Effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures

A DOCTORAL THESIS

Submitted to the University of Mysore,
for the award of degree of
Doctor of Philosophy (Ph.D.) in Audiology

by

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DECLARATION

I declare that this thesis entitled **'Effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures'** which is submitted for the award of the degree of Doctor of Philosophy in Audiology to the University of Mysore, is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysuru, under the guidance of Dr. Manjula P., Professor of Audiology, All India Institute of Speech and Hearing, Mysuru. I further declare that the results of this work have not been previously submitted for any other degree.

Place: Mysuru
Sharath Kumar K. S.

Date:

CERTIFICATE

This is to certify that the thesis entitled **'Effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures'** submitted by Mr. Sharath Kumar K. S., for the degree of Doctor of Philosophy in Audiology to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru, under my guidance. I further declare that the results of this work have not been previously submitted for any other degree.

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This is to certify that the thesis entitled **'Effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures'** submitted by Mr. Sharath Kumar K. S., for the degree of Doctor of Philosophy in Audiology to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru.

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DEDICATED TO

GOD ALMIGHTY,

APPA, AMMA & MEGHA

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ABSTRACT

The study evaluated the effectiveness of noise reduction algorithms (NRA) in two hearing aids through acoustic and perceptual measures. The output from the hearing aid with noise reduction (NR) ON at three gradations (NR minimum, NR medium, & NR maximum) and NR OFF; at three signal to noise ratios (SNR) for five types of noise (cafeteria, fan, speech babble, traffic, & white noise) were recorded. The effect of NR was quantified through acoustic (Phase I) and perceptual (Phase II) measures among individuals with normal hearing (NH group) and those with hearing impairment (HI group). The data were collected on measures such as intensity of noise at the hearing aid output, Waveform Amplitude Distribution Analysis - Signal to Noise Ratio (WADA-SNR), Envelope Difference Index (EDI), Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS), quality judgment tasks, and speech identification.

The results from acoustic analysis revealed that the overall LAeq (dB) and LA90 (dB) values for NR ON condition was lower than that for NR OFF condition, for all types of noise. The NR max provided the greatest reduction of noise followed by NR med and NR min gradations. The WADA-SNR at the hearing aid output was increased and the EDI values were lower, with NR ON compared to NR OFF condition, for all the types of noise. The NR max gradation brought about the highest SNR and lowest EDI values followed by the NR med and NR min gradations. The PESQ (MOS) did not show change across the NR gradations. Further, the speech language pathologists rated the hearing aid output as less noisy as the WADA-SNR value increased, and they rated formant representation to be better at the output of the hearing aid as EDI values decreased across NR gradation.

Likewise, the perceptual analysis revealed that the participants in both Groups (NH & HI), preferred NR max as it was less noisy, whenever it was compared with NR OFF, NR min and NR med, for cafeteria and traffic noise, in noise alone condition. In speech in noise condition, there was a negligible improvement in the mean SIS in different NR gradations for NH group. The NR max had better SNR-50 scores than NR OFF, with cafeteria and traffic noise for HI group. In the quality judgment, at NR max, the sample was rated clearer and less noisy than the other aided conditions in NH and HI groups.

Thus, it can be inferred that the NRA do bring about reduction in noise, and statistically significant improvement in speech perception in noise. The amount of NR depends on the acoustic characteristics of the input noise, how different it is from the speech signal, the input SNR and the noise reduction algorithm technology employed in the hearing aid.

Key words: Noise reduction algorithm, acoustic measure, perceptual measure, LAeq, LA90, PESQ (MOS), WADA-SNR, EDI, quality judgment, SIS, SNR-50.

CHAPTER 1

INTRODUCTION

Noise degrades the perception of speech for individuals with normal hearing as well as those with hearing impairment (Alcántara, Dooley, Blamey, & Seligman, 1994). It has been reported in literature that there is a decrease in speech identification ability in the presence of noise compared to that in quiet (Wilson, Zizz, Shanks, & Causey, 1990). Dubno, Dirks, and Morgan (1984) have reported that individuals with even a mild hearing loss, whose speech discrimination in quiet is almost as good as that in listeners with normal hearing, may have difficulty in understanding speech in the presence of noise. It has also been reported that, hearing aid users have great difficulty in understanding speech in the presence of noise (Cox & Alexander, 1991; Duquesnoy & Plomp, 1983; Plomp, 1986).

During conversation, the presence of human speech in the background can itself become a competing noise and this is the most common type of interference encountered during conversation. In addition to this, the other environmental noises that interfere in normal conversation are traffic noise and wind noise (Plomp, 1978). In real life, the characteristics of the background noise differ from situation to situation. An individual can encounter many different types of noise with different spectral and temporal characteristics. Hence, it is necessary that a hearing aid be able to reduce the noise and enhance the speech perception in such a situation.

The Digital Signal Processing (DSP) was introduced in hearing aids in the year 1996 (Edwards, 2007). Since then, there have been many strategies such as noise reduction algorithms (NRA), in addition to the directional microphones, in hearing aids in order to reduce the effect of noise. It has been noted by Bray and Nilsson

(2000) that when noise and speech originated from the same direction, directional microphones provide limited benefits. Therefore, NRA have become a focal point in research. According to Jamieson, Brennan, and Cornelisse (1995), benefits of noise reduction (NR) include reduced upward spread of masking and reduced distortion. Other benefits include ease of listening, increased tolerance for noise, reduced effort in listening to speech and improved speech quality (Mueller, Weber, & Hornsby, 2006; Palmer, Bentler, Mueller, 2006; Sarampalis, Kalluri, Edwards, & Hafter, 2009; Zakis, Hau, & Blamey, 2009).

Several algorithms have attempted to improve speech recognition in noise. Bentler, Anderson, Niebuhr, and Getta (1993a, 1993b), and Walden, Surr, Cord, Edwards, and Olson (2000) have reported ease-of-listening with a variety of NRA but did not find improvement in speech intelligibility. Similar findings have been reported by Ricketts and Hornsby (2005). However, Alcántara, Moore, Kuhnel, and Launer (2003) did not report any reduction of noise at the output of the hearing aid nor ease-of-listening. This could be attributed to the differences in the NRA and the types of noise used in different studies.

Even with the advancements in technology, the hearing aid users continue to complain of difficulty in hearing to speech in noise (Kerckhoff, Listenberger, & Valente, 2008). According to the MarkeTrak VII data by Kochkin (2005), only 51% of the hearing aid users were satisfied while listening in noisy situations. The quality / technology of NR available in some models of hearing aids, impacts the ability of the user to benefit from NRA. When a comparison is made between different digital hearing aids with NRA, there are several factors that might influence the findings.

Digital hearing aids employ a number of different noise reduction strategies / algorithms to effectively separate speech from noise. In a multi-band hearing aid, speech and noise can be processed in different bands. According to Smriga (2000), the gain for a speech signal is reduced, when the speech is found in a band designated for noise, as the gain in a specific band is reduced. Problems arise when the noise resembles speech and the algorithms do not recognize it as noise. Theoretically, Summe (2003) stated that it would be easy for an algorithm to detect steady-state noises and separate them from speech since speech consists of peaks and valleys that make it clearly distinct from a broadband signal. However, not all unwanted noise signals are steady-state. Some noises have the same peaks and valleys in their spectrum as that of speech, thus mimicking the real world speech.

In order to study these effects, several investigators have considered different types of noise that mimic the real-life situation and different types of hearing aid which have different NR strategies (Bray & Nilsson, 2000; Cord, Leek, & Walden, 2000; Shields & Campbell, 2001; Summe, 2003; Ricketts & Hornsby, 2005; Bentler, Wu, Kettel, & Hurtig, 2008; Zakis et al., 2009; Chung, 2012; Brons, 2013). The results show that there was an improvement while using some strategies and for a few types of noise.

The acoustic measures of NRA have been investigated by some investigators (Hickson, Thyer, & Bates, 1999; Summe, 2003; Nilsson & Bray, 2004; Rout, Hanline, & Halling, 2007; Chong & Jenstad, 2010; Chong & Jenstad, 2011; Chung, 2012) while others have investigated the perceptual measures (Boymans, Dreschler, Schoneveld, & Verschuure, 1999; Bray & Nilsson, 2000; Alcántara et al., 2003; Ricketts & Hornsby, 2005; Mueller et al., 2006; de Oliveira, Lopes, & Alves, 2010; Brons, Houben, & Dreschler, 2013). There are a few studies comparing the acoustic and perceptual measures with different types of noise (Zakis & Wise, 2007; Miller, 2013; Neher, Wagener, & Fischer, 2016; Miller, Bentler, Wu, Lewis, & Tremblay, 2017). The studies evaluating NR with acoustic measures have shown a decrease in noise and improvement in SNR at the output of the hearing aid. However, the effects of NRA on perceptual measures have shown equivocal results across the studies. Some studies have shown that participants preferred NR (Boymans & Dreschler, 2000; Ricketts & Hornsby, 2005), whereas others have shown that participants did not find any difference in listening comfort or sound quality due to NR (Alcántara et al., 2003; Bentler et al., 2008). Thus, the present study is being under taken to address some of these important issues.

1.1 Need for the study

There are a lot of advancements in hearing aid technology in the recent years. One of the signal enhancing strategies in hearing aids include use of NRAs. Even though there are advancements in technology, it is very difficult to meet the satisfaction of the hearing aid user to the fullest extent. Hence, it's necessary to study the effects of NRA on different types of noise across different SNRs and with different NR gradation.

1.1.1 Need to select different types of noise

Noise reduction algorithms (NRA) have a variety of processing strategies, some of which include modulation detection, spectral subtraction, Wiener filtering, synchrony detection, etc. The idea behind these strategies is that it should reduce the unwanted noise while enhancing the speech signal of interest. According to Boymans and Dreschler (2000) and Summe (2003), it is easy for an algorithm to detect steady-state noises and separate them from speech. Since speech consists of peaks and valleys, it is makes it clearly different from the steady, non-varying noise. For instance, the spectral subtraction method, presumes that the speech is always varying, and that the noise is steady. However, the noise in the environment may not always be steady over time (Levitt, 2001). Some noises even have similar peaks and valleys as that of speech. It is known that, if competing noises are speech shaped noise or speech signal itself, then they significantly degrade the primary desired speech signal. If the NRA can attenuate speech-weighted noise effectively, then there will be improved speech perception in noise (Summe, 2003). It is also hypothesized by Plomp (1978) that speech babble is considered as one of the most commonly encountered background noises. It is also known that an individual can encounter many situations in daily life. Each situation can be challenging because as the environment changes, the type of noise in the environment also changes. Thus, the most frequently encountered noises in the Indian context are selected in the study for evaluating the effectiveness of NR in hearing aids.

Thus, the objective of the present study was to evaluate the effect of NRA in hearing aids on the acoustic measures. This was done with five different types of noise such as cafeteria noise, fan noise, speech babble, traffic noise and white noise. Further, the effectiveness of NRA on perceptual measures was also evaluated. This was done in presence of cafeteria noise and traffic noise.

1.1.2 Need to study effect of NRA using acoustic measures

With the introduction of digital hearing aids, its performance was assessed using coupler and/or probe microphone measurements to represent its gain and output characteristics. In the early years of digital signal processing, Cox and Studebaker (1979) have evaluated the hearing aid processed speech during hearing aid fitting.

However, this was found to be inappropriate, as each individual will have different gain requirements. Bentler and Chiou (2006) have stated that verification of the way the NR scheme actually works for a given individual is an important process in hearing aid fitting. Bentler and Chiou (2006) found that modulation based digital noise reduction in hearing aids would identify speech and reduce noise in the frequencies other than the speech frequency. This is done without reducing gain in the speech frequencies. However, the algorithm also identified International Collegium for Rehabilitative Audiology (ICRA) noise as speech and provided no gain reduction. This could be due to the assumption of the NRA which may not be effective in attenuating the noise that has speech-like features.

Summe (2003) analyzed the speech spectrum of phonemes in words before and after the noise reduction. It was concluded that NRA did not attenuate the environmental sounds such as ocean waves, rain noise, subway noise and jet noise. Further, they reportedly attenuated speech-weighted babble, in three of the four hearing aids tested. Only one hearing aid effectively attenuated the environmental sounds in a desired manner. However, the differences in the hearing aid NR processing might have led to ineffectiveness of hearing aids in reducing different types of noise.

The above two studies have shown that studying acoustic measures provide a good understanding on the effect of NR to find out if the NR is efficiently reducing the noise or not. In order to ascertain the effect of various NRA on different types of noise and to quantify the reduction in terms of signal-to-noise ratio (SNR), acoustic analysis of the hearing aid output has been employed in recent years. This will help us to understand the processing used by noise reduction algorithms according to Rout et al. (2007).

Further, the ineffectiveness of some algorithms in reducing noise may be due to the selection of smaller segments of speech such as phoneme or words (Galster & Pisa, 2010). Some of the recent NRA analyze the noise in between the segments or pauses of a speech signal and consider this in reducing the noise across the entire signal. Hence, in the present study, sentences were used to study the effect of NR in hearing aids on acoustic aspects of speech in the presence of noise using acoustic measures.

In addition, the SNR changes observed in the acoustic analysis can be associated with the speech perception. This can be a clinically useful measurement for predicting the outcomes from the hearing aid (Miller, 2013). Hence, it is essential to evaluate if the hearing aid with NR results in appropriate changes in the SNR at the hearing aid output and verify if the changes in SNR is bringing about similar changes in the speech perception. Thus, Waveform Amplitude Detection Analysis- SNR (WADA-SNR) measure was chosen to estimate the relative SNR in the hearing aid output.

Rohdenburg (2008) opines that subjective tests are time consuming and depend on participant factors like degree of hearing loss, experience with the hearing aid, practice effect, and their ability to comprehend the instructions. Hence, objective measures that quantify the subjective quality judgments may be utilized to understand the speech perception. Thus in the present study, Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS) was utilized to objectively evaluate the perceived speech quality.

Literature shows that Envelope Detection Index (EDI) is often being measured to evaluate the temporal distortions in the hearing aid output after applying compression and digital noise reduction (DNR) algorithm (Jenstad & Souza, 2005; Jenstad & Souza, 2007; Walaszek, 2008; Chong & Jenstad, 2011; Souza, Hoover & Gallun, 2012; Geetha & Manjula, 2014). Hence, to study the temporal distortions in speech in noise condition that may arise from the NRA, the EDI analysis was utilized to check on the temporal changes that the NRA can bring about in the hearing aid output.

1.1.3 Need to study effect of NRA using perceptual measures

It is known that the recent digital processing approaches are providing new NRA to enhance speech perception in noise. It is important to assess whether the new noise reduction algorithms are helpful in enhancing the speech perception in noisy conditions. Though the acoustic parameters show that these algorithms are performing well, it can be validated only when there is patient satisfaction. In the recent years, there are many studies which have assessed the effectiveness of NRA by analyzing the output of the hearing aid perceptually. Walden et al. (2000) studied the effect of omni-directional microphone, dual-microphone directionality, and a combination of noise reduction circuit with dual-microphone directionality on speech perception. They assessed the performance using the connected speech test (CST). Further, subjective ratings of speech understanding, listening comfort, and sound quality/naturalness were also obtained using eleven-point interval scales. It was found that the dual microphones had more advantage in speech recognition test over the omni-directional microphone in noise. However, participants generally did not perceive these large advantages in everyday listening. The noise reduction with directionality provided improved listening comfort but little changes in speech understanding.

Ricketts and Hornsby (2005) used a paired-comparison approach to determine preference for both directional microphone and DNR features. The subjects were also made to rate their preference. Even though speech perception measure did not show any improvement with DNR, a significant and strong preference for the DNR was indicated, in both low and high noise levels. The authors suggest that because the instructions were to choose the (directional vs. DNR) of preference, the subjects were responding to listening comfort rather than quality.

The above two studies support the fact that the NRA are more effective in improving the listening comfort when compared to the primitive noise reduction methods such as directional microphone and dual microphones. Alcántara et al. (2003) concluded that their participants found no preference for DNR ON or OFF condition. They attribute this to the reduction of speech information in the bands where the noise reduction is acted on. This finding is incongruent with that of previous studies.

The performance of adult individuals with sensorineural hearing loss was assessed by de Oliveira et al. (2010), with a NRA called Speech Sensitive Processing, in the presence of noise. Sentence recognition threshold in noise were obtained with and without the algorithm being enabled. The results revealed that the algorithm provided a benefit in SNR for most individuals with hearing impairment. The results pointed to a statistically significant difference when the algorithm was ON, compared to when the algorithm was OFF. These findings are also in agreement with those reported by Boymans and Dreschler (2000) and Galster and Pisa (2010).

The results are equivocal across the studies on the perceptual effects of hearing aid noise reduction. Some studies showed that the listeners preferred noise reduction over no noise reduction (Boymans & Dreschler 2000; Ricketts & Hornsby 2005; Sang et al., 2015); whereas others found no difference in listening comfort or sound quality due to noise reduction (Alcántara et al., 2003; Walden et al., 2000). In addition, it is seen that individuals usually report increased tolerance for noise, decreased listening effort and stronger preference for noise reduction enabled than when the noise reduction was disabled (Mueller et al., 2006; Palmer et al., 2006; Sarampalis et al., 2009; Zakis et al., 2009; Brons, Houben, & Dreschler, 2014; Brons, Houben, & Dreschler, 2015).

Hence, studying the acoustic changes at the hearing aid output along with the speech perception measurements could provide clues about what changes are perceptible to listeners. This may help to resolve the conflicting reports between speech perception and subjective benefits with NRA (Miller, 2013). And to date, studies have independently evaluated the effectiveness of NR feature in reducing background noise using either the acoustic or perceptual measures, and very few studies have evaluated both. Furthermore, studies have evaluated NR along with either directionality or Wide Dynamic Range Compression (WDRC). A small number of authors have evaluated only NR by excluding the effects of all other digital signal processing. Thus, there is a need to evaluate the independent effect of NR feature on sentences in reducing background noise, using both the acoustic and perceptual measures, in a hearing aid. In addition, the acoustic and perceptual findings need to be verified for better understanding of signal processing through hearing aids.

Moreover, Quackenbush, Barnwell, and Clements (1988) opine that only one objective measure will not be able to predict the subjective quality rating of hearing aid output. Houben, Dijkstra, and Dreschler (2011) suggested that to evaluate the overall effectiveness of a noise reduction system, researchers should consider broader range of speech, different noise types and a range of input SNRs. Similarly, the present study focused on evaluating the effectiveness of NR with different types of noise, at different input SNRs (+5, 0, & -5 dB), and with varied NR gradations.

1.2 Aim of the study

The aim of the study was to evaluate the effectiveness of Noise Reduction Algorithms (NRA) in two different hearing aids on acoustic and perceptual measures.

1.3 Objectives of the study

The specific objectives of the study included:

1. To evaluate the effect of NRA on acoustic measures in different types of noise and across different NR conditions, in noise only condition.
2. To evaluate the effect of NRA on acoustic measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in speech in noise condition.
3. To evaluate the effect of NRA on perceptual measures in different types of noise and across different NR conditions, in noise only condition, in participants with normal hearing and hearing impairment.
4. To evaluate the effect of NRA on perceptual measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in

speech in noise condition, in participants with normal hearing and hearing impairment.

1.4 Null Hypotheses

The null hypotheses have been stated for each objective of the study:

1. There is no effect of NRA on the acoustic measures in different types of noise, across different NR conditions, in noise only condition.

2. There is no effect of NRA on acoustic measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in speech in noise condition.

3. There is no effect of NRA on perceptual measures in different types of noise and across different NR conditions, in noise only condition, in participants with normal hearing and hearing impairment.

4. There is no effect of NRA on perceptual measures in different types of noise at three input SNRs (+5, 0 & -5 dB) across different NR conditions, in speech in noise condition, in participants with normal hearing and hearing impairment.

CHAPTER 2

REVIEW OF LITERATURE

Individuals with hearing loss often complain of difficulty in understanding speech, especially in the presence of noise. It has been documented in literature that hearing aid users also often report of having difficulty in understanding speech in noisy environments (Duquesnoy & Plomp, 1983; Plomp & Duquesnoy, 1982; Plomp, 1986; Cox & Alexander, 1991). In a study by Kochkin (2005) on customer satisfaction with hearing aids from MarkeTrak VII, it was reported that only 51% of individuals are satisfied using hearing aid in the presence of noise.

In order to improve understanding of speech in presence of noise, researchers have tried different noise reduction (NR) features in the form of tonal switch (N-H) to cut-off the low frequencies which was available in the hearing aids since 1970s (Bentler & Chiou, 2006). Since then there have been many attempts to reduce the background noise in the hearing aids through advanced digital algorithms. Though directional microphones are designed to take advantage of spatial separation between speech and noise, noise reduction algorithms (NRA) are designed to take advantage of the temporal separation and spectral differences between speech and noise (Chung, 2004). When noise and speech originate from the same direction, directional microphones provide limited benefits in reducing the noise (Bray & Nilsson, 2000).

The ultimate goal of any NR algorithm is to increase listening comfort and speech intelligibility (Chung, 2004). It is a known fact that an improvement of 1 dB in SNR around the SRT can lead to increase in speech understanding of 10-15% in every day communication (Plomp & Mimpen, 1979). Thus, many noise cancellation techniques bloomed and were incorporated in the digital hearing aids.

2.1 Types of noise reduction algorithms

Noise reduction algorithms (NRA) of each hearing aid manufacturer are trademarked and hence each have different signal detection methods, decision rules, and time constants. In the analog era, Zeta Noise Blocker algorithm was the only algorithm which used a digital chip into the hearing aid circuitry. The Digital Noise Reduction (DNR) revolutionised the hearing aid industry. With DNR, it was possible to incorporate more complex algorithms which included decision rules to manage the amount of noise reduction and frequency where the reduction should be applied in the hearing aid circuitry (Bentler & Chiou, 2006).

The primary goal of the NRA is to improve the signal-to-noise ratio (SNR) at the output of the hearing aid. Since noise and speech spectra do not differ drastically, it becomes a challenge to reduce the gain in the frequency region of the interfering noise source alone. The Wiener filter that was used in the field of photography to restore images corrupted by noise and/or blurring, was first used by Levitt, Bakke, Kates, Neuman, and Weiss (1993) to study the reduction of noise in a hearing aid circuitry. Levitt et al. (1993) showed that incorporating Wiener filter in hearing aid circuitry would help individuals with hearing impairment in presence of noise. Bentler and Chiou (2006) stated that in the present day most of the hearing aid manufacturers incorporate Wiener filtering in the hearing aid algorithm.

The common feature among the algorithms from different hearing aid manufacturers is the detection of modulation in the incoming signal and to identify the presence or absence of the speech signal (Chung, 2004). The modulation based algorithm works on the assumption that speech has a modulation rate centred at 4 to 6 Hz and noise in the environment has either a constant temporal characteristic or a modulation rate outside the range of speech. In addition speech has co-modulations that are produced due to closing and opening of the vocal folds (Chung, 2004). NRA uses the modulation rate and depth of the incoming signal to estimate presence of speech and the SNR of the incoming signal (Chung, 2004; Bentler & Chiou, 2006; Kates, 2008; Chung, 2010). Once the algorithm estimates the speech and SNR, decision rules are applied to decide how much gain reduction should be implemented. For example, if the modulation rate is low (e.g., speech dominated) and the modulation depth is high (favourable SNR), then the gain is minimally reduced (Chung, 2010). If the modulation rate is high and the modulation depth is low, then the gain reduction is greater. The amount of gain reduction and how quick the changes are applied is dependent on the modulation depth, rate, overall level of the signal, and the type of noise (Chung, 2004; Bentler & Chiou, 2006; Chung, 2010). Dillon (2012) remarked that modulation based noise reduction system does not improve the SNR within each channel, but may improve the overall SNR of the input signal.

Walden et al. (2000) studied the listening comfort and speech understanding in individuals with hearing impairment using a digital hearing aid with modulation based NRA. Their results indicated that the NR circuit provided improved listening comfort but did not bring about changes in speech understanding.

Bentler et al. (2008) studied the modulation based NRA in a commercial hearing aid with self-reports, speech in noise tests and speech quality measurements individuals with hearing impairment. Though the speech in noise tests did not show any improvements between NR ‘ON’ and NR ‘OFF’, participants rated ease of listening significantly better in NR ‘ON’ condition. Self-report measures also indicated significantly higher aversiveness in the NR ‘OFF’ condition.

Zakis et al. (2009) studied the effects of four configurations of an environmental noise reduction (ENR) algorithm on preferences, speech understanding and satisfaction. Sentence reception thresholds were measured in quiet and noise; and satisfaction was rated with speech in noise. They reported that the gain reduction at 0 dB modulation depth was either 10 dB in all channels (ENR strong flat) or shaped from 2 to 10 dB across channels according to a speech importance function. They concluded that the ENR significantly improved satisfaction for listening comfort, ease of speech understanding, and sound quality.

On reviewing the studies reported in literature, it could be inferred that the modulation based NR algorithm would not only aid in reducing the noise at the hearing aid output but also aid in ease of listening for individuals with hearing impairment.

Spectral subtraction method, another algorithm for reduction of noise in the hearing aids, uses the estimated spectra of the noise and speech plus noise to implement the decisions about gain reduction. The noise spectrum is obtained during pauses in the speech and is subtracted from the speech-plus-noise spectrum when speech is present again. The amount of gain reduction here depends on the SNR and the type of noise. Bray and Nilsson (2000) compared a new model of the hearing aid having nine channels with a spectral subtraction noise algorithm to the original (Sonic innovations Natura) hearing aid. The new model had NRA that could suppress steady-state noise. Speech-weighted babble was used as a background noise. The new NRA improved the SNR by 3.6 dB compared to the original. Ricketts and Hornsby (2005) evaluated a recent version of a spectral subtraction algorithm. The results of the study showed that there was no difference in speech perception in noise between noise reduction activated and deactivated. Thus, spectral subtraction based NRA may not be very efficient in reducing noise.

The main challenge for the NRA is to reduce background noise while retaining the level and quality of target speech (Brons, 2013). If the input signal has noise, the NRA should decide the way in which it will adjust the hearing aid gain in order to reduce the noise. The extent of noise reduction depends on the accuracy in which the algorithm differentiates the speech and noise and the means by which that information is translated in changes in the hearing aid gain (Brons, 2013). The decision rules of algorithms differ from each manufacturer in terms of gain reduction (in which frequencies or channels), the speed of gain reduction (time constants), and the SNR at which the algorithm would activate to reduce the gain (Bentler & Chiou, 2006).

The amount of gain reduction depends on the way the NRAs are implemented in a particular hearing aid. The decision rules for altering the gain for speech signals will not change across the different manufacturers. But the decision rules for noise like inputs are variable (Bentler & Chiou, 2006). If too much of gain is reduced for noise like inputs, audibility might be compromised for individuals requiring higher gain (e.g., individuals with severe hearing loss). Hoetink, Körössy, and Dreschler (2009) compared the reduction of gain of different noise reduction systems. They varied the levels of the input signal, signal to noise ratios, and different audiogram configurations. The gain reduction of 12 different hearing aids was compared both qualitatively and quantitatively by means of principal value decomposition. The results showed that the hearing aids differ considerably in providing the overall gain reduction. Also, the frequency response is varied either to decrease the low frequency or to increase the high frequency.

The NR is able to improve SNR of the input signal as it can apply changes separately for different frequency channels (Chung, 2004). In a time frame, the SNR within a frequency channel is not changed. The NR only adjusts the overall gain in a frequency channel. Reduction of gain in the noise dominated channels and preservation of gain in the speech dominated channels will improve the overall SNR of the signal. However, the number of channels in a hearing aid cannot be increased as it can increase the processing delay.

The amount of gain reduction in a channel is usually proportional to the estimated SNR for that channel (Chung, 2004; Dillon, 2012). At good input SNR, the NR algorithm should not reduce the gain and preserve the speech information. At very low input SNRs, the NR algorithm should reduce the gain maximally in the channel where noise is present. However, the maximum amount of gain that can be reduced is limited even if the input SNRs is poorer (Chung, 2004; Bentler & Chiou, 2006). If this maximum limit is set very low, the noise level in the background will not be reduced. If the maximum limit to reduce the gain is set very high, speech quality from the hearing aid will be poor and the overall gain of the hearing aid will be reduced (Loizou & Kim, 2011).

The effectiveness of noise reduction is also determined by how fast the noise reduction reacts to changes in the environment (Bentler & Chiou, 2006; Brons, 2013). Chung (2004) has identified four different time constants for NR algorithms:

- the time between the NRA detecting noise in any channel and the time at which the gain begins to decrease
- the time between the beginning of gain reduction and maximum gain reduction

- the time between the NRA detecting the absence of noise in any channel and the time at which the gain begins to increase
- the time between the start of the gain recovery and 0 dB gain reduction.

The time that an algorithm needs to reach its maximum gain reduction after noise has started varies between the algorithms (Brons, 2013). It can take a few milliseconds to more than 30 seconds. If the time constants are fast, it can quickly be able to reduce noise. However, this might affect speech intelligibility (Brons, 2013). On the contrary, the NRA which have slow time constants, adjust gain slowly. This might lead to more residual noise with speech information. Some hearing aid manufacturers aim at preserving the audibility of speech than reducing too much gain during speech.

The impact of the different onset times was investigated by Bentler (2006). The results indicated that the onset time did not influence the performance in individuals with hearing impairment. The authors report that the onset time ranged from 5 to 20 seconds. This range of onset time may be too narrow to note any perceptual changes. Galster and Ricketts (2004) evaluated two NRAs with slow and fast time constants. Speech recognition thresholds were obtained using the Hearing in Noise Test (HINT) with active and inactive NR processing. The results indicated poor thresholds with NR having slow time constant and good thresholds with NR having fast time constant. They speculate that as the NRA do not alter the SNR in each band instantaneously. Release from temporal masking of the speech stimulus and release from upward spread of masking across hearing aid channels may have contributed to the improved performance in fast NR time constants.

By recognising the various factors that determine the output from a NRA, it is necessary to study the effects of these on speech that is processed through the NRA. To understand the functionality of the NRA, by excluding the patient related variables like age, hearing loss, cognition, it would be appropriate to study the effects of NRA through acoustical measures.

2.2 Acoustical analysis of output from the hearing aid

Recording the output from the hearing aids was done way back in 1970s by Harris and Hudgson (1974). They compared the discrimination ability for recorded PB words processed by the hearing aid under clinical conditions. They concluded that hearing aid processed stimuli could give useful information about aided speech discrimination. Cox and Studebaker (1979) described a new protocol for obtaining and utilising the hearing aid processed signals in hearing aid research or hearing aid trial. Their data showed the discrepancy of ±2 dB with the direct aided condition and hearing aid processed signal spectra, recorded from a KEMAR.

In the initial years, acoustical analysis of the recorded output from the hearing aid was used to study the speech perception through different parameters of the hearing aid. Most commonly studied parameters were compression and noise reduction. Hickson et al. (1999) performed acoustic analysis of the hearing aid processed consonant-vowel (CV) syllables to study the consonant-vowel ratio (CVR). The CV syllables were recorded by varying the compression ratio and crossover frequency of two-channel syllabic compression. The acoustical analysis of the hearing aid processed syllables revealed that, with increased compression, the CVR increased and the greatest effect was seen in the high frequency channels. Compression in the low frequency channels did not affect the CVR. As CVR is an important cue for perception of consonants, it was concluded that care must be exercised when compression is applied.

Nilsson and Bray (2004) estimated the changes in the signal to noise ratio (SNR) of noise processed through hearing aids. The stimuli were HINT sentences presented with noise in-phase and out-of-phase. The SNR was estimated by comparing the SNR at the output with the known SNR at the input. They called the resulting change in SNR as ‘Noise Reduction Index’ (NRI). The SNR was estimated by studying the output from the hearing aid with noise reduction in omni-directional and directional modes. The results revealed that the SNR improved with noise reduction activated with directionality. As the SNR improved, there was an improvement in hearing in noise test (HINT) scores.

Bentler and Chiou (2006) showed an overall level reduction of 4.25 dB and 13.6 dB for random noise with NRAs incorporated in hearing aids with two different manufacturers. In contrast, there was no gain reduction from one of the hearing aids; rather the overall level was increased by 3 dB for random noise at 85 dB. Similarly, Dreschler, Verschuure, Ludvigsen, and Westermann (2001) also noted that gain for clear speech decreased when the DNR was activated. Hence, Bentler and Chiou (2006) suggested that verification of the hearing aid features like NR should be done at various stages in the fitting process.

Ghent, Nilsson, and Bray (2007) validated the NRI by using it to estimate the change in input SNR using audio devices such as linear hearing aids (with & without directional microphones), a directional microphone designed for noise rejection on a concert stage, an ear trumpet, and a multichannel hearing aid with a digital NRA enabled and disabled. The results indicate that the NRI was a robust and valid method for estimating this change in SNR. The digital hearing aid with an omni-directional microphone had a NRI of -0.7 dB without any other signal processing being active. When DNR was enabled, it improved the SNR by 1.9 dB and while using a directional microphone alone it yielded an improvement of 3.1 dB. This implies that NR would improve SNR and reduce the noise.

Rout et al. (2007) studied the multichannel noise reduction in hearing aids from four different manufacturers. The stimuli included steady-state noise of three different bandwidths which were embedded at six different frequencies (0.25, 0.5, 1, 2, 3, & 4 kHz). In addition, speech shaped noise and ICRA noise at 0 dB SNR were also included as stimuli. The average overall gain reduction for speech shaped steady-state noise varied from as small as 2.5 dB to 13 dB. The degree of noise reduction also varied across frequencies from one manufacturer to the other. Some provided greater noise reduction at higher frequencies and some provided greatest noise reduction at lower frequencies. The authors concluded that, as more sophisticated NRAs are launched in the market, it is important that the performance of the hearing aids is available to the audiologists.

