression system with an RMS detector compression scheme and with a knee-point 5 to 8 dB higher if the hearing aid uses a peak compression detector.
4. A disabled feedback management system, or a feedback management system that uses gain reduction or a more sophisticated form of phase feedback cancellation (either one with short attack time and long attack time or one that only operates on a restricted range of frequencies such as over 2000 Hz).
5. If the noise reduction system cannot be disabled, a circuit that distinguishes between low (4-6 Hz) and high (10-100 Hz) modulation rates may be useful for

differentiating speech from music, and automatically turning on a "music program."

Mishra and Abraham (2007) compared the processing of music in an analog body level (BL) hearing aid, analog Behind-The-Ear (BTE) hearing aid and a four channel digital hearing aid. Musical sounds of guitar, flute, piano, and violin were selected in this study. The unprocessed and the processed music samples through the hearing aids were subjected to objective analysis and subjective ratings by ten listeners having normal hearing. Objective analysis was done to compare the spectrum of unprocessed music and music processed by hearing aids. From the graphs, the researchers observed that the music processed through analog BTE represented the processed music the best among the hearing aids. The subjective ratings also showed a preference for the analog BTE. Further, the analog BTE represented the sound of piano optimally compared to other musical sounds. Overall, music processed through all the hearing aids showed a poor representation of waveform in the lower frequencies. Researchers have shown that low frequency information is essential for sound quality judgment of music and hence for ideal perception of music processed through the hearing aids. Hence, the hearing aid should provide more low frequency information. Secondly, it is seen that for piano the minimal spacing between energy concentrations is 100 Hz in other words no two harmonics fall within the same critical bands. So this instrument is speech-like, in the sense, that it generates mid-frequencies, fundamental frequencies with even spaced harmonics. Guitar and violin also produced even spaced harmonics but for both the instruments ideal perception of quality is obtained when one hears the exact relationship between the low frequency fundamental and the high frequency harmonics. Since the relationship is disturbed, good representation was only obtained for piano. Some instruments such as the clarinet and flute are quarter wave generators (odd numbered harmonics) at least for the lower frequencies notes, i.e., they are unlike speech. Hence, poorer ratings were obtained for the flute.

2.5 Studies on Noise Reduction System and Feedback Management System in Hearing Aids

Dillion (2001) noted that hearing aids allow for some degree of signal processing in reducing the effects of noise. Levitt (2001) went further to show that for time invariant noise, the noise reduction system in the present day hearing aids assume that most of the noise power is concentrated in the low frequencies, the speech is masked in this frequency region. The following figure depicts the long-term average spectra of noise and speech (Figure2.1)

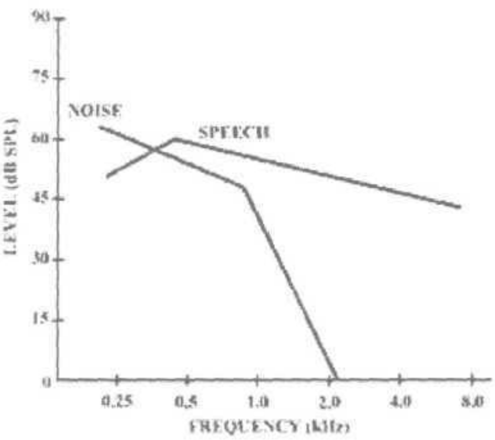

Fig. 2.1: Long term average spectra of noise and speech

The speech and noise spectra differ substantially and it is possible to eliminate much of the noise and a relatively small portion of the speech by means of a high-pass filter. Eliminating both speech and noise in the low frequency region will have no effect on intelligibility since the speech is already masked by the noise. The noise components in this frequency region are the most intense, and eliminating these components has the desired effect of reducing the loudness of the noise and improving overall sound quality.

Valente (1996) noted that there are mainly two types of feedback management schemes that are used in present hearing aids, namely, the band pass filtering and the notch filtering. In notch filtering, it is possible to invert a band pass filter and remove the part of the peak in frequency response. It generally removes a narrow part of the spectrum centered around the frequency of the filter. This type of filtering is used to counter acoustic feedback, where the notch is tuned to remove a narrow band of frequency around the offending frequency (Agnew, 1993). Chasin (2003) and Mishra, Kunnathur and Rajalakshmi (2005) have noted that there is a high probability for the hearing aid to confuse music to be noise and feedback and hence both the systems, should be turned off while the hearing aid is being programmed for music.

The studies which were reviewed showed that research was undertaken to evaluate the quality of music processed by hearing aids when the hearing aids were programmed essentially for speech and/or music. The strongest motivation for the study was that there is a dearth in research that has been undertaken to see the quality of music processed by hearing aids incorporating the suggestions put forward in the previous studies and making the changes in the parameters optimal for music perception through hearing aids. Hence, the present study was undertaken.

Chapter III

METHOD

The purpose of this study was to evaluate the efficacy of the hearing aids in the processing of music. The efficacy of the hearing aids was evaluated using the subjective perception and objective analysis of the music sample.

Subjects

Three groups of subjects were participated in this study, namely, Group I (Non-musicians group), Group II (Musicians-Singers group) and Group III (Musicians-Instrumentalists Group).

Group I (Non-musicians group)

15 subjects with no formal education in music were considered. They had hearing sensitivity within normal limits and no significant history of external or middle ear infection or malformation of the ear. The age of the subjects ranged from 18 to 25 years with mean age of 20.75 years. It was taken care that all the subjects selected in the study enjoyed listening to music.

Group II (Musicians-Singers group)

15 subjects, with at least 10 years experience in professional singing, were selected. The age range of the subjects was from 24 years to 59 years, with the mean age being 39.90 years. The subjects had hearing sensitivity within normal limits with no significant

history of external or middle ear infection or malformation of the ear. The average experience with singing in this group was 24.8 years in professional music, with the lowest being 10 years and the highest being 39 years. In order to have homogeneity in the group, it was taken care to see that all the subjects were practicing the Carnatic style of singing.

Group III (Musicians-Instrumentalists Group)

10 subjects were selected in this group. All the subjects were practicing 'Odissi' style of playing the instrument. Three of the instrumentalist played sitar, two of them played the flute, three played the sarod and two of them played the veena. The age range of the subjects was between 36 and 52 years, with the mean age of the subjects being 48.10 years. The subjects had hearing sensitivity within normal limits with no significant history of external or middle ear infection or malformation of the ear. The average experience in professional music for this group was 27.2 years, with the minimum experience being 24 years and the maximum experience being 32 years.

Instruments used

Hearing Aids

Two commercially available digital Behind-The-Ear (BTE) hearing aids were used in the study. The first hearing aid (Hearing aid A) was a six-channeled hearing aid and the second hearing aid (Hearing aid B) was a fifteen-channeled hearing aid. These two hearing aids were selected because, apart from the number of channels, the signal processing strategy, the microphone technology and the noise canceller were technically similar. Both the hearing aids used wide dynamic range compression (WDRC), dynamic noise canceller (dNC) and an omni directional microphone technology. Both these hearing aids had an option of switching off the noise cancellation system and the feedback management system.

Computers and Hi-Pro

A Personal computer installed with NOAH (3.0 version) software and connected with Hi-Pro were used to program hearing aids. Two laptops operating on Windows XP and Praat software were also used in this study. While recording the music sample, Frontech speakers, 340 Watt PMPO, were connected to the laptop that played the music. The volume was set at a comfortable loudness level. The music samples were recorded to a laptop using the Praat software. These samples were later transferred to an audio compact disc. The music samples were played to the listeners from a laptop through the head phones (Fontopia MDR-EX51LP Consumer Headphones from Zebronix Company), using the Praat software.

Coupler

A 2 cc coupler (HA-2) was used for collecting the output from the hearing aids while recording.

Microphone

An omni directional microphone was connected to the coupler using fun tak to record the output from the hearing aid on the laptop using the Praat software.

Music Sample

A music sample recorded on an audio compact disc was used. Carnatic music which was being played instrumentally was selected in the study. The music sample had the lead music played by violin and the other instrument being played was the mrudhagam. The music sample was chosen from the music album titled "lagudi" and the music was based on raaga 'Mohana Kalayani'. A 90 second duration of the sample was selected for the purpose of evaluation.

Room Setting

A sound treated air conditioned room was selected for recording the music sample from the hearing aids. The ambient noise levels inside the room were within permissible limits (re: ANSI 1991, cited in Wilber, 1994).

Procedure

For the purpose of the study, the study was divided into 4 stages:

Stage 1: Programming of the hearing aid

Stage 2: Recording of the hearing aid processed music samples

Stage 3: Subjective analysis of the music samples

Stage 4: Measurement of spectra of the music samples

Stage 1: Programming of the Hearing Aid

The hearing aids were programmed for a hypothetical flat sensorineural hearing loss, with air conduction threshold being 50 dB HL in all the audiometric frequencies. A flat hearing loss was used so that the compression characteristic remained same across all the frequencies. The digital hearing aid was connected, through a Hi-Pro, to the Personal Computer (PC) with software for programming. After the hearing thresholds were fed into the software (NOAH 3.0), the digital hearing aids were programmed based on the NAL-NL1 prescriptive procedure in the hearing aid programming software. An acclimatization level of 2 was used while programming.

