EFFECT OF WIDE DYNAMIC RANGE COMPRESSION ON A FEW TEMPORAL CHARACTERISTICS AND SPEECH IDENTIFICATION.

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CERTIFICATE

This is to certify that this masters dissertation entitled **Effect of Wide Dynamic Range Compression on a few temporal characteristics and speech identification** is a bonafide work submitted as a part for the fulfilment for the degree of Master of Science (Audiology) of the student with Registration Number: 18AUD010. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysuru

July, 2020

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CERTIFICATE

This is to certify that this masters dissertation entitled **Effect of Wide Dynamic Range Compression on a few temporal characteristics and speech identification** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this masters dissertation entitled **Effect of Wide Dynamic Range Compression on a few temporal characteristics and speech identification** is the result of my own study under the guidance of Dr. P. Manjula, Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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ABSTRACT

The study investigated the effect of wide dynamic range compression (WDRC) in hearing aid on a few temporal characteristics of speech, speech identification and speech quality. These effects were investigated in three aided conditions, i.e., hearing aid in linear amplification, WDRC with a compression ratio of 2:1, and WDRC with a compression ratio of 4:1. The study was conducted in three phases. The Phase I included acoustic measurement, the effect of the three aided conditions on a few temporal characteristics, such as the voice onset time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD) were measured for relevant speech sounds. The speech sounds in VCV context were /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/, /asa/, /aʃa/, /aʧa/, and /aʤa/. The recorded speech sounds were routed to the audiometer and presented through the loud speaker that was placed at a distance of one meter and zero degree azimuth from the hearing aid connected to the ear simulator of the KEMAR. The output from the hearing aid was recorded using a precision sound level meter and analyzed acoustically using the Praat software.

In the Phase II and Phase III, sixteen adults with bilateral moderate to moderately severe, flat, sensorineural hearing loss in the test ear were included. In Phase II, the speech identification scores (SIS) for VCV syllables and PB words were obtained in the three aided conditions. In the Phase III, the parameters of speech quality such as clarity, pleasantness, loudness, and overall impression were rated, on a scale of zero to ten, by the participants in the three aided conditions. The scores and the ratings obtained in the Phase I and Phase II were subjected to statistical analysis. Since all the data did not follow normal distribution. Friedman test and Wilcoxon signed ranks test (when indicated) were administered.

The results reveal that SIS for both VCV syllables and PB words were significantly better in the linear condition, followed by WDRC with a compression ratio of 2:1 and then by 4:1. For the parameters of speech quality such as clarity, pleasantness and overall impression, ratings were significantly better in the linear condition, followed by WDRC with a compression ratio of 2:1, and then by 4:1. From the acoustical analysis, it was seen that there were changes in the temporal characteristics of speech sounds induced by WDRC.

The study infers that there is deterioration in the speech identification and speech quality with the WDRC, especially with higher compression ratios. WDRC induced alterations on the temporal characteristics of speech sounds were also noted in the study. Though, WDRC is beneficial in providing comfortable loudness for individuals with hearing loss, it reduces the performance in terms of speech identification and quality.

Key words: Wide dynamic range compression (WDRC), compression ratio, temporal characteristics, speech identification, speech quality.

Chapter 1

INTRODUCTION

Wide dynamic range compression (WDRC) is being used extensively in digital hearing aids owing to its usefulness in providing adequate and comfortable amplification for individuals with hearing loss. Most individuals with sensorineural hearing impairment who have reduced dynamic range and experience loudness discomfort benefit from this. There has been a lot of research in the past focusing on the benefits of WDRC in terms of providing sufficient audibility of sounds and providing comfort to the users, when compared to traditional linear amplification (Fortune, 1999; Jenstad et al., 2000; Larson et al., 2000).

Certain studies indicate the improvement in speech intelligibility with the utilization of WDRC (Humes et al., 1999). There have also been studies indicating the negative impacts of WDRC on the quality and intelligibility of speech (Plomp, 1988; Festen et al., 1990; Verschuure et al., 1996; Boothryod, et al.,1998; Souza & Turner, 1998). The effects of WDRC on speech intelligibility in quiet and noisy situations has also been investigated. Among those, there is literature indicating no substantial improvement in noisy situations (Boike & Souza, 2000).

There are researches which report that the benefit of WDRC is dependent on the type of noise (Verschuure et al., 1998; Boike & Souza, 2000). According to Souza, 2002, the greatest benefit from WDRC is demonstrated when the speech is presented at lower intensities, and with no background noise. In contrast to these studies, there are some studies that show that WDRC does not influence speech recognition and quality (Souza & Turner, 1996). Recent studies, have also studied the effect of WDRC on the spatial plane and the effects when the hearing aids are used binaurally (Wiggins & Seeber, 2011). The effects of

WDRC on localisation abilities has also been researched of late (Ibrahim et al., 2013; Korhonen et al., 2015). Thus, equivocal findings are reported in literature that discuss about the benefits of WDRC and this could be because of the involvement of several parameters.

A lot of other parameters affect the speech identification and the sound quality. It includes the subject-related parameters like the age, type, degree of hearing impairment, audiogram configuration, the cognitive abilities of the individual, pre-lingual or post-lingual hearing impairment, whether the participants have prior experience in using hearing aid or are naïve hearing aid users at the time of testing. There are several other parameters that can be modified by the clinician such as the compression threshold, the compression ratio, the time constants, the prescription formula used, single channel or multichannel hearing aid, and the type of hearing aid. Therefore, the combination and the interaction among these parameters also influence the speech quality and speech intelligibility (Kates, 2010).