Summe (2003) analysed the speech spectrum before and after noise reduction. It was concluded that NRAs did not attenuate the environmental sounds such as ocean waves, rain noise, subway noise and jet noise. There was more reduction in noise for some of the types of noise viz., jet noise and fan noise by 4.6 dB and 2.4 dB respectively, with NR algorithm ‘ON’ and only for a few hearing aids. Further, they reportedly attenuated speech-weighted babble, in three of the four hearing aids tested. Only one hearing aid effectively attenuated the environmental sounds in a desired manner. The differences in the hearing aid NRAs might have led to ineffectiveness of hearing aids in reducing different types of noise.

Chong and Jenstad (2011) investigated the effects of DNR algorithm on noise and speech using acoustic measures. Non-sense words were used as speech stimuli. Three types of noise (steady-state speech-weighted noise, speech modulated ICRA noise, & cafeteria noise) were used for the study. The stimuli were presented and recorded from the hearing aid mounted on a Knowles Electronic Manikin for Acoustic Research Manikin (KEMAR) at 3 signal to noise ratios (0, -5, & -10 dB SNR). The spectral analysis was done using FFTs and temporal analysis was done using Envelope Difference Index (EDI). The authors reported that the DNR was effective in reducing pink and cafeteria noise, but ineffective for the ICRA noise. The reduction in noise was greater as the number of channels increased. With increased number of channels, fricatives were enhanced up to 10 dB, particularly in pink noise and also the spectrum of fricatives changed as compared to DNR 'OFF' condition. Though the authors did not measure the output SNR in their study, they construed that NRAs may potentially improve the SNR.

Chung (2012) examined the effect of wide dynamic range compression (WDRC) and modulation based NRAs on wind noise levels at the hearing aid output. The hearing aid output was recorded using KEMAR. The NRA reduced wind noise at the output of the hearing aid. However, the amount of wind noise reduction differed for different microphone modes, frequency regions, and head angles.

Chong (2016) studied the single microphone noise reduction with two hearing aids with NR gradation set to maximum in both the hearing aids. The amount of reduction of noise was studied. The results showed that the amount of noise reduction increased with increase in the input level of noise for hearing aid 1. The amount of reduction of noise varied from 1.1 to 4.8 dB for steady-state pink noise when input noise levels were increased from 55 to 75 dB A. They report that for each 5 dB increase in the input noise level, the amount of noise reduction increased by 1 dB. For hearing aid 2, the amount of noise reduction was increased from 5 to 6 dB for pink noise with an increase in input noise levels from 55 to 65 dB A. The author attributed to the difference in the amount of noise reduction between the two hearing aids to the difference in manufacturer's specifications for NRA between the two hearing aids. Hence, it can be concluded from the reviewed studies that analysing the acoustic features of the hearing aid output and measuring the output SNRs would be beneficial in understanding the functionality of the NRA under study.

2.2.1 Emergence of objective tools for acoustic analysis of speech recorded from the hearing aid

Objective method of acoustic analysis of speech recorded from the hearing aid precludes the participant involvement and also is less time consuming. However, the objective tools that are developed should accurately predict the quality of the recorded data across various conditions. Hence, robustness is the most desirable quality of an objective measure (Kressner, Anderson, & Rozell, 2012). Recently, a few techniques were developed to measure acoustic changes to speech and noise, when presented simultaneously to the hearing aid (Bell, Creeke, & Lutman, 2010; Hagerman & Oloffson, 2004). They are briefly described in the following sections.

Estimating the signal-to-noise ratio (SNR)

The acoustic measures of the hearing aid output have been studied for hearing aid parameters such as compression, noise reduction algorithms or with a combination of both (Eneman et al., 2008; Hickson et al., 1999; Lai et al., 2013; Miller, 2013; Nilsson & Bray, 2004; Peeters, Kuk, Lau, & Keenan, 2009; Rout et al., 2007; Chong, 2016). However, there were many technical difficulties faced in separating the speech from noise. One of the techniques to study acoustical parameters of a hearing aid included a simple measure like estimation of signal-to-noise ratio (Hu & Loizou, 2008). Though the SNR procedure was simple and basic, they have good predictive abilities (Kressner, 2011).

Hagerman's phase-inversion technique. Hagerman's phase-inversion technique involves simultaneous presentation of speech and noise signals to a hearing aid. The speech and noise signals are separated at the output of the hearing aid by taking two measurements. The first measure is taken by presenting the original speech and noise signals in phase and the second measure by inverting the phase of the signals. The output of the hearing aid will be speech and noise signals with an error. The error is assumed to be from the internal noise in the hearing aid, interactions from the speech and noise, and distortion produced from the hearing aid processing.

Hagerman and Olofsson (2004) assume that the hearing aid treats the combined input signals similarly and that output signals can be added to extract the speech and noise levels. This technique is called 'superposition', which means that the output of a system with a number of independent inputs presented simultaneously should be equal to the sum of the outputs if each input were presented alone (Harrington & Cassidy, 1999). Provided the error signals are negligible, the SNR at the output of the hearing aid can be calculated by extracting the root mean square (RMS) levels on each signal. This can be measured across frequency. To obtain a single SNR value, an average SNR across frequency can be calculated.

Several studies have used Hagerman's phase inversion method to quantify the acoustic changes in terms of SNR at the hearing aid output (Olsen, Oloffson, & Hagerman, 2005; Souza, Jenstad, & Boike, 2006; Naylor & Johannesson, 2009; Chong & Jenstad, 2010). Olsen et al. (2005) studied the benefit from compression measured objectively using the Hagerman and Olofsson (2004) technique and correlated to the speech intelligibility benefit measured for compression. The benefit from compression measured objectively was defined as the SNR improvement estimated for compression over linear amplification using the phase inversion technique. Speech intelligibility was measured with sentences for linear and compression processing. Testing was done at four SNRs (0, -5, -10, and -15 dB). The results showed that the performance was better with compression than with linear amplification through all of the tested conditions. Performance with compression was always better than with linear processing at negative SNRs. They concluded that SNR changes measured through phase-inversion method correlated well with speech intelligibility scores.

Souza et al. (2006) studied the changes in compression by measuring the long-term SNR at the output of the hearing aid using the modified version of the Hagerman and Olofsson's (2004) phase inversion method. Hearing aids with single channel and two channel compression were chosen. Connected Speech Test (CST) was used as the input stimuli with speech shaped noise at -2, +2, +6, and +10 dB SNRs. Linear amplification mode in the hearing aid was taken as the control. The results showed that the SNR did not change in the linear amplification mode. In both single- and two-channel compression, the SNR at the output of the aid was reduced by 1 to 4 dB at poor input SNRs. These results are contrary to the results obtained by Olsen et al. (2005).

Naylor and Johannesson (2009) measured the output SNR of a single channel hearing aid and systematically varied the compression parameters and input SNR, using the phase-inversion approach by Hagerman and Olofsson (2004). Their findings indicated that at positive SNR inputs, compression reduced the output SNR to a less favourable level. At negative SNR inputs, compression increased the output SNR to a more favourable level. They concluded that the deviation between input SNR and output SNR depends on the modulation characteristics of the signal and noise and the deviation increases with more strong compression. These findings from by Naylor and Johannesson (2009) study explains that results obtained by Olsen et al. (2005) and Souza et al. (2006). i.e., the output SNR depends on the change in input SNR and on the compression settings in the hearing aids.

Miller (2013) quantified the amount of change in SNR made by hearing aid processing and to predict the changes in speech perception from the output of the hearing aid. Both individuals with normal hearing and with hearing impairment were included in the study. The SNR at the output was quantified using acoustic measures by measuring the output SNR of the hearing aid using the Hagerman and Olofsson (2004) phase inversion technique. Connected Speech Test (CST) was used as the stimuli and output from three different hearing aids were taken. The results indicated that the activation of WDRC and NRA modified the SNR from the input to the output of the hearing aid between -1.75 to 0.25 dB, with a mean change of -0.25. However, the changes in SNR were not correlated to changes in speech perception. The authors attribute the lack of correlation to speech perception to the following reasons: 1) little variability in SNR or SII made by hearing aid processing with WDRC and NR, 2) the CST not being sensitive test to capture the small changes in SNR or SII at the output of the hearing aid, 3) the hearing aid processing may be modifying the long-term SNR, but not the instantaneous SNR when speech was present.

Studies have attempted to quantify the distortions or errors in Hagerman's phase-inversion technique (Naylor & Johannesson, 2009; Zakis & Jenstad, 2011; Hartling, Wu, & Bentler, 2012). They report that it is feasible to use this method to calculate SNR, if care is taken in measuring the output and estimating the errors. Furthermore, the calculation of SNR using this method is hard as the error calculation must be done for every noise and speech stimulus used. Hence, it may be difficult to use this method to calculate the output SNR using many types of noise, different input SNRs and different NR gradations. Varying all the above parameters simultaneously may make the process of output SNR calculation more difficult.

In addition to Hagerman's phase-inversion technique for estimating SNR, there are many more techniques for estimating the SNR (Kim & Stern, 2008). One of the approaches is to separate spectra of noise and speech and another approach is based on measurement of the energy. The widely used Signal-To-Noise-Ratio algorithm developed by National Institute of Standards and Technology (NIST STNR) is based on measurement of the energy. Some of the other approaches are based on statistics that are obtained from waveform samples rather than from energy or spectral coefficients (Kim & Stern, 2008).

In segmental SNR measures, the SNR is first calculated for signal portions of 10 to 30 milliseconds and then averaged over the time segments. However, if there are intervals of silence in the speech sample, any noise in the silent segments will give rise to large negative SNRs for that segment, in turn biasing the overall SNR of the signal.

Frequency weighted SNR (fwsegSNR) exists in different forms. One of the methods includes the signal distortions between the unprocessed and processed signals. This method is proven to be robust estimate even though it assumes a separate estimate of the noise (Kim & Stern, 2008).

Waveform Amplitude Distribution Analysis - Signal-to-Noise Ratio (WADA-SNR). WADA-SNR was developed by Kim and Stern (2008). Kim and Stern (2008) evaluated the performance of the WADA-SNR on signals corrupted by white noise, background music, and interfering speech. The WADA-SNR is based on the amplitude distribution of a waveform, usually can be characterized by a gamma distribution (Kim & Stern, 2008). The assumptions of WADA-SNR as enumerated by Kim and Stern (2008) are: (1) the speech and background noise are independent, (2) clean speech follows a gamma distribution with a fixed shaping parameter, and (3) the background noise has a Gaussian distribution.

Kim and Stern (2008) reported that the WADA-SNR algorithm showed less bias and less variability with respect to the type of noise compared to the other standard SNR estimation methods. As SNR methods have good predictive abilities (Kressner, 2011), this method was used in the present study to analyse the output from the hearing aid. The measurement procedure was incorporated in a MATLAB code version 0.3 developed by Ellis (2011). This code automatically calculates the SNR in dB by comparing the sentences recorded in the presence of noise, while the NRA was enabled and disabled.

Though many techniques for estimating the SNR have been discussed earlier, most of the studies in the literature have used Hagerman’s phase-inversion technique. To our knowledge, there are no studies in the literature comparing two or many SNR estimating techniques, to prove Hagerman's phase-inversion method is better over the other SNR measurement techniques. However, Kim and Stern (2008) have reported that WADA-SNR showed less bias and less variability with respect to the type of noise compared to the other standard SNR estimation methods like frequency weighted SNR (fwsegSNR) and NIST-STNR. Further, the input to the hearing aid is not altered in the WADA-SNR method. But in case of Hagerman's phase-inversion method, the input speech and noise stimulus are manipulated to obtain the SNR. Hence, WADA-SNR was used in the present study to estimate the SNR in the hearing aid output.

Estimating temporal variations in the hearing aid output

Envelope of the speech is important in speech perception. The modulation depth of temporal envelopes is reduced with background noise. This introduces unwanted modulations and masks the relevant speech modulations (Houtgast & Steeneken, 1985). The alteration of speech envelope with the background noise is one of the major factors for reduced speech perception (Drullman, Festen, & Plomp, 1994a; Drullman, Festen, & Plomp, 1994b; Drullman, 1995a; Drullman, 1995b). Hence, it is important to study the envelope changes that the hearing aid can bring about in the process of reducing noise in the presence of speech with NR algorithm.

Envelope Difference Index (EDI). Envelope Difference Index (EDI) is a non-standardized MATLAB code based on the method given by Fortune, Woodruff, and Preves (1994). The EDI, being a temporal measure, was used to evaluate how close the two signals are in their envelopes. The EDI values range from 0 to 1. The value of 0 indicates perfectly similar envelopes and the value of '1' indicates completely dissimilar envelopes. Several studies have explored use of the Envelope Difference

Index (Jenstad & Souza, 2005; Jenstad & Souza, 2007; Walaszek, 2008; Souza et al., 2012; Geetha & Manjula, 2014).

Jenstad and Souza (2005) revealed that phoneme recognition was improved when the EDIs were larger. They attributed this improved phoneme recognition from the fast acting compression. Again in 2007, Jenstad and Souza reported that a larger EDI tended to decrease sentence recognition. Authors attributed the discrepancy in the results of their two studies to: 1. Audibility was controlled in the second study, 2. the sentence material may have contained more prosodic cues and thus the envelope could be more important in recognition of phonemes. It can be concluded that larger EDI tends to decrease sentence recognition.

Souza et al. (2012) studied the EDI values for 16 vowel-consonant-vowel non-sense syllables (aCa), presented in quiet at input levels of 65 dB SPL (representing conversational speech) and 80 dB SPL (representing loud speech). The EDI values ranged from 0.05 to 0.27 (mean 0.12) for the 65 dB SPL input level, and from 0.06 to 0.36 (mean 0.14) for the 80 dB SPL input level.

Walaszek (2008) tested fast-acting and slow-acting WDRC. Danish sentences were used in presence of background single female talker and in ICRA noise. The output signals were recorded in a Bruel and Kjaer ear simulator. The mean EDI values varied from 0.12 to 0.22 depending on the speed of the compression and type of background noise. The authors observed that the values are generally higher for the background of the one-talker speech than in the background of two-talker modulated speech-shaped noise.

Chung (2004) hypothesized that activating NR in the WDRC hearing aid might result in a better speech transmission index and they attributed this enhancement in the temporal envelope to the NR algorithm. Hence, EDI may be one of the tools to understand the temporal variations of a signal processed through the hearing aid. Further research is necessary to understand the temporal changes brought about by manipulating the NR algorithm alone.

Estimating the quality of the hearing aid output.

The quality from the hearing aid has always been assessed through perceptual measures. However, assessing the quality of hearing aid every time a new technology or algorithm is introduced in the industry is time consuming. In addition factors such as methodological variations, subjective variations, tester variations are introduced. This would create difficulties in comparing the results across the studies. Hence, estimating quality of the hearing aid output using an objective method would reduce the interference of these factors on the outcomes of the study.

Hearing Aid Speech Quality Index (HASQI). For judging the quality of hearing aid output, Kates and Arehart (2010) developed Hearing Aid Speech Quality Index (HASQI). The HASQI is an objective measure of quality, designed and validated to predict subjective quality for distorted speech. The HASQI has great potential since it was developed specifically to capture quality when speech is subjected to a wide variety of distortions commonly found in hearing aids (Kates & Arehart, 2010). They reported very high correlation between HASQI and subjective scores for individuals with normal hearing ($r = 0.942$) and for those with hearing impairment ($r = 0.978$).

Huber, Parsa, and Scollie (2014) evaluated the performance of objective speech and audio quality measures for the prediction of the perceived quality of frequency compressed speech in hearing aids. Acoustical quality measures that are available in the market were used to study the hearing aid processed speech signals. The results of the quality measures were compared with the subjective ratings in children and adults with normal hearing and hearing impairment that were obtained from the author's earlier study. Of the many acoustical quality measures, HASQI showed good rank correlations and moderate linear correlations with data from hearing impairment, but only low correlations with data from normal hearing. Authors report that the results of their study are in contrast to the results reported Kates and Arehart, (2010). They attribute the difference in results to the quality overestimation of the low pass condition of their study.

Sang et al. (2015) studied the benefits of single channel NRAs on speech quality in individuals with hearing impairment and normal hearing. They compared the speech quality between the Sparse Coding Shrinkage (SCS) algorithm with cepstral smoothing wiener filter algorithm (CS-WF). Subjective quality ratings were obtained using the Interpolated Paired Comparison Rating (IPCR) to quantitatively link the benefit of speech intelligibility and speech quality. The objective measures included frequency-weighted segmental signal-to-noise ratio (fwsegSNR), perceptual evaluation of speech quality mean opinion scores (PESQ MOS), and hearing aid speech quality index (HASQI). The results revealed that both algorithms benefited all listeners in terms of speech quality. However, individuals with hearing impairment got more benefits from the NRAs in speech quality than individuals with normal hearing. The results from the objective measures fwsegSNR and PESQ (MOS) highly correlated with subjective measures, while HASQI did not correlate with subjective measures. Thus, the algorithms that do not show better outcomes with normal hearing individuals, might still benefit individuals with hearing impairment. Hence there is a need to study the effects of NRA separately in participants with normal hearing and those with hearing impairment.

Since HASQI is based entirely on the signal envelope, distortions in the fine temporal structure are ignored (Kressner, 2011). This may be especially important for individuals with normal hearing, as individuals with normal hearing make better use of temporal fine structure than individuals with hearing impairment.

Perceptual Evaluation of Speech Quality (PESQ). Perceptual Evaluation of Speech Quality (PESQ; ITU-T Recommendation P.862) is the most popularly used objective quality assessment measure incorporating an auditory model (Huber et al., 2014). The PESQ is an objective method for predicting the subjective quality of speech. This was developed by the International Telephone Union (ITU) for assessing the sound quality in telephone systems. The PESQ predicts how close the target signal is in terms of its quality, in comparison to the original signal. The PESQ provides a value between 0 and 4.5. If the value is 4.5, then the target speech is same as unprocessed speech in terms of quality. This measurement procedure was incorporated in a MATLAB code developed by Ellis (2011), version 0.3. The code estimates the PESQ with the given input. The PESQ mean opinion score (PESQ MOS) is algorithmically estimated by predicting mean opinion score (MOS) through objective quality models which are developed and trained using human MOS rating.

Parsa, Singh, Chen, and Umapathy (2004) investigated the performance of six NRAs using objective measures and subjective ratings of speech quality. Subjective ratings obtained from individuals with normal hearing and those with hearing impairment showed improvements in speech quality at positive SNRs for algorithms based on short-time spectral amplitude estimation. The objective measure, PESQ (MOS), exhibited a good degree of correlation with quality ratings from the participants. From the results of the study, authors concluded that the PESQ (MOS) measure can potentially be of use in the development and optimization of NRAs.

Rohdenburg, Hohmann, and Kollmeier (2005) have also opined that PESQ (MOS) is best suited objective measure for assessing the perceived speech signal distortion or overall quality in a NRA.

A few studies have tested the PESQ (MOS) measure in predicting speech intelligibility (Beerends, van Wijngaarden, & van Buuren, 2005; Ma, Hu, & Loizou, 2009). A high correlation ($r = 0.9$; $r = 0.77$ to 0.79) was reported for predicting intelligibility of consonants and sentences in noise.

Kitawaki and Yamada (2007) explored the relevance of using the PESQ (MOS) for evaluating the output from the hearing aid using the four NRAs. The subjective and objective quality assessment were done. The results showed that the PESQ (MOS) correlates relatively well with the subjective MOS. The authors proposed that PESQ (MOS) can be used as an objective test for estimating the word intelligibility in the NRAs.

Lai et al. (2013) evaluated the correlation between scores for PESQ (MOS) and variations of dynamic range (VDR) in assessing speech quality for the three compression ratios (CR). The results indicated that PESQ (MOS) scores were 3.56, 2.25, and 1.98, and VDR scores were 2.5, 2.9, and 3.6 dB for CRs of 1.0, 2.0, and 4.0, respectively. The VDR and PESQ (MOS) methods provided similar assessments of speech quality and the authors concluded that high PESQ (MOS) and low VDR scores, indicate good speech quality.

Huber et al. (2014) evaluated the performance of objective speech and audio quality measures for the prediction of the perceived quality of frequency compressed speech in hearing aids. Their results on the PESQ (MOS) measure showed poor correlations with subjective ratings from individuals with normal hearing, but moderate and even high correlations with ratings from adults and children with hearing impairment, respectively. The authors attribute the poor scores in individuals with normal hearing to the overestimation of the low pass filtered items that were used as stimuli. Without the low pass filtering, the correlation increased even for individuals with normal hearing.

Hu and Loizou (2008) compared seven objective tools [segmental SNR (segSNR), weighted-slope spectral distance (WSS), Perceptual evaluation of Speech Quality (PESQ MOS), log-likelihood ratio (LLR), Itakura-Saito distance measure (IS), cepstrum distance measures (CEP), and frequency-weighted segmental SNR (fwsegSNR)] available for evaluating the performance of speech enhancement algorithms. Based on the correlation analysis they concluded that of the seven basic objective measures tested, the PESQ (MOS) measure yielded the highest correlation with overall quality and signal distortion. The segSNR measure yielded a very poor correlation coefficient with overall quality. Hence, they concluded that segSNR measure is not suitable for evaluating the performance of speech enhancement algorithms.

Kressner (2011) unveiled that HASQI (r = 0.85) falls short of only PESQ (MOS) (r = 0.89) and Log Likelihood Ratio (r = 0.86) when Pearson's correlation was used as a statistical measure to study the correlation between subjective and objective methods of speech perception in studying the NR algorithms. However, Kressner (2011) concluded that Spearman's rank correlation coefficient would be ideal, since ranking the perceptual quality results would provide very valuable information when evaluating NRAs. And the results using Spearman rank correlation coefficient found that HASQI actually performed worse than all the other objective methods used to study the NR algorithms.

Similarly Sang et al. (2015) also revealed that the objective measures fwsegSNR and PESQ (MOS) highly correlated with subjective measures, while HASQI did not correlate with subjective measures. Hence, it can be seen that PESQ (MOS) can be used as an objective test for studying the NRAs. Hence, in the present study, WADA-SNR, PESQ (MOS), and EDI were selected as objective tools in order to evaluate the SNR, quality, and temporal variations brought about by NR processing in the hearing aid.

2.3 Perceptual analysis of output from the hearing aid

In order to understand the perceptual effects of noise reduction in a hearing aid, subjective measures are used. The participants are asked to rate the sound quality within a specific condition, or to choose the most comfortable one from different conditions (Brons, 2013). Also, one of the traditional and gold standard methods to study the benefit from the hearing aid was to evaluate the speech perception. Alcántara et al. (2003) evaluated the effectiveness of noise reduction system by studying the Speech Recognition Threshold (SRT) and sound quality measures in four types of background noise. Their results revealed that both SRTs and sound quality measures were very similar with and without noise reduction. Also, Walden et al. (2000) did not find significant improvement in ease of listening or listening comfort when DNR was activated. Boymans and Dreschler (2000) reported a slight advantage on outcome measures with DNR, only for selected items of the aversiveness subscale of the APHAB questionnaire.

Ricketts and Hornsby (2005) studied the aided speech recognition and sound quality measures in hearing aid users with NR ON and OFF. The results revealed that speech recognition in noise with NR ON and OFF did not change. However, the sound quality measurements done through paired-comparisons showed a strong preference for NR ON condition. Hence, the authors conclude that though NR does not improve speech recognition, it is capable of providing improved sound quality. This study showed encouraging results on DNR. Further, the acceptability of the hearing aid would be better with improved quality of hearing aid output.

Powers, Branda, Hernandez, and Pool (2006) evaluated the real world benefit of NRA in experienced hearing aid users. The hearing aids of the users were configured for two listening programs; NR ON and set to maximum, the other with NR OFF. On ten days of field trial, the results of the rating across the ten days revealed that 73.3% of the subjects favoured the DNR ON setting and only 19% favoured DNR OFF.

Palmer et al. (2006) studied the perception of noise annoyance and aversiveness for traffic noise and dining table noise with NR enabled and compared the findings with individuals having normal hearing. They reported that the perception of annoyance and aversiveness increased with amplification. This was similar to that observed for individuals with normal hearing. Less annoyance was observed for traffic noise than for the dinner table noise. The authors concluded that the hearing aid users should understand that the noise that are perceived as annoying through the hearing aid are also perceived as annoying for individuals with normal hearing.

Similarly, Mueller et al. (2006) evaluated the speech intelligibility and acceptable noise level (ANL) using the HINT with DNR ON and DNR OFF. They found a significant improvement in the ANL and no improvement in the HINT for the DNR ON condition. Hence, the authors concluded that DNR might help in ease of listening for speech-in-noise conditions.

Zakis and Wise (2007) studied the acoustical and perceptual effects of single channel and multichannel NRAs. It was noted that sentence reception threshold was statistically significant for the multichannel algorithm. However, both the algorithms reduced noise. The single channel algorithm reduced more noise in static conditions and multichannel algorithms reduced noise that is fluctuating (increasing and decreasing in noise levels) in nature.

Sarampalis et al. (2009) studied the cognitive effort required for speech reception though dual-task experiment. The dual-task involved one task to repeat the sentences or words in noise at various signal-to-noise ratios (SNR) and secondary task was to either recall words or to respond to a visual reaction-time task. It was found that at low SNR, there was no improvement in the speech reception with NR. However, there was good performance in the word recall task and faster responses in visual reaction-times. The authors conclude that NR reduces the listening effort and frees the cognitive resources.

Chung, Tufts, and Nelson (2009) tested the effectiveness of modulation based NR in hearing protection devices with four types of military noises. Overall noise levels, speech intelligibility, and listening preferences were evaluated by recording the output from the hearing aid using Knowles Electronic Manikin for Acoustic Research (KEMAR) at three SNRs (0, -5, & -10) with NR ON and NR OFF. The results revealed that the overall level of noise was reduced by 4 to 7 dB. The perceptual measures showed higher speech intelligibility scores (only at -10 dB SNR with NR ON) and enhanced sound quality in individuals with normal hearing.

A multicentre evaluation of NR algorithms (Luts et al., 2010) using speech reception threshold (SRT) with multi-talker babble, listening effort scaling, and preference rating were evaluated. The results showed that there was no improvement in SRT scores in most of the NR algorithms used in the study, except for multi-channel Wiener filtering. Among the algorithms, some were preferred ON than OFF. In addition, for those algorithms where the SRT scores were poorer, the listening effort was less. This implies that the NR is able to bring about reduction in listening effort and this was evident even at 0 dB SNR.

In contrast to the above studies, de Oliveira et al. (2010) reported that recognition of sentences in noise was significantly improved than when the NR was ON as against NR OFF in individuals with hearing impairment.

Healy, Yoho, Wang, and Wang (2013) evaluated the speech intelligibility using monaural speech-segregation algorithm. Sentences were mixed with speech shaped noise (at -2, -5, or -8 dB SNR) and with speech babble (0, -2, or -5 dB SNR). The results showed that the speech intelligibility scores were increased with processed speech (NR ON) than unprocessed (NR OFF) for both individuals with normal hearing and hearing impairment. However, the researchers report that the improvement in speech intelligibility scores were better for individuals with hearing impairment with modulated noise.

Brons et al. (2013) studied perceptual effects (intelligibility, listening effort, & preference) of noise reduction. They compared the perceptual scores to determine if NR algorithms differ perceptually and assessed the factors that underlie the overall preference. They recorded output from the hearing aid with and without NR activated in the presence of speech with babble noise and used these as the stimuli for performing the speech intelligibility tests, listening effort ratings, and paired-comparison ratings. Ten individuals with normal hearing served as the subjects. It was seen that hearing aid noise reduction was able to reduce the annoyance for babble noise at -4 dB SNR and at +4 dB SNR. Also, results showed that individuals with normal hearing preferred noise reduction ON at +4 dB SNR. In individuals with normal hearing, the overall preference correlated with noise annoyance and speech naturalness, but did not correlate with intelligibility or listening effort. The authors inferred that to obtain a more complete impression of the effect of noise reduction, one should investigate a much broader range of speech, noise types, and SNRs (Houben, Dijkstra, & Dreschler, 2011).

Brons et al. (2014) replicated the above study in individuals with hearing impairment. The results were similar as seen for individuals with normal hearing. The NR algorithms did not improve speech intelligibility, but reduced the annoyance due to noise. The noise reduction that scored best in noise annoyance and preference, had the worst intelligibility scores.

Again, Brons et al. (2015) studied the acoustical and perceptual effects of combined and individual effect of noise reduction and compression in hearing aids. Acoustical analyses revealed that for speech babble at +4 dB input SNR, there was a change in gain for noise reduction, compression and for combined processing. The combined processing did not influence speech intelligibility but reduced annoyance of noise. However, the combined processing was not preferred by most of the participants (individuals with hearing impairment) and they attribute it to reduction in the output SNR with activation of compression even for positive input signals. The authors concluded that the influence of the compression must be considered while evaluating the NRAs.

Miller et al. (2017) evaluated the effects of noise reduction and compression using acoustical and perceptual measures. The amount of SNR change and the corresponding change in the speech perception was studied in individuals with normal hearing and hearing impairment. The change in SNR with NR was between -1.75 and 0.25 dB, with a mean change of -0.25 dB. However, the change in SNR did not correlate to changes in speech perception. The authors attribute the lack of correlation with speech perception to the following reasons: 1) little variability in SNR made by hearing aid processing with compression and NR, 2) the speech perception test used not being sensitive test to capture the small changes in SNR at the output of the hearing aid, 3) the hearing aid processing may be modifying the long-term SNR, but not the instantaneous SNR when speech was present.

Kortlang et al. (2017) reported that single channel NR significantly increased the output SNR for speech babble and speech shaped noise. In addition, the NRA also decreased noise annoyance, and increased listening comfort and overall quality in steady-state noise at +6 dB SNR and babble noise at both 0 and +6 dB SNR in individuals with normal hearing. Individuals with hearing impairment did not show much improvement, especially at 0 dB SNR.

Thus, from the literature it was seen that there are equivocal reports on speech intelligibility with NR ON. Some of the studies report improvements with NR ON and some report only ease of listening and increase in listening comfort with NR ON. Hence, an attempt was made to evaluate the speech perception with modulation based NR algorithm.

The NR algorithms are incorporated in the hearing aids with different gradations / strength. By choosing different gradations/strength, one can adjust the amount of gain reduction required, when NR is ON. Bentler and Chiou (2006) showed the effect of minimum, medium, and maximum settings of DNR using a steady-state random noise stimulus. It was seen that as the setting increased to maximum, there was a predictable change in measured gain across frequencies.

Houben et al. (2011) performed paired comparisons on different settings for the strength of NR in an algorithm designed for hearing aids. They found significant inter-individual differences in preferences for individuals with normal hearing. They hypothesized that as stronger noise reduction introduces more speech distortion, listeners differ in their preference between noise annoyance and speech distortion.

Similarly, in a number of recent studies, Neher (2014); Neher, Grimm, Hohmann, and Kollmeier, (2014); and Neher et al. (2016), have investigated the influence of individual factors on speech recognition with different NR strength. Their results revealed that there was considerable inter-individual variability in preferring the NR strength. The results also revealed that preferred NR strength varied with input signal-to-noise ratio (SNR), i.e., participants generally favoured stronger NR processing at +4 dB SNR than at 0 and -4 dB SNR. In addition, participants with higher pure-tone thresholds (PTAs) and poorer cognitive performance, preferred stronger NR than participants with lower PTAs and better cognitive performance. Hence, the authors construed that turning ON the NR processing and its strength should be personalized during programming of the hearing aid.

In continuation with the previous series of studies by Neher et al. (2016), Neher and Wagener (2016) once again found that at +4 dB SNR, participants preferred stronger NR setting than at 0 dB SNR. The authors hypothesize this phenomenon to the fact that at higher input SNRs the adverse effects of NR processing (i.e., speech distortions) decrease while its positive effects (i.e., noise attenuation) increase. Neher and Wagener (2016) confirmed that the above hypothesis by measuring the outputs from the HA. They reported that the speech-weighted SNR improvements due to moderate and strong NR setting ranged between 1.7 and 2.8 dB for an input SNR of 0 dB, and to 2.3 and 3.8 dB for an input SNR of 4 dB. Thus, it can be seen that higher the NR strength setting, higher is the output SNR, especially at the higher input SNRs. And higher NR strength also resulted in speech distortion at the output of the hearing aid, at lower input SNRs.

To conclude, the results are not uniform across the studies on the perceptual effects of hearing aid noise reduction. Some studies showed that listeners preferred noise reduction over no noise reduction (Boymans & Dreschler, 2000; Ricketts & Hornsby, 2005), whereas others found no difference in listening comfort or sound quality due to noise reduction (Alcántara et al., 2003; Walden et al., 2000). In addition, it is seen that individuals usually had increased tolerance for noise, decreased listening effort and stronger preference for noise reduction ON than when the noise reduction is OFF (Mueller et al., 2006; Palmer et al., 2006; Sarampalis et al., 2009; Zakis et al., 2009).

Hence, studying the acoustic changes at the hearing aid output along with the speech perception measurements could provide clues as to what changes are perceptible to listeners. This may help to resolve the conflicting reports between speech perception and acoustic measure with NR algorithms (Miller, 2013).

CHAPTER 3

METHODS

The aim of the study was to evaluate the effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures. An experimental, factorial design was employed in the study. The following methods were adopted to study the objectives.

3.1 Participants

The data were collected from participants in the age range from 25 to 55 years. They were classified into group with normal hearing (NH) and group with hearing impairment (HI). The data for NH group were collected from 32 ears with normal hearing, from 32 participants (N=32) with a mean age of 31.6 years (age range: 25 to 55 years). The data for HI group were collected from 30 ears with mild to moderate sensorineural hearing loss, from 30 participants (N=30) with a mean age of 33.4 years (age range: 25 to 55 years), with either flat or gradual sloping audiogram configuration.

3.1.1 Selection criteria:

The selection criteria for NH group and HI group were as follows:

Selection criteria for NH group

The following inclusion criteria were employed while selecting the participants in NH group:

- Normal hearing sensitivity, with pure tone thresholds ≤15 dB HL at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz for air-conduction; and ≤15 dB HL at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz for bone-conduction in both ears.