Stage 2: Recording of the Hearing Aid Processed Music

For the comparison of the effect of channels on processing of music, two digital hearing aids were taken; one comprising of 6 channels (Hearing aid A) and the other comprising of 15 channels (Hearing aid B). The knee-point of both the hearing aids was at 54 dB when programmed for the speech in quiet (default program). The knee-point was raised by 18 dB to make it 72 dB. The music samples were recorded with noise cancellation and feedback management systems off. Apart from the difference in number of channels the other signal processing parameters in the hearing aids were similar.

A sample was recorded from the fifteen channeled hearing aid (Hearing aid B) with knee-point set at 18 dB higher than the default knee-point setting for the speech as recommended by the first fit of the programming software. This time, both the noise cancellation system and the feedback management system were turned on.

For recording the other music samples, a 6-channeled digital hearing aid (Hearing aid A) was selected. Music sample was played to the programmed hearing aids. The hearing aid processed music was recorded. The hearing aid A was taken and the hearing aid processed music was recorded in each of the following conditions; knee-point set at 72 dB, both the noise cancellation system and feedback management systems were switched off initially. Then a music sample was recorded with the knee-point high and switching on the noise cancellation system with the feedback management system off. Later another music sample was recorded with the knee-point being high by switching on the feedback management system with the noise cancellation system off. Finally, a music sample was recorded with the noise cancellation system and feedback management system being switched on with the knee-point being high.

On the whole, there were eight music samples; two from the fifteen channeled hearing aid, five from the six channeled hearing aid and the original music sample recorded through the coupler. They are given in the following Table 3.1.

Table 3.1: The music samples recorded with different settings of the hearing aids.

Music samples	**Conditions of recording**
Sample 1	Original music sample recorded through 2 cc coupler
Sample 2	Hearing aid B with knee-point high, noise cancellation and feedback management off
Sample 3	Hearing aid A with knee-point high, noise cancellation and feedback management off
Sample 4	Hearing aid B with knee-point high, noise cancellation and feedback management on
Sample 5	Hearing aid A with knee-point high, noise cancellation and feedback management on
Sample 6	Hearing aid A with knee-point at default, noise cancellation and feedback management off
Sample 7	Hearing aid A with knee-point high, noise cancellation on and feedback management off
Sample 8	Hearing aid A with knee-point high, noise cancellation off and feedback management on

The block diagrams of the instrument set-up used for recording the music without and with the hearing aid are shown in Figures 3.1 and 3.2 respectively. The music recordings were done in a sound treated room so that the external noise did not affect the recording.

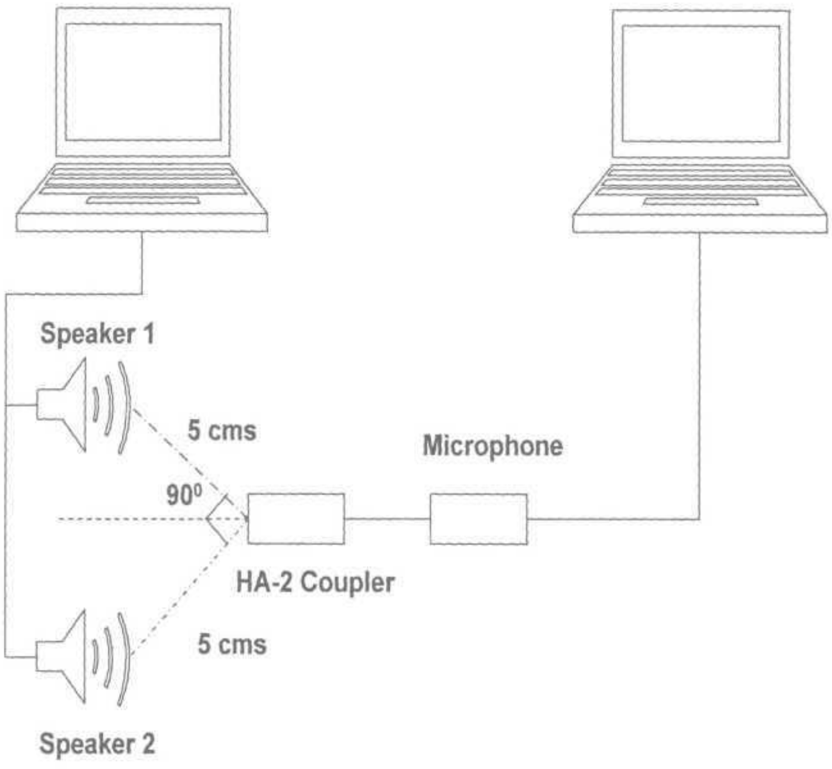

Fig. 3.1: Block diagram of set-up for recording the original music without the hearing aid.

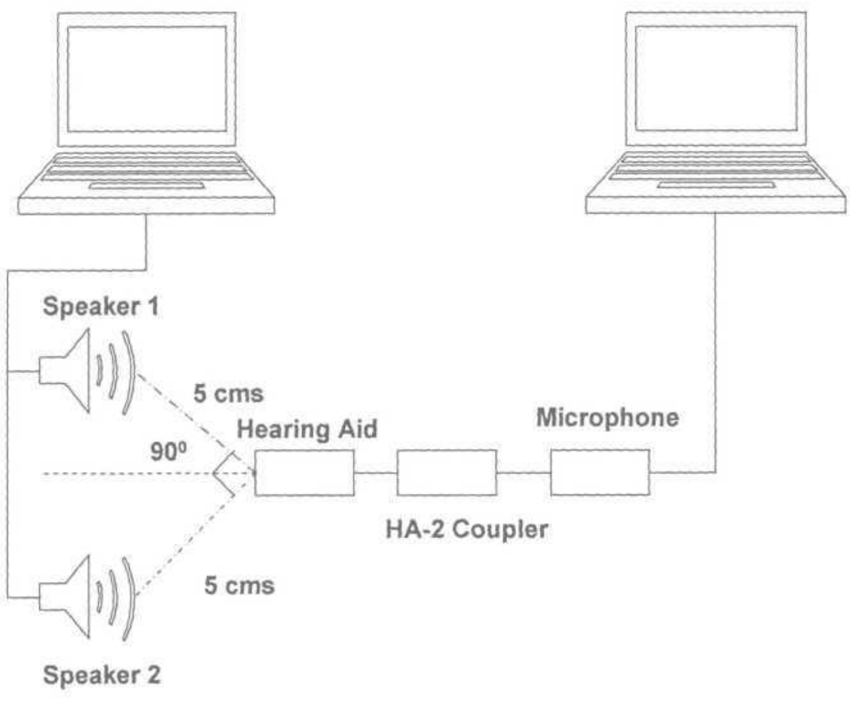

Fig. 3.2: Block diagram of set-up for recording the original music with the hearing aid.

Thus, the recording of the music sample without and with the hearing aid was done. These eight recorded music samples were later used for the subjective ratings and the acoustic analysis. The music sample was played using Praat software from a laptop through the speakers. The hearing aid was placed at equivalent distance of 5 cm from either of the speakers and at 90° Azimuths, as shown in the figure. A foam sheet was placed below the hearing aid so that it did not pick-up any noise due to vibration of the table. It was taken care that the microphone of the hearing aid was at the level of centre of the speakers. The digital hearing aid was connected to a HA-2 (2 cc) coupler which in turn was connected to the recording microphone. The recording microphone was connected to the computer for recording the music sample using the Praat software. All the recordings in Praat software were done using 16 bit mono recording. Thus, the music processed by the hearing aid in each of the seven different programmed settings of the hearing aids, was recorded.

In order to make all the music samples equivalent, the original music sample was also played in the same condition and recorded through the coupler to make the unprocessed music sample equivalent to the music sample processed through the hearing aids. The music samples were not normalized. The samples were then transferred to an audio compact disc.

Stage 3: Subjective analysis of the music samples

Measures of sound quality judgment were obtained using five, five-point perceptual rating scales that was relevant to music. This is a modification of the work of Gabrielsion and colleagues (1974, 1991) that have been used extensively in the hearing aid industry

(Chasin & Russo, 2004). The subjects were asked to rate the music samples on the perceptual parameters of loudness, fullness, crispiness, naturalness and overall fidelity. Subjects were given the following definitions of the five perceptual parameters (Chasin and Russo, 2004). Loudness was defined as the music that is sufficiently loud in contrast to faint, ranging from 5 to 1 on the rating scale. Fullness was defined as the music being full in contrast to thin, ranging from 5 to 1 on the rating scale. Clearness was defined as the music being clear and distinct in contrast to being blurred or diffused, ranging from 5 to 1 on the rating scale. Naturalness being defined as the music seems to be as if there is no hearing aid, and the music sounds as "I remember it", ranging from 5 to 1 on the rating scale. Overall fidelity being defined as that the dynamics and range of the music is not constrained or narrowed, ranging from 5 to 1 on the rating scale.

