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., 10th 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.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Age (in years)</th>
<th>Gender</th>
<th>PTA (dB HL)</th>
<th>SIS (in percent)</th>
<th>Ear</th>
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<tr>
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<td>M</td>
<td>41.25</td>
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<td>45</td>
<td>F</td>
<td>42.5</td>
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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 Astera²), 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.
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 ‘جاجمانا جارا: لپاها: رئالا لستا’ 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 ((holder $g$:$a$:litpa$\theta$a $ha$:risalu $\iota$ta) 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 (holder $g$:$a$:litpa$\theta$a $ha$:risalu $\iota$ta) 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, tammanje ga:jpata ha:rsalu rṣṭā) 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 (tammanje ga:jpata ha:rsalu rṣṭā) 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 I A: 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 90th percentile (i.e., LA90) were computed for the hearing aid output for each type of noise. The Leq at the 90th 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.

![Waveform and wide band bar type spectrogram of speech sample displayed in PRAAT software for obtaining rating from speech language pathologists.](image)

**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.
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.