- Speech identification scores (SIS) at 40 dB SL (ref: speech recognition threshold, SRT) being > 90 % in both ears.
- Normal middle ear function, assessed by the middle ear analyzer with Type A tympanogram (middle ear peak pressure ranging from +50 to -100 daPa, & the admittance ranging from 0.5 to 1.75 ml), with the probe tone frequency of 226 Hz. The acoustic reflex being present bilaterally (ipsi & contra) at 500 Hz, 1000 Hz, and 2000 Hz (Wiley, Oviatt & Block, 1987).
- Native speakers of Kannada language with normal speech and language skills, as observed informally by the examiner.
- Minimum of higher secondary education, i.e., 10^{th} standard or equivalent.

The participants having any complaint or history of psychological problem, otological problem and / or neurological problems were excluded from the study.

Selection criteria for HI group

The following inclusion criteria were employed while selecting the participants in the HI group:

- Pure tone average (PTA) between 26 and 55 dB HL with sensorineural hearing loss, elevated air-conduction and bone-conduction thresholds; and bone-conduction thresholds within 10 dB of the air-conduction thresholds. Figure 3.1 illustrates the mean air-conduction thresholds of the participants. The demographic details of HI group are provided in Table 3.1.
- Ears with Speech Identification Scores (SIS) of ≥ 80% at 40 dB SL (ref: SRT).

- Either right or left ear (ear with better SIS) was selected in case of symmetrical hearing loss, the better ear was selected in case of asymmetrical hearing loss.
- Ears having normal middle ear function assessed by the middle ear analyzer with Type A tympanogram (middle ear peak pressure ranging from +50 to -100 daPa, & the admittance ranging from 0.5 to 1.75 ml), with the probe tone frequency of 226 Hz. The acoustic reflex being present or absent (ipsi & contra) at 500 Hz, 1000 Hz, and 2000 Hz. If reflex was present, it was ensured that the reflex was within the acceptable sensation levels with respect to degree of hearing loss.
- Post-lingually acquired hearing loss with normal speech and language as observed informally by the examiner; naïve hearing aid users.
- Native speakers of Kannada language with a minimum education of 10th standard or equivalent.

Participants having any complaint or history of psychological problem, otological problem other than sensorineural hearing loss (like ear discharge, ear pain & other middle ear related disorders), unilateral hearing loss, and / or neurological problems were excluded.

Written informed consent was obtained from all the participants in both the groups. It was ensured that the ethical guidelines for bio behavioral research involving human subjects (AIISH ethical guidelines, 2009) were adhered to. Approval from AIISH ethical committee was obtained prior to the study.

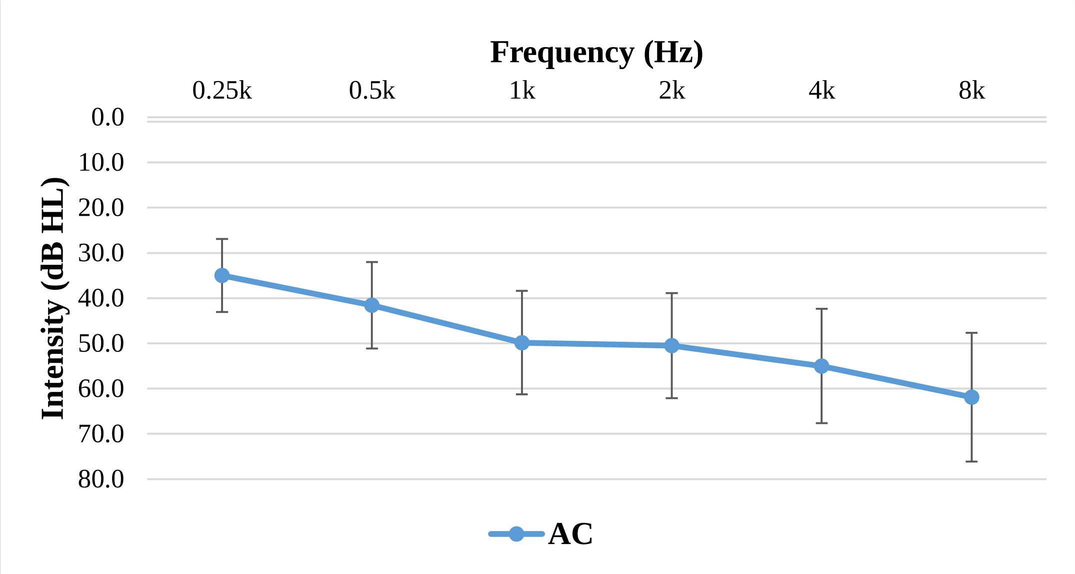


Figure 3.1. Mean and SD of air-conduction (AC) thresholds in the test ears, in HI group.

Table 3.1.

Demographic details of HI group.

Sl. No.	Age (in years)	Gender	PTA (dB HL)	SIS (in percent)	Ear
1.	42	M	41.25	92	R
2.	32	F	45	88	L
3.	48	F	52.5	84	L
4.	30	F	48.75	92	L
5.	26	M	48.75	100	R
6.	28	M	34.75	100	L
7.	26	M	46.25	96	R
8.	32	M	32.5	92	R
9.	34	F	55	80	R
10.	30	F	46	100	R
11.	27	F	51.25	92	R
12.	25	M	36.5	92	L
13.	34	M	42.5	92	R
14.	28	M	45	88	L
15.	33	F	55	84	R

16.	27	F	42.5	96	R
17.	26	M	38	96	R
18.	25	M	42.5	92	L
19.	28	M	53.75	88	R
20.	26	M	55	88	R
21.	35	M	53.75	84	L
22.	34	M	55	92	L
23.	50	M	48.7	100	L
24.	27	F	36.25	100	L
25.	37	F	31.25	100	R
26.	46	M	37.5	100	L
27.	50	M	47.5	96	R
28.	43	M	42.5	96	R
29.	28	M	50	96	R
30.	45	F	42.5	100	L

Note: M: Male, F: Female, R: Right, L: Left,

3.2 Instrumentation

The following instruments were used to record the speech output and collect the data.

- A calibrated two-channel clinical audiometer (Madsen Astera[2]), with TDH39 earphones with MX-41/AR supra-aural ear cushion, was used to estimate the air-conduction thresholds, Speech Recognition Thresholds (SRT) and Speech Identification Scores (SIS). Radio Ear B-71 bone vibrator was used to estimate the bone-conduction thresholds. Martin (model C-115) free-field loud speaker was used for assessing perceptual measures in HI group.
- A calibrated Grason-Stadler TympStar (version 2) middle ear analyzer was used to ensure normal functioning status of the middle ear.

- A personal computer installed with Adobe audition software (version 3.0) was used to edit and play the output recorded from the hearing aid, with NRA OFF and NRA ON [noise reduction at minimum gradation (NR min), noise reduction at medium gradation (NR med), noise reduction at maximum gradation (NR max)] and also to edit the unamplified recorded sentences.
- Two commercially available digital Receiver-In-Canal (RIC) hearing aids were selected. Hearing aid 1 (HA 1) had sixteen channels and Hearing aid 2 (HA 2) had twelve channels. These two hearing aids were chosen as they provided reliable results when tested under various conditions (with three SNRs & five types of noise). The HA 1 had NR feature which utilized a modulation based noise detection and multi-channel noise reduction facility. Whereas, the HA 2 had NR feature which was modulation based but with single channel noise reduction facility. Both the hearing aids had NR with multiple gradations (minimum, medium, & maximum). However, the amount of noise reduction in dB across the NR gradation varied between the hearing aids. HA 1 had a maximum NR of 15 dB (at maximum gradation) and HA 2 had a maximum reduction of 8 dB (at maximum gradation), as claimed by the hearing aid manufacturer in the programming software. Hearing aids selected had a fitting range from mild to severe degree of hearing loss with maximum gain of 70 dB for both the hearing aids. The frequency range of both the hearing aids ranged between 100 Hz to 7100 Hz. The total harmonic distortion was 2 dB, 2 dB and 1 dB for frequencies 500 Hz, 800 Hz and 1600 Hz respectively for both the hearing aids. The equivalent input noise was 18 dB for both the hearing aids. The above mentioned electroacoustic characters were measured from a 2cc

coupler. The fitting range of both the hearing aids could accommodate both flat and sloping sensorineural hearing loss.

- The hearing aid specific software installed in personal computer, NOAH Link and programming cables, were used to program the hearing aids.
- Behringer B-2 Pro-Large Diaphragm Multi-Pattern Studio Condenser Microphone connected to personal computer was used for recording the single sentence for acoustic analysis.
- Brüel & Kjær (B & K) Type 2270 with sound level meter software, enhanced logging software, and sound recording option connected with pre-polarized ½ inch free-field microphone (Type 4189) was used to record cafeteria, fan and traffic noise.
- The G.R.A.S. 45BB Knowles Electronics Manikin for Acoustic Research (KEMAR) with the ear simulator RA0045 and ½ inch microphone (Type 40AG) located in the KEMAR in turn connected to hand-held analyzer B & K Type 2270. This was used for recording the output from the hearing aid, and to monitor, record and store the hearing aid output. Further, the level of the input stimulus was monitored with B & K 2270 hand-held analyzer during the recording process.
- A personal computer installed with PRAAT software (version 5419), was used for evaluating the acoustic measure (visual rating task by speech language pathologist on noisiness & formant representation of the HA output).
- A personal computer installed with Adobe Audition (version 3.0) with Sennheiser HDA 200 headphone was used for perceptual task for NH group.
- A personal computer with MATLAB software (version 2009-b) was used to estimate the Waveform Amplitude Distribution Analysis - Signal to Noise Ratio

(WADA-SNR), Envelope Difference Index (EDI), Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS).

- A personal computer installed with Cubase software connected to Lynx Sound card (Lynx AES 16 card, two Aurora 16 A to D convertor) was used to present the input stimulus to the hearing aid and the stimulus was presented through Genelec (Model 8020B Bi - Amplified) loudspeaker with built in amplifier.

3.1.1 Set-up for recording the output from the hearing aid

The G.R.A.S. 45BB KEMAR with the ear simulator RA0045 was placed at the center of the test room on a chair. The programmed RIC hearing aid was placed on the pinna of the KEMAR and the receiver was placed in the ear canal with an appropriately sized double dome ear tip. The stimulus was played through a personal computer routed via Lynx Sound card (Lynx AES 16 card, two Aurora 16 A to D convertor) and presented through Genelec (Model 8020B Bi - Amplified) loudspeaker with built in amplifier. The loudspeaker was at a distance of one meter and 0 degree Azimuth from the KEMAR. The speech and noise signals were always presented together from the loudspeaker. Figure 3.2 shows the instrumental set-up.

The output from the hearing aid was picked up using ½ inch microphone (Type 40AG) located in the KEMAR, monitored, recorded, and stored using the hand-held analyzer (Brüel & Kjær Type 2270). The level of the input stimulus was also monitored through Brüel & Kjær 2270 hand-held analyzer during the recording process.

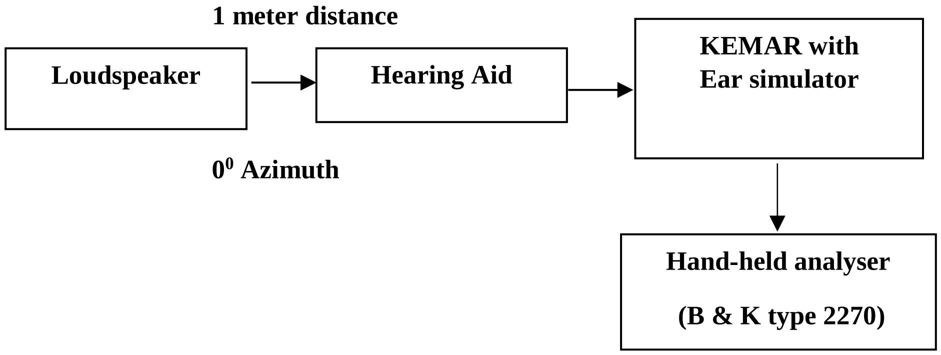


Figure 3.2. Block diagram of the instrumental set-up for recording the hearing aid output.

3.3 Stimuli

The Speech Identification Score (SIS) was obtained using the Phonemically Balanced (PB) Kannada word test developed by Yathiraj and Vijayalakshmi (2005). Kannada sentence lists from the Kannada sentence identification test (Geetha, Kumar, & Manjula, 2014) were used to study the effect of noise reduction algorithms (NRA). Sentences were chosen as test material as it is used in real-world for communication (Dobie & Van Hemel, 2004).

Five different types of noise, that occur commonly in the environment i.e., cafeteria noise, fan noise, speech babble, traffic noise, and white noise were selected for the study. Eight-talker babble developed by Anitha and Manjula (2003) was used as speech babble. White noise of sixty seconds was generated using the Adobe Audition software (version 3.0). Other three noises were audio recorded using the Hand-held Analyser, in the respective naturalistic situations.

3.3.1 Recording of test stimulus

The procedure that was followed to record the different types of noise and speech is given below.

Recording of sentences

An adult male speaker, whose mother tongue was Kannada, with normal speech and language characteristics, was chosen to utter the Kannada sentence from the Kannada sentence identification test (Geetha et al., 2014). The original sentence identification test has a recorded version from a female speaker. Recording from a male speaker was essential for studying the acoustic measures as most of acoustic analysis and its prototypes are based on male voice. A single sentence ‘t̪ammanɪgɛ gaːɭɪpaʈa haːrɪsalu ɪʂʈa’ was chosen randomly among the many sentences which represented low-, mid- and high- frequency components from the sentence list developed by Geetha et al. (2014). The uttered sentence was recorded.

The sentence was recorded using a personal computer with Adobe Audition software (version 3.0), via the Behringer B-2 Pro - Multi - Pattern Studio Condenser Microphone (with omni-directional mode) placed at a distance of 10 cm from the mouth of the speaker (Winholtz & Titze, 1997). The 16-bit processor at 44,100 Hz sampling frequency was used for recording. The speaker was made to repeat the sentence five times. A goodness test was performed on ten individuals with normal hearing by asking them to validate the recorded sentence in terms of overall quality of recording (using a 5-point rating scale, with ‘1’ being very poor & ‘5’ being excellent) and for appropriate pronunciation of the words in the sentence. The recordings with a rating of ‘5’ for quality and with appropriate pronunciations were chosen for the study. The recording by the male speaker was considered only for acoustic analysis and quality judgement. The perceptual measurement (SIS & SNR-50), was carried out using the recorded version of the sentence test (Geetha et al., 2014, recorded by adult female speaker).

Recording of noise

Cafeteria noise, fan noise and traffic noise, were recorded using the hand-held analyzer, Brüel & Kjær (B & K) Type 2270 with sound level meter software, enhanced logging software, and sound recording option. The cafeteria noise was audio recorded, in a busy café during the moderate crowd hours, using the hand-held analyzer, B & K Type 2270. The pre-polarized ½ inch free-field microphone (Type 4189) of the hand held analyser was kept on the centre of the table. A thirty minute sample was recorded and stored in the hand-held analyser, B & K Type 2270.

The fan noise from a ceiling fan running at a moderate speed (speed '3' out of '5' on the fan regulator) was audio recorded using the hand-held analyzer, B & K Type 2270. A pre-polarized ½ inch free-field microphone (Type 4189) of the Hand-held Analyser, was held vertically upwards facing the ceiling fan. This position was chosen to simulate the natural situation in a living room. The noise was recorded for a total duration of thirty minutes.

The traffic noise was recorded in a busy circle of Mysuru city during the peak hours of traffic flow. The pre-polarized ½ inch free-field microphone (B & K Type 4189) attached to the Hand-held Analyser, was held facing the traffic from the centre of the circle. The noise sample was recorded for a duration of thirty minutes.

These three types of recorded noise were then transferred to a personal computer and were edited. Eight-talker babble developed by Anitha and Manjula

(2003) was used as speech babble. White noise of sixty seconds was generated using the Adobe Audition software (version 3.0). The five types of noise were edited using Adobe Audition software (version 3.0) to decrease the total duration and equalise the length. All types of noise were normalized to -6 dB. The mid sixty second sample of the total recorded noise sample were considered for the study.

Recording of the reference unprocessed sentence through KEMAR

A single sentence (t̪ammanɪgɛ gaːɭɪpat̪a haːrɪsalu ɪʂt̪a) at 65 dB SPL (LAeq) was presented as the stimulus. This sentence was chosen among the many sentences which represented low, mid and high- frequency components from the sentence list developed by Geetha et al. (2014). The output was recorded in the ear of the KEMAR, without the hearing aid. This served as the reference 'unprocessed speech' for comparison with all other conditions. Figure 3.3 depicts the waveform and wide band bar type spectrogram of the sentence used in the study.

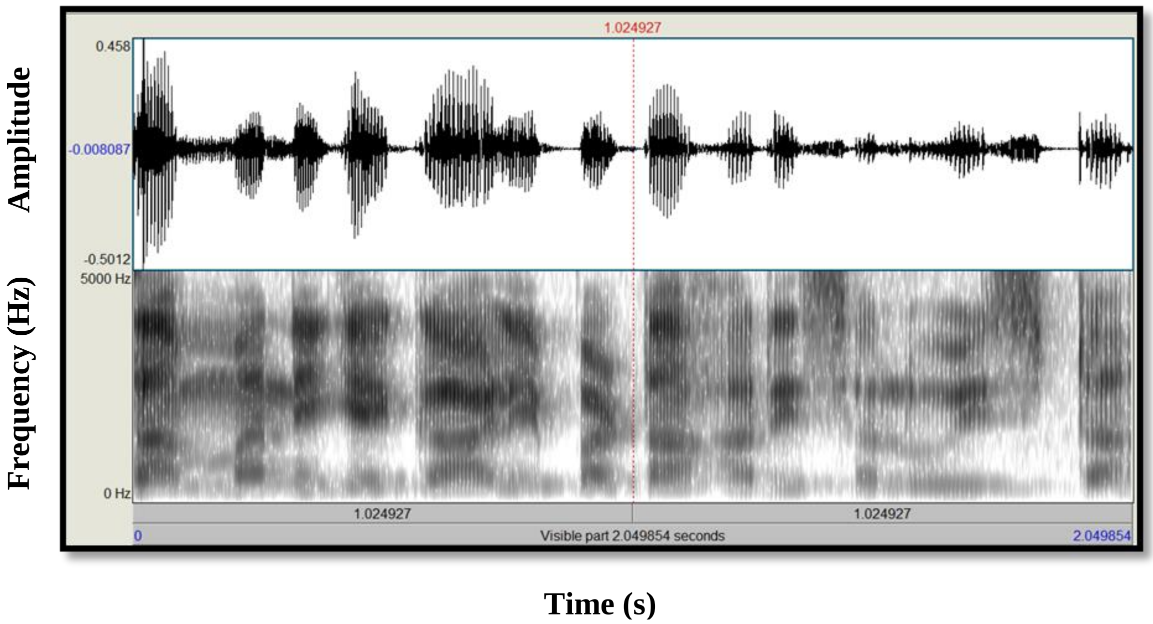


Figure 3.3. Waveform of the unprocessed speech (t̪ammanɪgɛ gaːɭɪpat̪a haːrɪsalu ɪʂt̪a) in the top panel, wide band bar type spectrogram of the sentence in the bottom panel.

Recording of the output from the hearing aid

The output from the hearing aid was recorded in the two input conditions. They were:

a) *Noise Alone Condition:* Cafeteria noise, fan noise, speech babble, traffic noise and white noise were given individually as input to the hearing aid fitted to the KEMAR, at 65 dB SPL (LAeq), for a total duration of 60 seconds. The hearing aid output at the ear of the KEMAR was recorded with NR ON [across minimum (NR min), medium (NR med), & maximum (NR max) gradations] and NR OFF conditions, with two hearing aids.

b) *Speech in Noise Condition:* Speech (a sentence, tammanıgɛ gaːɭıpaʈa haːrısalu ıʂʈa) and noise were presented through loudspeaker kept at 0 degree Azimuth at one meter distance from the KEMAR, simultaneously. The level of the input noise was monitored to reach the levels approximating to 60, 65, and 70 dB SPL (LAeq) at the KEMAR (unaided) to obtain SNRs of +5, 0, and -5 dB respectively for all types of noise. The output was measured using a hand-held analyzer, Brüel & Kjær (B&K) Type 2270 to verify the overall level of the noise. The noise was presented for 15 seconds prior to the onset of speech in order to activate the NRA in the hearing aid. The noise levels were varied to get different signal-to-noise ratios (SNRs) (i.e., +5, 0, & -5 dB) at the input of the hearing aid. The level of speech input was kept constant at 65 dB SPL (LAeq).

   i. *For acoustic analysis:* A single sentence (t̪ammanıgɛ gaːɭıpaʈa haːrısalu ıʂʈa) was presented individually with five different types of noise (cafeteria noise, fan noise, speech babble, traffic noise, & white noise), at the three input SNRs (+5, 0, & -5 dB), with NR OFF and NR ON conditions. The three gradations of the NR ON condition were NR minimum (NR min), NR medium (NR med) and NR maximum (NR max) gradations. This was done for both the hearing aids (HA 1 & HA 2). The output recorded from the two hearing aids across all the above said conditions were used for analyses.

ii. *For perceptual analysis:* Sixteen sentence lists, each list containing ten sentences, were used as speech stimulus. Hence, each condition (NR OFF, NR min, NR med & NR max, at 0 dB SNR) was recorded with a different sentence list across two types of noise only, i.e., cafeteria and traffic noise. This was done with two hearing aids. The output from the two hearing aids, with all the above said conditions, was recorded from the ear of the KEMAR. This served as stimuli for perceptual evaluation (for measuring SIS) with NR ON (NR min, NR med, & NR max) and NR OFF with cafeteria and traffic noise, for NH group.

Test environment

All the tests were carried out in an air-conditioned double room set-up. It was ensured that the room was acoustically treated according to ANSI S3.1-1999 standards.

3.4 Procedure

The following sections elaborate the procedures used to study the objectives.

3.4.1 Hearing aid programming

The two receiver-in- the-canal (RIC) hearing aids were programmed by using the procedure given in the following section:

Hearing aid programming for recording the output of the hearing aid for acoustic analysis and for testing participants in NH group

Two RIC digital hearing aids with the features as explained in the instrumentation section were programmed through NOAH Link, using the hearing aid specific software that was installed in the personal computer. The audiogram was simulated to a flat 50 dB sensorineural hearing loss as the mean PTA of HI group was approximating to 50 dB (49.2 dB). In addition, the changes in effect of NRA on acoustic measures due to sloping configuration in audiogram was not known. Hence, to avoid the influence of audiogram configuration which may become an additional variable, the audiogram was simulated to flat configuration.

The hearing aids were programmed to match the targets provided by the NAL-Nonlinear 2 (NAL-NL2) formula by applying the ‘first fit’. The acclimatization level was set to ‘new hearing aid user’. Thus, at the time of programming the hearing aid, the ‘first fit’ setting was applied. The microphone was set to omni-directional mode. The compression in the hearing aid was disabled to rule out the influence of compression over the hearing aid output. This was verified by performing an electroacoustic measurement of the programmed hearing aid. This programmed RIC was considered for recording the output of the hearing aid when fitted on the ear of the KEMAR using an appropriately sized double dome ear tip. The same procedure was followed to program the second hearing aid. The output of the hearing aid recorded using this procedure was used for acoustic analysis [a single sentence with different NR conditions (NR OFF and NR ON at three gradations NR min, NR med, & NR max) & different types of noise & three SNRs] and for testing the participants in NH group (16 lists of sentences were recorded with different NR conditions in presence of cafeteria & traffic noise separately at 0 dB SNR for SIS testing & a single sentence recorded at 0 dB SNR for acoustic analysis was used for quality judgement task).

Hearing aid programming for testing participants in HI group

The procedure of hearing aid programming was same as explained above. However, the audiogram of the test ear for each participant in HI group was plotted in the NOAH software. The audibility of Ling's six sounds was ensure by optimizing the gain provided by NAL-NL2 prescriptive formula while programming the hearing aid. That is, if the participant was not able to identify any of Ling's six sounds, then the gain was optimized until participant identified it correctly. The programmed hearing aid was fitted on the participant to measure speech perception, i.e., SNR-50 and quality judgement task across different test conditions.

3.4.2 Study design

The data were collected in two phases. Phase I involved evaluating the effect of NRA on acoustic measures. Phase II involved evaluating the effect of NRA on perceptual measures in NH group and HI group.

3.4.3 Phase I: Evaluating the effect of NRA on acoustic measures

This phase involved evaluating the effect of NR on acoustic measures. For this, subjective and objective analyses of the noise alone and speech in noise samples were done.

Phase IA: Evaluating the effect of NRA on acoustic measures in noise only condition

The output recorded from the hearing aids for five different types of noise (cafeteria noise, fan noise, speech babble, traffic noise, & white noise), in noise only, condition with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) were subjected to acoustic analysis. An audiogram simulating a flat 50 dB sensorineural hearing loss was plotted in the hearing aid specific software. The hearing aid was programmed using the NAL-NL2 prescriptive formula with 'first fit' setting, as described in the hearing aid programming section. The noise was presented at 65 dB SPL (LAeq) through loudspeaker of the audiometer located at 0 degree Azimuth, from a distance of one meter. Two different digital RIC hearing aids, each with NRA feature, were selected. The output from the hearing aid was recorded as mentioned in the instrumental set-up for recording the output from the hearing aid. The same procedure was carried out with five different types of noise as input to the hearing aid (cafeteria noise, fan noise, speech babble, traffic noise, & white noise) and across NR OFF and NR ON at three gradations (NR min, NR med, & NR max). The output from hearing aids was analyzed for overall reduction in noise and also to study the changes across frequency and temporal domains of noise.

To study the changes across frequency and temporal domains of noise, the Long-Term Average Speech Spectrum (LTASS) was analyzed. This was done with NR ON across three gradations (NR min, NR med, & NR max) and NR OFF, for the two hearing aids.

In order to study the overall reduction in noise, the hearing aid output was analyzed using the virtual Sound Level Meter (SLM), a MATLAB code developed by

Lanman (2006). This code is based on graphic user interface. Total Leq in dB (A) (i.e., LAeq) and Leq in dB (A) at the 90^{th} percentile (i.e., LA90) were computed for the hearing aid output for each type of noise. The Leq at the 90^{th} percentile is the sound pressure level of noise level that exceeded for 90% of the measurement time. i.e., for 90% of the time, the noise level is above this measured level. The analysis of hearing aid output in the noise alone condition, with NR OFF and NR ON conditions, was done for the final 40 seconds duration out of the total 60 seconds of stimulus duration. The difference between the LAeq values with NR ON and NR OFF provided the amount of reduction of noise brought about by the NRA. The value of overall LAeq and LA90 [in dB (A)] were noted and tabulated for NR ON (at NR min, NR med, & NR max gradations) and NR OFF conditions for each hearing aid. This was done for each type of noise with the two hearing aids.

Phase IB: Evaluating the effect of NRA on acoustic measures in speech in noise condition

Similar to the noise only condition, the output recorded from the hearing aids with NR ON (at NR min, NR med, & NR max gradations) and NR OFF, for five types of noise, and three input SNRs (+5, 0, & -5 dB) were analyzed. The effect of NR was studied by plotting the power spectrum and waveform of the hearing aid output in speech in noise condition. The objective and subjective analyses were carried out to study the hearing aid output with speech in noise.

The objective analysis was done using the Waveform Amplitude Distribution Analysis of signal to noise ratio (WADA-SNR), Envelope Difference Index (EDI), and Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS) measures. The effect of NRA in hearing aids was investigated using these acoustic measures.

The SNR obtained through Waveform Amplitude Distribution Analysis (WADA-SNR) was used as a tool for measuring the SNR by measuring the amplitude distribution of the speech in the presence of different types of noise. In order to measure the alteration of the envelope of signal due to the combined effect of all processing parameters, envelope difference index (EDI) was used. To compare the unprocessed signal with the degraded signal (speech in presence of different types of noise) and to objectively understand the perceptual changes brought about by the NRA with different conditions, Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS) was used.

Waveform Amplitude Distribution Analysis (Kim & Stern, 2008) was used to estimate the SNR, henceforth referred to as WADA-SNR. The measurement procedure was incorporated in a MATLAB code developed by Ellis (2011), version 0.3. This code calculates the relative SNR, in dB, by analyzing amplitude distribution across the sentence. This was done with NR ON (at NR min, NR med, & NR max gradations) and NR OFF for five types of noise, with the three input SNRs, and, with two hearing aids.

Envelope Difference Index (EDI) was calculated based on the MATLAB code given by Fortune, Woodruff, and Preves (1994). The EDI, being a temporal measure, was used to evaluate how close the two signals are in their envelope. The EDI values range from 0 to 1. The EDI value of '0' indicates perfectly similar envelopes and the value of '1' indicates completely dissimilar envelopes of interest. The envelopes between speech in noise with NR ON condition (with NR min, NR med, & NR max) and the unprocessed speech; and speech in noise with NR OFF and the unprocessed speech were compared in order to obtain the EDI. The stimulus was cross-correlated and time aligned before analyzing them through the EDI MATLAB code to avoid errors arising from time misalignment.

Perceptual Evaluation of Speech Quality (PESQ) being an objective method for predicting the quality of speech, and developed by the International Telephone Union (ITU), (ITU-T P.835, 2003) was used for assessing the sound quality in telephone systems. The PESQ (MOS) predicts how close the target signal in terms of its quality is in comparison to the original signal. In the present study, the comparison has been done between speech in noise with NR ON (with NR min, NR med, & NR max) and the unprocessed speech. The comparison was done also for speech in noise with NR OFF and the unprocessed speech. The PESQ (MOS) provides a value between 0 and 4.5. If the value of PESQ (MOS) is 4.5, then the target speech is the same as the unprocessed speech in terms of quality. This measurement procedure was incorporated in a MATLAB code developed by Ellis (2011), version 0.3. The code estimates the PESQ (MOS) with the given input. PESQ (MOS) is algorithmically estimated by predicting MOS through objective quality models which are developed and trained using human MOS rating. The same was employed in the present study as each NR gradation (NR min, NR med, & NR max) were compared with unprocessed speech. Higher value of PESQ (MOS) in a NR gradation implied that the NR gradation was more close to unprocessed speech.

The subjective analysis involved rating of the speech in noise samples with NR ON (with NR min, NR med, & NR max) and NR OFF. This was done individually for five types of noise and at three input SNRs. Three speech language pathologists

(SLPs) with a minimum of ten years of experience in spectrogram analysis were given the speech in noise samples as represented on the spectrograms on the computer monitors. The visual samples of spectrograms were coded to conceal the identity of the sample. This task was considered as an objective measure as the task of SLPs was to make the judgment based on the visual display of the speech sample (i.e., waveform & spectrogram); and they did not listen to the speech sample.

The recorded output from the hearing aid across NR OFF and NR ON at three gradations (NR min, NR med, & NR max) were placed sequentially in the PRAAT software (version 5419). This grouping (each group containing four samples) of the recorded speech in noise samples were made for each noise type with the three SNRs. The display on the computer indicated acoustic waveform on the top panel and spectrogram on the bottom panel. Figure 3.4 depicts the sample of the display provided to the SLPs. The SLPs were free to zoom in and out of the samples in order to visualize the formants. The order of appearance of the samples among the SLPs was randomized. The SLPs were asked to rate the sample that appeared less noisy on the spectrogram out of the four samples given in each set. A rating of '1' was given for sample that was less noisy and a rating of '4' was given to the sample that was most noisy. Same rating was utilized if the two samples in the group were judged as same in terms of noisiness, visualized on the spectrogram. The noisiness for the purpose of the study was defined as 'the quality or state of being noisy as visualized on a spectrogram'.

Similarly, rating was also obtained after judging the sample that had good formant representation. A rating of '1' was given to the sample that had the best formant representation, identified visually, and a rating of '4' was given to the sample that had poor formant representation on the spectrogram. Same rating was utilized if the two samples in the group were judged as same in terms of formant representation. The judgment for noisiness and formant representation was done by visualizing the same sample of the spectrogram.

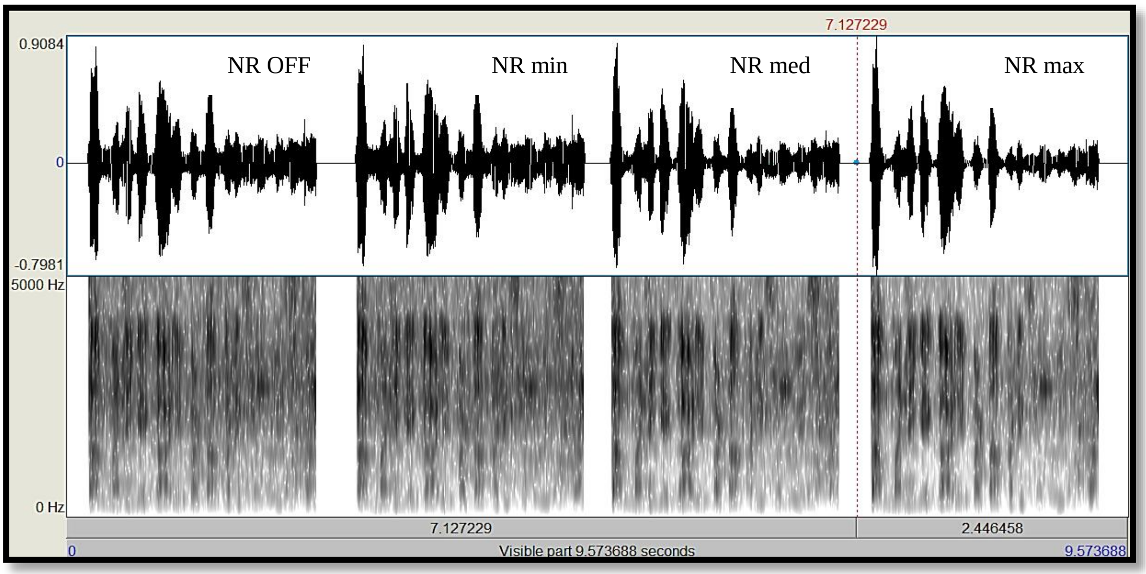


Figure 3.4. Waveform and wide band bar type spectrogram of speech sample displayed in PRAAT software for obtaining rating from speech language pathologists.