Specifically, the subjects were asked to rate from 1 (poorest) to 5 (best) on the following perceptual scales: loudness, fullness, crispiness, naturalness and overall fidelity. Thus, a perfect perceptual reproduction score was 25 considering all the five parameters on the scale. The scales for rating on the five parameters were as follows.

1. For loudness: 1 (faint)..................5 (sufficiently loud)
2. For Fullness: 1 (thin)..................5 (full)
3. For Clearness: 1 (blurred)..................5 (distinct and clear)
4. For Naturalness: 1 (unnatural)..................5 (natural)
5. For Overall Fidelity: 1 (restricted)..................5 (wide and not constrained).

The music samples are played from a computer using the Praat software through the head phones (Fontopia MDR-EX51LP Consumer Headphones from Zebronix

Company) and the subjects were instructed to listen to the samples at their comfortable loudness level.

Environment

All the subjects in the three groups were made to listen to the music samples in similar conditions. A relatively quiet room was selected, away from traffic noise and other noises. Each subject was made to listen to the eight different music samples mentioned above.

Instruction

The listeners were given an identical set of instruction in a written format, in English, so that the instruction for all the subjects remained essentially the same. Four subjects in Group III asked for instruction written in oriya, hence a translation of the instruction was done which was verified by two graduate students in oriya for the correctness of the meaning. A written instruction provided to the subjects is provided in Appendix A. The instructions were further clarified by the experimenter before the subjects rated the music sample, if required. It was made certain that the subjects were absolutely clear with the terminology and were completely certain about the rating scale before they rated the music samples.

Stage4 - Measurement of spectra of the music samples

The selected music sample, from the recorded music samples, as processed by the hearing aid were subjected to spectrum analysis using the Praat software. Three ten-second duration of the music samples were selected for analysis with Praat software as the Praat software could analyze the music sample of less than 10 second duration. Spectral analysis of three ten-second duration of the music samples was obtained in the Hammin window. For the precise comparison, equivalently paired samples were taken from the music samples and the hearing aid processed music. In each of the samples recorded, the samples for analysis were taken at the interval of 14 to 24 seconds, 48 to 58 seconds and 74 to 84 seconds. The energy concentration at the octave and the mid-octave frequencies (from 200 to 8000 Hz) were measured and tabulated.

Chapter 4

RESULTS

The main objective of the study was to compare the processing of music through the different hearing aids, subjectively using a rating scale and objectively using the spectral analysis.

Subjective Analysis

For the subjective analysis, the samples were first presented to 45 listeners to be rated on a rating scale. The original music sample and seven hearing aid processed music samples were rated on a five-point rating scale. There were a total of eight music samples. Details of these samples are provided in Table 4.1.

45 participants rated the above music samples. These ratings were tabulated. The statistical analysis was carried out with the help of the Statistical Package for the Social Sciences (SPSS, Version 10). The non- parametric test was used in the statistical analysis. The data, in terms of the five parameters, were analyzed for the comparison of the three groups of subjects using Kruskal-Wallis test (Non-parametric equivalent of one-way ANOVA). Mann Whitney U test was used to see the pair-wise difference between the groups, where the comparisons were made taking two groups at a time. Later, the original music sample was compared with all the other music samples using the Wilcoxon Signed Rank test. These analyses were repeated for all the five parameters.

Table 4.1: Different music samples recorded with different settings of the hearing aid

Music Samples	Settings of the Hearing Aid
Sample 1	Original music sample without being processed by hearing aid
Sample 2	Hearing aid B with knee-point high, noise cancellation and feedback management off
Sample 3	Hearing aid A with knee-point high, noise cancellation and feedback management off
Sample 4	Hearing aid B with knee-point high, noise cancellation and feedback management on
Sample 5	Hearing aid A with knee-point high, noise cancellation and feedback management on
Sample 6	Hearing aid A with knee-point at default, noise cancellation and feedback management off
Sample 7	Hearing aid A with knee-point high, noise cancellation on and feedback management off
Sample 8	Hearing aid A with knee-point high, noise cancellation off and feedback management on

Parameter 1 - Loudness

Comparison of loudness rating between the groups of subjects

The mean and standard deviation (SD) values of the rating obtained on a five-point rating scale for loudness are given in Table 4.2 for different settings of the hearing aids.

Table 4.2: Mean and standard deviation (SD) values of loudness rating

Music Samples	Mean (SD)		
	Group		
	Non-Musicians	Singers	Instru-mentalists
Sample 1	4.53 (0.74)	3.67(0.81)	4.90(0.31)
Sample 2	4.20 (0.56)	3.53(1.68)	3.90 (0.73)
Sample 3	2.86 (0.74)	2.0(1.06)	2.00(1.49)
Sample 4	2.80 (0.94)	2.93(1.03)	2.70(1.33)
Sample 5	2.20 (0.77)	1.86(0.83)	1.60(0.84)
Sample 6	2.00 (0.84)	1.46(0.74)	1.70(1.05)
Sample 7	2.60 (0.82)	1.67(0.81)	1.80(1.31)
Sample 8	2.40 (0.59)	1.73(0.88)	1.70(0.82)

From the mean values, it was observed that the highest rating was given to the music sample 1 (original music sample recorded without the processing of the hearing aid) as can be expected. The music sample 2 (Hearing aid B with knee-point high, noise cancellation and feedback management off) and music sample 3 (Hearing aid A with knee-point high, noise cancellation and feedback management off) were given the second and third highest rating respectively. The rating of the rest of the music samples had a very little difference, the lowest rating being given to the music sample 6 (Hearing aid A with the knee-point at default, noise cancellation and feedback management off).

The ratings given to the loudness parameter in different hearing aid settings were subjected to Kruskal-Wallis test to find out if the groups of subjects showed any difference in the rating that they gave.

Table 4.3: Difference in loudness rating between three groups of subjects

Loudness in different music samples	Chi-Square d(f)=2
Sample 1	15.64**
Sample 2	0.69
Sample 3	7.05*
Sample 4	0.43
Sample 5	3.34
Sample 6	3.33
Sample 7	8.89*
Sample 8	5.87

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Kruskal-Wallis test revealed that there was a significant difference between the groups in the rating given for loudness in music sample 1 (Original music track recorded without the processing by the hearing aid, at 0.01 level of significance), Sample 3 (Hearing aid A with knee-point high, noise cancellation and feedback management off, at 0.05 level of significance) and Sample 7 (Hearing aid A with knee-point high, noise cancellation on and feedback management off, at 0.05 level of significance).

The groups of subjects were compared amongst themselves taking two groups at a time, using the Mann-Whitney U test to see the pair-wise differences.

Table 4.4: Difference in loudness rating between pairs of groups

	Group I & Group II	Group I & Group III	Group II & Group III
Sample 1	2.774**	1.375	3.587**
Sample 3	2.416*	2.034*	0.445
Sample 7	2.718**	2.250*	0.154

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Mann Whitney U test revealed that there was a significant difference between the mean loudness rating given by the non-musicians and singers for samples 1 and 7 (at 0.01 level of significance) and for sample 3 (at 0.05 level of significance). The non-musicians and the instrumentalists differed between each other for the samples 3 and 7 (at 0.05 level of significance) only. The singers and instrumentalists differed at 0.01 level of significance only for the sample 1.

The original music sample was compared with the music samples recorded in different setting of the hearing aids using the Wilcoxon Signed Rank test. In the Wilcoxon paired test, the Non-Musicians (Group I) were taken separately and the Singers (Group II) and Instrumentalist (Group III) were grouped to form the musicians group. The Singers and the Instrumentalist were grouped together as there was no significant difference in the rating given by these two groups in majority of the music samples.

Table 4.5: Difference between the original sample and the other samples by non-musicians and musicians

Comparison of original music sample with other samples	Non-musicians /Z/	Musicians /Z/
Sample 2	1.68	1.27
Sample 3	3.48**	3.94**
Sample 4	3.22**	3.38**
Sample 5	3.50**	4.32**
Sample 6	3.47**	4.32**
Sample 7	3.50**	4.15**
Sample 8	3.46**	4.24**

** Significant difference at 0.01 level

The Wilcoxon Signed Rank test revealed that both the groups (Non-Musicians and Musicians) rated loudness of the music samples in different hearing aid settings to be significantly different from the original music. However, they rated the music sample 2 (Hearing aid B with the knee-point high, noise cancellation system and feedback management system off) to be not different from the original music sample, even at 0.05 level of significance.