3.4.4 Phase II: Evaluating the effect of NRA on perceptual measures

In Phase II, the participants with normal hearing (NH group) and individuals with hearing impairment (HI group) judged the loudness of the output from the hearing aids with noise only and speech in the presence of noise. Only cafeteria and traffic noise were used for evaluating the perceptual measures. Only two types of noise (out of five) were chosen as the number of conditions (three SNRs, two hearing aids, three NR gradations) was more. Traffic noise is frequently encountered in everyday life and cafeteria noise involves both speech and non-speech characteristics, simulating cock-tail party effect. In addition, cafeteria and traffic noise are the widely studied types of noise for evaluating speech in the presence of noise for individuals with hearing impairment.

The effect of NRA on perceptual measures was investigated in the following steps:

Phase IIA: Measurement of the effect of NRA on perceptual measures, in noise only condition

The procedure given in the following section was carried out to evaluate the effect of NR on perceptual measures, with noise alone, for NH group and HI group. For the NH group, the output recorded from the hearing aid in noise only condition with NR OFF and NR ON at three gradations (NR min, NR med, & NR max), with the cafeteria and traffic noise, served as the stimulus. As the stimulus was recorded output from the hearing aid, it was presented through Sennheiser HDA 200 headphones to avoid the binaural hearing benefits that would occur by presenting the stimulus through the loudspeaker. In addition, the testing was done monaurally for individuals in HI group. Hence, the stimulus was presented through headphones for participants in NH group.

However, for HI group, individuals were fitted with HA on the better ear. Hence, the stimulus (cafeteria & traffic noise) was presented directly through loudspeaker. The NR gradations were manipulated to keep the HA in place while the HA was on the participant.

Measurement of the effect of NRA on overall loudness in noise only condition, for NH group. An audiogram simulating a flat 50 dB of sensorineural hearing loss was plotted in the hearing aid programming software. The test hearing aids (2 nos.) were programmed using the NAL-NL2 prescriptive formula as described in the hearing aid programming section.

The recorded output from the hearing aid in noise only condition with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) was presented individually through a personal computer using Adobe Audition software (version 3.0). The participant was made to sit comfortably on a chair in the test room. The recorded output from the hearing aid was presented monaurally through Sennheiser HDA 200 headphones routed via a calibrated personal computer. Each sample of noise was played for a minimum duration of 15 seconds (excluding the initial 15 seconds of the total 60 second stimulus). Pair-wise comparisons were made for two noise types (i.e., cafeteria noise & traffic noise) between NR ON (at NR min, NR med, & NR max gradations) and NR OFF. This gave rise to six pairs for comparison within each type of noise (NR OFF with NR max, NR OFF with NR med, NR OFF with NR min, NR med with NR min, NR max with NR med, NR max with NR min). The participant was instructed to judge which sample in the pair was less noisy or to rate it same if both were perceived similar. Five trials were taken for each pair. The condition (e.g., NR max) that was chosen as less noisy maximum number of times, out of the five trials, were considered as their choice of preference. This was considered as Loudness Judgment for Noise (LJN). The above procedure was repeated with the output recorded from the second hearing aid. This procedure was followed for each participant from NH group.

Measurement of the effect of NRA on overall loudness in noise only condition, for HI group. The participant was seated comfortably on a chair in the audiometric test room. The programmed HA was fit to the better ear of the participant. Cafeteria noise and traffic noise were presented individually through a personal computer using Adobe Audition software (version 3.0). The noise was held constant at 45 dB HL. The noise was routed via audiometer and presented through loudspeaker (Martin C-115 model) kept at 0 degree Azimuth at 1 meter distance from participant. The hearing aid was programmed to NR OFF and NR ON at three gradations (NR min, NR med, & NR max) as the hearing aid was connected using the NOAH Link. That is, the NR conditions were manipulated between the NR OFF and NR ON at three gradations (NR min, NR med, & NR max) of the hearing aid while the hearing aid was on the participant. Each sample of noise was played for a minimum duration of 30 seconds, to ensure that the NR in the hearing aid was activated. Then the participant was made to compare between the three NR gradations (at NR min, NR med, & NR max) and NR OFF within each noise type. This gave rise to six pairs for comparison within each type of noise (NR OFF with NR max, NR OFF with NR med, NR OFF with NR min, NR med with NR min, NR max with NR med, NR max with NR min). The participant was instructed to judge which sample in the pair was less noisy. Five trials were taken for each pair. The condition (e.g., NR max) that was chosen as less noisy maximum number of times, out of the five trials, were considered as their choice of preference. This was considered as Loudness Judgment for Noise (LJN). This procedure was repeated with the second hearing aid. This procedure was followed for each participant from HI group.

Phase IIB: Measurement of the effect of NRA on speech perception in presence of noise

Two measures were collected from each participant of NH group and HI group. This included the speech identification scores (SIS) and quality judgement for NH group; and, SNR-50 and quality judgement for HI group in order to quantify the effect of NR on speech in noise.

For the NH group, the output recorded from the hearing aid with 16 sentences from the Kannada sentence identification test (Geetha et al., 2014) with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) within each type of noise (cafeteria noise & traffic noise) at 0 dB SNR, served as the stimulus for obtaining the SIS. As the stimulus was recorded output from the hearing aid, it was presented through Sennheiser HDA 200 headphones. This was done to avoid the binaural hearing benefits that would occur by presenting the stimulus through loudspeaker for participants in NH group, while performing speech test (SIS). In addition, a single sentence (used for acoustic analysis) recorded at 0 dB SNR from the hearing aid was used for quality judgment task for NH group.

However, for HI group, individuals with hearing impairment were fitted with HA on the better ear. The sentence lists from the Kannada sentence identification test were presented with cafeteria and traffic noise directly through loudspeaker to obtain SNR-50. The NR gradations were manipulated while the HA was on the participant. In addition, a single sentence (used for acoustic analysis) was used for quality judgment task. This single sentence was presented directly to the individuals with hearing impairment fitted with HA, through loudspeaker.

Evaluating the effect of NRA on speech perception in presence of noise for NH group. For participants of NH group, the hearing aids were programmed as mentioned earlier under the noise only condition. The recorded output from the hearing aid (speech in noise condition) served as the stimuli. This stimulus was presented using Adobe Audition software (version 3.0) from the personal computer through Sennheiser HDA 200 headphones. The SIS were obtained by asking the participant to repeat the recorded sentences with NR OFF and NR ON at three gradations (NR min, NR med, & NR max), within each type of noise (cafeteria noise & traffic noise) at 0 dB SNR. Different sentence lists (pre-recorded with noise as explained earlier) were used while measuring SIS for each type of noise and at different NR gradations, to avoid practice effect. The SIS was obtained separately with the recorded output of the two hearing aids.

In order to obtain the quality judgement, the pre-recorded speech in noise at 0 dB SNR (single sentence with noise that was used for acoustic analysis) from the hearing aid was presented individually through a personal computer using Adobe Audition software (version 3.0) through HDA 200 headphones, monaurally. Pair-wise comparisons were made for two noise types (cafeteria noise & traffic noise) and with three NR gradations (NR min, NR med, & NR max) and NR OFF as described in noise alone condition. The participants were made to compare the pairs on the overall clarity of speech (denoted as QJC- Quality Judgement for Clarity); noisiness (denoted as QJN- Quality Judgement for Noisiness) and overall preference (denoted as OP).

For measuring the quality in terms of the clarity of speech (QJC), the participants were asked to concentrate on speech signal in the presence of noise, and judge which sample in the pair had better speech clarity. For measuring noisiness

(QJN), the participants were asked to concentrate on noise and judge which sample in the pair was less noisy. Later, the participants were asked to choose a sample in the pair which they preferred to hear in terms of the overall preference (OP) of the signal. Five trials were taken for each pair. The condition (e.g., NR max) that was chosen as best in terms of good clarity/ less noisy/ better overall quality, maximum number of times, out of the five trials, was considered for tabulation and analyses.

Measurement of the effect of NRA on speech perception in presence of noise for HI group. For participants in HI group, the hearing aid was programmed and optimized by using the procedure described earlier under hearing aid programming section. The programmed digital RIC was fitted to the test ear of the participant using a double dome. The participant was made to sit comfortably at 0 degree Azimuth, one meter away from the free-field speaker (Martin C-115 model) of the audiometer.

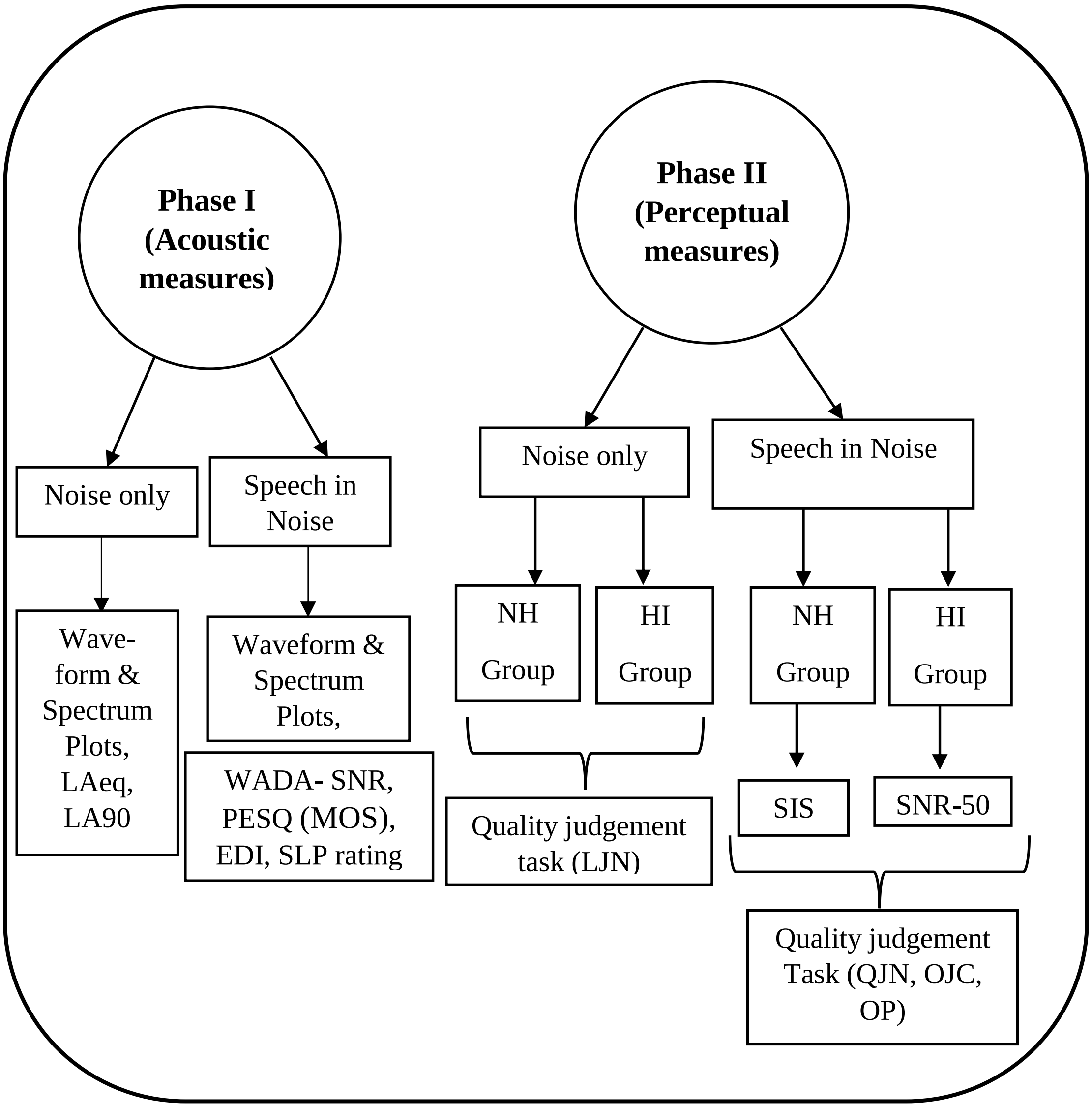
The SNR-50 was obtained as a measure of speech perception. The SNR-50 is operationally defined as the difference between the intensity of speech stimuli and the intensity of the competing noise, in dB, when the participant correctly repeats at least 50% of the speech that is presented in the presence of competing noise. The SNR-50 was measured using Kannada sentences (Geetha et al. 2014). The speech stimuli were presented at a constant level of 45 dB HL. The level of noise (cafeteria or traffic) was varied to obtain the SNR-50. The initial presentation level of the noise was 20 dB HL. The participant was instructed to repeat the sentences heard in the presence of the competing noise. From the sentence list, one sentence was presented to the participant at each presentation level of noise. If the participant repeated at least 50% of the key words in the sentence, then the level of noise was increased in 2 dB steps. At each step, one sentence was presented. If the participant failed to repeat at least 50% of the words correctly, the level of noise was decreased in 4 dB steps. This was continued until the highest level of noise was reached, that was sufficient for the participant to repeat at least 50% of the key words in a sentence. The SNR-50 value is the difference between the average intensity levels of the noise at the reversal points (average of eight reversal points) and the intensity level of speech, in dB (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004).

The SNR-50 was calculated with NR OFF and NR ON at three NR gradations (NR min, NR med, & NR max) for two different types of noise (cafeteria noise & traffic noise). This procedure was followed for both the hearing aids for each participant from HI group.

For the quality judgement task, the hearing aid was programmed to NR OFF, NR ON (NR min, NR med, & NR max) online, using the NOAH Link. That is, the NR of the hearing aid was manipulated while the HA was on the participant. The noise was held constant at 40 dB HL. Speech level was held constant at 45 dB HL i.e., + 5 dB above the noise level to obtain a SNR of + 5 dB. The quality judgments were obtained at +5 dB SNR, since most of the participants could not perform well at 0 dB SNR. Each sample of noise was played 15 seconds prior to the presentation of the speech, to ensure that the NR in the hearing aid was activated. Then the participant was made to compare between the three NR gradations and NR OFF within each noise type. Pair-wise comparisons were made between the two noise types and three NR gradations and NR OFF as described in noise alone condition. The participant was made to compare the pairs on the clarity of speech (denoted as QJC- Quality Judgement for Clarity); noisiness (denoted as QJN- Quality Judgement for Noisiness) and overall preference (denoted as OP).

For measuring the clarity of speech (QJC), the participant was asked to concentrate on speech signal in the presence of noise, and judge which sample in the pair had better speech clarity in terms of intelligibility. For measuring noisiness (QJN), the participant was asked to concentrate on noise and judge which sample in the pair was less noisy. Lastly, the participant was asked to choose a sample in the pair which they preferred to hear in terms of the overall preference (OP) of the signal. Five trials were taken for each pair. The condition (e.g., NR max) that was chosen as best in terms of good clarity/ less noisy/ better overall quality, maximum number of times, out of the five trials, was noted. The quality judgement was obtained for clarity, noisiness, and overall preference separately.

Thus, for each participant, the following data were collected and tabulated. The data were collected for the two hearing aids, across three NR gradations (NR min, NR med, & NR max) and NR OFF, three input SNRs, and for different types of noise. Figure 3.5 provides a glimpse of various measures collected in the two phases of the study.



Note: NH Group: Normal Hearing group, HI Group: Hearing Impaired Group, LJN: Loudness judgement for noise, QJC: Quality Judgement for Clarity; noisiness, QJN- Quality Judgement for Noisiness and OP: overall preference.

Figure 3.5. *Flow chart of tests conducted for different groups.*

3.5 Statistical analyses

The data obtained from Phase I (acoustic measures) and Phase II (perceptual measures) were tabulated and analysed statistically. As the data obtained from Phase I were from a single sentence, only descriptive statistics were enumerated. The data obtained from Phase II were subjected to test the normality. The Shapiro-Wilk test of normality revealed that the data obtained from Phase II did not assume normal distribution ($p < 0.05$). Hence, non-parametric tests were performed to study the effect of NRA on perceptual measures. McNemar test was done to study the differences across the NR conditions (NR OFF, NR min, NR med & NR max) for the loudness judgment task (LJN) in noise alone condition and quality judgment for clarity (QJC), quality judgment for noise (QJN), and overall preference (OP) in speech in noise condition. This was performed for both cafeteria noise and traffic noise for both NH and HI group individually.

Friedman's test and Wilcoxon's signed rank test were performed for data obtained from speech perception measures. To test if the SIS and SNR-50 values differed significantly across NR gradations, Friedman's test was performed. Whenever, Freidman's test showed significant main effect, Wilcoxon's signed rank test was administered in order to study the NR gradation that was significantly different within each type of noise for both NH and HI group.

CHAPTER 4

RESULTS

The objectives of the study were to evaluate the effect of noise reduction algorithms (NRA) in hearing aids on acoustic and perceptual measures across different types of noise, three signal to noise ratios (SNR) and with noise reduction (NR) OFF and NR ON [at NR minimum (NR min), NR medium (NR med), & NR maximum (NR max)] with two hearing aids. The data obtained were in nominal and ordinal scale of measurement. The data were subjected to statistical analyses.

Descriptive statistics was performed for the data obtained from Phase I (acoustic measures) as the data were for a single sentence. The data obtained from Phase II were subjected to test the normality. The Shapiro-Wilk test of normality revealed that the data obtained from Phase II did not assume normal distribution ($p<0.05$). Hence, non-parametric tests were performed to study the effect of NRA on perceptual measures. Friedman's test was done to know if there was any significant main within the condition; and Wilcoxon's signed rank test was performed when indicated to find out significant difference between the pair. Mc Nemar test was done for the data obtained on quality judgment tasks. The results have been enumerated under effect of NRA on acoustic measures (Phase I) and perceptual measures (Phase II).

4.1 Effect of NRA on acoustic measures

4.1.1 Effect of NRA on acoustic measures, in noise only condition

i. Effect of NRA on wave plots, in noise only condition

ii. Effect of NRA on overall level of noise, in noise only condition

4.1.2 Effect of NRA on acoustic measures in speech in noise condition

i. Effect of NRA on wave plots, in speech in noise condition

ii. Effect of NRA on WADA-SNR

iii. Effect of NRA on EDI

iv. Effect of NRA on PESQ (MOS)

v. Effect of NRA on subjective rating

4.2 Effect of NRA on perceptual measures

4.2.1 Effect of NRA on perceptual measure, in noise only condition

i. Effect of NRA on overall loudness, in noise only condition, in NH group

ii. Effect of NRA on overall loudness, in noise only condition, in HI group

4.2.2 Effect of NRA on speech perception in noise

i. Effect of NRA on speech identification measures in NH group

ii. Effect of NRA on quality judgment in NH group

iii. Effect of NRA on speech identification measures in HI group

iv. Effect of NRA on quality judgment in HI group

However, the comparison between the two hearing aids (HA 1 & HA 2), comparison between acoustic and perceptual measures and between NH and HI group were not performed due to the following reasons:

1. The data obtained from acoustic measures was a single value. This could not be compared statistically with perceptual measures.
2. Further, the speech perception measure for NH and HI group were different (SIS & SNR-50) and quality judgment was done at different SNRs (0 dB for NH group & +5 dB for HI group). Hence, comparison between the groups was not attempted.
3. The Hearing aid 1 (HA 1) and Hearing aid 2 (HA 2) were from the same manufacturer having modulation based NRA. Both the hearing aids varied only in the amount of noise reduction, in dB, across the NR gradation. HA 1 had a maximum NR of 15 dB (at maximum gradation) and HA 2 had a maximum NR

of 8 dB (at maximum gradation). Hence, comparison were not done between the two hearing aids.

4. Moreover, the above comparisons were not the objectives of the study.

The number of aided conditions for acoustic measures were 120. They were two hearing aids, each in four conditions (NR OFF, NR min, NR med, & NR max), five types of noise (cafeteria noise, fan noise, speech babble, traffic noise, & white noise), and three SNRs (-5, 0, & +5 dB). As the stimulus was a single sentence, statistical test could not be administered on the data collected from Phase I (acoustic measures) in order to check the difference between the different aided conditions.

4.1 Effect of NRA on acoustic measures

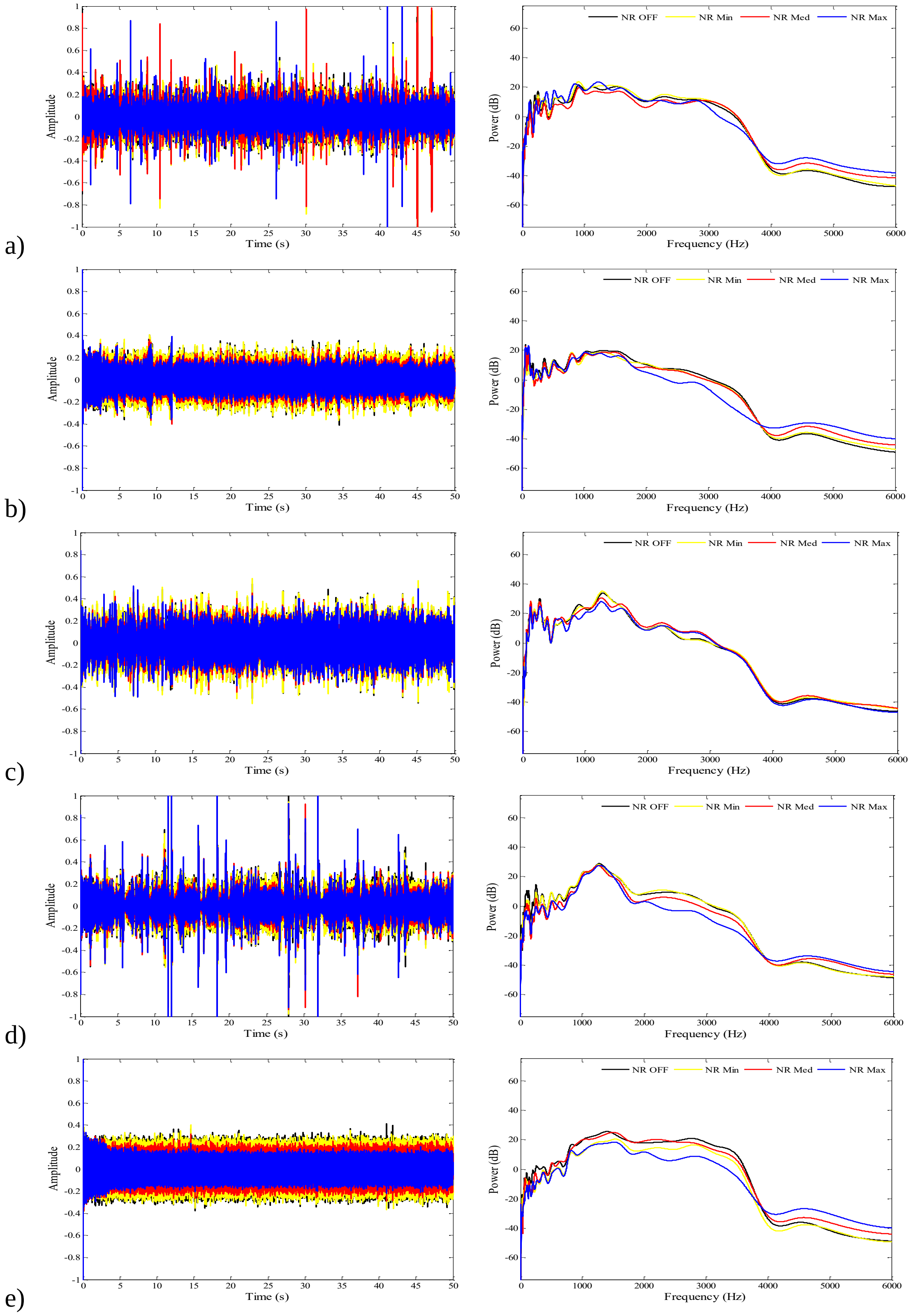
The data obtained through acoustic measurement of the output of the hearing aid for an input (i.e., a sentence along with five types of noise) under different noise reduction (NR) conditions (NR OFF, NR min, NR med, & NR max) were tabulated and analysed. Kumar and Manjula (2017) who assessed the effect of noise reduction in hearing aid on ten sentences in the presence of five types of noise (similar to that used in the present study), noted that the difference in the acoustic measures between different NR gradations across the ten sentences were very similar. Hence, the use of a single sentence for acoustic measurements was justified in the present study.

4.1.1 Phase IA: Effect of NRA on acoustic measures, in noise only condition

The effect of NRA in noise only condition was evaluated by analysing the wave plots and by measuring the overall noise level at the output of the hearing aid, with NR OFF and NR ON at three gradations (NR min, NR med, & NR max); for five types of noise.

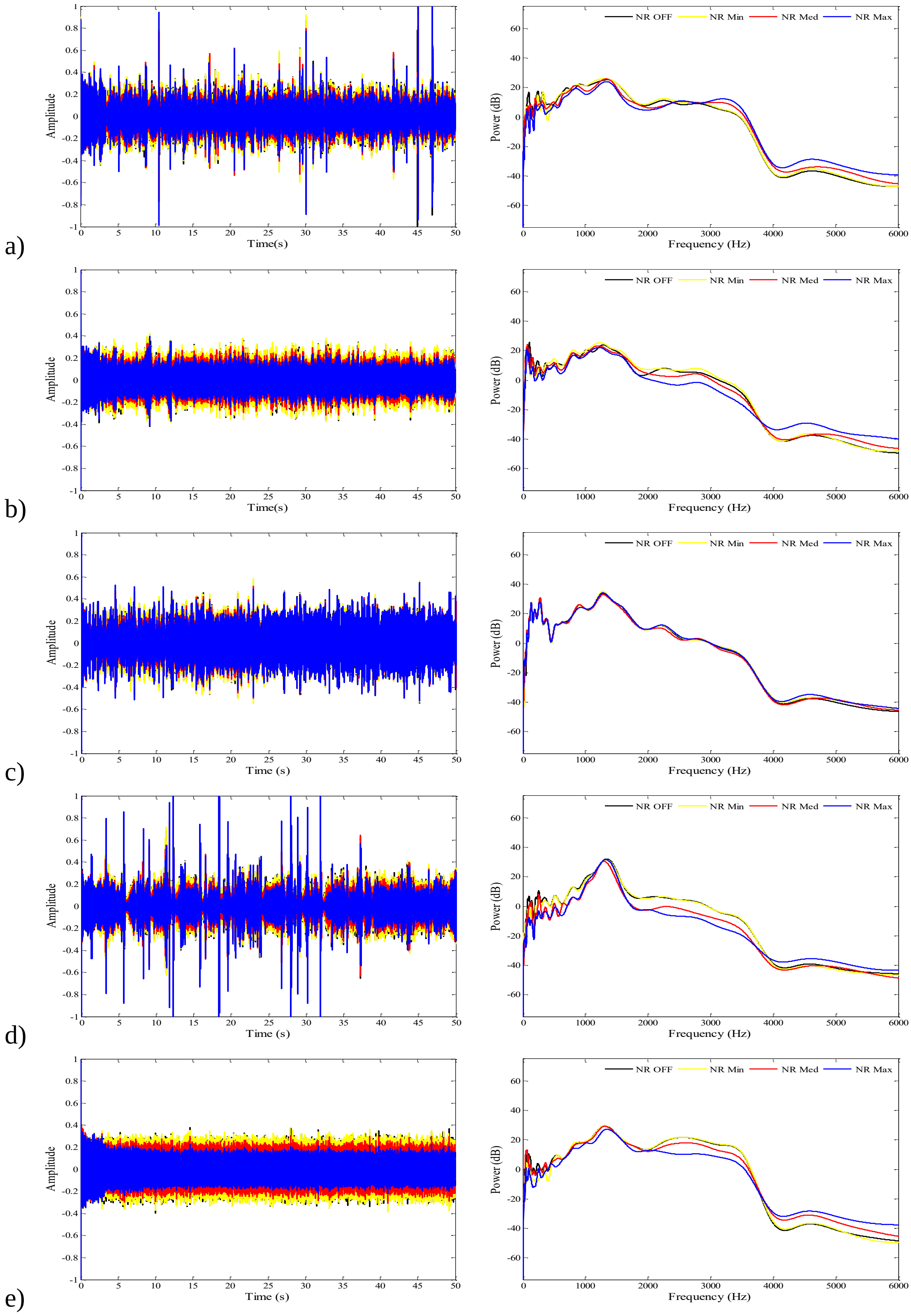
Effect of NRA on acoustic measure analyzed by wave plots, in noise only condition

The output of hearing aid in noise alone condition were analysed by plotting the power spectrum and waveform. This was done for five types of noise (cafeteria, fan, speech babble, traffic, & white noise) with NR OFF and NR ON (at NR min, NR med, & NR max); for the two hearing aids (HA 1 & HA 2). Figures 4.1 and 4.2 depict the waveform (left panel), and power spectrum (right panel) in different NR conditions in five different noises for HA 1 and HA 2 respectively.



Note: X axis: Time(s) for left panel, Frequency (Hz) for right panel; Y axis: Amplitude for left panel, Power (dB) for right panel.

Figure 4.1. Output of HA 1 for noise alone condition. Waveform (left panel) and spectrum (right panel). a). Cafeteria noise, b). Fan noise, c). Speech babble, d). Traffic noise, and e). White noise with different noise reduction conditions: NR OFF (black), NR minimum (yellow), NR medium (red) and NR maximum (blue).



Note: X axis: Time(s) for left panel, Frequency (Hz) for right panel; Y axis: Amplitude for left panel, Power (dB) for right panel.

Figure 4.2. Output of HA 2 for noise alone condition. Waveform (left panel) and spectrum (right panel). a). Cafeteria noise, b). Fan noise, c). Speech babble, d). Traffic noise and e). White noise with different noise reduction conditions: NR OFF (black), NR minimum (yellow), NR medium (red) and NR maximum (blue).

The decrease in noise levels at NR max (depicted in blue colour in the Figures 4.1 & 4.2) can be distinctly observed for white noise followed by fan noise, traffic noise, and cafeteria noise for both HA 1 and HA 2. It can be observed that the output from the hearing aid increased beyond 4 kHz when the NR was set at maximum, for all types of noise. However, at frequencies below 4 kHz, the NR max has less output than NR min, NR med, and NR OFF conditions. No distinctions can be made across the NR gradations for speech babble. Further, the amount of noise reduction in HA 1 was relatively higher than in HA 2 for white noise, traffic noise, and fan noise.

Effect of NRA on overall level of noise, in noise only condition

The overall loudness of the hearing aid output for an input of noise was measured and tabulated in terms of overall LAeq (dB) and LA90 (dB). The levels noted for five different types of noise (cafeteria, fan, speech babble, traffic, & white noise) with NR ON (in three gradations NR min, NR med, & NR max) and NR OFF, for one hearing aid (HA 1) are tabulated in Table 4.1. The results showed that the overall LAeq and LA90 values for NR ON condition was lower than that for NR OFF condition, for all types of noise. As each noise has varying acoustic characteristics and some would fluctuate along the time domain (e.g., traffic noise, cafeteria noise), the reduction of noise was seen in the 90th percentile (LA90). Further, LA90 (dB) values were considered to discuss the results. In the NR ON condition, NR max had greatest reduction of noise followed by NR med and NR min. The NR min had least effect on the noise, i.e., the NR at minimum gradation was almost equivalent to NR OFF condition.

The amount of noise reduction i.e., the difference in output of the hearing aid in conditions between NR max and NR OFF, was highest for traffic noise i.e., 6.9 dB followed by white noise (4.9 dB) and cafeteria noise (4.6 dB). The speech babble had the least amount of noise reduction, i.e., 1.5 dB. From this, it can be deduced that the extent of noise reduction depends on the type of noise, when the NR was enabled in the hearing aid. This reduction is most effective at NR max compared to NR med followed by NR min gradations.

Table 4.1.

Overall LAeq (dB) and LA90 (dB) and difference LAeq in dB for an input of 65 dB SPL for five different types of noise, with NR ON (with three gradations) and NR OFF with HA 1.

Types of noise	LAeq & LA90 (dB SPL)								Difference (in dB) between NR OFF & NR max	
	With NR OFF		With NR ON							
			NR min		NR med		NR max			
	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90
Cafeteria noise	71.9	69.3	71.9	69.2	70.4	66.6	69.3	64.6	2.6	4.6
Fan noise	71.6	69.9	71.4	69.5	69.5	67.5	67.8	65.7	3.6	3.8
Speech babble	71.6	68.4	71.5	68.3	71.1	67.7	70.7	66.9	0.8	1.5
Traffic noise	72.3	68.2	72.3	68.1	71.4	64.3	71.2	61.3	1.1	6.9
White noise	72.6	72.3	72.3	72	70.4	70.1	67.8	67.4	4.8	4.9

Note:-NR: Noise reduction; NR min: Noise reduction at minimum gradation; NR med: Noise reduction at medium gradation; NR max: Noise reduction at maximum gradation.

Similar trend in values of LAeq (dB) were obtained for the second hearing aid (HA 2) also. This is enumerated in Table 4.2. The mean overall LAeq and 90th percentile LA90 values, in dB, for NR ON condition was lower than that for NR OFF condition, for all types of noise. In the NR ON condition, NR max had greatest reduction of noise followed by NR med and NR min. The NR min had the least effect on the noise, i.e., the LAeq with NR min gradation was almost equivalent to that in NR OFF condition.

The reduction of noise is depended on the type of noise in the environment. Traffic noise had maximum reduction i.e., 6.9 dB (difference between NR max & NR OFF) followed by white noise (4.4 dB) and cafeteria noise (4 dB). The speech babble had the least noise reduction of 1 dB. From this, it can be deduced that there is an effective reduction in the level of noise when NR feature in the hearing aid was enabled. This reduction is more effective at NR max than at NR med and NR min gradations.

Table 4.2.
Overall LAeq (dB) and LA90 (dB) and difference LAeq in dB for an input of 65 dB SPL for five different types of noise, with NR ON (with three gradations) and NR OFF with HA 2.

Types of noise	LAeq & LA90 (dB SPL)								Difference (in dB) between NR OFF & NR max	
	With NR OFF		With NR ON							
			NR min		NR med		NR max			
	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90	Overall LAeq	LA90
Cafeteria noise	72.3	69.6	72.2	69.4	71	67.8	69.9	65.4	2.3	4
Fan noise	71.9	70.2	71.5	69.6	70.1	68.1	68.4	66.3	3.1	3.3
Speech babble	72.9	69.4	72.7	69.2	72.3	68.7	72.3	68.2	0.4	1
Traffic noise	73.2	68.7	73.0	68.6	72.3	66	72.1	61.7	0.9	6.9
White noise	72.7	72.3	72.6	72.2	71	70.5	68.4	67.8	4.2	4.4

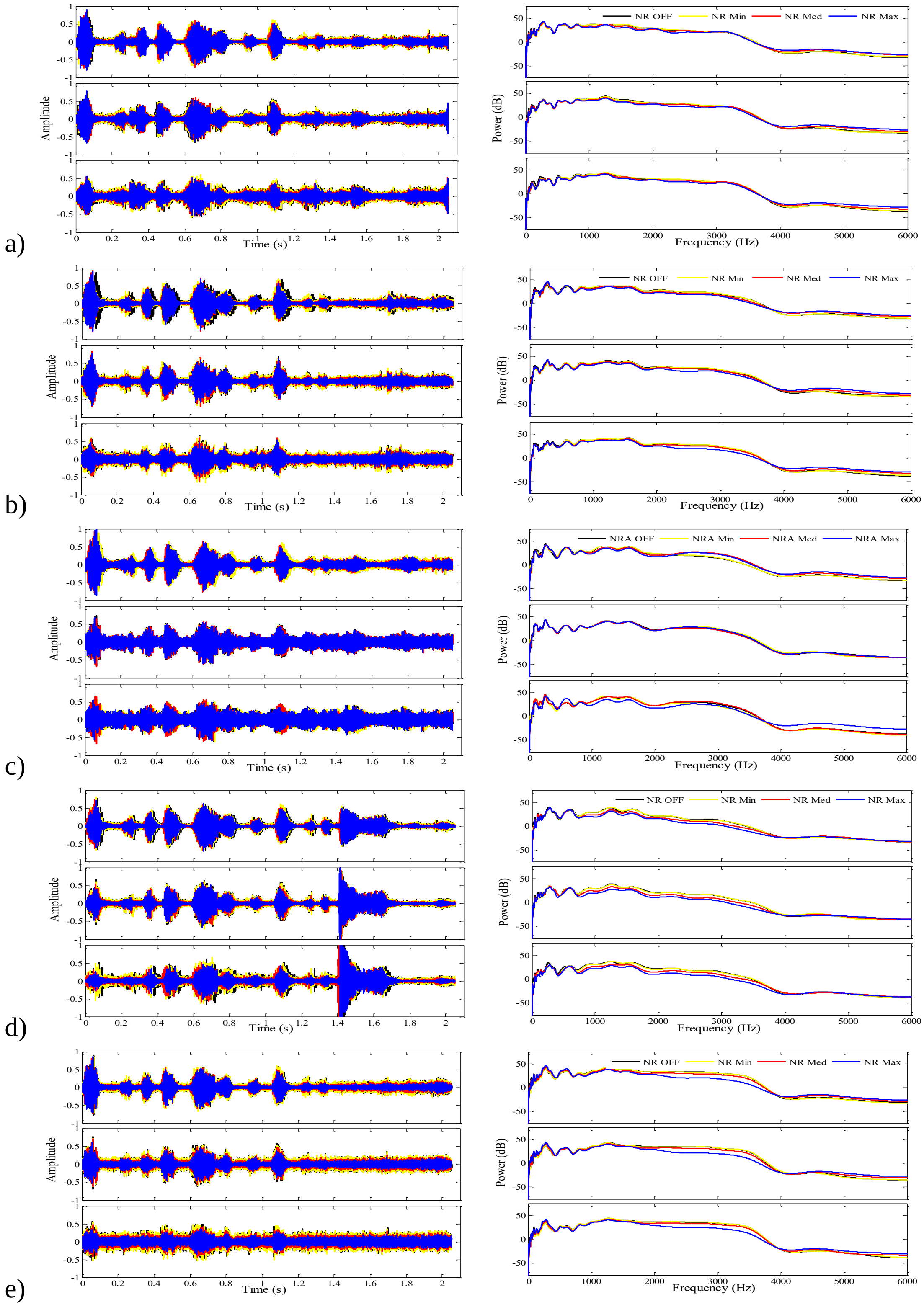
Note: NR: Noise reduction; NR min: Noise reduction at minimum gradation; NR med: Noise reduction at medium gradation; NR max: Noise reduction at maximum gradation

4.1.2 Phase IB: Effect of NRA on acoustic measures in speech in noise condition

The following sections contain the results of the acoustic analysis of the output from two hearing aids for a sentence, with NR OFF and NR ON at three gradations (NR min, NR med, & NR max); at three input SNRs (+5, 0, & -5 dB); for five types of noise. The effect of NR was studied by plotting the power spectrum and waveform of the hearing aid output in speech in noise condition. The effect of NRA on acoustic measure was further objectively analysed using objective tools such as WADA-SNR for measuring the output SNRs, EDI to measure the temporal variations, and PESQ (MOS) to measure the perceptual sound quality.

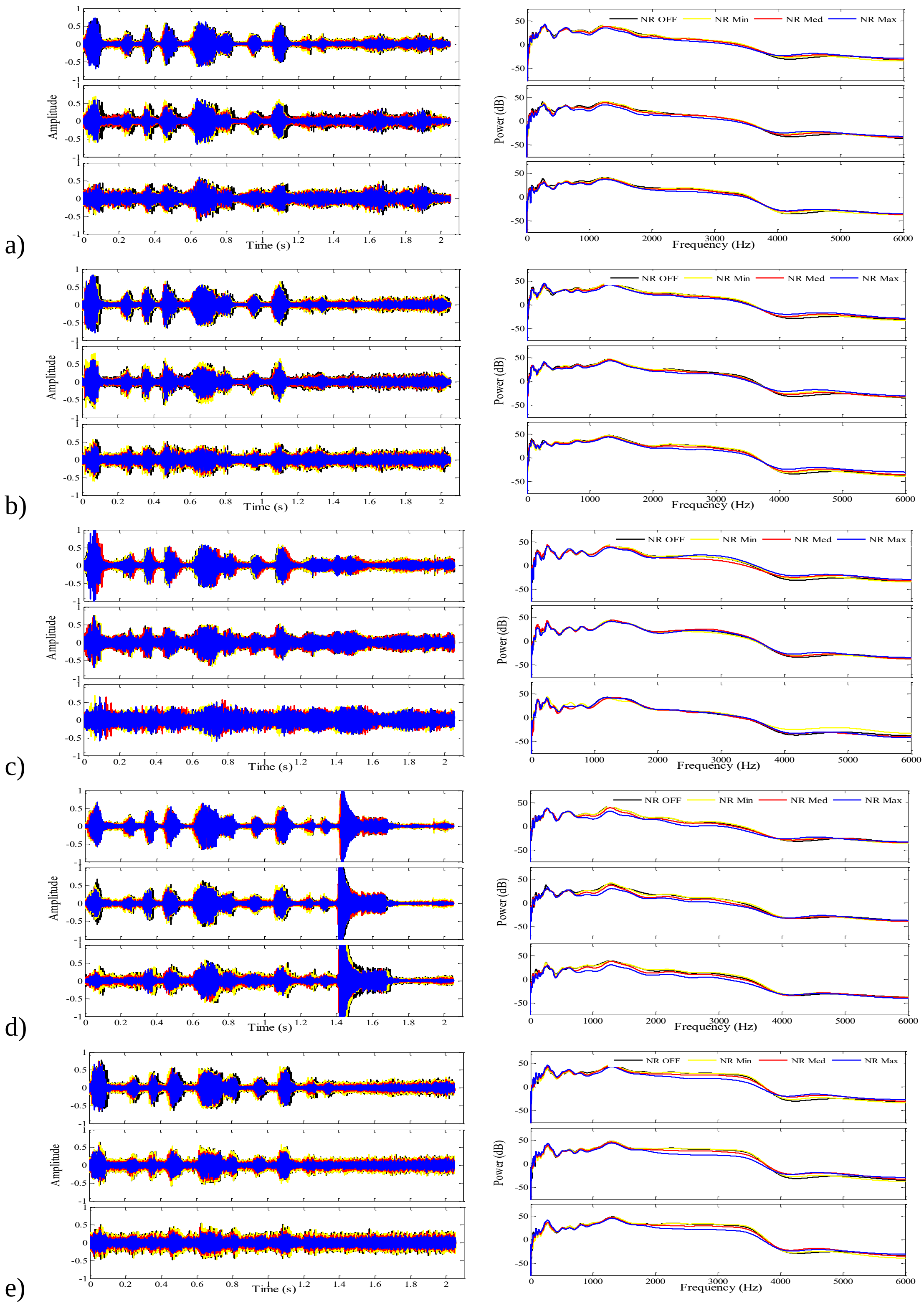
Effect of NRA on wave plots in speech in noise condition

The waveform and the power spectrum of the hearing aid output for speech in noise condition were plotted and analysed. This was done for five types of noise (cafeteria, fan, speech babble, traffic, & white noise) with NR OFF and NR ON (at NR min, NR med, & NR max); and with three SNRs (-5, 0, & +5 dB) for HA 1 and HA 2. Figures 4.3 and 4.4 depict the waveform (left panel), and power spectrum (right panel) in different NR conditions in five different noises, for HA 1 and HA 2 respectively.



Note: X axis: Time(s) for left panel, Frequency (Hz) for right panel; Y axis: Amplitude for left panel, Power (dB) for right panel.

Figure 4.3. Output of HA 1 for speech in noise condition. The waveform (left panel) and the spectrum (right panel) of a sentence in a). Cafeteria noise, b). Fan noise, c). Speech babble, d). Traffic noise and e). White noise, with different noise reduction conditions, NR OFF (black), NR minimum (yellow), NR medium (red) and NR maximum (blue), and at three SNRs (+5 dB top panel, 0 dB middle panel, & -5 dB bottom panel).



Note: X axis: Time(s) for left panel, Frequency (Hz) for right panel; Y axis: Amplitude for left panel, Power (dB) for right panel.

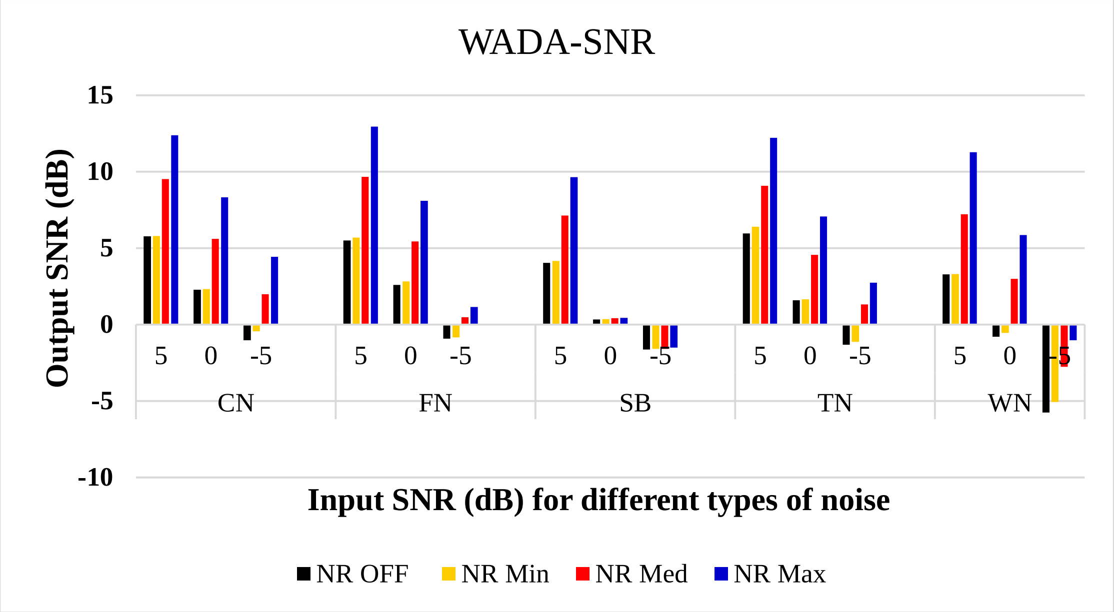
Figure 4.4. Output of HA 2 for speech in noise condition. The waveform (left panel) and the spectrum (right panel) of a sentence in a). Cafeteria noise, b). Fan noise, c). Speech babble, d). Traffic noise & e). White noise, with different noise reduction conditions, NR OFF (black), NR minimum (yellow), NR medium (red) and NR maximum (blue), and at three SNRs (+5 dB top panel, 0 dB middle panel, & -5 dB bottom panel).

The decrease in noise levels at NR max (depicted in blue colour in the Figures 4.3 and 4.4) can be observed predominantly for white noise followed by traffic noise and fan noise for both HA 1 and HA 2. However, no distinctions can be made across the NR gradations for cafeteria noise and speech babble. In addition, the decrease in noise levels was seen distinctly at +5 dB SNR than at 0 and -5 dB input SNR. Further, the amount of noise reduction in HA 1 was relatively higher than HA 2 for white noise, traffic noise, and fan noise at NR max.

Effect of NRA on WADA-SNR

The following section represents the SNRs in the output of the hearing aid assessed through WADA-SNR. This was done with speech and noise as the input for five different types of noise with three input SNRs for the two hearing aids (HA 1 & HA 2) with NR OFF and NR ON at three gradations (NR min, NR med, & NR max). The results have been elucidated for each hearing aid.

Results from the Figure 4.5 illustrates the WADA-SNR for different types of noise, with NR OFF, NR min, NR med, and NR max; and three input SNRs (+5, 0, & -5 dB) for HA 1. The Figure 4.5 reveals that the SNR at the hearing aid output was higher (increased) with NR ON compared to NR OFF condition for all the types of noise. Among the three NR gradations, NR max gradation brought about the highest SNR followed by the NR med and NR min gradations. The NR min gradation had the least effect on the noise, i.e., NR ON at minimum gradations was almost equivalent to NR OFF condition. This was true for all the five types of noise. Among the different types of noise, the improvement in SNR with NR max was least for speech babble compared to other types of noise in the study.



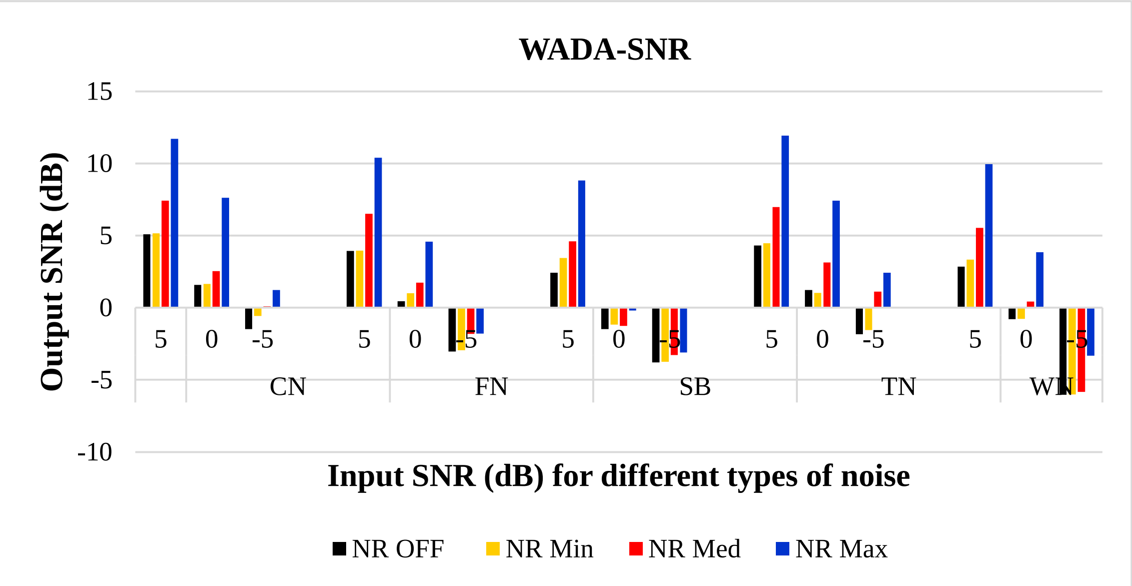
Note: CN - Cafeteria noise, FN - Fan noise, SB - Speech babble, TN - Traffic noise, WN - White noise

Figure 4.5. WADA-SNR in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 1.

It is apparent from Figure 4.5 that the WADA-SNR is increasing with corresponding increase with the input SNR. The output SNR was reducing with poor input SNR (-5 dB). However, with an input SNR of -5 dB and NR max gradation, the output SNR improved for cafeteria noise, fan noise, traffic noise and white noise. This improvement in SNR was greater for cafeteria noise followed by traffic noise and fan noise. From this it can be assumed that the NR max gradation would aid in improving the SNR at the hearing aid output even when the input SNRs are poor.

However, for speech babble, the SNR at the output was better at +5 dB input SNR and there was a drastic drop in the output SNR at 0 dB input SNR. Though, the output SNRs became very poor at -5 dB SNRs even with NR max, for speech babble, the SNR at the output was better than the SNR at the input of the hearing aid with NR med and NR max gradations. The SNR was poorer at the output compared to the input for white noise at an input SNR of -5dB in NR OFF and NR min gradations.

The results from the Figure 4.6 demonstrates the WADA-SNR for different types of noise, with NR OFF and NR ON at three gradations (NR min, NR med, & NR max); and three input SNRs (+5, 0, & -5 dB) for HA 2. The results of HA 2 followed a similar pattern as that of HA 1. However, the improvements in overall output SNR were higher in HA 1 than with HA 2. In addition, the output SNR with NR med and NR max in HA 1 was higher than with HA 2. The improvements in output SNR was smaller (less) in HA 2, than in HA 1 at -5 dB input SNR, with NR max gradation for all types of noise. In addition, at 0 dB and -5 dB input SNRs, the output SNRs from HA 2 was lesser than HA 1 for speech babble. The numeric data of WADA-SNR from the output of the hearing aid with HA 1 is provided in Appendix 1 and for HA 2 is provided in Appendix 2.



Note: CN - Cafeteria noise, FN - Fan noise, SB - Speech babble, TN - Traffic noise, WN - White noise

Figure 4.6. WADA-SNR in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 2.

Comparison of SNR (dB) between NR max and NR OFF. Since the maximum benefit with the NR ON was noted at NR max gradation, the amount of improvement in output SNR was computed from SNR at NR max and NR OFF conditions. Results from the Table 4.3 illustrates the difference in SNR (dB) between NR max and NR OFF for HA 1 across the different types of noise and input SNRs.

Results from the Table 4.3, it can be noted that the maximum improvements in output SNR was seen for the fan noise followed by cafeteria noise and traffic noise for HA 1. The least improvement in output SNR was seen for the speech babble. With decrease (worsening) in the input SNRs, the output SNRs for cafeteria noise and traffic noise did not worsen as much compared to fan noise and speech babble. The output SNR for speech babble worsened drastically with decrease in the input SNR. Even in challenging input SNRs, the output SNR was better for cafeteria, traffic noise, and white noise compared to speech babble and fan noise.

Table 4.3.
Output SNR (dB) with NR OFF and NR Max and the difference in SNR (in dB) for five different types of noise, between NR max and NR OFF for different input SNRs (+5, 0, & -5 dB) with HA 1.

Types of noise	**Difference in output SNR (in dB) (NR max - NR OFF)**		
	+5 dB SNR	**0 dB SNR**	**-5 dB SNR**
Cafeteria noise	6.62	6.04	5.46
Fan Noise	7.44	5.51	2.08
Speech Babble	5.61	0.1	0.12
Traffic Noise	6.27	5.48	4.06
White Noise	7.99	6.65	4.73

Similar results were seen for HA 2. With reference to HA 1, with decrease (worsening) in the input SNRs, the output SNRs of all the types of noise worsened with HA 2 also. The output SNRs were higher with HA 1 than HA 2 for all types of noise. Further, though cafeteria noise, fan noise, traffic noise, and white noise showed a gradual decrease in output SNR, speech babble had a drastic reduction in the output SNR as the input SNRs decreased in both HA 1 and HA 2. Table 4.4 illustrates the same.

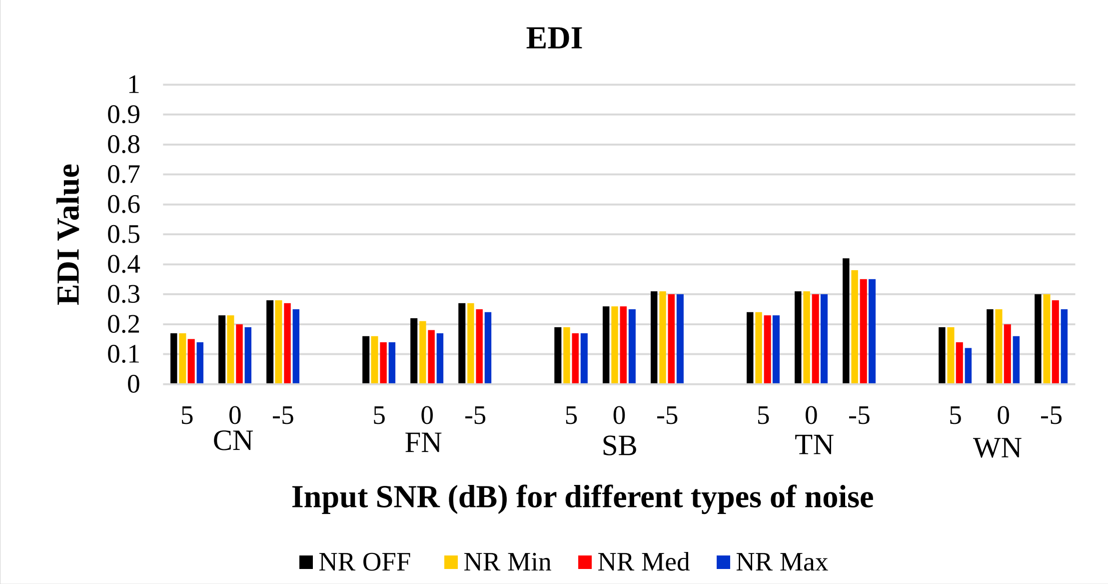
Table 4.4.
Output SNR (dB) with NR OFF and NR Max and the difference in SNR (in dB) for five different types of noise, between NR max and NR OFF for different input SNRs (+5, 0, & -5 dB) with HA 2.

Types of noise	**Difference in output SNR (dB) (NR max - NR OFF)**		
	+5 dB SNR	**0 dB SNR**	**-5 dB SNR**
Cafeteria noise	6.62	6.04	2.71
Fan Noise	6.47	3.59	1.14
Speech Babble	5.38	0.97	0.7
Traffic Noise	7.47	6.39	4.26
White Noise	7.1	4.65	2.71

Effect of NRA on EDI

The following section gives the results of temporal variations as measured through EDI. The EDI was measured between the speech (sentence) without being processed by the hearing aid (unprocessed speech) and the hearing aid output for speech (sentence) in noise condition, with NR OFF and NR ON at three gradations (NR min, NR med, & NR max); for five different types of noise with three input SNRs, for the two hearing aids (HA 1 & HA 2). The results have been provided with different types of noise, NR gradations, and the three input SNRs for each hearing aid.

Figure 4.7 gives the EDI for different types of noise at NR OFF and NR ON at three gradations (NR min, NR med, & NR max); with three input SNRs. It must be noted that the EDI ranges from 0 to 1, a lower EDI value (nearing 0) indicates perfectly similar envelopes and a higher EDI value (nearing 1) indicates completely dissimilar envelopes.



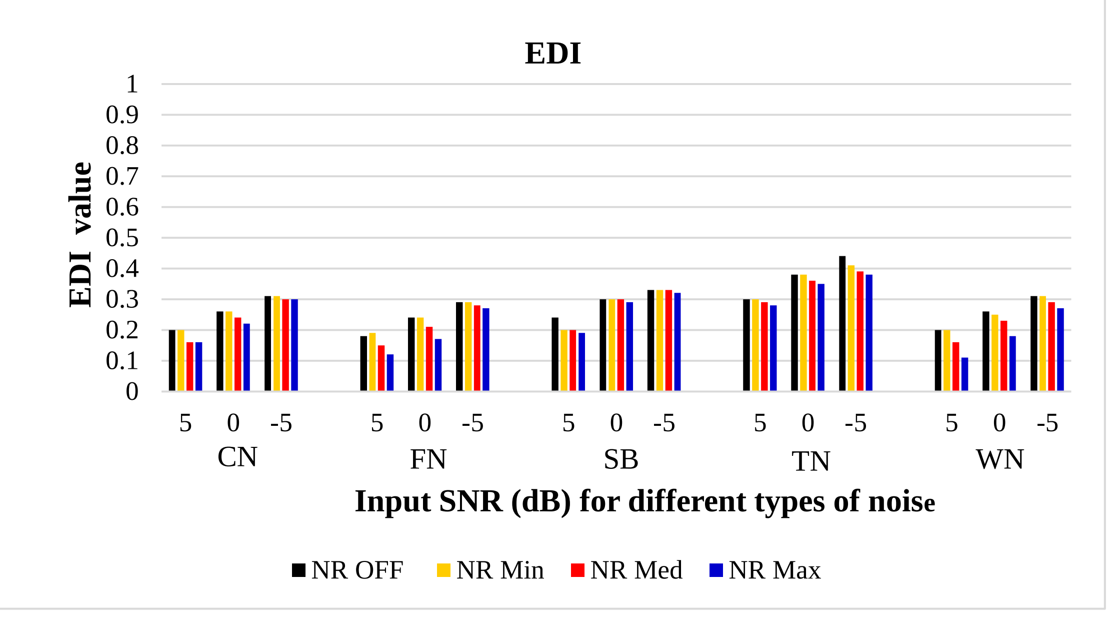
Note: CN - Cafeteria noise, FN - Fan noise, SB - Speech babble, TN - Traffic noise, WN - White noise

Figure 4.7. EDI in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 1.

Results from the Figure 4.7 reveals that the EDI values were lower with NR ON as against NR OFF condition, for all the types of noise. Among the three NR gradations, the NR max gradation showed lowest EDI values than NR med and NR min i.e., NR max better than NR med which in turn was better than NR min. The NR min gradation was almost equivalent to NR OFF condition for all the types of noise. When the traffic noise was the input, the EDI values were higher than all the other types of noise.

Across the input SNRs, it can be noted that the EDI values were lower at +5 dB input SNR than at -5 dB for all the types of noise. Though the EDI values were increasing (compared to +5 & 0 dB input SNR) with poor SNR (-5 dB input SNR), with NR max gradation, the EDI values were lower for all the types of noise except for speech babble. Lower EDI values at poor input SNRs was observed for traffic noise followed by white noise and fan noise. From this it can be construed that NR max gradation would assist in preserving the temporal envelope of the speech even if the input SNRs are poor.

Similar and comparable results were obtained with HA 2. The results have been given in Figure 4.8. The numeric data of EDI from the output of the hearing aid with HA 1 is provided in Appendix 3 and for HA 2 is provided in Appendix 4.



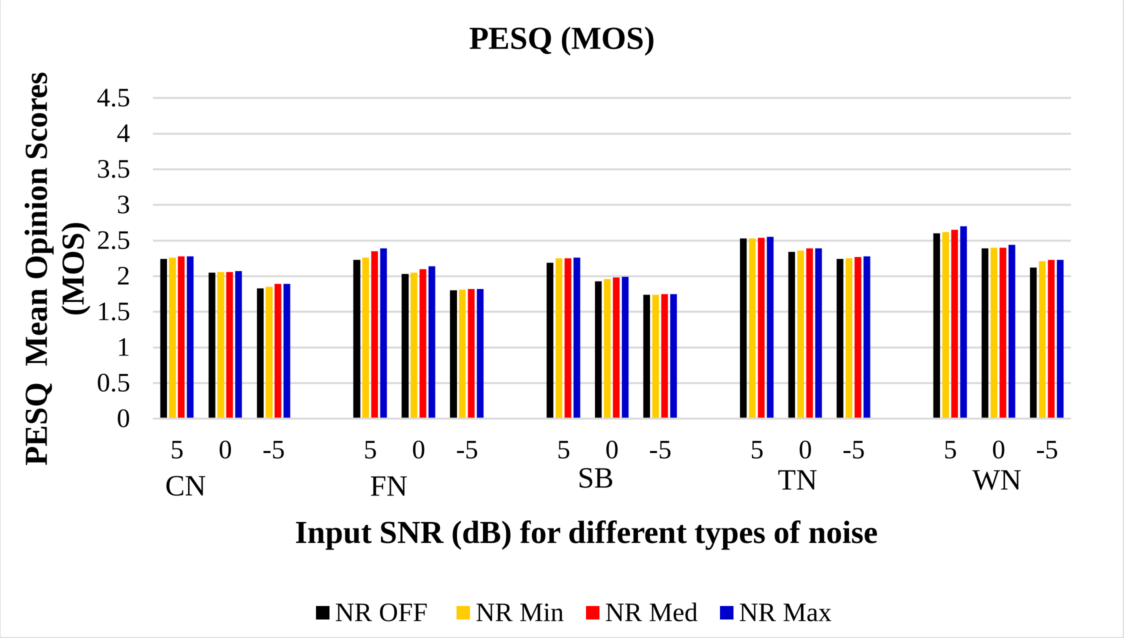
CN- Cafeteria noise, FN- Fan noise, SB- Speech babble, TN- Traffic noise, WN- White noise

Figure 4.8. EDI in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 2.

Effect of NRA on PESQ

The following section reveals the results of speech quality measurements of the hearing aid output, assessed objectively through Perceptual Evaluation of Speech Quality mean opinion scores (PESQ MOS). The PESQ (MOS) was measured between the speech (sentence) without being processed (unprocessed speech) by the hearing aid and the hearing aid output for speech (sentence) in noise condition, with NR OFF and ON (with gradations of NR min, NR med, & NR max) for five different types of noise with three input SNRs for the two hearing aids (HA 1 & HA 2). The results have been provided for different noise, NR gradations and the three input SNRs for each hearing aid. It can be recalled that the PESQ (MOS) provides a value between 0 and 4.5, with a PESQ (MOS) value closer to 4.5 indicating that the target speech is the same as unprocessed speech in terms of quality.

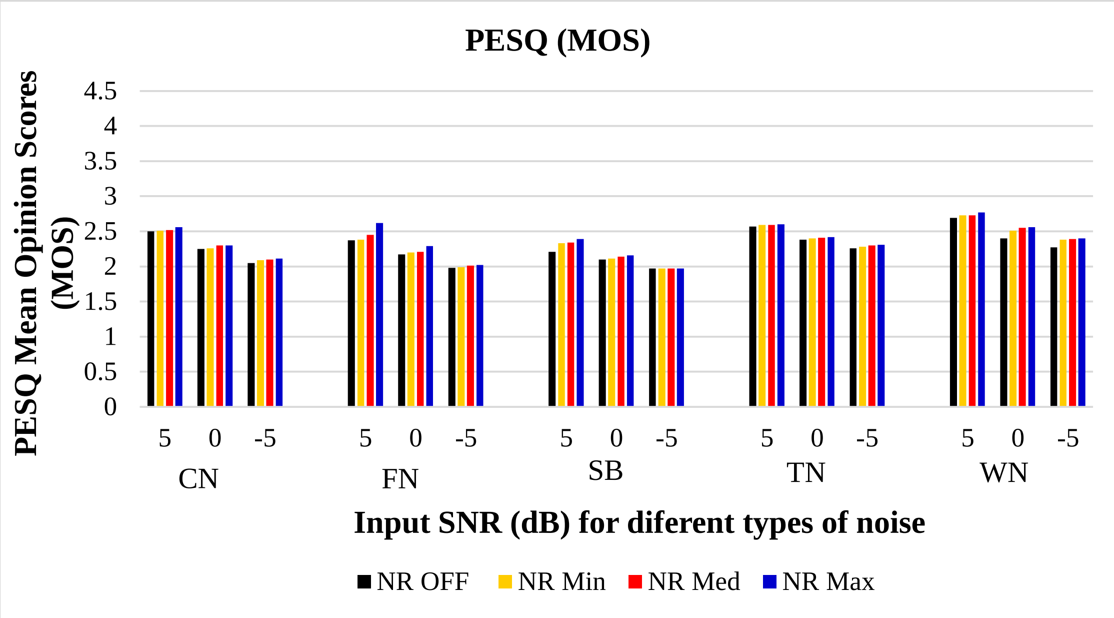
Results from the Figure 4.9 illustrates the PESQ mean opinion scores (PESQ MOS) for different types of noise with NR OFF and NR ON at three gradations (NR min, NR med, & NR max); and three input SNRs (+5, 0 & -5 dB) for HA 1. In contrast to the WADA-SNR and EDI, the MOS of PESQ did not show a trend across the NR gradations. The NR OFF condition was almost equivalent to NR ON at all the three gradations (NR min, NR med, & NR max) for cafeteria noise, speech babble, and traffic noise. However, there was a slight improvement in the PESQ (MOS) for fan noise and white for NR max only at +5 dB input SNR. Overall, PESQ (MOS) was better for white noise, fan noise, and cafeteria noise than for traffic noise and speech babble.



Note: CN - Cafeteria noise, FN - Fan noise, SB - Speech babble, TN - Traffic noise, WN - White noise

Figure 4.9. PESQ (MOS) in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 1.

On comparison of input SNRs, +5 dB had better PESQ (MOS) than 0 dB and -5 dB. In addition, no changes were seen in the PESQ (MOS) with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) within each input SNR for all the types of noise, except for fan noise and white noise. Similar results were observed with HA 2, which has been shown in Figure 4.10. The numeric data of PESQ (MOS) from the output of the hearing aid with HA 1 is provided in Appendix 5 and for HA 2 is provided in Appendix 6.



CN- Cafeteria noise, FN- Fan noise, SB- Speech babble, TN- Traffic noise, WN- White noise

Figure 4.10. PESQ (MOS) in the presence of five different types of noise with NR OFF, NR minimum, NR medium, and NR maximum; and at three input SNRs (+5, 0, & -5 dB) with HA 2.