Similar analysis was carried out for the other parameters on the perceptual rating scale.

Parameter 2 - Fullness

Comparison of fullness rating between the groups of subjects

The mean and the standard deviation (SD) values of the rating obtained on the five-point rating scale for fullness are given below (Table 4.6) for the different music samples.

Table 4.6: Mean values and standard deviation (SD) values of rating on fullness

Music samples	Mean (SD)		
	Groups		
	Non-Musicians	Singers	Instrumentalists
Sample 1	3.93(1.16)	3.60(1.39)	4.50 (0.97)
Sample 2	3.60(0.81)	3.33(1.54)	3.70(1.05)
Sample 3	2.73 (0.79)	2.20(1.32)	1.70(1.05)
Sample 4	2.53 (0.99)	2.40(1.12)	2.30 (0.94)
Sample 5	2.53 (0.83)	1.60(0.73)	1.50(0.70)
Sample 6	2.20 (0.77)	2.00(1.16)	1.80(1.22)
Sample 7	2.66 (0.89)	1.60(0.91)	1.50(0.70)
Sample 8	2.26 (0.59)	1.93(1.16)	1.70(0.94)

From the mean values, it was noted that the highest rating was given to the music sample 1 (original music sample recorded without the processing of the hearing aid). The rating given to the music sample 2 (Hearing aid B with knee-point high, noise cancellation and feedback management off) was given the second highest. The mean of the rest of the music samples had a very little difference. The ratings given to the parameter fullness by the three groups of subjects, in the different recording conditions, were subjected to Kruskal-Walis test.

Table 4.7: Difference of fullness ratings between the three groups of subjects

Fullness in different music samples	Chi-Square d(f)=2
Sample 1	3.570
Sample 2	0.280
Sample 3	6.831*
Sample 4	0.468
Sample 5	11.331**
Sample 6	2.590
Sample 7	12.465**
Sample 8	4.013

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Kruskal-Wallis test revealed there was a significant difference between the three groups in the rating attributed to fullness in Sample 3 (Hearing aid A with knee-point set high with noise cancellation and feedback management off), Sample 5 (Hearing aid A with knee-point set high, noise cancellation and feedback management on) and Sample 7 (Hearing aid A with knee-point set high, noise cancellation on and feedback management off).

Table 4.8: Difference in fullness rating between pairs of groups

	Group I & Group II	Group I & Group III	Group II & Group III
Sample 3	1.62	2.60*	1.01
Sample 5	2.85**	2.81**	0.34
Sample 7	2.99**	2.93**	0.10

* Significant difference at 0.05 level
** Significant difference at 0.01 level

On fullness rating, the non-musicians and singers differed only on sample 5 and 7, at 0.01 level of significance. The non-musicians and the instrumentalists differed significantly for the samples 5 and 7, at 0.01 level of significance, and for sample 3, at 0.05 level of significance. The singers and the instrumentalists did not differ in fullness rating on any music sample.

The original music sample was compared with the music sample recorded in different settings of the hearing aids using the Wilcoxon Signed Rank test. In the Wilcoxon paired test, the Non-Musicians (Group I) were taken separately and the Singers (Group II) and Instrumentalists (Group III) were taken together. The Singers and the Instrumentalists group were grouped together as the there was no significant difference in the rating on fullness given by these two groups.

Table 4.9: Difference in between the original sample and the other samples by the non-musicians and the musicians

Comparison of original music sample with recording of different music samples	Non-Musicians /Z/	Musicians /Z/
Sample 2	0.91	1.18
Sample 3	2.44**	3.70**
Sample 4	2.96**	3.61**
Sample 5	2.84**	4.23**
Sample 6	3.19**	3.58**
Sample 7	2.95**	4.17**
Sample 8	3.10**	3.64**

** Significant difference at 0.01 level

The Wilcoxon Signed Rank test revealed that both the groups (Non-Musicians and Musicians) rated fullness of the music samples in different conditions to be significantly different from the original music; but ratings of the music sample 2 (Hearing aid B with the knee-point high, noise cancellation system and feedback management system off) was not different that from the original music sample, even at 0.05 level of significance.

Parameter 3 - Clearness

Comparison of clearness between the groups of subjects

The mean and the standard deviation (SD) values of the rating obtained on the five-point rating scale for clearness are given in Table 4.10, for the different music samples.

Table 4.10: Mean and standard deviation (SD) values of Clearness rating

Music samples	Mean (SD)		
	Groups		
	Non-Musicians	Singers	Instrumentalists
Sample 1	4.33 (0.97)	3.46(1.18)	4.50(1.26)
Sample 2	4.06 (0.88)	3.26(1.48)	3.60 (0.84)
Sample 3	3.00 (0.84)	1.67(1.11)	1.70(1.33)
Sample 4	2.46(0.91)	2.13(1.06)	2.40 (0.69)
Sample 5	2.53 (0.74)	1.86(0.91)	1.90(0.87)
Sample 6	2.33 (0.81)	1.80(0.77)	2.20(1.13)
Sample 7	3.20 (0.67)	1.53(0.91)	1.60(0.96)
Sample 8	2.86 (0.83)	1.53(0.91)	1.90(0.99)

From the mean values, it was observed that the highest rating was given to the music sample 1 (original music sample recorded without the processing of the hearing aid). The rating given to the music sample 2 (Hearing aid B with knee-point high, noise cancellation and feedback management on) was given the second highest rating. The mean clearness rating of the rest of the music samples were not differing much. The ratings given to the parameter clearness for different music samples were subjected to Kruskal-Wallis test.

Table 4.11: Difference of clearness ratings between the three groups

Clearness in different music samples	Chi-Square d(f)=2
Sample 1	9.36*
Sample 2	2.73
Sample 3	13.64**
Sample 4	1.34
Sample 5	4.79
Sample 6	3.37
Sample 7	19.42**
Sample 8	13.98**

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Kruskal-Wallis test revealed there was a significant differenc, at 0.05 level of significance, to the rating attributed to clearness in sample 1 (Original music track recorded without the processing of the hearing aid), sample 3 (Hearing aid A with knee-point set high, noise cancellation and feedback management off), sample 7 (Hearing aid A with knee-point set high, noise cancellation on and feedback management off) and sample 8 (Hearing aid A with knee-point set high and noise cancellation off and feedback management on).

Table 4.12: Difference in fullness ratings between pairs of groups

	Group I & Group II	Group I & Group III	Group II & Group III
Sample 1	2.28*	0.91	2.74**
Sample 3	3.36**	2.75**	0.29
Sample 7	3.93**	3.42**	0.26
Sample 8	3.54**	2.41*	1.18

* Significant difference at 0.05 levels
** Significant difference at 0.01 levels

The mean ratings on the clearness were significantly different in Non-musicians and Singers groups in four samples (1, 3, 7, 8). The Non-musicians and the Instrumentalists differed significantly on the rating for clearness only for sample 3, 7 and 8. The Singers and the Instrumentalists differed significantly on clearness rating, only on music sample 3.

The original music sample was compared with the music samples recorded in different settings of the hearing aids using the Wilcoxon Signed Rank test. On the Wilcoxon paired test, the Non-Musicians (Group I) were grouped separately and the Singers (Group II) and Instrumentalists (Group III) were grouped together as Musicians. The Singers and the Instrumentalists group were taken together as there was no significant difference in the rating given by these two groups in majority of the samples.

Table 4.13: Difference in between the original sample and the other samples by the non-musicians and the musicians

Comparison of original music sample with recording of different music samples	Non-Musicians /Z/	Musicians /Z/
Sample 2	1.01	1.44
Sample 3	2.59*	3.88**
Sample 4	3.17**	3.75**
Sample 5	3.14**	3.79**
Sample 6	3.34**	3.74**
Sample 7	2.98**	4.05**
Sample 8	2.71**	3.94**

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Wilcoxon Signed Rank test revealed that both the groups (Non-musicians and Musicians) rated the music sample in different conditions to be significantly different from the original music. They rated the music sample 2 (Hearing aid B with the knee-point high, noise cancellation system and feedback management system off) to be not significantly different from the original music sample, even at 0.05 level of significance.

Parameter 4 - Naturalness

Comparison between the groups of subjects

The mean and the standard deviation (SD) values of the rating on naturalness obtained on the five-point rating scale are given in Table 4.14, for the different samples.