Effect of NRA on subjective rating

The data obtained from rating the hearing aid output displayed on the computer monitor by the speech language pathologists (SLPs) were tabulated and analysed. The SLPs were asked to rate the sample (hearing aid output) that was less noisy out of the four samples given. A rating of ‘one’ indicated that the given sample was less noisy and a rating of ‘four’ indicated that the given sample was most noisy. A same rating was utilized if any of the two samples in the group were judged to be the same. Similarly, rating was obtained to judge the sample that had good formant representation on the computer display.

The subjective rating were obtained only from three SLPs. The reliability test of the sample revealed low reliability of the SLP rating for noisiness (Cronbach α ranging between 0.5 & 0.89) and formant representation (Cronbach α ranging between 0.45 & 0.83). In addition speech babble showed the least reliability for noisiness ($\alpha = 0.5$) and for formant representation ($\alpha = 0.45$). Hence, an attempt is made to graphically represent the rating obtained from SLPs and associate the results with some of the objective analysis performed earlier. The samples that were rated for noisiness were compared with the WADA-SNR value and the rating for formant representation was correlated with the EDI value.

Figures 4.11 and 4.12 depict the median values of the rating given by the SLPs for noisiness in the spectrogram of the hearing aid output, in comparison with actual WADA-SNR value for NR OFF and NR ON at three gradations (NR min, NR med, & NR max); for three SNRs (-5, 0, & +5) and five types of noise with HA 1 and HA 2. From the plots it can be noted that as the WADA-SNR value increased across NR gradation, the SLPs rated the sample as less noisy. When the difference between the WADA-SNR values of two NR gradations was less, the SLPs have also rated the two gradations as same (i.e., both gradations sounding equally noisy). As seen in the WADA-SNR, the maximum SNR difference was between NR OFF and NR max. Similarly, the SLPs have rated the NR OFF as more noisy and NR max as less noisy than between the other gradation pairs (NR min & NR med). However, there was a little agreement between the SLPs rating for NR min and NR med gradations. The above results were more evident for cafeteria noise, fan noise, traffic noise, and white noise. However, for speech babble, the similarity with WADA-SNR and SLP rating was evident only at + 5 dB SNR. This trend was seen with both HA 1 and HA 2.

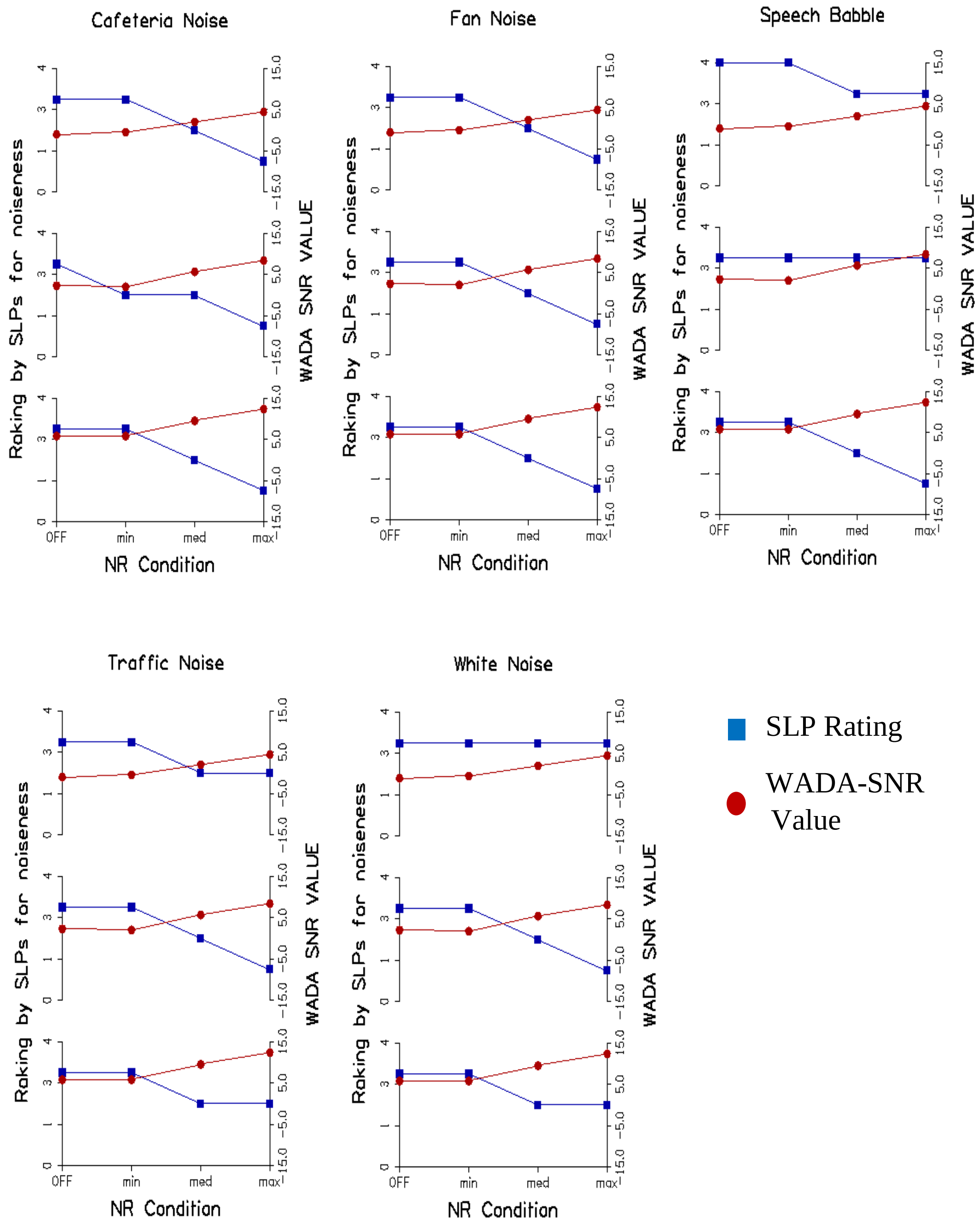


Figure 4.11. The rating by SLPs on noisiness (median) in comparison with WADA-SNR value for NR OFF, NR minimum, NR medium, and NR maximum and at three SNRs (-5 dB top panel, 0 dB middle panel, & +5 dB bottom panel within each noise) in the presence of five different noises with HA 1.

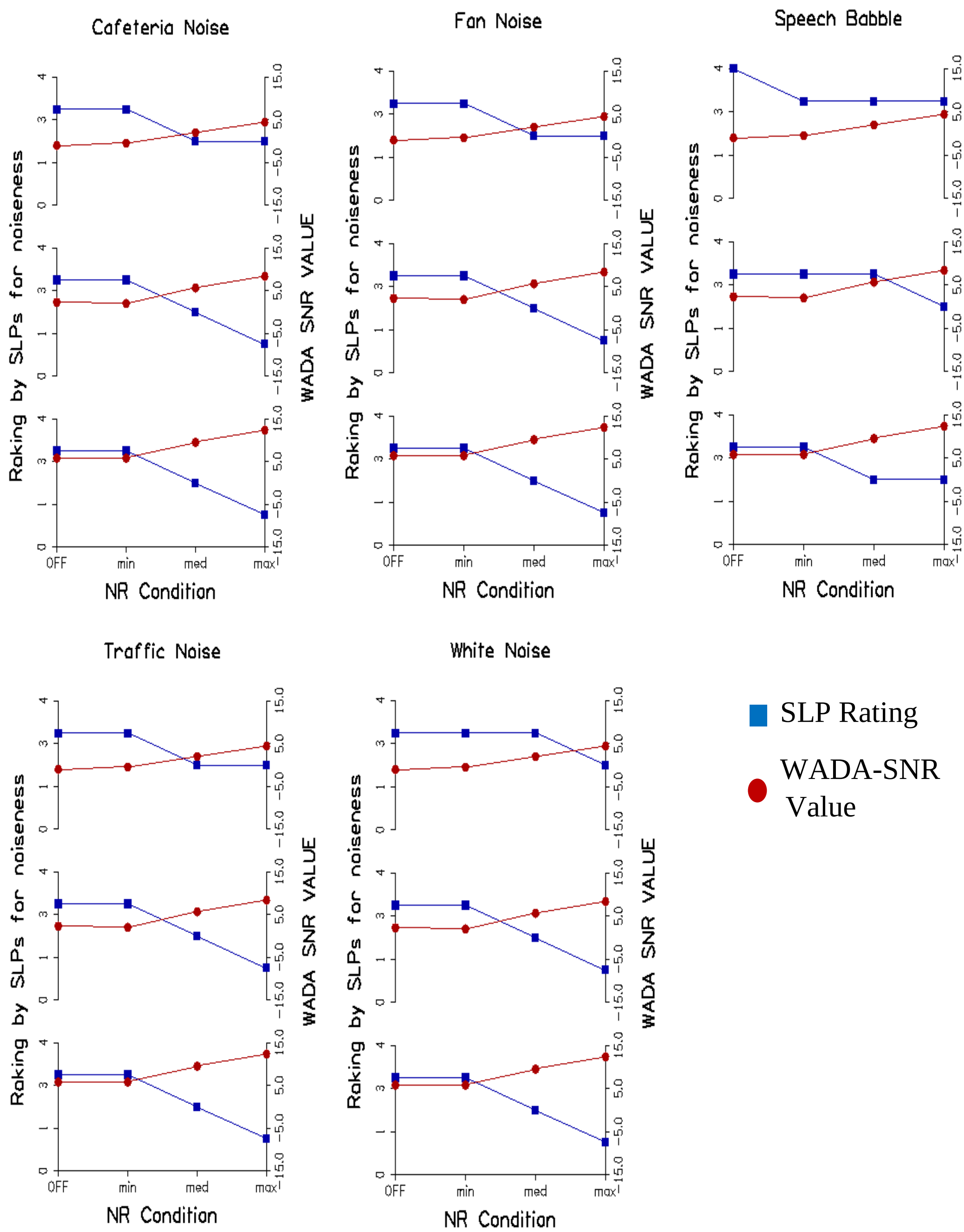


Figure 4.12. The rating by SLPs on noisiness (median) in comparison with WADA-SNR value for NR OFF, NR minimum, NR medium, and NR maximum and at three SNRs (-5 dB top panel, 0 dB middle panel, & +5 dB bottom panel within each noise) in the presence of five different noises with HA 2.

Figures 4.13 and 4.14 depict the rating by SLPs for formant representation of the spectrum at the output of the hearing aid displayed on the computer monitor. This was compared with the EDI value for NR OFF and NR ON at three gradations (NR min, NR med, & NR max); and at three SNRs (-5, 0, & +5) for five types of noise, with HA 1 and HA 2. From the figures it can be noted that as the EDI value decreased across NR gradation, the SLPs rated the sample as having better formant representation. However, as the EDI values are small (range being 0 to 1), this trend cannot be visualised in the figure. From the results reported earlier on EDI, it may be recalled that the EDI values were lower at NR max gradation than at med and min gradations.

When the difference between the EDI values of two NR gradations was less, the SLPs have rated the two gradations as same (both gradations having similar formant representation). As seen in the EDI, the minimum EDI value was for NR ON. The SLPs have also rated NR ON as having better formant representation than the other gradations (NR min & NR med). However, there was little agreement between the SLPs rating for NR min and NR med gradations. The above results were more evident for cafeteria noise, fan noise, traffic noise and white noise. For speech babble, the similarity with EDI and SLP rating was evident only at + 5 dB SNR. This trend was seen with both HA 1 and HA 2.

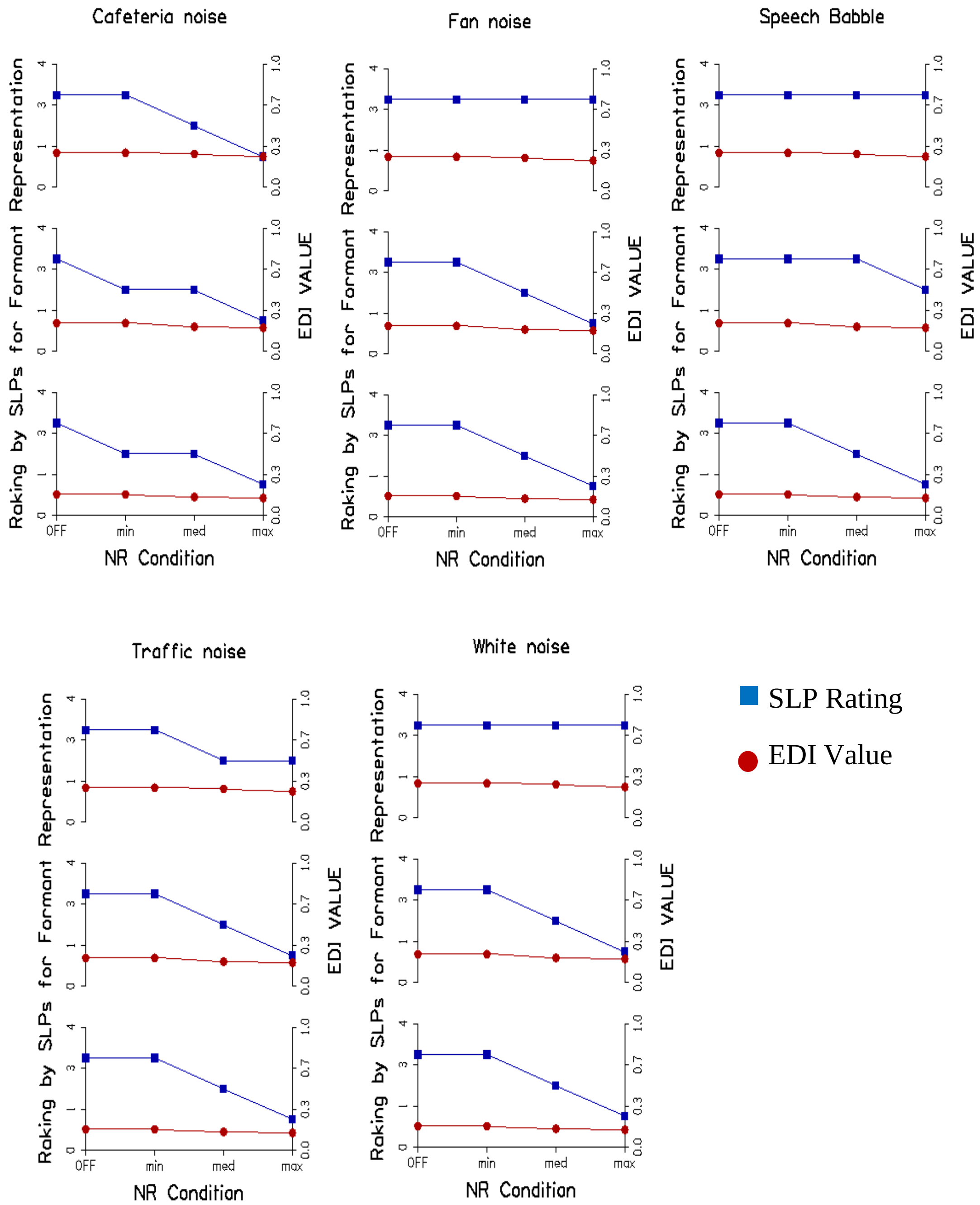


Figure 4.13. The rating by SLPs on formant representation (median) in comparison with EDI value for NR OFF, NR minimum, NR medium, and NR maximum; and at three SNRs (-5 dB top panel, 0 dB middle panel, & +5 dB bottom panel within each noise) in the presence of five different noises with HA 1.

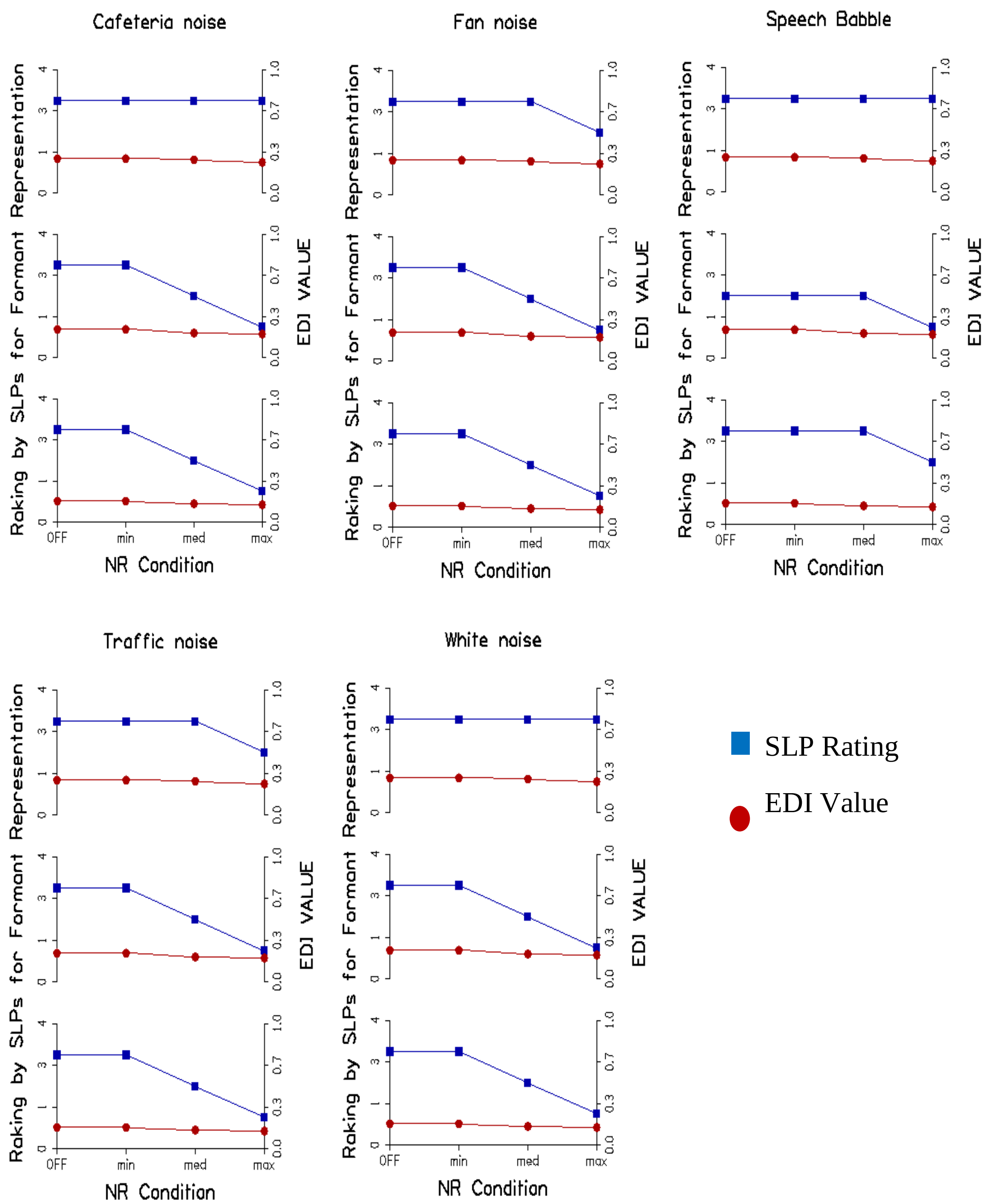


Figure 4.14. The rating by SLPs on formant representation (median) in comparison with EDI value for NR OFF, NR minimum, NR medium, and NR maximum; and at three SNRs (-5 dB top panel, 0 dB middle panel, & +5 dB bottom panel within each noise) in the presence of five different noises with HA 2.

Table 4.5 summarizes the results obtained from Phase I of the study.

Table 4.5.
Summary of results for the effect of NRA using acoustic measures (Phase I).

Condition	Acoustic measure	Statistical tool	Results
Noise only	LAeq & LA90	Descriptive Statistics	1. The overall LAeq (dB) and LA90 (dB) values for NR ON condition was lower than that for NR OFF condition, for all types of noise. 2. NR max had the greatest reduction of noise followed by NR med and NR min 3. The extent of noise reduction (difference in noise reduction between NR max & NR OFF) was highest for traffic noise i.e., 6.9 dB followed by white noise (4.9 dB) and cafeteria noise (4.6 dB). 4. The noise reduction was least for speech babble. 5. Effective noise reduction was observed when the NR in the hearing aid was ON. This reduction was more effective at NR max than at NR med and NR min gradations.
Speech in noise	WADA-SNR, PESQ (MOS), EDI, waveform & spectrogram		**A. Objective analysis** *WADA-SNR* 1. The SNR at the hearing aid output was better (increased) with NR ON compared to NR OFF condition for all the types of noise. 2. The NR max gradation brought about the highest output SNR than the NR med and NR min gradation. 3. At poor input SNR of -5 dB, with NR max gradation, the output SNR improved for cafeteria noise, fan noise traffic noise, and white noise.

4. The output SNRs became very poor at -5 dB SNRs even with NR max for speech babble.

EDI

1. EDI values were lower with NR ON compared to NR OFF condition, for all the types of noise.
2. Among the three NR gradations, the NR max gradation showed lowest EDI values than the NR med and NR min.
3. The EDI values were increasing (compared to +5 & 0 dB input SNR) with poor input SNR. However, with an input SNR of -5 dB, with NR max gradation, the EDI values were lower for all the types of noise except for speech babble.

PESQ

1. PESQ (MOS) did not show a pattern across the NR gradations.

2. NR OFF condition was almost equivalent to NR ON across all the three gradations for cafeteria noise, speech babble, and traffic noise.

3. At input SNRs of +5 dB, the PESQ (MOS) showed slight improvement across NR gradations than at 0 dB and -5 dB SNR.

B. Subjective analysis

1. As the WADA-SNR value increased, the SLPs rated the hearing aid output as less noisy, and they rated formant representation to be better at the output of the hearing aid as EDI values decreased across NR gradations.

	2. When the difference of WADA-SNR between of two NR gradations was less, subjective rating showed that the SLPs rated the hearing aid output of the two gradations as same (i.e., both gradations as equally noisy), and they rated both gradations having similar formant representation as the difference of EDI values decreased between two NR gradations. 3. The rating for cafeteria noise, fan noise, traffic noise, and white noise were rated less noisy than for speech babble.

4.2 Phase II: Effect of NRA on perceptual measures

It can be recalled that the perceptual measures were obtained in noise (cafeteria & traffic) alone condition and in speech in noise condition. These measurements were obtained by quality (loudness) judgement task in noise alone condition; speech identification measures and quality judgement task in speech in noise condition.

The response pattern obtained from the participants for the quality judgement tasks was to choose one among the three options (e.g. NR OFF/ NR min/ both are same) provided by the researcher. To analyse this data, non-parametric McNemar test was chosen. McNemar test was performed individually on each pair with the three noise gradations, for the quality judgement tasks in noise alone condition and speech in noise condition. The raw data were further re-arranged to perform the McNemar test. The Table 4.6 illustrates the arrangement for McNemar test.

Table 4.6.
Illustration of data arrangement for performing McNemar test.

Pair-wise quality judgement	**Options given to the participants**	**Participant's choice**	**Pattern of scoring**	
			NR OFF	**NR max**
NR OFF – NR max	NR OFF / NR max/ both are same	NR OFF	1	0
NR OFF – NR max	NR OFF / NR max/ both are same	NR max	0	1
NR OFF – NR max	NR OFF / NR max/ both are same	Same	1	1

The pattern of scoring is illustrated in Table 4.6. The sample of the data for different pair-wise conditions to run the McNemar test is given in Table 4.7.

Table 4.7.
Sample of Illustration of the data for McNemar.

Participant no.	Illustration 1		Illustration 2		Illustration 3	
	OFF	Max	OFF	Med	OFF	Min
1.	0	1	1	1	1	1
2.	0	1	0	1	1	1
3.	0	1	1	1	0	1
4.	0	1	0	1	1	1
5.	0	1	1	1	1	1
6.	0	1	0	1	0	1

Note: 0 = not preferred; 1 = preferred

The illustration is provided only for six participants. In the Illustration 1, it can be noted that all six participants preferred NR max. In illustration 2, three participants preferred NR med only and three of them indicated that both NR OFF and NR med as same. None of them preferred NR OFF only. In illustration 3, two participants preferred NR min only and four of them indicated that both NR OFF and NR min as same. None of them preferred NR OFF only. Likewise, the data from participants in normal hearing (NH) group and hearing impairment (HI) group were arranged across six pairs (NR OFF - NR min, NR OFF - NR med, NR OFF - NR max, NR max - NR min; NR max - NR med, NR med - NR min). This was done for all the quality judgment tasks namely, loudness judgment for noise (LJN), quality judgment for clarity (QJC), quality judgment for noise (QJN), and overall preference (OP). The

McNemar test was run for all the six pairs individually for each quality judgment task. If a pair in the McNemar test is significant, then it suggests that either one sample among the pair was preferred more than the other.

4.2.1 Phase IIA: Effect of NRA on perceptual measure in noise only condition

The results of the effect of NRA on perceptual measure in noise only condition is elaborated for group with normal hearing group (NH group) and group with hearing impairment (HI group).

Effect of NRA on overall loudness, in noise only condition, in NH group

The data on loudness judgment for noise only condition (LJN) were tabulated for cafeteria noise and traffic noise with HA 1 and HA 2. The response for loudness judgment was to choose one among the three choice given to the participants, i.e., the participants were to choose the sample that was less noisy in the given pair. If both the stimulus were equally noisy, the participant had to choose the option 'same'. The results of McNemar test for the loudness judgment task for NH group are given in Table 4.8. Further, results from the Table 4.8 illustrates the percentage (%) of participants (in parentheses) preferring one among the pair (when statistically significant) in the judgment task. e.g.: For the pair NR OFF - NR min, cafeteria noise, and traffic noise had statistically significant difference in the LJN task for NH group. This implies that there was a difference in loudness of noise between the NR OFF - NR min condition for cafeteria noise and traffic noise. When the raw data were analysed, 37.5% of the participants had preferred NR min for cafeteria noise and 50% of the participants had preferred NR min for traffic noise in the LJN task. The difference in percent, i.e., 62.5 % for cafeteria noise and 50% for traffic noise, indicates that the participants had rated the loudness of noise in NR OFF and NR min as the same.

The participants in NH group had preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med. Further, NR med was chosen whenever it was compared with NR min with HA 1 for two types of noise (cafeteria noise & traffic noise). Between the NR OFF and NR min pair, NR min was chosen by the participants. However, the percentage of participants preferring NR min was lower than other pairs with HA 1. This implies that participants could not differentiate the loudness of noise between the NR OFF and NR min pair.

With HA 2, there was no significant difference in the loudness judgment for cafeteria noise between the pair NR OFF and NR min. In traffic noise, though there was significant difference between NR OFF and NR min, it was observed that only 18.7% of the NH participants had preferred NR min and 82.3 % of the participants judged the pair as having same loudness. The same was observed between NR med and NR min pair. Only 40.6 % and 56.2 % participants had chosen NR med and 60.6% and 44.8 % of the participants had judged the pair as having same loudness for cafeteria noise and traffic noise respectively. Further, all the other pairs (NR OFF - NR med, NR OFF - NR max, NR max - NR min, NR max - NR med) had significant difference between the conditions for both cafeteria and traffic noise.

Table 4.8.

Significant difference in loudness judgement for noise (LJN) in the presence of cafeteria and traffic noise among the pairs of NR gradation with HA 1 and HA 2, in NH group, on McNemar test.

	NH group			
Pairs of aided conditions	**HA 1**		**HA 2**	
	Cafeteria Noise	**Traffic Noise**	**Cafeteria Noise**	**Traffic Noise**
NR OFF - NR min	S (37.5%) NR min > NR OFF	S (50%) NR min > NR OFF	NS	S (18.7%) NR min > NR OFF
NR OFF - NR med	S (100%) NR med > NR OFF	S (96.8%) NR med > NR OFF	S (84.3%) NR med > NR OFF	S (93.7%) NR med > NR OFF
NR OFF - NR max	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF
NR max - NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min
NR max - NR med	S (100%) NR max > NR med	S (96.8%) NR max > NR med	S (87.5%) NR max > NR med	S (96.8%) NR max > NR med
NR med - NR min	S (78.1 %) NR med > NR min	S (84.3%) NR med > NR min	S (40.6 %) NR med > NR min	S (56.2%) NR med > NR min

Note: S-significant difference ($p<0.05$), NS- No significant difference ($p>0.05$); 100% indicates that all the participants preferred the greater value condition; in case of value less than 100% indicates those many percentage of participants preferred the greater sign (>) condition and the rest of the participants judged that both the aided conditions in the pair were same in terms of LJN

Effect of NRA on overall loudness, in noise only condition, in HI group

Results from the Table 4.9 illustrates the percentage (%) of participants (in parentheses) preferring one among the pair (when statistically significant) in the loudness judgment task. For example, for the pair NR OFF and NR min, cafeteria noise and traffic noise had statistically significant difference in the LJN task for HI group. The participants in HI group judged the NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med. However, the percentage of participants choosing NR max in the NR max and NR med pair was drastically lower than that observed for NH group. A similar trend was seen with the NR med and NR min pair. This implies that most of the participants in HI group could not differentiate the loudness of noise between the NR max and NR med; and NR med and NR min pairs. There was no significant difference in loudness for the NR OFF and NR min pair. This implies that the participants in HI group could not differentiate the loudness of noise between the NR OFF and NR min pair. These findings were true for HA 1 for both cafeteria noise and traffic noise.

Table 4.9.
Significant difference in loudness judgement for noise (LJN) in the presence of cafeteria and traffic noise among the pairs of NR gradation with HA 1 and HA 2, in HI group, on McNemar test.

Pairs of aided conditions	**HI group**			
	HA 1		**HA 2**	
	Cafeteria Noise	**Traffic Noise**	**Cafeteria Noise**	**Traffic Noise**
NR OFF - NR min	NS	NS	NS	NS
NR OFF - NR med	S (76.6%) NR med > NR OFF	S (76.6%) NR med > NR OFF	S (30%) NR med > NR OFF	S (30%) NR med >NR OFF
NR OFF - NR max	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (96.6%) NR max > NR OFF	S (100%) NR max > NR OFF
NR max - NR min	S (96.6%) NR max > NR min	S (96.6%) NR max > NR min	S (86.6%) NR max > NR min	S (86.6%) NR max > NR min
NR max - NR med	S (46.6%) NR max > NR med	S (40%) NR max > NR med	NS	NS
NR med - NR min	S (50%) NR med > NR min	S (36.6%) NR med > NR min	NS	NS

Note: S-significant difference ($p<0.05$), NS- No significant difference ($p>0.05$); 100% indicates that all the participants preferred the greater value condition; in case of value less than 100% indicates those many percentage of participants preferred the greater sign (>) condition and the rest of the participants judged that both the aided conditions in the pair were same in terms of LJN

With HA 2, there was a significant difference between the pairs NR OFF and NR max, and, NR max and NR min pair for both cafeteria and traffic noise. This suggests that NR max was chosen by the HI participants whenever it was compared with NR OFF and NR min. Though there was a significant difference in NR OFF and NR med pair, only 30% of the participants preferred NR med. There was no significant difference across all the other pairs of NR with HA 2 for both cafeteria and traffic noise.

To brief, participants in both NH group and HI group preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med. This was true with both HA 1 and HA 2, and two types of noise (cafeteria noise & traffic noise).

4.2.2 Phase IIB: Effect of NRA on speech perception in noise

The data on the effect of NR on speech perception in noise, speech identification testing, and quality judgment tasks were tabulated. The results have been given separately for each group (NH & HI) for two hearing aids across NR OFF and NR ON at three gradations (NR min, NR med, & NR max); for cafeteria noise and traffic noise.

Effect of NRA on speech identification measures in NH group

To study the effect of NRA on speech perception in noise, speech identification scores (SIS) and quality judgment were collected from participants in NH group. The Shapiro-Wilk's test of normality revealed that the data did not assume normal distribution ($p<0.05$). Hence, non-parametric test was indicated to test the main effect of NRA on speech identification measures for NH group.

The speech identification scores (SIS) obtained at 0 dB SNR for cafeteria noise and traffic noise with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) were tabulated and analyzed. Results from the Table 4.10 illustrates the mean, median and standard deviation of SIS values for cafeteria noise and traffic noise, with NR OFF and NR ON at three gradations (NR min, NR med, & NR max). The maximum SIS was 40, the SIS was retained as raw score and was not converted into percentage.

Table 4.10.

Mean, median, and standard deviation (SD) of speech identification scores (SIS, Max=40) in the presence of cafeteria noise and traffic noise with NR OFF and NR ON across gradation in NH group with HA 1 and HA 2.

Test condition		SIS at 0 dB SNR (Max. = 40)					
		HA 1			HA 2		
		Mean	Median	SD	Mean	Median	SD
CN	NR OFF	38.25	38.00	0.80	38.40	39.00	0.83
	NR min	38.40	39.00	0.79	38.46	39.00	0.80
	NR med	38.50	39.00	0.76	38.68	39.00	0.69
	NR max	38.81	39.00	0.69	38.90	39.00	0.92
TN	NR OFF	38.93	39.00	0.56	38.84	39.00	0.72
	NR min	38.96	39.00	0.78	38.71	39.00	0.68
	NR med	38.90	39.00	0.85	39.09	39.00	0.73
	NR max	39.25	39.00	0.71	39.31	40.00	0.89

Note: CN-Cafeteria noise; TN-Traffic noise; HA- Hearing aid

From the results enumerated in Table 4.10, it can be noted that there was a negligible improvement in the mean SIS in different NR gradations. Overall, the mean

SIS was better with NR max gradation than at NR OFF condition for both the types of noise and with the two hearing aids.

To test if the difference in SIS scores was significant across different NR gradations, non-parametric Friedman's test was performed. Comparisons were made between the NR OFF and NR ON at three gradations (NR min, NR med, & NR max); for each type of noise with each hearing aid separately. The results of Friedman's test are provided in Table 4.11. The results from the Friedman's test indicated that there was a significant main effect seen in the SIS across the NR gradations for each type of noise (cafeteria noise & traffic noise) and with each hearing aid (HA 1 & HA 2).

Table 4.11.
Significant difference in SIS in the presence of cafeteria and traffic noise across NR gradations with HA 1 and HA 2 in NH group, on Friedman's test.

Condition		χ^2	**df**	**p**
HA 1	**CN**	35.027	3	0.000*
	TN	8.964	3	0.030**
HA 2	**CN**	15.811	3	0.001**
	TN	26.417	3	0.000*

CN- cafeteria noise, TN- traffic noise; HA- hearing aid, χ^2-Chi-squre value
* Significant at 0.001 level (p<0.001).

In order to study the NR gradation that was significantly different within each type of noise, Wilcoxon's signed rank test was administered. The results of Wilcoxon's signed rank test have been provided in Table 4.12. The 'Z' and 'p' values of Wilcoxon's signed rank test are provided in Appendix 7.

Table 4.12.
Significant difference in SIS, in the presence of cafeteria noise and traffic noise in NH group, between the NR gradations with HA 1 and HA 2 on Wilcoxon's signed rank test.

Noise	Test condition	HA 1			HA 2		
		NR min	NR med	NR max	NR min	NR med	NR max
CN	NR OFF	NS	S*	S**	NS	S*	S**
	NR min		NS	S**		NS	S**
	NR med			S**			NS
	NR max						
TN	NR OFF	NS	NS	S**	NS	S*	S**
	NR min		NS	S*		S**	S**
	NR med			S*			NS
	NR max						

Note: CN-Cafeteria noise; TN-Traffic noise; HA- Hearing aid; NS- Not Significant; S- Significant; * ($p<0.05$), ** ($p<0.01$)

The results of Wilcoxon's test revealed that there was a significant difference in the SIS between the pairs NR OFF and NR max, and, NR max and NR min for both the hearing aids, for cafeteria noise and traffic noise ($p<0.01$). That is, SIS scores were higher with increase in NR gradation from NR OFF to NR max. In addition, there was a significant difference in the SIS between the pairs NR max and NR med for cafeteria noise and traffic noise only for HA 1 ($p<0.01$). Further, there was a significant difference between the pairs NR OFF and NR med for cafeteria noise in HA 1 and for traffic noise with HA 2. However, the SIS for the pair NR med and NR min was significantly different only for traffic noise with HA 2.

Effect of NRA on quality judgment in NH group

As discussed in the noise only condition, the data obtained from the quality judgment task, were tabulated to perform McNemar test (Table 4.13). The subjective judgment tasks included quality judgment for clarity (QJC), quality judgment for noise (QJN), and overall preference (OP). On similar lines of LJN, if a pair is significant in a QJC task, then it implies that there was a difference in clarity of speech in the presence of noise between the gradations in a particular pair. If a pair is significant in QJN task, then it suggests that there is a difference in perceived noisiness between the gradations in a particular pair. Similarly, if a pair is significant in OP, then there is a difference in overall preference of the sample. Table 4.13 enumerates the results of quality judgment task for participants in NH group for cafeteria noise and traffic noise, with HA 1 and HA 2. In addition, the table illustrates the percentage (%) of participants (in parentheses) preferring one among the pair (when statistically significant) in the judgment task.

Table 4.13.

Significant difference and percentage (%) of participants (in parenthesis) preferring one among the pair on QJC, QJN, OP tasks among the pairs of NR gradation, with HA 1 and HA 2, in NH group, on McNemar test.

Pairs of aided conditions	**HA 1**						**HA 2**					
	QJC		**QJN**		**OP**		**QJC**		**QJN**		**OP**	
	CN	**TN**	**CN**	**TN**	**CN**	**TN**	**CN**	**TN**	**CN**	**TN**	**CN**	**TN**
NR OFF - NR min	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
NR OFF - NR med	S (84.3%) NR med > NR OFF	S (90.6%) NR med > NR OFF	S (87.5%) NR med > NR OFF	S (96.8%) NR med > NR OFF	S (78.1%) NR med > NR OFF	S (90.6%) NR med > NR OFF	S (59.3%) NR med > NR OFF	S (81.2%) NR med > NR OFF	S (65.6%) NR med > NR OFF	S (90.6%) NR med > NR OFF	S (40.6%) NR med > NR OFF	S (71.8%) NR med > NR OFF
NR OFF - NR max	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF
NR max - NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (96.8%) NR max > NR min
NR max - NR med	S (93.7%) NR max > NR med	S (96.8%) NR max > NR med	S (90%) NR max > NR med	S (100%) NR max > NR med	S (93.7%) NR max > NR med	S (96.8%) NR max > NR med	S (96.8%) NR max > NR med	S (96.8%) NR max > NR med	S (100%) NR max > NR med	S (96.8%) NR max > NR med	S (93.7%) NR max > NR med	S (90.6%) NR max > NR med

NR med - NR min	S (46.8%) NR med > NR min	S (68.7%) NR med > NR min	S (71.8%) NR med > NR min	S (84.3%) NR med > NR min	S (43.7%) NR med > NR min	S (78.1%) NR med > NR min	NS	S (46.8%) NR med > NR min	NS	S (53.1%) NR med > NR min	NS	S (43.7%) NR med > NR min

Note: S-significant difference (p<0.05), NS- No significant difference (p>0.05);

QJC - Quality judgment for clarity, QJN - Quality judgment for noise, OP - overall preference.

100% indicates that all the participants preferred the greater sign (>) condition; in case of value less than 100% indicates those many percentage of participants preferred the greater value condition and the rest of the participants judged that both the aided conditions in the pair were same.

There was a significant difference among all the pairs of noise reduction except for NR OFF and NR min. This indicates that there was no significant perceptual difference in the clarity and noisiness between the NR OFF and NR min conditions. This was true for both cafeteria noise and traffic noise with HA 1 in all the quality judgment tasks. When the data were compared across the gradation with HA 1, the NR max was chosen whenever it was compared with NR OFF, NR min and NR med; NR med was chosen whenever it was compared with NR min for both cafeteria noise and traffic noise. When the NR max was compared with NR min and NR OFF conditions, 100% of the participants preferred the NR max. This implies that when speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was clearer and less noisy than other conditions.

With HA 2, there was a significant difference among all the pairs of noise reduction except for NR OFF and NR min. This was true only for traffic noise with HA 1 across all the quality judgment tasks. However, for cafeteria noise, there was no significant difference for the NR med and NR min pair in addition to NR OFF and NR min. Though there was a significant difference for the NR med and NR min pair with traffic noise, the percentage of participants preferring NR med was lower than with HA 1.

Effect of NRA on speech identification measure in HI group

To study the effect of NRA on speech perception in noise, data on SNR-50 and quality judgment tasks were tabulated and analysed for participants in HI group. Shapiro-Wilk's test of normality revealed that the data did not assume normal distribution ($p<0.05$). Hence, non-parametric test was indicated to test the main effect of NRA on speech identification measures for HI group. The data on SNR-50 in the presence of cafeteria noise and traffic noise with NR OFF and NR ON at three gradations (NR min, NR med, & NR max) were tabulated for participants in HI group. Table 4.14 illustrates the mean, median, and standard deviation values of SNR-50 for cafeteria noise and traffic noise with NR OFF and NR ON at three gradations (NR min, NR med, & NR max).

Table 4.14.
Mean, median, and standard deviation (SD) of SNR-50 values in the presence of cafeteria noise and traffic noise with NR OFF and NR ON across gradation in HI group HA 1 and HA 2.

SNR- 50 (dB)							
Test Condition		**HA 1**			**HA 2**		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**
CN	**NR OFF**	4.86	5.00	2.72	5.06	5.00	2.75
	NR min	4.66	5.00	2.83	4.93	5.00	2.80
	NR med	3.23	3.00	2.99	4.53	4.00	2.90
	NR max	2.33	3.00	2.84	3.20	3.00	2.79
TN	**NR OFF**	4.66	5.00	3.24	4.80	5.00	2.74
	NR min	4.46	5.00	3.27	4.80	5.00	2.74
	NR med	3.03	3.00	3.20	4.53	5.00	2.81
	NR max	2.00	3.00	3.26	2.93	3.00	2.59

Note: CN-Cafeteria noise; TN-Traffic noise; HA- Hearing aid

From the results enumerated in Table 4.14 it can be noted that the mean SNR-50 improved with different NR gradations. The NR max had better SNR-50 (lower) than the NR OFF, with cafeteria noise and traffic noise, for both HA 1 and HA 2. Further, between the two hearing aids, the SNR-50 with HA 1 was better than with HA 2. Overall, SNR-50 was better with NR max than at NR OFF for both the types of noise across the two hearing aids.

To test if the SNR-50 values differed significantly across NR gradations, non-parametric Friedman's test was performed. Comparisons were made between the NR OFF and NR ON at three gradations (NR min, NR med, & NR max) for each type of noise with each hearing aid separately. The results are tabulated in Table 4.15.

Table 4.15.
Significant difference in SNR-50 in the presence of cafeteria and traffic noise across NR gradations with HA 1 and HA 2 in HI group, on Friedman's test.

Condition		χ^2	**df**	**p**
HA 1	**CN**	74.092	3	.000*
	TN	75.151	3	.000*
HA 2	**CN**	62.168	3	.000*
	TN	74.182	3	.000*

CN- cafeteria noise, TN- traffic noise; HA- hearing aid, χ^2-Chi-squre value
* Significant at 0.001 level (p<0.001).

The results from the Friedman's test indicated that there was a significant main effect seen in the SNR-50 values across the NR gradations for each types of noise (cafeteria noise & traffic noise), in each of the hearing aid. In order to study the NR gradation that was significantly different within each type of noise, Wilcoxon's signed rank test was administered. The results of Wilcoxon's signed rank test have been tabulated in Table 4.16. The 'Z' & 'p' values of Wilcoxon's signed rank test are provided in Appendix 8.

Table 4.16.
Significant difference in SNR-50, in the presence of cafeteria noise and traffic noise in HI group, between the NR gradations with HA 1 and HA 2 on Wilcoxon's signed rank test.

Noise	Test condition	HA 1			HA 2		
		NR min	NR med	NR max	NR min	NR med	NR max
CN	NR OFF	NS	S**	S**	NS	S*	S**
	NR min		S**	S**		S*	S**
	NR med			S**			S**
	NR max						
TN	NR OFF	NS	S**	S**	NS	S*	S**
	NR min		S**	S**		S*	S**
	NR med			S**			S**
	NR max						

Note: CN-Cafeteria noise; TN-Traffic noise; HA- Hearing aid, NS- Not Significant; S- Significant; * ($p<0.05$), ** ($p<0.01$)

The results of Wilcoxon's test revealed that there was a significant difference in the SNR-50 scores between all the pairs, except for the pair NR OFF and NR min, for both the hearing aids (HA 1 & HA 2). That is, SNR-50 scores were higher with increase in NR gradation from NR OFF to NR max. This was true for both cafeteria noise and traffic noise.

Effect of NRA on quality judgment in HI group

As discussed in the noise only condition, the data obtained from the quality judgment task, were tabulated to perform McNemar test (Table 4.17). Judgment tasks included quality judgment for clarity (QJC), quality judgment for noisiness (QJN) and overall preference (OP). On similar lines of LJN, if a pair is significant in a QJC task, then it implies that there was a difference in clarity of speech in the presence of noise between the gradations in the pair. If a pair is significant in QJN task, then it suggests that there is a difference in perceived noisiness between the gradations in the pair. Similarly, if a pair is significant in OP, then there is a difference in overall preference of the sample.

Table 4.17.

Significant difference and percentage (%) of participants (in parenthesis) preferring one among the pair on QJC, QJN, OP tasks among the pairs of NR gradation, with HA 1 and HA 2, in HI group, on McNemar test.

Pairs of aided conditions	HA 1						HA 2					
	QJC		QJN		OP		QJC		QJN		OP	
	CN	TN	CN	TN	CN	TN	CN	TN	CN	TN	CN	TN
NR OFF - NR min	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
NR OFF - NR med	S (46.6%) NR med > NR OFF	S (43.3) NR med > NR OFF	S (90%) NR med > NR OFF	S (73.3%) NR med> NR OFF	S (40%) NR med> NR OFF	S (40%) NR med > NR OFF	NS	NS	S (36.6) NR med > NR OFF	S (26.6%) NR med > NR OFF	S (20%) NR med > NR OFF	S (20%) NR med > NR OFF
NR OFF - NR max	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max > NR OFF	S (100%) NR max> NR OFF	S (100%) NR max > NR OFF	S (96.6%) NR max > NR OFF	S (90%) NR max >NR OFF	S (100%) NR max > NR OFF	S (96.6%) NR max > NR OFF	S (100%) NR max > NR OFF	S (96.6%) NR max > NR OFF
NR max - NR min	S (86.6%) NR max > NR min	S (96.6) NR max > NR min	S (100%) NR max > NR min	S (100%) NR max > NR min	S (90%) NR max > NR min	S (93.3%) NR max > NR min	S (63.3%) NR max > NR min	S (60%) NR max > NR min	S (83.3) NR max > NR min	S (80%) NR max > NR min	S (66.6) NR max > NR min	S (63.3%) NR max > NR min
NR max - NR med	NS	S (20%) NR max > NR med	S (36.6%) NR max > NR med	S (36.6%) NR max > NR med	NS	NS	NS	NS	NS	NS	NS	NS

NR med- NR min	NS	NS	S (30%) NR med> NR min	S (20%) NR med > NR min	NS	NS	NS	NS	NS	NS	NS	NS

Note: S-significant difference (p<0.05), NS- No significant difference (p>0.05);
CN-cafeteria noise, TN- traffic noise. Quality judgment for clarity- QJC, Quality judgment for noise- QJN and overall preference – OP.
100% indicates that all the participants preferred the greater sign (>) condition; in case of value less than 100% indicates those many percentage of participants preferred the greater value condition and the rest of the participants judged that both the aided conditions in the pair were same.

Table 4.17 enumerates results of quality judgment task for participants in HI group for cafeteria noise and traffic noise, with HA 1 and HA 2. Further, the table illustrates the percentage (%) of participants (in parentheses) preferring one among the pair of NR gradations (when statistically significant) in the judgment task.

There was a significant difference (the sample was clearer & less noisy as the NR gradation changed from NR OFF to NR max) only for the pairs NR OFF and NR med, NR OFF and NR max, and NR max and NR min. However, the percentage of participants preferring NR med in the pair NR OFF - NR med was low in QJC and OP. In addition, there was a significant difference between the pairs NR max and NR med, and, NR med and NR min only in QJN. However, the percentage of participants preferring NR max in the pair NR max and NR med was low (36.6%). There was no significant difference between all the other pairs, which indicated that there was no perceptual difference in the clarity and noisiness between the other conditions. This was true for both cafeteria noise and traffic noise with HA 1 across all the quality judgment tasks.

When the data were compared across the gradation with HA 1, NR max was chosen whenever it was compared with NR OFF, NR min and NR med for both cafeteria noise and traffic noise. When NR max was compared with NR OFF conditions, 100% of participants preferred NR max. This implies that when speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was clearer and less noisy than in other conditions.

Similar results were seen with HA 2. However, there was no significant difference with NR max and NR med, and NR med and NR min pairs. As seen with HA 1, the percentage of participants preferring NR med in the pair NR OFF and NR med was again low in QJN (36.6% & 26.6% for cafeteria noise & traffic noise respectively) and OP (20 % for both cafeteria noise & traffic noise). There was no significant difference observed in QJC with both cafeteria noise and traffic noise.

To summarize, there was a negligible improvement in the mean SIS in different NR gradations for NH group. The SNR-50 values improved with NR ON for HI group. NR max had better SNR-50 (lower) than the NR OFF, with cafeteria noise and traffic noise. Whenever speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was rated clearer and less noisy than other conditions, in both NH group and HI group. Table 4.18 summarizes the results obtained from Phase II of the study.

Table 4.18.
Summary of results for the effect of NRA using perceptual measures (Phase II).

Condition	Task	Statistical tool	Results
Noise only	Quality judgement task (LJN)	McNemar test	**NH group** 1. Preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med. 2. Could not differentiate the loudness of noise between the NR OFF - NR min pair. 3. This was true for both HA 1 and HA 2, and for both types of noise (cafeteria & traffic) **HI group** 1. NR max was judged as less noisy, whenever it was compared with NR OFF, NR min, and NR med. 2. The percentage of participants choosing NR max in the NR max and NR med pair was drastically lower for HI group than that observed for NH group. 3. Performance with HA 1 was better than with HA 2.
Speech in noise	Speech perception and Quality judgement task (QJN, QJC, OP)	Descriptive Statistics, Friedman test, Wilcoxon signed rank test, McNemar test	**NH group** 1. Though there was a significant difference in the SIS between the pairs NR OFF and NR max, and, NR max and NR min with both the hearing aids, for cafeteria noise and traffic noise, there was a negligible improvement in the mean SIS (raw scores) in different NR gradations. 2. There was no perceptual difference in the clarity and noisiness between the NR OFF and NR min conditions for both cafeteria and traffic noise.

	3. Whenever speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was rated clearer and less noisy than other conditions. **HI group** 1. Mean SNR-50 values improved with different NR gradations for participants in HI group. The NR max had better SNR-50 (lower) than the NR OFF, with cafeteria noise and traffic noise, for both HA 1 and HA 2. 2. SNR-50 scores increased with increase in NR gradation from NR OFF to NR max for both the hearing aids with cafeteria noise and traffic noise. 3. Significant difference was observed only for the pairs NR OFF and NR med, NR OFF and NR max, and, NR max and NR min in quality judgment task. As the NR gradation increased from NR OFF to NR max, the sample was rated clearer and less noisy. 4. NR max was chosen whenever it was compared with NR OFF, NR min and NR med for both cafeteria noise and traffic noise. When NR max was compared with NR OFF conditions, 100% of participants preferred NR max. 5. Similar results were seen with HA 2.

CHAPTER 5

DISCUSSION

The aim of the study was to evaluate the effectiveness of noise reduction algorithms (NRA) in two different hearing aids on perceptual and acoustic measures. The discussion has been provided under acoustic measures (Phase I) and perceptual measures (Phase II).

5.1 Phase I: Effect of NRA on acoustic measures

The data on acoustic analysis of the output from the hearing aids under various conditions, viz., five types of noise with NR ON (with gradations NR min, NR med, & NR max) and NR OFF; in noise only condition; and speech in noise condition were statistically analysed and the details of which are provided in the previous chapter. The discussion for the effect of NRA on acoustic measures in noise only condition and speech in noise condition has been provided in the following sections.

5.1.1 Effect of NRA on acoustic measures, in noise only condition

The results from the noise alone condition revealed that there is an effective reduction in the level of noise in NR ON condition. In the NR ON condition, NR max had the greatest reduction of noise followed by NR med and NR min. The reduction of noise when NR was ON is analogous with that reported in most of the studies in the literature (Bray & Nilsson, 2000; Summe, 2003; Bentler & Chiou, 2006; Ghent et al., 2007; Rout et al., 2007; Chong & Jenstad, 2011).

Among the types of noise, traffic noise (TN) had maximum reduction, by 6.9 dB (difference between NR max & NR OFF at 90th percentile) followed by white noise (4.9 dB) and cafeteria noise (4.6 dB). Speech babble had the least reduction, by 1.5 dB. Similar findings have been noted by Summe (2003). In her study, reduction in noise was found only for a few types of noise viz., jet noise and fan noise by 4.6 dB and 2.4 dB respectively. Summe (2003) reported that the type of noise influences the amount of reduction brought about by the NRA. The steady-state noise is easily identified as noise than highly modulated noise which has more modulations like speech (Naylor & Johannesson, 2009). Likewise, Rout et al. (2007) studied the effectiveness of NRA with 20 new stimuli. Among the stimuli used in the study, speech-shaped steady-state noise provided an average reduction in noise varying from 2.5 dB to 13 dB with different hearing aids. In addition, Chung et al. (2009) reported that modulation based NR reduced the overall noise level by approximately 4 to 7 dB. Chong and Jenstad (2011) observed that the DNR was effective in reducing pink and cafeteria noise, but not effective for the ICRA (International collegium of rehabilitative audiology) noise. As ICRA noise has speech-like characteristics, there was no reduction in noise (Bentler & Chiou, 2006). Thus, it can be inferred that the capacity or functionality of a NRA depends on the changes in the time and frequency domain characteristics of an input signal. Hence, there are variations in the amount of noise reduction for different types of input noise.

The maximum difference in noise reduction between NR OFF and NR max was about 6.9 dB for traffic noise (TN), at 90^{th} percentile in the present study. However, Bentler and Chiou (2006) have reported that the maximum gain reduction can be around 20 dB at the maximum gradation / stronger gradation in some hearing aids. On the other hand, there can be only 5 dB reduction for the minimum gradation / milder NR setting (Chung, 2004; Yuen, Kam, & Lau, 2006; Bentler & Chiou, 2006) for steady-state white noise with modulation based NRA. Ricketts and Hornsby (2005) reported that in practice, gain reduction for a 70 dB SPL input using the maximum setting varies from 0 to 14 dB and it specifically depends on the modulation rate and modulation depth of the input signal. Alcántara et al. (2003) showed that the amount of noise reduction for a speech in noise signal (steady-state ICRA with single talker modulated ICRA noise) at 0 dB SNR was between 8 and 10 dB. Likewise, Bentler et al. (2008) evaluated the single microphone NR and reported that the amount of noise reduction for white noise varied from 9 to 18 dB for an increase in input noise levels from 65 to 81 dB SPL. In the present study, the input noise levels were kept constant at 65 dB SPL. Hence, the amount of reduction of noise in the present study is comparable and is within the range reported in the literature.

Chung (2004) points that multichannel modulation based NRA rely more on modulation to detect the presence of noise. Hence, it is difficult to detect the input signals that have similar modulation patterns like that of a speech signal. If the input signal has noise that has similar modulations and acoustic patterns as that of the speech signal, the NRA will not be able to differentiate the speech from the noise signal. Hence, the amount of reduction in the output for speech babble is not as much as is seen for other types of noise in the present study. These changes were again different with NR ON for a few hearing aids (Chung, 2004). However, in the present study, the amount of reduction in noise with both HA 1 and HA 2 were similar since the two hearing aids selected had modulation based NRA and differed only in the number of channels, number of noise reduction channels, and the amount of output reduction brought about by NR gradations.

Chong (2016) studied the single microphone noise reduction with two hearing aids with NR gradation set to maximum in both the hearing aids. The amount of reduction of noise was studied. Results showed that the amount of noise reduction increased with increase in the input level of noise for HA 1. The amount of reduction of noise varied from 1.1 to 4.8 dB for steady-state pink noise when input noise levels were increased from 55 to 75 dB A. They reported that for each 5 dB increase in the input noise level, the amount of noise reduction increased by 1 dB. For HA 2, the amount of noise reduction was 5 to 6 dB for pink noise with an input increase in noise levels from 55 to 65 dB A. The researcher attributed this difference in the amount of noise reduction between the two hearing aids to the difference in manufacturer's specifications for NRA between the two hearing aids. The actual decision rules of an NRA are typically patented by most manufacturers (Bentler & Chiou, 2006). In the present study, there was a negligible difference between the two hearing aids in the amount of noise reduction. These differences may be due the differences in amount of noise reduction across gradation, i.e., HA 1 had reduction of 15 dB and HA 2 had reduction of 8 dB at NR max, as specified by hearing aid manufacturer.

The amount of gain reduction depends on the predetermined decision rules. These rules are trademarked to each hearing aid manufacturer. These decision rules depends on various factors such as the input noise levels, input SNR, time constants, the gradation of NR, the amount of reduction within each gradation, modulation depth of the input signal and type of noise. Hence, different models of hearing aid exhibit different amounts of reduction in noise for the same input signal (Chung, 2004; Hoetink et al., 2009). Thus, the differences in the amount of noise reduction in the literature and in the present can be attributed to some of these factors such as input noise levels, the gradation of NR, the amount of reduction within each gradation, and type of noise.

Hence the null hypothesis ‘there is no effect of NRA on the acoustic measures in different types of noise, across different NR conditions, in noise only condition’ is rejected.

5.1.2 Effect of NRA on acoustic measures, in speech in noise condition

Acoustic analysis of the hearing aid output for speech in noise condition was done with both objective and subjective tools. The input was a recorded sentence in the presence of five types of noise with NR OFF and NR ON at three gradations (NR min, NR med, & NR max). The output data for three input SNRs (+5, 0, & -5 dB) were analysed. The results of WADA-SNR, EDI, PESQ (MOS) and subjective analysis are discussed.

Effect of NRA on WADA-SNR

The SNR at the output of the hearing aid was improved with NR ON compared to NR OFF condition, for all the types of noise. Among the three NR gradations, NR max gradation showed the best SNR at the output followed by NR med and NR min gradations. The fan noise had the maximum output SNR of 12.9 dB, followed by cafeteria noise (12.3 dB) and traffic noise (12.2 dB) at NR max when the input SNR was +5 dB with HA 1. However, the improvement in SNR with NR max was lesser for speech babble (9.6 dB with HA 1) compared to other types of noise in the study, with both the hearing aids.

Improvement in output SNR with NR ON has been documented in the literature. Ghent et al. (2007) showed that when DNR was enabled, it improved the SNR by 1.9 dB for uncorrelated broad-band noise with single microphone technology. Miller (2013) indicated that the activation of WDRC and NRA improved the SNR from the input to the output of the hearing aid with a mean change in SNR (with reference to linear mode) between 0.25 and -1.74 dB across different hearing aid brands (Oticon, Phonak & Widex) and different hearing aid conditions (linear +NRA, WDRC, WDRC+NRA) in Connected Speech Test (CST) with six talker babble. Hagerman and Oloffson (2004) showed an improvement in SNR by 3 to 5 dB with simulated NRA only for steady-state noise and not for multi-talker babble. As opined by Levitt (2001), the NRA will work more effectively if the difference between the speech and noise in their acoustic characteristics is larger. Sang (2012) remarked that reducing babble noise is still a challenge for noise reduction algorithms especially at low input SNRs. In the present study too, the improvement in SNR with NR ON at all NR gradation was less for speech babble compared to other types of noise.

The difference in the amount of improvement in SNR from the literature to the current study may be due to two reasons. They are 1. In the present study all the other processing circuits like compression, directionality were disabled, and only the NRA was either activated (NR ON) or deactivated (NR OFF); 2. By informal observation of the made by the researcher during the acoustic measures, the NRA under study was taking 6 to 7 seconds to get activated. Hence, the noise was presented 15 seconds prior to the presentation of speech to ensure that the noise reduction was activated. In addition, noise in the background was continuous with speech stimulus presented in between. Hence, the NRA was already activated when the speech was presented. Whereas in the other studies, the SNR was recorded in combination of directionality and NR, or WDRC and NR (Naylor & Johannessen, 2009; Miller, 2013). Further, the hearing aid may not be tested in linear mode activating only NR. In addition, most of the studies usually utilise either CST or HINT as stimulus and may not contain the noise onset prior to the presentation of speech.

Naylor and Johannessen (2009) revealed that at positive SNR inputs, compression reduced the output SNR to a less favourable level. At negative SNR inputs, compression increased the output SNR to a more favourable level. They concluded that the deviation between input SNR and output SNR depends on the modulation characteristics of the signal and noise and the deviation increases with more strong compression. The output SNR depends on the change in input SNR and on the compression settings in the hearing aids. Chong and Jenstad (2011) suggested that noise reduction algorithms reduce the level of steady-state and cafeteria noise by 5 to 7 dB on average, while not changing the level of fricatives. This suggests that the output SNR may be improving with the activation of noise reduction in hearing aid.

Brons et al. (2014) have remarked that at lower SNRs, the NRA it finds difficult to differentiate between speech and noise; and thus, the reduction of noise would be accompanied by distortion of speech. In a similar way, the results of the present study showed that the output SNR increased with corresponding increase with the input SNR, with NR max position. Though the output SNR was reducing with poor input SNR; it was noted that at -5 dB input SNR, at NR max gradation, the output SNR was improving for cafeteria noise, fan noise, traffic noise, and white noise. This finding was again confirmed by Neher and Wagener (2016). They reported that the speech-weighted SNR improvements due to moderate and strong NR setting amounted to 1.7 and 2.8 dB for an input SNR of 0 dB; and to 2.3 and 3.8 dB for an input SNR of 4 dB (Neher, 2014). It was seen that, there is an increase in the output SNR especially at the higher input SNRs at higher NR gradation. In the present study, at positive SNRs (+5 dB) and at maximum NR gradation, the SNRs improved much more than lower input SNRs and lower NR gradations. From this it can be assumed that NR max gradation would aid in improving the output SNR even if the input SNRs are poor.

Thus, both input SNRs and NR gradation play a role in deciding the output SNRs when the NR is ON.

Effect of NRA on EDI

The EDI values were lower with NR ON compared to NR OFF condition for all the types of noise. Among the three NR gradations, NR max position showed lower EDI values than NR med and NR min positions. This indicates that the temporal variations of the speech in noise signal were better preserved even at NR max gradation.

The traffic noise had relatively higher EDI values (larger variation in the temporal envelope) than all the other types of noise. Traffic noise was composed of sounds from the vehicle and its horn. This may have varied the overall temporal envelope of the signal. Hence, the EDI values were relatively higher for traffic noise. The EDI values were higher with poor SNRs. However, at an input SNR of -5 dB, with NR max gradation, the EDI values were lower for all the types of noise except for speech babble. Jenstad and Souza (2007) reported that a larger EDI tended to decrease sentence recognition. Hence at poor SNRs, with speech babble as the competing signal, speech perception may be hampered even with NR is set at maximum and this was reflected by larger EDI values for speech babble in the present study.

Walaszek (2008) reported that the mean EDIs varied from 0.12 to 0.22 for Danish sentences in the presence of a single female talker background noise or in the presence of the ICRA noise. The EDI depends on the type of background noise. The authors observed that the values are generally higher for the background of the one-talker speech than in the background of two-talker modulated speech-shaped noise. Similar results were seen in the present study, i.e., The EDI values were almost similar at all NR gradations for speech babble, i.e., the NR did not have an impact on speech babble. Geetha and Manjula (2014) reported that mean EDI values for DNR only condition approximately ranged between 0.3 and 0.33. This indicated that the hearing aid with DNR ON did not bring about much change in the temporal envelope at the hearing aid output.

From this it can be assumed that NR max gradation would aid in preserving the temporal envelope of the speech even if the input SNRs are poor. Chung (2004) hypothesized that activating NR in the WDRC hearing aid might result in a better speech transmission index and they attributed this enhancement in the temporal envelope to the NRA. Hence, EDI may be one of the tools to understand the temporal variations of a signal processed through the hearing aid.

Effect of NRA on PESQ (MOS)

The PESQ (MOS) did not show any specific pattern with the NR gradations. The NR OFF condition was almost equivalent to NR ON at all the three gradations (NR min, NR med, & NR max) for cafeteria noise, speech babble, and traffic noise. However, there was a slight improvement in the PESQ (MOS) for fan noise and white noise for NR max only at +5 dB input SNR. Among the input SNRs, +5 dB had better PESQ (MOS) scores than 0 dB and -5 dB in all conditions which suggests that PESQ (MOS) values obtained from the present study was valid. These findings are on par with findings from Parsa et al. (2004) who reported improvements in speech quality (measured subjectively & objectively through PESQ MOS) at positive SNRs for NRA based on short-time spectral amplitude estimation. Thus, speech quality assessed objectively, was improving with increase in input SNR.

The PESQ (MOS) ranges between 0 and 4.5, with the PESQ (MOS) value closer to 4.5 indicating that the target speech is the same as the unprocessed speech in terms of quality. One of the inputs for the PESQ (MOS) measurement should be unprocessed speech (clean speech) to compare with another speech in noise signal processed by the hearing aid. It was observed from the raw scores that the PESQ (MOS) was correlating to approximately 50% (PESQ (MOS) of 2.5 to 2.7 was observed in the present study) to the unprocessed speech. Since the comparison of each NR gradation was done with unprocessed speech, variations within the NR gradations may not be evident in terms of improvement in PESQ (MOS) scores. Due to methodological limitations in applying PESQ (MOS) to compare with speech in noise stimulus itself, it was not possible to substantiate the above statement.

Effect of NRA on subjective rating

The rating for noisiness and formant representation of the speech in the output spectrum by three Speech Language Pathologists revealed that rating the sample as less noisy as the WADA-SNR value increased and having good formant representation as the EDI values decreased, across NR gradation. As seen in the WADA-SNR, the maximum SNR difference was between NR OFF and NR max conditions; and the SLPs have rated the NR OFF as being more noisy and NR ON as less noisy. Similarly, the minimum EDI value was for NR ON and correspondingly, the SLPs have rated NR ON as having better formant representation.

Visual inspection of the spectrum at the output of the hearing aid after NR processing was not done earlier in literature. This procedure was taken as a novel method to study the variations in the acoustic features in the hearing aid output. However, inter-subject reliability was low. Since the number of SLPs who participated in analysing the acoustic signal was less (N=3), the feasibility of this method in studying the acoustic changes could not be proven.

Hence, the null hypothesis 'there is no effect of NRA on acoustic measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in speech in noise condition' is rejected.

5.2 Phase II: Effect of NRA on perceptual measures

Quality judgement tasks were obtained in noise alone and speech in noise condition. In addition, speech identification measures were obtained in speech in noise condition at a fixed SNR (0 dB) for the participants in NH group, and adaptive SNR (SNR-50) for participants in HI group.

5.2.1 Effect of NRA on perceptual measure, in noise only condition

The results of effect of NRA on overall loudness in noise only condition, for NH group and HI group are discussed. Loudness judgment for noise (LJN) was done for cafeteria noise and traffic noise with HA 1 and HA 2, for NH group and HI group. This was done to evaluate if noise alone condition brought about changes in perception with NR ON. The participants in NH group had preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med; NR med was preferred whenever it was compared with NR min with both HA 1 and HA 2, and the two types of noise (cafeteria noise & traffic noise). Between the NR OFF and NR min pair, NR min was chosen by the participants. However, the percentage of participants preferring NR min was lower (37%) than other pairs with HA 1. This implies that individuals with normal hearing could not differentiate the loudness of noise between the NR OFF and NR min pair, for both cafeteria and traffic noise. Though, there was a reduction in the output (0.8 dB) for NR min (as seen in acoustic analysis), this small change in output is probably not perceived by the listeners and hence there was no difference between NR OFF and NR min pair.