Table 4.14: Mean and standard deviation (SD) values of Naturalness rating on samples

Music samples	Mean (SD)		
	Group		
	Non-Musicians	Singers	Instrumentalists
Sample 1	4.20(1.01)	4.06 (0.79)	4.60(1.26)
Sample 2	3.80(1.01)	3.06(1.43)	3.50(0.97)
Sample 3	2.93 (0.88)	2.33(1.34)	1.50(0.97)
Sample 4	2.13 (0.99)	2.06(1.09)	2.20 (0.78)
Sample 5	2.66 (0.89)	2.26(1.27)	1.80(0.91)
Sample 6	2.33 (0.72)	2.26(1.38)	2.20(1.31)
Sample 7	3.00(1.00)	1.80(1.14)	1.40(0.69)
Sample 8	2.86(1.12)	1.86(1.24)	1.80(0.78)

From the mean values, it was noted that the highest ratings were given to the music sample 1 (original music sample recorded without the processing of the hearing aid). The rating given to the music sample 2 (Hearing aid B with knee-point high, noise cancellation and feedback management off) and music sample 3 (Hearing aid A with knee-point high, noise cancellation and feedback management off) were given the second and third highest rating respectively. The mean of the rest of the music samples had a very little difference. The ratings given to the parameter of naturalness in the different samples were subjected to Kruskal-Walis test.

Table 4.15: Difference of naturalness ratings between the three groups of subjects

Naturalness in different music samples	Chi-Square d(f)=2
Sample 1	5.05
Sample 2	1.86
Sample 3	9.66**
Sample 4	0.61
Sample 5	3.88
Sample 6	0.90
Sample 7	13.53**
Sample 8	8.12*

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Kruskal-Wallis test revealed there was a significant difference to the rating attributed to naturalness only in sample 3 (Hearing aid A with knee-point set high, noise cancellation and feedback management off), sample 7 (Hearing aid A with knee-point set high, noise cancellation on and feedback management off) and sample 8 (Hearing aid A with knee-point set high, noise cancellation off and feedback management on).

Table 4.16: Difference in naturalness ratings between pairs of groups

	Group I & Group II	Group I & Group III	Group II & Group III
Sample 3	1.54	3.08**	1.79
Sample 7	2.71**	3.40**	0.75
Sample 8	2.47*	2.32*	0.36

* Significant difference at 0.05 level
** Significant difference at 0.01 level

In the parameter of naturalness, there was a significant difference between the ratings given by Non-musicians and Singers in sample 7 and 8 only. There was a significant difference in the ratings given by Non-musicians and Instrumentalists group in samples 3, 7 and 8. However, the Singers and the Instrumentalists did not differ significantly on samples 3, 7 and 8.

Table 4.17: Difference in between the original sample and the other samples by the non-musicians and the musicians

Comparison of original music sample with recording of different music samples	Non-Musicians /Z/	Musicians /Z/
Sample 2	1.10	2.78**
Sample 3	2.50*	3.98**
Sample 4	3.20**	4.19**
Sample 5	2.86*	3.85**
Sample 6	3.30**	4.0**
Sample 7	2.36*	4.12**
Sample 8	2.23*	4.01**

* Significant difference at 0.05 levels
** Significant difference at 0.01 levels

The Non-musicians (Group I) rated the music sample 2 (Hearing aid B with the knee-point high, with noise cancellation and feedback management off) as significantly not being different from the original music sample. But the musicians group rated the music sample 2 to be significantly different from the original sample. All other samples were rated as significantly different from sample 1.

Parameter 5 - Overall fidelity

Comparison on overall fidelity ratings between the groups of subjects

The mean and the standard deviation (SD) values of the rating obtained on the five-point rating scale for overall fidelity are given in Table 4.18, for the different samples.

Table 4.18: Mean and standard deviation (SD) values of overall fidelity ratings on samples

Music samples	Mean (SD)		
	Groups		
	Non-Musicians	Singers	Instrumentalists
Sample 1	4.06 (0.88)	3.80(1.20)	4.50(1.26)
Sample 2	3.73 (0.79)	3.06(1.38)	3.50 (0.84)
Sample 3	2.86 (0.74)	1.93(1.27)	1.40(0.96)
Sample 4	2.66(1.04)	2.13 (0.91)	2.30 (0.82)
Sample 5	2.60 (0.63)	1.80(0.86)	1.40(1.10)
Sample 6	2.46 (0.74)	1.93(1.09)	1.90(0.99)
Sample 7	3.00(1.00)	1.80(1.14)	1.40(0.69)
Sample 8	2.53 (0.74)	1.86(1.27)	1.90(0.96)

From the mean values, it was noted that the highest rating was given to the music sample 1 (original music sample recorded without the processing of the hearing aid). The rating given to the overall fidelity of the music sample 2 (Hearing aid B with knee-point high, noise cancellation and feedback management off) and music sample 3 (Hearing aid A with knee-point high, noise cancellation and feedback management off) were given the second and third highest rating respectively. The mean of the rest of the music samples did not differ much. The ratings given to the parameter of overall fidelity by different groups of subjects for different music samples were subjected to Kruskal-Wallis test.

Table 4.19: Difference of overall fidelity ratings between the three groups of subjects

Overall fidelity in different music samples	Chi-Square d(f)=2
Sample 1	4.80
Sample 2	3.41
Sample 3	2.16
Sample 4	6.86*
Sample 5	13.93**
Sample 6	5.84*
Sample 7	13.36**
Sample 8	1.85

* Significant difference at 0.05 levels
** Significant difference at 0.01 levels

The Kruskal-Wallis test revealed that there was a significant difference between the three groups on the rating attributed to overall fidelity in sample 4 (Hearing aid B with knee-point set high, noise cancellation and feedback management on), sample 5 (Hearing aid A with knee-point set high, noise cancellation and feedback management on), sample 6 (Hearing aid A with knee-point at default, noise cancellation and feedback management off) and sample 7 (Hearing aid A, noise cancellation on and feedback management off) at 0.05 level of significance.

Table 4.20: Difference in overall fidelity ratings between pairs of groups

	Group I & Group II	Group I & Group III	Group II & Group III
Sample 3	2.55*	3.40**	1.30
Sample 5	2.49*	1.90	0.09
Sample 7	3.20**	3.06**	0.51
Sample 8	2.19*	1.88	0.03

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Non-musicians and the Singers groups differed significantly on the ratings of overall fidelity, on 3rd and 7th samples only. Singers and Instrumentalists did not differ in their ratings of any of the samples.

Table 4.21: Difference in between the original sample and the other samples by the non-musicians and the musicians

Comparison of original music sample with music samples	Non-musicians /Z/	Musicians /Z/
Sample 2	1.27	2.14*
Sample 3	2.97**	3.93**
Sample 4	2.96**	4.03**
Sample 5	3.02**	3.95**
Sample 6	3.10**	3.95**
Sample 7	2.82**	3.94**
Sample 8	3.10**	3.84**

* Significant difference at 0.05 level
** Significant difference at 0.01 level

The Non-musicians rated the music sample 2 (Hearing aid B with the knee-point high, with noise cancellation and feedback management off) to be different from the original music sample. The musicians rated the sample 2 to be significantly different from the original music sample, at 0.05 level of significance. All other samples were rated as significantly different from sample 1.

After the subjective analysis of the data collected from the subjects, the music samples were subjected to spectral analysis.

Spectral Analysis

The result of analysis of the objective measures was similar that of the subjective measures. Since on the Praat software, a sample of maximum 10 seconds could be analysed, the sampling for each music sample was done at intervals of 12 to 22 seconds, 48 to 58 seconds and 74 to 84 seconds. The energy concentration at each of octave and mid-octave frequency was measured and was plotted as graphs as shown in Figure 4.1.

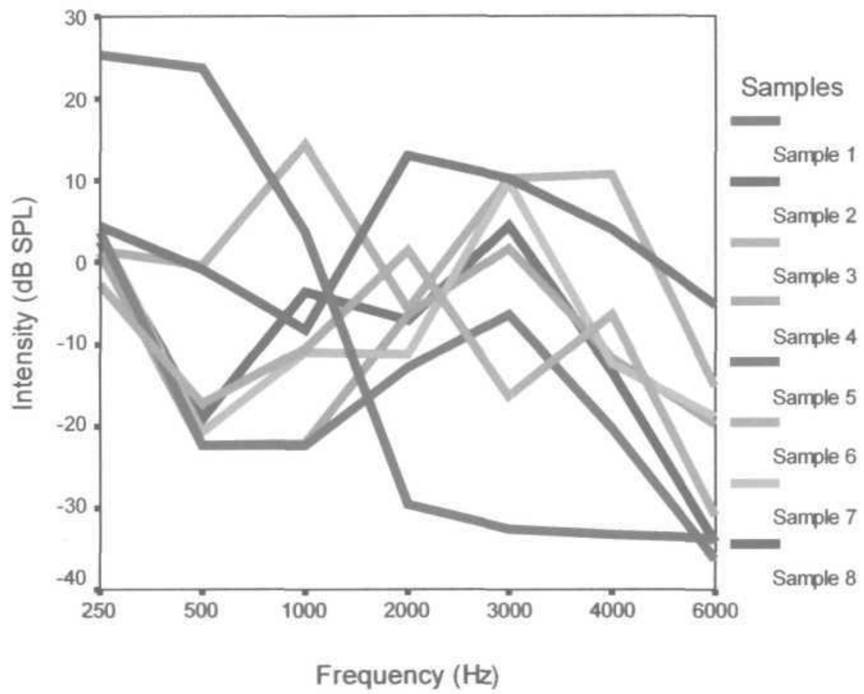

Fig 4.1: Hearing aid output at different frequencies for different samples, in 12 to 22 seconds interval

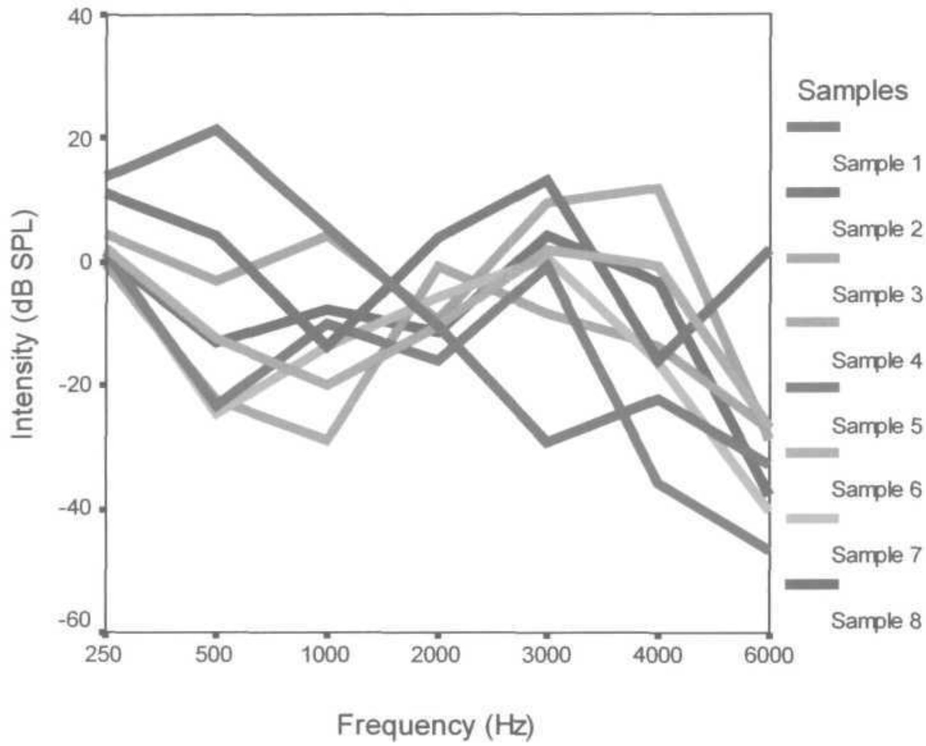

Fig. 4.2: Hearing aid output at different frequencies for different samples, in 48 to 58 seconds interval

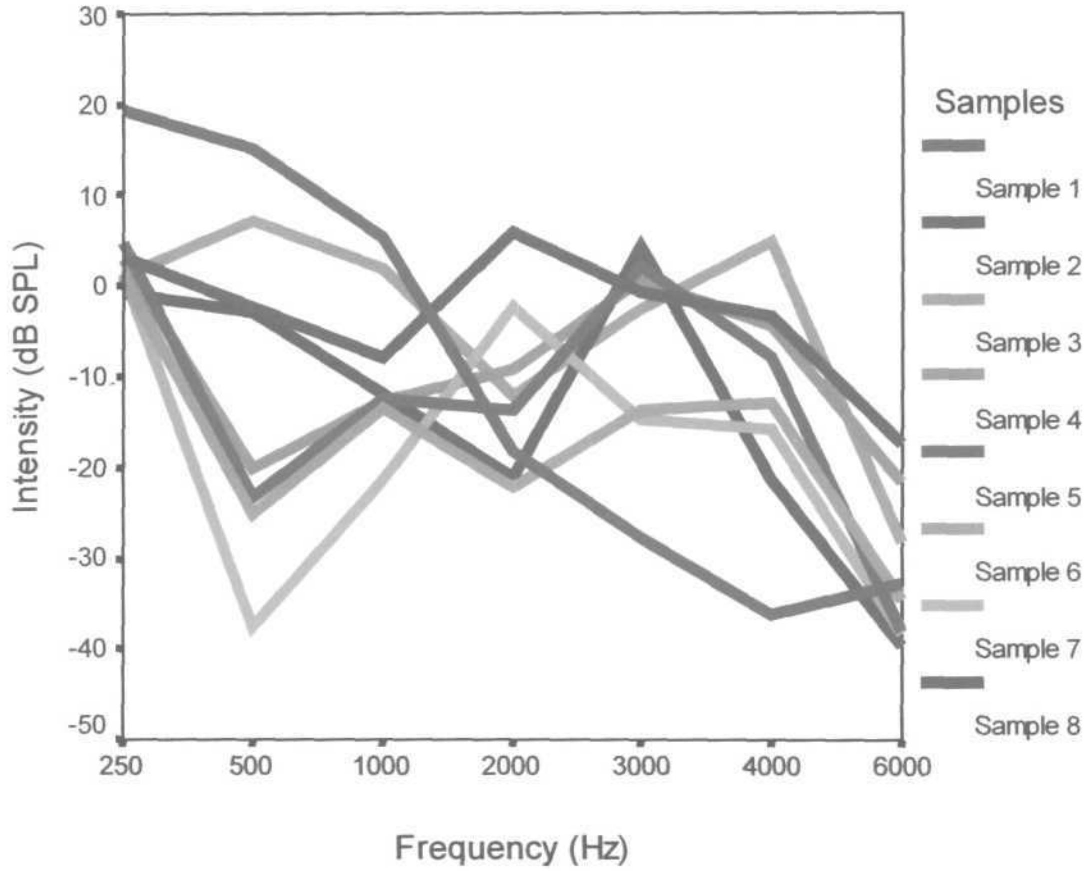

Fig 4.3: Hearing aid output at different frequencies for different samples, in 74 to 84 seconds interval

NOTE : The readings on the y-axis is realtive (ref: 2 x 10^{-5} pascals).

In all these figures, descriptions of the music samples are given in Table 4.1. From the figures, it is evident that the music sample 2 (Hearing aid B with knee-point set high, noise cancellation system and the feedback management system turned off) gave the best representation of the music sample. The music sample 3 (Hearing aid A with knee-point high, noise cancellation and feedback management off) and music sample 4 (Hearing aid B with knee-point high, noise cancellation and feedback management on) gave the second and third best representation of the original music sample, respectively. From the graph, it was evident that activation of the noise cancellation system or the feedback management system in the hearing aids led to degradation of the sample in terms of reduction of energy level in the low frequencies and increase of energy level in mid- and high- frequencies.

In the figures, it was evident that the outputs from the hearing aids were lower than the original in the lower frequency. But from the mid-frequency, around 1 kHz to 4 kHz, the hearing aid amplified the music. The activation of the feedback system and noise cancellation system (Sample 4, 5 & 8) led to a reduction of energy at the frequency about 2 kHz, which is evident as a dip in the energy output. It is quite evident from the graphs that the output through hearing aid B gave a better representation of the original music.

Chapter 4

DISCUSSION

The study involved perceptual rating given to the music samples processed by the hearing aids by the listeners and spectral analysis of the music samples. The perception of music is dependent on various factors such as the relationship of the harmonics in the lower frequency fundamentals and the higher frequency harmonics, the concentration of energy in the lower frequency, the temporal resolution of the music in the ear in order to be judged of good quality. Hence, the objective spectral evaluation of the output alone will not provide a clear picture of the quality of music processed by a hearing aid. The finding from the objective study should be complimented by a subjective study. A perceptual rating inherently has many problems which are dependent on the subject. The experimenter has no control over the subject-dependent factors such as motivation, understanding and biasness of the subjects. Hence, the study evaluated the music samples processed by hearing aids both subjectively and objectively. The results are discussed separately for subjective and spectral analyses. Discussion is also attempted on integration of the findings from both the evaluations.

Subjective Evaluation of the Music Samples

All the three groups of subjects (non-musicians, musician-singers and musicisn-instrumentalists) gave much poorer rating to the music samples recorded as output from the hearing aids compared to the original music sample. This is in agreement with the studies by Chasin and Russo (2004), Mishra, Kunnathur and Rajalakshmi (2004 & 2005), and Mishra and Abraham (2007). In all these studies, subjects with normal hearing were asked to rate music samples on a five-point perceptual scale. In the present study, the music processed from a fifteen channeled hearing aid, with the knee-point set at 72 dB SPL, was rated closest to that of the original music sample recorded without the processing by the hearing aid.