Further, participants in HI group preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med. However, the percentage of participants choosing NR max in the NR max and NR med pair was drastically lower than that observed for NH group. A similar trend was seen with the NR med - NR min pair. This suggests that most of the participants in HI group could not differentiate the loudness of noise between the NR max and NR med, and, NR med and NR min pairs.

The amount of noise reduction of NR gradation between NR max and NR med, and NR med and NR min may not be sufficient in bringing about change in loudness for individuals with hearing impairment to identify the subtle differences in reduction of noise. This can attributed to the impaired intensity resolution in individuals with hearing impairment. Thus, the individuals with hearing impairment could differentiate the reduction in loudness with NR ON only if the NR gradation was set to maximum position. Ricketts and Hornsby (2005) indicated that digital noise reduction (DNR) 'on' condition (noise reduction set to maximum) was selected significantly more often than the DNR 'off' condition (noise reduction set to 'off '), regardless of noise level or microphone mode. Further, they found that this preference was seen with the low noise levels (positive SNRs of +6 dB). The marginal variations in preferences between the hearing aids may be due to the signal processing.

Hence, the null hypothesis 'there is no effect of NRA on perceptual measures in different types of noise and across different NR conditions, in noise only condition, in participants with normal hearing and hearing impairment' is rejected.

5.2.2 Effect of NRA on speech perception in noise

The perceptual measures were evaluated with speech identification scores and SNR-50 in individuals with normal hearing and with hearing impairment respectively. However, SNR-50 could not be assessed for individuals with normal hearing as the recorded output from the HA served as the stimulus. Hence, SIS was measured to assess the speech perception in noise, at 0 dB SNR, for individuals with normal hearing. In addition quality judgment task was done for both NH group and HI group.

Effect of NRA on speech identification measures in NH group

To study the effect of NR on speech perception in noise, at 0 dB SNR, SIS and quality judgment tasks was measured in participants with normal hearing (NH group). There was a significant difference in the SIS between the pairs NR OFF and NR max, and, NR max and NR min with both the hearing aids, for cafeteria noise and traffic noise. However, when the raw scores were observed, there was a negligible improvement in the mean SIS within the NR gradations, and between NR ON and NR OFF. Sang et al. (2015) showed improvement in speech intelligibility with NR ON for individuals with hearing impairment and not for individuals with normal hearing. In addition, they reported that improvement seen in speech intelligibility was less in the presence of speech babble. Likewise, they concluded that noise reduction algorithms perform better at higher SNRs where individuals with hearing impairment can benefit whereas, individuals with normal hearing would have reached ceiling in their performance. There was no difference in the performance with NR gradations for individuals with normal hearing on inspection of the SIS even in the present study.

Effect of NRA on quality judgment in NH group

In the quality judgement task, there was no perceptual difference in the clarity and noisiness between the NR OFF and NR min conditions. When NR max was compared with NR min and NR OFF conditions, 100% of participants preferred NR max. This signifies that when speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was clearer and less noisy than in other conditions. Similar to the current study, Brons et al. (2013) reported that individuals with normal hearing preferred noise reduction ‘On’ at +4 dB SNR. Kortlang et al. (2017) reported that a single channel NR significantly decreased noise annoyance, and decreased listening effort and increased overall quality in steady-state noise at +6 dB SNR, and babble noise at both 0 and +6 dB SNR in individuals with normal hearing. In the present study, the quality judgement was done at 0 dB SNR with cafeteria and traffic noise. Thus, the results of the current study are comparable and are on par with that of the previous study.

Effect of NRA on speech identification measure in HI group

To study the effect of NR on speech perception in noise, SNR-50 and quality judgment tasks were measured in individuals with hearing impairment (HI group). The SNR-50 was better with NR max than at NR OFF position, for both the types of noise, and with the two hearing aids. When comparison was made between the pairs, except for NR OFF - NR min pair, all other pairs had significant difference (higher gradation had better SNR-50 among the pairs) in SNR-50 values for both cafeteria noise and traffic noise. These findings are in contrast to most of the findings in the literature (Ricketts & Hornsby, 2005; Sarampalis et al., 2009; Luts et al., 2010; Brons et al., 2014). Alcántara et al. (2003) have opined that lack of improvement in speech intelligibility may be due to reduction in speech information in the process of reducing noise by the NRA. This may have resulted in loss of speech information from attenuated bands. Chung (2004) hypothesises that NRA reduces gain at the frequencies which are dominant in noise. In the process of reducing the noise, NR reduces the audibility of speech in that frequency. Hence, the speech intelligibility scores may not have enhanced in most of the studies in the literature.

In addition, Hu and Loizou (2008) remarked that single channel noise reduction algorithms often do not adequately preserve the low energy characteristics of consonants at low SNRs. These noise reduction algorithms provide only limited information on the important narrowband speech modulation cues (Ives et al., 2014). Further, Miller (2013) reported that the most of the listeners in their study required an SNR-50 between 0 and 4 dB SNR. He concluded that if the experiment was done at multiple fixed SNRs, results might have been more systematic.

However, Chung (2004) reported that studies by Bray and Nilsson (2000); and Johns, Bray, and Nilsson (2002) revealed improvement in speech intelligibility measured through SNR-50 in individuals with hearing impairment. The findings of the present study are comparable with that reported by de Oliveira et al. (2010); Healy et al. (2013) and Sang (2012) who showed improved speech intelligibility with NR ON for individuals with hearing impairment.

In the present study, the SNR-50 was measured by varying the noise level while keeping the level of the speech stimulus constant. Though the noise levels were varied, the presentation of the noise was continuous for each condition. It can be postulated that since the NRA was activated prior to the presentation of speech, the SNR-50 scores might have improved. In addition, reduced load on cognition may have enhanced the performance in SNR-50 for individuals with hearing impairment (Sarampalis et al., 2009; Desjardins & Doherty, 2014; Desjardins, 2016).

Further, whenever the speech intelligibility was measured using HINT or CST as in earlier studies from the literature, the effectiveness of NRA in improving speech intelligibility may not be shown as speech and noise are presented simultaneously.

Effect of NRA on quality judgment in HI group

Pair-wise comparisons were made between the NR OFF and NR ON at three gradations (NR min, NR med, & NR max). Quality Judgement for Clarity (QJC) (for Speech), Quality Judgement for Noisiness (QJN) and overall preference (OP) were assessed among the aided pairs for three types of noise. From the results, it can be seen that NR ON condition was preferred compared to the NR OFF conditions for all the tasks with the two types of noise. Ricketts and Hornsby (2005) showed that the sound quality measurements done through paired comparisons showed a strong preference for NR ON condition. Likewise, Powers et al. (2006) showed that 73.3% of the subjects favoured the DNR 'On', set to maximum and only 19% favoured DNR 'Off'. In addition, Zakis et al. (2009) have also reported that most of the participants (90%) preferred NR ON to NR OFF condition. In the present study, none of the participants preferred NR OFF. As all the participants were naïve hearing aid users and hence may have preferred better listening comfort and reduction in loudness of noise. In addition, better quality might have resulted with NR ON compared to NR OFF at +5 dB SNR, as the quality judgement was done. Sang (2012) remarked that individuals with hearing impairment are more sensitive and give more importance to 'loudness of noise' and less sensitive to 'speech distortion' when rating their preference for overall quality of a speech in noise signal. In addition, Sang (2012) have stated that NRAs perform better at higher input SNRs. This was observed in the present study also.

Kortlang et al. (2017) reported that single channel NR significantly decreased annoyance due to noise, and decreased listening effort and overall quality in steady-state noise at +6 dB SNR and speech babble at both 0 and +6 dB SNR, in individuals with hearing impairment. However, they reported that the improvements were less pronounced for individuals with hearing impairment especially at 0 dB SNR. Literature review has always shown positive results on speech quality measurements with NR ON in individuals with hearing impairment. Likewise, in the present study, the quality judgment was done at +5 dB SNR for individuals with hearing impairment and hence the results of quality judgment tasks of the present study are comparable with results of Kortlang et al. (2017).

Most of the studies revealing no improvements in speech perception measure, have shown definite improvements in speech quality with NR ON (Ricketts & Hornsby, 2005; Sarampalis, et al., 2009; Luts et al., 2010; Brons et al., 2014; Miller etal., 2017). In addition studies also report of reduced listening effort, increase comfort and decreased annoyance with NR ON as against NR OFF (Palmer et al., 2006; Mueller et al., 2006). Hence, the results of quality judgment in the present study are analogous with most of these previous studies in the literature.

The NR max was preferred by the participants whenever it was compared with NR OFF, NR min and NR med for both cafeteria noise and traffic noise. When NR max was compared with NR OFF conditions, 100% of the participants preferred NR max. This implies that when speech was presented with either cafeteria noise or traffic noise, with NR at maximum gradation, the sample was clearer and less noisy than other conditions. This finding is complimenting with the results from a study by Neher et al. (2016); and Neher and Wagener (2016). The participants in their study generally favoured stronger NR processing at +4 dB SNR than at 0 and -4 dB SNR. In the present study, the quality judgment tasks were done only at positive SNRs (+5 dB SNR). Neher (2014) attribute this phenomenon to the fact that at higher input SNRs the adverse effects of NR processing (i.e., speech distortions) decrease while its positive effects (i.e., noise attenuation) increase. Thus, at higher gradations of the NR, there is an increase in the output SNR especially at the higher input SNRs. A higher gradation of NR results in speech distortion at the output of the HA, at lower input SNRs. Hence, turning 'ON' the NR processing and its strength should be personalized during programming of the hearing aid (Neher & Wagener, 2016).

Hence, the null hypothesis 'There is no effect of NRA on perceptual measures in different types of noise at three input SNRs (+5, 0 & -5 dB) across different NR conditions, in speech in noise condition, in participants with normal hearing and hearing impairment' is rejected.

5.3 Comparison between acoustic and perceptual measures

The acoustic measures were evaluated using many objective tools and subjective measures. Likewise, perceptual measures were also assessed using subjective (quality judgment tasks) and objective (SIS & SNR-50) tools. As acoustic analysis was done using a single sentence and at three input SNRs, these measures could not be compared statistically with the perceptual measures. The perceptual measures were done at either 0 dB SNR for participants with normal hearing (NH group) or +5 dB SNR for participants with hearing impairment (HI group). Furthermore, speech identification scores at SNR of 0 dB were used as a speech perception measure for individuals with normal hearing and SNR-50 was used as a speech perception measure for individuals with hearing impairment. Due to the structure of the method designed, it was not possible to correlate the results statistically from acoustic analysis to the perceptual measures. Hence, an attempt was made to discuss both the measures, descriptively.

The reduction in the amount of noise as observed from the LAeq in the acoustic analysis reveals that when NR was ON and at maximum gradation, the amount of noise reduction was more than with other settings. Similarly, when NR max was compared with NR OFF conditions, 100% of participants from NH group and HI group preferred NR max in loudness judgment of noisiness in the perceptual analysis. Thus, the reduction of noise seen in the acoustic measure is reflected in the perceptual quality measure.

Analysis of the signal-to-noise ratio (SNR) from the acoustic measures showed that the SNR at the hearing aid output was better (increased) with NR ON (NR max gradation) when compared to NR OFF condition, for all the types of noise. The NR min gradation had the least effect on the output SNR. Similarly, in the quality judgment task, when quality judgment for noisiness was observed, the NR max was chosen whenever it was compared with NR OFF, NR min and NR med for both cafeteria noise and traffic noise. When NR max was compared with NR OFF conditions, 100% of participants from NH group and HI group preferred NR max in judgment of noisiness. Improvement in output SNR may be bringing about reduction of noise and thus enhancing the speech. It is shown in the literature that individuals with hearing impairment usually had increased tolerance for noise, decreased listening effort and stronger preference for noise reduction ON than when the noise reduction is OFF (Mueller et al., 2006; Palmer et al., 2006; Sarampalis et al., 2009; Zakis et al., 2009). Further, Sang et al. (2015) showed that the SNR improvement had a positive value with Interpolated Paired Comparison Rating (IPCR) which indicated that noise reduction algorithms improved speech quality. The individuals with hearing impairment had larger median values for preference for NR and noise loudness. This indicates that individuals with hearing impairment have larger SNR improvements. Thus, improvement in the output SNR from the hearing aid may be attributing to the improvement in clarity and reduction of noisiness in the quality judgment.

Likewise, the NR max had better SNR-50 (lower) than the NR OFF, with cafeteria noise and traffic noise for individuals with hearing impairment. It is known from the literature that 1 dB change in SNR approximates a 10% change in speech perception (Laurence, Moore, & Glasberg, 1983; Nilsson, Soli, & Sullivan, 1994). Miller (2013) remarked stating that a possible change in the acoustic SNR could be bringing about changes in speech perception. Though MacPherson and Akeroyd (2014) have stated that individuals with hearing impairment do not benefit from changes in SNR, the present study has shown benefit from the increase in output SNR for individuals with hearing impairment. However, Sang (2012) has revealed that the speech intelligibility depends on input SNR levels. Similarly, with increase in the input SNRs, the SNR-50 scores improved in the present study. Similarly, Healy et al. (2013) showed high scores in speech intelligibility as the SNR increased. They opine that the algorithm used in their study was capable of giving better output SNR which in turn was capable of providing good speech perception for individuals with hearing impairment and normal hearing across a range of SNRs. The same may hold good for the present study.

Miller et al. (2017) revealed that the output SNR changes did not correlate with the speech perception. The authors attribute the lack of correlation to speech perception to the following reasons: 1) negligible changes noted in SNR through hearing aid processing with compression and NR, 2) the speech perception test used not being sensitive test to capture the small changes in SNR at the output of the hearing aid, 3) the hearing aid processing may be modifying the long-term SNR, but not the instantaneous SNR when speech was present. However in the present the study, the changes in SNR as observed in the acoustic analysis were comparable to the changes / improvements seen in the speech perception measures for individuals with hearing impairment.

The difference of opinion between the Miller et al. (2017) and the present study may be due to the following reasons: In the present study 1. All the other types of signal processing like compression, directionality were disabled and only NR were either activated or deactivated; 2. The noise was presented 15 seconds prior to the presentation of speech to ensure that the noise reduction was activated. 3. The output SNR obtained was much higher (increased) in the present study.

Further, there was no significant difference in the SIS when raw scores were examined in individuals with normal hearing. This may be due to the ceiling effect in the NH group as explained previously in the perceptual measures.

The EDI values were lower with NR ON as against NR OFF condition, and NR max gradation had lowest EDI values than NR med and NR min for all the types of noise as validated from acoustic analysis. From this, it can be inferred that the temporal envelope of a speech in noise signal is nearing the unprocessed speech signal. This may be due to reduction of noise by the activation of NR at the maximum gradation. This phenomenon is again observed with quality judgment for noisiness and clarity. The sample was rated as less noisy and clearer at NR max than other conditions by participants in both NH group and HI group.

Further, when speech perception scores were analysed, there was a significant difference in the SIS between the pairs NR OFF and NR max, and, NR max and NR min for NH group. But, there was a negligible improvement in the mean SIS, in different NR gradations, when raw scores were scrutinized. This again can be due to the ceiling effect in the performance of individuals in NH group. For HI group, the NR max had better (lower) SNR-50 values than the NR OFF, with cafeteria noise and traffic noise.

Studies on the effect of WDRC processing on the output of the hearing aid have shown that WDRC modifies the temporal envelope of the output signal (Jenstad & Souza, 2005; Geetha & Manjula, 2014). Greater the distortion in the temporal envelope, lesser is the benefit in speech perception. Even if there is improvement in the output SNR, due to temporal envelope changes induced by compression, the individuals with hearing impairment may not benefit in speech perception (Miller et al., 2017). In the present study, the temporal envelope changes were measured using EDI. The EDI values were lower (indicating less temporal variations) with increase in input SNR (+5 dB) and at NR max gradation. In addition, the compression in the hearing aid was disabled. Fortune et al. (1994) reported that linear mode resulted in almost no temporal alteration of the envelope (EDI = 0.04). Hence, in the present study, improvement in the temporal envelope at NR max as observed in the EDI may be contributing to the better SNR-50 scores in individuals with hearing impairment at NR max i.e., improved temporal resolution with NR max is being reflected in the improved SNR-50 in perceptual measure.

It was observed that PESQ (MOS) did not show improvements across the NR gradations. At input SNRs of +5 dB, PESQ (MOS) was better than with input SNR of 0 dB and -5 dB. Though there was negligible change seen in PESQ (MOS) at 0 dB SNR, the participants in NH group had rated the speech sample as clearer when speech was presented with noise (either cafeteria noise or traffic noise) only, with NR max gradation, even at 0 dB SNR. It must be noted here that PESQ (MOS) was analysed by comparing the clear speech with speech in noise samples at different gradations. However, in the quality judgment task, speech in noise samples were compared between gradations and with NR OFF. As individuals with normal hearing have good stream segregation abilities, it may be possible to perceive the changes when compared between gradations. Hence, the speech sample was judged as clearer when speech was presented with cafeteria and traffic noise at NR max gradation even at 0 dB SNR for participants in NH group.

In addition, the participants in HI group rated the sample clearer (preferred NR max) only when NR max was compared with NR OFF and NR min conditions only. The quality judgment for HI group was done at +5 dB SNR. Hence, the results of quality judgment for clarity and PESQ (MOS) scores at +5 dB input SNR are comparable for HI group. A high correlation has been reported in the literature for PESQ (MOS) when correlated with speech quality measurements (Hu & Loizou, 2008; Kressner, 2011; Lai et al., 2013; Sang et al., 2015). This may imply that the quality differences between the NR max and NR OFF, and, NR max and NR min may be perceptible to individuals with hearing impairment at favourable SNR (+5 dB) and at NR max gradation. There was no significant difference observed between other pairs, like NR OFF and NR min, NR OFF and NR med, and, NR med and NR min, which may be due to a slight difference in clarity between the above pairs. These findings were comparable with PESQ (MOS) scores, where PESQ (MOS) scores did not show improvement across above mentioned NR gradations.

Further, though there was a significant difference in the SIS (higher SIS scores with higher NR gradation) for NH group, there was a negligible improvement in the mean SIS (raw scores) at 0 dB SNR in different NR gradations. This comparison may be inappropriate, as individuals with normal hearing might have reached ceiling in performance at NR OFF position itself. In addition, a PESQ (MOS) score between 2.5 and 3 yielded a word intelligibility score of ~ 90% for medium-high word familiarity (Yamada, Kumakura, & Kitawaki, 2008). Hence, there is a possibility that a PESQ (MOS) score of 2.5 (for traffic noise) and 2.2 (for cafeteria noise) for a sentence may bring about >90 % score in speech perception for individuals with normal hearing as perception of sentences are easier than perception of words.

Thus, to summarize, studies on NRA have been reported in the literature. Some studies report more reduction in noise with NR ON and some report negligible reduction. This reduction was again dependent on many factors. Similarly, the findings on the effect of NR on speech perception are equivocal across different studies. The possible reasons for the same have been discussed. The similarities in the speech quality measures and divergence in speech perception measures from the previous studies for individuals with hearing impairment has been deliberated.

In addition, an attempt was made to compare acoustic and perceptual measures. Similarities and comparisons drawn between the two measures reflected that most of the parameters assessed in acoustic measures were comparable to perceptual measures. This implies that the changes observed in the acoustic measures were also perceptible to the listeners. However, the two measures could not be compared statistically.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The aim of the study was to evaluate the effectiveness of noise reduction algorithms (NRA) in two different hearing aids on acoustic and perceptual measures. The specific objectives of the study included:

1. To evaluate the effect of NRA on acoustic measures in different types of noise and across different NR conditions, in noise only condition.
2. To evaluate the effect of NRA on acoustic measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in speech in noise condition.
3. To evaluate the effect of NRA on perceptual measures in different types of noise and across different NR conditions, in noise only condition, in participants with normal hearing and hearing impairment.
4. To evaluate the effect of NRA on perceptual measures in different types of noise at three input SNRs (+5, 0, & -5 dB) across different NR conditions, in speech in noise condition, in participants with normal hearing and hearing impairment.

To evaluate the above objectives, two digital RIC hearing aids with modulation based NRA were chosen. The output from the hearing aid was recorded using the KEMAR. Both acoustic and perceptual measures were obtained. Acoustic and perceptual measures were studied subjectively and objectively. Perceptual measures were obtained from both individuals with normal hearing and with hearing impairment.

The effect of NRA on different types of noise using acoustic measures was studied by analyzing the reduction of noise [overall LAeq (dB) & 90^{th} percentile LA90 (dB)] at the output of the hearing aid with NR OFF and NR ON at three gradations (NR min, NR med, & NR max). The NR ON condition had more reduction in noise at the output of the hearing aid than the NR OFF condition, for all types of noise. In the NR ON condition, NR max had greatest reduction of noise followed by NR med and NR min gradation. The NR min was almost equivalent to NR OFF position. Among the types of noise, non-speech like noise had more reduction in noise (traffic noise had maximum reduction of 6.9 dB; white noise: 4.9), than highly modulated noise, which have more modulations like speech (speech babble had least reduction by 1.5 dB).

Likewise, the effect of NRA on the acoustic aspects of the hearing aid output in speech in noise condition was evaluated using objective and subjective methods. Among the objective measures, as documented in the literature, the output SNR was better (increased) with NR ON compared to NR OFF condition for all the types of noise. Among the three NR gradations, NR max position showed better output SNR than medium and minimum positions. The NR ON at minimum gradation was almost equivalent to NR OFF position. This was true for all the five types of noise. However, larger the difference between the speech and noise in their acoustic characteristics, more was the improvement in SNR. Thus, the improvement in SNR with NR max was decreased for speech babble compared to other types of noise in the study. The output SNR was increasing with corresponding increase with the input SNR. Though the output SNR was reducing with poor input SNR, it was noted that at -5 dB input SNR, at NR max gradation, the output SNR was improving for cafeteria noise, fan noise, traffic noise and white noise. The EDI values were lower with NR ON compared to

NR OFF condition for all the types of noise. The EDI values were increasing with poor SNR. However, at poor input SNR (-5 dB) with NR max gradation, the EDI values were lower than other NR gradations for all the types of noise except for speech babble. Thus, the NR max gradation would aid in preserving the temporal envelope of the speech even if the input SNRs are poor. The PESQ (MOS) did not show a trend with the NR gradations. However, among the input SNRs, +5 dB had better PESQ (MOS) scores than 0 dB and -5 dB. This may be due to the fact that speech inherently would have better quality at positive input SNR. The results from PESQ (MOS) show that NR could not bring about improvements in the quality of the speech in noise signal between gradations.

In the subjective analysis, the rating for noisiness and formant representation of the speech in noise spectrum showed that the SLPs rated the hearing aid output as less noisy as the WADA-SNR value increased, and they rated formant representation to be better at the output of the hearing aid as EDI values decreased across NR gradation. The SLP rating for noisiness of the speech in noise spectrum had very low inter-subject reliability. Since the number of SLPs who participated in analyzing the acoustic signal was less, the feasibility of this method in studying the acoustic changes could not be proven.

Further, the effect of NRA on different types of noise using perceptual measures was evaluated by loudness judgment for noise (LJN). Individuals with normal hearing had preferred NR max as less noisy, whenever it was compared with NR OFF, NR min and NR med; and NR med was chosen whenever it was compared with NR min. This was true for both HA 1 and HA 2 and the two types of noise (cafeteria noise & traffic noise). However, individuals with hearing impairment could differentiate the reduction in loudness with NR ON only if the NR gradation was set to maximum position.

The effect of NRA on speech perception in the presence of different types of noise using perceptual measures was studied using speech perception measures and quality judgement task. In individuals with normal hearing, though there was a significant difference in the SIS (higher SIS scores with higher NR gradation), when raw scores were observed, the mean SIS improved negligibly within the NR gradations and between NR ON and NR OFF. This can be attributed to the ceiling effects in the performance of individuals with normal hearing. In the quality judgment task, when speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was clearer and less noisy than other conditions for individuals with normal hearing.

In individuals with hearing impairment, the SNR-50 was better with NR max than at NR OFF for both the types of noise and with the two hearing aids. Though this finding was disparate with most of the findings in the literature, most of the recent studies have shown improvement in speech perception with NRA ON. In the quality judgment task, NR ON condition was preferred as against NR OFF conditions for all the tasks with cafeteria noise and traffic noise. All the participants were naïve hearing aid users, and none of them preferred NR OFF. This may be due the fact that individuals with hearing impairment require better listening comfort and reduction in overall level of noise. Further, when speech was presented with noise (either cafeteria noise or traffic noise) with NR at maximum gradation, the sample was rated clearer and less noisy than other conditions.

To conclude, noise reduction algorithms do help in reducing the noise. The amount of reduction depends on the acoustic characteristics of the input noise and how different it is from the speech signal. The amount of noise reduction is relatively more for steady-state noise as against noise having similar features as that of speech. Likewise, larger the difference between the speech and noise in their acoustic characteristics, more was the improvement in SNR. The output SNR was increasing with corresponding increase with the input SNR. The NR when ON and at maximum gradation had greatest reduction in noise. Individuals with hearing impairment could differentiate the reduction in noise level with NR ON only if the NR gradation was set to maximum position. The speech perception did not improve within the NR gradations and between NR ON and NR OFF for individuals with normal hearing. However, speech perception scores were better with NR max than at NR OFF in individuals with hearing impairment and this finding was on par with the quality judgment. However, as each noise reduction accommodated in digital signal processing circuitry would vary, caution must be exercised while generalising the study to other algorithms.

6.1 Implications of the study

The following implications were drawn from the study:

- As there was different effect of NR on different types of noise, it provides insight about how noise reduction algorithms behave with different types of noise. This would aid in counselling the hearing aid users regarding the benefit that they would obtain from the hearing aid in different situations.

- The effect of NR gradation would aid in programming and fine tuning the hearing aid for a hearing aid user. This would help in personalizing the needs of the hearing aid users while fine tuning a hearing aid.
- The results of present study can give direction to Audiologist's that the NR does not work the same way for different noises, SNRs, and gradations.
- It helps in counselling patients regarding the use of specific NR gradations in different situations.
- The results of the present study can give direction also to the hearing aid manufactures that NR does not work the same way for different noises, SNRs and gradation. This would support in development of more advanced technology and overcome the deficits in the present day technology.

6.2 Future directions

- It is important that a new hearing aid with NRA be evaluated through acoustic / perceptual measures before it is utilized clinically.
- Researchers can replicate the study using limited parameters and hence draw correlations between acoustic and perceptual measures.
- Acoustic analysis can be done with latest advanced measures which can be directly correlated with speech perception measures.
- Effect of noise reduction can be studied by varying the input noise levels.

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APPENDIX

Appendix 1

WADA-SNR for HA 1

Noise NR Gradation	Input SNR	Cafeteria Noise	Fan Noise	Speech Babble	Traffic Noise	White Noise
NR OFF	**5**	5.76	5.5	4.04	5.95	3.28
	0	2.28	2.58	0.34	1.59	-0.8
	-5	-1.03	-0.93	-1.63	-1.33	-5.76
NR min	**5**	5.8	5.69	4.15	6.39	3.3
	0	2.31	2.83	0.35	1.64	-0.54
	-5	-0.45	-0.85	-1.6	-1.14	-5.07
NR med	**5**	9.51	9.66	7.14	9.08	7.22
	0	5.6	5.43	0.42	4.55	2.98
	-5	1.99	0.47	-1.59	1.32	-2.76
NR max	**5**	12.38	12.94	9.65	12.22	11.27
	0	8.32	8.09	0.44	7.07	5.85
	-5	4.43	1.15	-1.51	2.73	-1.03

Appendix 2

NR Gradation \ Noise	Input SNR	Cafeteria Noise	Fan Noise	Speech Babble	Traffic Noise	White Noise
WADA-SNR for HA 2						
NR OFF	**5**	5.15	3.94	2.42	4.31	2.86
	0	1.59	0.46	-1.48	1.22	-0.8
	-5	-1.48	-3.04	-3.8	-1.83	-6.03
NR min	**5**	5.09	3.96	3.44	4.47	3.33
	0	1.66	1	-1.17	1.04	-0.76
	-5	-0.58	-2.94	-3.75	-1.54	-6.01
NR med	**5**	7.42	6.52	4.61	6.99	5.54
	0	2.55	1.74	-1.26	3.15	0.43
	-5	0.1	-1.81	-3.29	1.12	-5.84
NR max	**5**	11.71	10.41	8.82	11.94	9.96
	0	7.63	4.59	-0.2	7.43	3.85
	-5	1.23	-1.8	-3.1	2.43	-3.32

Appendix 3

EDI for HA 1						
Noise / NR Gradation	**Input SNR**	**Cafeteria Noise**	**Fan Noise**	**Speech Babble**	**Traffic Noise**	**White Noise**
NR OFF	**5**	0.17	0.16	0.19	0.24	0.19
	0	0.23	0.22	0.26	0.31	0.25
	-5	0.28	0.27	0.31	0.42	0.3
NR min	**5**	0.17	0.16	0.19	0.24	0.19
	0	0.23	0.21	0.26	0.31	0.25
	-5	0.28	0.27	0.31	0.38	0.3
NR med	**5**	0.15	0.14	0.17	0.23	0.14
	0	0.2	0.18	0.26	0.3	0.2
	-5	0.27	0.25	0.3	0.35	0.28
NR max	**5**	0.14	0.14	0.17	0.23	0.12
	0	0.19	0.17	0.25	0.3	0.16
	-5	0.25	0.24	0.3	0.35	0.25

Appendix 4

EDI for HA 2

Noise NR Gradation	Input SNR	Cafeteria Noise	Fan Noise	Speech Babble	Traffic Noise	White Noise
NR OFF	**5**	0.2	0.18	0.24	0.3	0.2
	0	0.26	0.24	0.3	0.38	0.26
	-5	0.31	0.29	0.33	0.44	0.31
NR min	**5**	0.2	0.19	0.2	0.3	0.2
	0	0.26	0.24	0.3	0.38	0.25
	-5	0.31	0.29	0.33	0.41	0.31
NR med	**5**	0.16	0.15	0.2	0.29	0.16
	0	0.24	0.21	0.3	0.36	0.23
	-5	0.3	0.28	0.33	0.39	0.29
NR max	**5**	0.16	0.12	0.19	0.28	0.11
	0	0.22	0.17	0.29	0.35	0.18
	-5	0.3	0.27	0.32	0.38	0.27

Appendix 5

PESQ (MOS) for HA 1

Noise / NR Gradation	Input SNR	Cafeteria Noise	Fan Noise	Speech Babble	Traffic Noise	White Noise
NR OFF	**5**	2.24	2.23	2.19	2.53	2.6
	0	2.05	2.03	1.93	2.34	2.39
	-5	1.83	1.8	1.74	2.24	2.12
NR min	**5**	2.26	2.26	2.25	2.53	2.62
	0	2.06	2.05	1.96	2.36	2.4
	-5	1.85	1.81	1.74	2.25	2.21
NR med	**5**	2.28	2.35	2.25	2.54	2.65
	0	2.06	2.1	1.98	2.39	2.4
	-5	1.89	1.82	1.75	2.27	2.23
NR max	**5**	2.28	2.39	2.26	2.55	2.7
	0	2.07	2.14	1.99	2.39	2.44
	-5	1.89	1.82	1.75	2.28	2.23

Appendix 6

PESQ (MOS) for HA 2						
Noise / NR Gradation	**Input SNR**	**Cafeteria Noise**	**Fan Noise**	**Speech Babble**	**Traffic Noise**	**White Noise**
NR OFF	**5**	2.5	2.37	2.21	2.57	2.69
	0	2.25	2.17	2.1	2.38	2.4
	-5	2.05	1.98	1.97	2.26	2.27
NR min	**5**	2.51	2.38	2.33	2.59	2.73
	0	2.26	2.2	2.11	2.4	2.51
	-5	2.09	1.99	1.97	2.28	2.38
NR med	**5**	2.52	2.45	2.34	2.59	2.73
	0	2.3	2.21	2.14	2.41	2.55
	-5	2.1	2.01	1.97	2.3	2.39
NR max	**5**	2.56	2.62	2.39	2.6	2.77
	0	2.3	2.29	2.16	2.42	2.56
	-5	2.11	2.02	1.97	2.31	2.4

Appendix 7

SIS - NH Group					
Test Condition		**HA 1**		**HA 2**	
		Z	**p**	**Z**	**p**
CN	**NR OFF - NR min**	-1.89	0.059	-0.53	0.593
	NR OFF - NR med	-2.00	0.046	-1.96	0.050
	NR OFF - NR max	-3.66	0.000	-2.99	0.003
	NR med- NR min	-1.00	0.317	-1.80	0.071
	NR max- NR min	-2.98	0.003	-3.50	0.000
	NR max- NR med	-2.88	0.004	-1.60	0.108
TN	**NR OFF - NR min**	-0.30	0.763	-1.41	0.157
	NR OFF - NR med	-0.27	0.782	-2.13	0.033
	NR OFF - NR max	-2.67	0.008	-3.44	0.001
	NR med- NR min	-0.50	0.617	-3.00	0.003
	NR max- NR min	-2.18	0.029	-4.14	0.000
	NR max- NR med	-2.29	0.022	-1.60	0.108

Appendix 8

SNR-50 - HI Group					
	Test Condition	**HA 1**		**HA 2**	
		Z	**p**	**Z**	**p**
CN	**NR OFF - NR min**	-1.73	.083	-1.00	.317
	NR OFF - NR med	-4.73	.000	-2.82	.005
	NR OFF - NR max	-4.93	.000	-4.93	.000
	NR med- NR min	-4.60	.000	-2.12	.034
	NR max- NR min	-4.91	.000	-4.91	.000
	NR max- NR med	-3.27	.001	-4.47	.000
TN	**NR OFF - NR min**	-1.73	.083	.00	1.000
	NR OFF - NR med	-4.73	.000	-2.00	.046
	NR OFF - NR max	-4.98	.000	-5.29	.000
	NR med- NR min	-4.48	.000	-2.00	.046
	NR max- NR min	-5.06	.000	-5.29	.000
	NR max- NR med	-3.77	.000	-4.89	.000