In the present study, the hearing aid A having six channels and hearing aid B having fifteen channels were taken. In both the hearing aids the recording of hearing aid processed music was done by setting the knee-point high, and the feedback management and noise cancellation system turned off. It was expected that the six channeled hearing aid (Hearing aid A) would give a better representation of music. But contrary to the expectation, the fifteen channel hearing aid with the noise cancellation system and the feedback management system turned off (Sample 2) was always given a better rating on all the five perceptual parameters compared to the six channel hearing aid, with the noise cancellation system and the feedback management system off (Sample 3). The mean rating for music sample 2 was significantly higher than the mean rating given to the music sample 3 in the parameters of loudness, fullness, clearness, naturalness and overall fidelity of the rating scale by all the three groups of subjects. Chasin (2003, 2006) and Chasin and Russo (2004) have recommended that either a single channel or a double channel hearing aid is ideal for music perception. Mishra, Kunnathur and Rajalakshmi (2005) noted that a multi-channel is better than single channel hearing aid for speech perception. Hence, they recommended that a multi-channel hearing aid, where all the channels are set for similar gain and compression, to be better for music perception.

Chasin and Russo (2004) had recommended that the knee-point should be set in between 65 dB and 75 dB for better perception of music through the hearing aid. The knee-point of the hearing aid A (Six channeled hearing aid) was set at 72 dB, 18 dB higher than the default setting for speech which is 54 dB. On the perceptual rating, there was no significant difference between the ratings given to the music recorded in the condition where the knee-point was at default setting (Sample 6) and where the knee-point was raised (Sample 3) with the feedback management and the noise cancellation system off for the hearing aid A. But the Singers and the Instrumentalists rated the overall music sample with the knee-point high (Sample 3) to be better than the default condition (Sample 6). Hence, this study also supports the notion that the knee-point should be set higher.

The activation of the noise cancellation system in hearing aid A with the knee-point being set high (Sample 7) led to poorer rating on the perceptual scale compared to the rating given to hearing aid A with the knee-point set high and the noise cancellation system and the feedback management system turned off (Sample 3) by the Instrumentalist and Singers groups. Chasin (2003 & 2006), Chasin and Russo (2004), and Mishra, Kunnathur and Rajalakshmi (2005) recommended that the noise cancellation system should be turned off. In the present study too it was found that the activation of the noise cancellation system led to poorer rating on all the perceptual parameters.

The activation of the feedback management system in hearing aid A with the knee-point high (Sample 8) also led to poorer rating on all the five perceptual parameters in the rating scale compared to the condition when both the feedback management system and the noise cancellation system was turned off (Sample 3). The Instrumentalist group (Group III), however, rated the music sample higher in the condition of activated feedback management (Sample 3) in the parameters of clearness, naturalness and overall fidelity, higher than the deactivated feedback management system (Sample 8). The rest of the subjects rated Sample 8 to be poorer than Sample 3 but the difference was not statistically significant. Chasin (2003 & 2006), Chasin and Russo (2004), and Mishra, Kunnathur and Rajalakshmi (2005) had also recommended the feedback management system to be turned off for the better perception of music through the hearing aids. The findings in the present study also conforms to this.

Spectral Analysis

The output from the hearing aid did not give a good representation of the original music sample in the lower frequencies. But in the mid-frequency, from 1 kHz to 4 kHz, the hearing aid amplified the music. Mishra and Abraham (2007) reported that the hearing aid outputs did not represent the original music sample well, especially in the lower frequencies.

From the figures 4.1, 4.2 and 4.3, it is evident that as in the analysis of the perceptual rating the hearing aid B (with knee-point set high and with the noise cancellation system and the feedback management system turned off), i.e., Sample 2, gave the best representation of the original music sample. The hearing aid A (with knee-point set 18 dB higher and deactivation of noise cancellation system and feedback management system), i.e., Sample 3, gave the next best representation of the music sample. Chasin (2003) had recommended a single or double channel hearing aid to be ideal for music perception. Subsequent studies reported a multi-channel hearing aid made to function as single channel hearing by setting the parameters same in all the channels was better for music perception (Chasin & Russo, 2004; Mishra, Kunnathur &

Rajalakshmi, 2005 and Chasin, 2006). That is, contrary to the expectation, the fifteen channeled hearing aid performed better than the six channeled hearing aid in this study.

In the three figures (4.1, 4.2 & 4.3) of the music samples, hearing aid A with knee-point raised, noise cancellation and feedback management system turned off (Sample 3) always gave output at higher energy level compared to hearing aid with default knee-point, noise cancellation and feedback management system turned off (Sample 6). Chasin and Russo (2004) had recommended that the knee-point should set within 65 dB to 75 dB for better music perception. While recording Sample 3, the knee-point was set at 72 dB. Hence, the spectral analysis result is agreement with that reported by Chasin (2006). From the figures, it was evident that activation of the noise cancellation system or the feedback management system in hearing aid A led to suppression of energy level and in case where both the systems were activated in hearing aid A, the energy concentrations were the lowest. The activation of the noise cancellation systems in both the hearing aids (Sample 4, 5 & 7) led to decrease in energy in the lower frequency. The activation of the feedback system in both hearing aids (Sample 4, 5 & 8) led to suppression of energy at around the frequency of 2 kHz which is evident as a dip in the energy output.

Integration of the Subjective and Spectral Analysis

All the music samples recorded through the hearing aid were given a poorer rating in the subjective rating by all the listeners. In the studies done in the past, hearing aid users have always preferred a lower cut-off frequency in judgment of the quality of music (Punch, 1978; Frank & Hall 1985). Chasin (2003) noted that the information in the low frequencies contributes significantly to the quality judgment of music. The figures depicting the hearing aid output at different frequencies for different samples revealed that neither the hearing aid A nor the hearing aid B represented the original music well in the lower frequency region. The output of the hearing aid was always poorer than the original music sample in the lower frequency region and the hearing aids were able to amplify the music after a frequency of around 1 kHz. Mishra and Abraham (2007) have also noted that overall, music processed through the hearing aids showed a poor representation of waveform in the low frequencies. It can be noted that the sample in which the hearing aids provided a good representation of the music in the lower frequency are rated higher by the listeners. The figures depicting the original music showed a concentration of energy in the lower frequency region and the energy falling precipitously after a frequency of 500 Hz. All the subjective/perceptual ratings indicated a much higher rating for the original music sample.

Two digital hearing aids were taken in this study, Hearing aid A having 6 channels and Hearing aid B having 15 channels. Both the hearing aids were taken from the same company, such that the other signal processing strategies remained the same. It was seen in this study that the hearing aid B having 15 channels represented the original music better on perceptual rating with the knee-point being set higher. The observation of the figures which represented the output from the hearing aid also depicted that the output from the Hearing aid B having the knee-point raised to 72 dB (Sample 2), gave better representation of the original music sample (Sample 1). Hearing aid A with the knee-point raised to 72 dB (Sample 3) followed the output from the Hearing aid B. In the perceptual rating also, the ratings given to the hearing aid B, with the knee-point high and the noise cancellation and feedback management off, was not significantly different from the original music.

The rationale for having a single channel or double channel hearing aid is that to have equal compression ratio across the entire frequency range remains equal so that the ratio of the energy in the low frequency and the high frequency remains essentially the same. If there is an imbalance in the amplification in the low frequencies and the high frequencies, timbre will be affected (Chasin & Russo, 2004).

Chasin (2003) noted that for wood wind instruments and quieter music or for clients with precipitous sloping audiometric configuration, a multi-channel hearing aid may be acceptable, since for the wood wind instruments the perceptual reliance is on the information in the lower frequencies. But the music sample selected in the present study did not contain any wood wind instrument and the lead instrument was violin.

Chasin and Russo (2004) had noted that some musical instruments like piano and violin are more speech-like. Such instruments are half wave resonator with evenly spaced harmonics. Since the lead instrument in the music sample in the present study was violin, this may be a reason why a fifteen channel hearing aid performed better than a six channeled hearing aid. It has been noted in various studies that multi-channel hearing aids improve speech perception.

The increase in the number of channels leads to different gain and compression setting in different frequency bands and there is disturbance between the low frequency fundamentals and the high frequency harmonics. In the analysis of the subjective results of the Group I (consisting of individuals not having any experience in professional music), there was no significant difference between the original music and the out put from the hearing aid B with knee-point raised by 18 dB. However, subjects in Group II and Group III (consisting of professional singers and instrumentalists) rated the music sample 2 to be similar to that given to the original music sample, except in two parameters in the perceptual rating, namely, the naturalness and overall fidelity. The differences in naturalness and reduced overall fidelity may be attributed to the disruption of ratio or balance of the low frequency fundamental and the high frequency harmonic structure. Such a difference was not perceived by the Group I, who indulged in listening to music just to seek pleasure. The variation may also be too subtle to be picked up an untrained listener. This draws attention to the fact that special care should be taken while prescribing hearing aids to the trained musicians as the demand of the musicians is far greater than the non-musicians who just appreciate music.

Chasin (2006) had recommended that the knee-point of the hearing aid should be set around 65 to 75 dB and the compression ratio should be low (e.g. 1.5:1). In the present study, the knee-point of the hearing aid was set at 72 dB. The knee-point while programming the hearing aid was 54 dB which was the first fit knee-point setting for speech. The subjective rating showed that the listeners had a preference for the hearing aid output where the knee-point that has been set to higher level for both the hearing aids (Sample 2 & 3). The graphs obtained for the outputs of the hearing aid in different condition also showed that setting the knee-point higher gave a better representation of the music in the lower frequency region. When the knee-point was set at the default setting for speech, the output of the hearing aid B was much lower in intensity in the low frequency region (Sample 6). On raising the knee-point, the output obtained from the hearing aid A was better compared to the default setting.

All the subjects gave poorer rating to the music samples in which the noise cancellation system was activated (Sample 4, 5 & 7). In the graphs depicting the output from the hearing aid in different settings it was noted that whenever the noise cancellation system was activated, it led to suppression of energy in the low frequency region. For time invariant noise, the noise cancellation system in the present day hearing aids assume that since most of the noise power is concentrated in the low frequencies, the speech is masked in this frequency region and filtering out both speech and noise over this frequency range will have little or no effect on intelligibility but will reduce the loudness and annoyance of the noise; i.e., overall sound quality will be improved (Levitt, 2001). The Figure 2.1 represents long-term spectra of noise and speech and reveals the difference between speech and noise in their concentration of energy. Hence, it can be assumed that the hearing aids under study were assuming the music sample to be a time invariant noise and hence there was a cancellation of energy in the low frequency region. As discussed previously, the concentration of energy in the low frequency region is essential for the judgment of quality of music. The findings of this study support that by Chasin (2003 & 2006), Chasin and Russo (2004), and Mishra, Kunnathur and Rajalakshmi (2005). The previous studies have noted that there is high probability for the hearing aid to confuse music to be noise and hence had recommended deactivation of the noise cancellation system.

The activation of the feedback management system led to low energy levels which in turn led to poorer rating by all the subjects. In the figures, it was noted that whenever the feedback management system was activated (Sample 4, 5 & 8), it led to a dip at the frequency region of around 2 kHz. In notch filtering of the feedback management system, it is possible to invert a band pass filter and remove the part of the peak in frequency response. It generally removes a narrow part of the spectrum centered around the frequency of the filter. This type of filtering is used to counter the acoustic feedback, where the notch is tuned to remove a narrow band of frequency around the offending frequency (Agnew, 1993). Most probably the activation of the feedback system led to employment of filter which nullified the gain at a frequency range centered around 2 kHz. Suppression of energy in a particular frequency will have a deleterious effect on music perception since the gain should be equal and balanced over the frequency region for the optimal perception of music.

The simultaneous activation of the noise cancellation system and the feedback management system led to greater deleterious effect on the perception of music both objectively and subjectively (Sample 4 & 5). It was worth noting that the hearing aid A had far more deleterious effect when both the noise cancellation system and the feedback management system were activated than hearing aid B by comparing outputs of sample 4 and sample 5 on the spectral analysis.

Mishra, Kunnathur and Rajalakshmi (2005) noted that that directional system leads to significant loss of low frequency sound which may remove valuable information for music. Hence, they recommended an omni-directional microphone for better perception of music. Even though the hearing aids (Hearing aid A and hearing aid B) in the present study had an omni-directional microphone, the output in the low frequency was reduced, may be because of the activation of the noise cancellation.

Chapter 6

SUMMARY AND CONCLUSIONS

The processing of music by hearing aids is a challenge which the hearing aid industry is facing today. The present study is an attempt to study the hearing aid processed music, while changing different parameters of the hearing aid. Thus, through controlled study design, the parameters in a hearing aid ideal for music perception were evaluated. The efficacy of the hearing aids was evaluated using the spectral measurement and subjective perception of the music samples processed by hearing aids. The music processed by the hearing aid in different programmed settings of the hearing aid was recorded. The hearing aid was connected to 2 cc coupler (HA-2) which inturn was connected to the microphone for recording. The original music sample was also recorded through the coupler to make the unprocessed music sample equivalent to the music sample processed through the hearing aids. The different music samples recorded with different settings of the hearing aids were as follows:

Sample 1: Original music sample without being processed by hearing aids

Sample 2: Hearing aid B with knee-point high, noise cancellation and feedback management off

Sample 3: Hearing aid A with knee-point high, noise cancellation and feedback management off

Sample 4: Hearing aid B with knee-point high, noise cancellation and feedback management on

Sample 5: Hearing aid A with knee-point high, noise cancellation and feedback management on

Sample 6: Hearing aid A with knee-point at default, noise cancellation and feedback management off

Sample 7: Hearing aid A with knee-point high, noise cancellation on and feedback management off

Sample 8: Hearing aid A with knee-point high, noise cancellation off and feedback management on.

The recorded music samples were subjected to perceptual analysis of the five parameters on a five-point rating scale and objective analysis was done using spectral slice in Praat software. The results of objective and subjective analysis implied the following settings of the parameters in the digital hearing aid to be better for music perception. All these conclusions are made with reference to the music samples, hearing aids, settings that were used in the study.

- A fifteen channeled hearing aid was better for music perception than a six channeled hearing aid for music perception.
- The knee-point for ideal music perception should be set as high as possible till it is not uncomfortable for the subject
- The feedback management and the noise cancellation system should be turned off

Limitations of the Study

The experimenter was quite aware of some limitation in the study, namely

- Both the hearing aids were programmed for a hypothetical flat hearing loss of 50 dB and not a high frequency hearing loss. This was done to reduce the variability in the compression characteristic and make the parameters equal across all the frequency range. But such hypothetical case is rare in real life situation.
- In this study, the coupler has been attached while recording music from the speaker through the hearing aids. But attaching the coupler brings changes in the output owing to the coupler characteristics, namely there is enhancement at the 2 kHz region. In order to make the all the samples equivalent the original music was also recorded in the same setting using the 2 cc coupler. But here a deviancy from the day-to-day situation could not be avoided.
- The five-point perceptual scale which has been used in this study may not be good enough for evaluation of Indian classical music. Indian classical music gives importance to features like "shruti", "alankar", etc. and it is very difficult to devise such a scale. But the scale used in this study has been widely used in the hearing aid industry for the judgment of music.
- The hearing loss has differential effects on frequency selectivity, temporal resolution, loudness perception/intensity discrimination and suprathreshold performance. These contribute to the difficulty of the individuals with hearing impairment to perceive and appreciate music. But since in this study, the music samples were played to normal hearing individuals, the subjective results of the study should interpreted cautiously for individual with hearing loss.

Future Research

Future research can be carried out for a hypothetical high frequency hearing loss, as such a hearing loss is commonly found in music-induced hearing loss or presbycusis. Another direction for study can be employing different schemes of the different processing strategy (e.g. noise cancellation system, feedback management system) employed by different hearing aid models to explore which gives parameter/setting would provide better perceptual and spectral representation of music or which one provides the least deleterious effect.

A study can be carried out for evaluating the adverse effect hearing loss on music perception, as the hearing loss has differential effects on frequency selectivity, temporal resolution, loudness perception/intensity discrimination and suprathreshold performance. In the field of music, a study may be undertaken to devise a scale for the perceptual rating of Indian classical music.

In conclusion, it can be said that music perception through hearing aid can be enhanced to a greater extent with appropriate changes in the parameters of the hearing aids, it was found from the results of the present study that a hearing with 15 channels (compared to 6 channels), disabling the noise cancellation and feedback management would improve the perception of music appreciably. The experimenter quite agrees with Chasin (2003) who noted that "a hearing aid ideal for music perception can be programmed to have good speech intelligibility but the vice-versa is not true".

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APPENDIX A

Instructions used for the purpose of perceptual rating of the music samples by the subjects in the study:

Respected Sir/ Madam,

This study is on the perception of quality of music. You will be given 8 samples of Carnatic music. It is requested that you listen to each of the samples attentively and rate each of the samples on the 5 parameters listed below. Definitions of the parameters used are also provided. But if you feel some of the terminology requires a further explanation you are most welcome for a clarification from us.

The scales for rating on the five parameters were as follows.

1. For loudness: 1 (faint)..................5 (sufficiently loud)
2. For Fullness: 1 (thin).................5 (full)
3. For Clearness: 1 (blurred).................5 (distinct and clear)
4. For Naturalness: 1 (unnatural)................5 (natural)
5. For Overall Fidelity: 1 (restricted)................5 (wide and not constrained).

The rating goes like this, if you find the sample to be poorer on a particular parameter, you will assign a lesser number to it and on the contrary if you find the music sample to represent the parameter adequately you may assign a higher number to it. If you need to hear the music sample more than once you may ask for the repetition. We are always open to your suggestion and clarifications.