Hence, it is important to understand if there is, in fact, any effect of the WDRC in terms of the changes in the acoustics of speech sound. There are very limited studies where the output from the hearing aid is acoustically analysed to find out the impacts of WDRC on the temporal and spectral parameters of speech. Some of these studies were carried out by simulating the hearing aid (Jenstad et al., 1999). Many studies state that the temporal characteristics are altered by the WDRC (Plomp, 1988; Dreschler, 1989; Festen et al., 1990; Turner et al., 1995; Verschuure et al., 1996; Boothryod et al., 1998; Kates, 2010). Individuals with higher degrees of hearing impairment, especially depend on the temporal characteristics for the recognition of speech (Wang et al., 2011).

This is because they are dependent on these cues, because most of the spectral information is not available to them. Through the acoustical analysis of the hearing aid output in different WDRC settings, it is possible to see if there are any direct effects of WDRC on the temporal characteristics of speech and if that can affect speech identification among individuals with hearing impairment. Therefore, more evidence is warranted on the impacts of WDRC on the temporal parameters of speech.

The temporal parameters of speech include the voice onset time (VOT), burst duration (BD), closure duration (CD), frication duration (FD) and transition duration (TD). The VOT is defined as the length of time from the release of the consonant to the initiation of vocal fold vibration. The time period of the burst of energy when the consonant is released is called the burst duration (BD). The interval of occlusion prior to the articulatory release is the closure duration (CD). The frication duration (FD) is the extended duration of aperiodicity or frication that is a characteristic of the fricatives. The articulatory movement from stop to vowel is accompanied by an acoustic change which is viewed as the shifting formants and the duration required for this transition is called the transition duration (TD) (Kent & Reed, 2002).

In speech, the spectral and temporal information are present. The amount of the spectral and temporal information available to an individual is based on several factors which includes the degree of hearing loss, type of hearing impairment, and configuration of audiogram. In addition, there are a lot of individual variations in the perception of speech sounds with regard to its intelligibility and speech quality depending on the amount of distortions at the peripheral auditory system, cognitive abilities, auditory working memory and processing speed (Helfer & Freyman, 2014). With previous literature providing varied evidences on the repercussion of WDRC on the speech intelligibility and speech quality, the present study intends to see if there is any association of the effect of WDRC on the alterations of certain acoustic characteristics of speech that in turn can have influence on speech identification scores and also on the speech quality. Studies indicate that WDRC in hearing aids can cause changes in the temporal characteristics of speech, most of which have used simulated hearing aid outputs. Most of these studies make use of natural speech that changes in temporal and spectral content simultaneously and they are assessed behaviorally.Therefore, it is not easy to segregate the effect of temporal alterations from the spectral distortions that would have also resulted from compression. Thus, the acoustical analysis of the actual/direct hearing aid output with different compression settings can provide information on any change in the temporal characteristics.

In addition, there is a dearth of these studies in Dravidian languages which differ significantly in temporal characteristics such as Voice Onset Time. Amongst the languages, there are differences in the VOT based on the place of articulation. The velar plosives exhibit the highest VOT and the bilabial stops exhibit the shortest in English language. Whereas, in Indian dravidian languages, alveolars have the shortest VOT (Smith, 1978; Savithri et al., 2001). Hence, there is a need for the acoustic analysis of the temporal parameters of speech processed by the hearing aid with WDRC. The previous literature suggests adverse effect and some of them indicate no benefit. Thus, further examination of the acoustic effect of WDRC on speech quality and identification in individuals with hearing impairment would add useful literature for clinicians.

Aim and Objectives of the Study

The aim of the study is to examine the effect of WDRC in hearing aid on a few temporal parameters and its impact on the speech identification and quality, in individuals with sensorinerual hearing loss.

The specific objectives of the study were:

1. To examine the effect of WDRC (with the compression ratio of 2:1) in hearing aid on certain temporal parameters of speech sounds, such as voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration(TD).
2. To examine the effect of WDRC (with the compression ratio of 4:1) in hearing aid on certain temporal parameters of speech sounds, such as voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration(TD).
3. To examine the effect of WDRC (with the compression ratio of 2:1) in hearing aid on speech identification.
4. To investigate the effect of WDRC (with the compression ratio of 4:1) in hearing aid on speech identification.
5. To examine the effect of WDRC (with the compression ratio of 2:1) in hearing aid on the speech quality.
6. To investigate the effect of WDRC (with the compression ratio of 4:1) in hearing aid on the speech quality.

Hypotheses

The following hypotheses were framed for the study-

1. There is no significant effect of WDRC (with the compression ratio of 2:1) on certain temporal parameters of speech sounds such as Voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD) when processed with linear amplification and WDRC.

2. There is no significant effect of WDRC (with the compression ratio of 4:1) on certain temporal parameters of speech sounds such as Voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD) when processed with linear amplification and WDRC.
3. There is no significant difference in the speech identification scores (SIS) when processed with linear amplification and WDRC (with compression ratio of 2:1).
4. There is no significant difference in the speech identification scores (SIS) when processed with linear amplification and WDRC (with compression ratio of 4:1).
5. There is no significant difference in the speech quality measures when processed with linear amplification and WDRC (with compression ratio of 2:1).
6. There is no significant difference in the speech quality measures when processed with linear amplification and WDRC (with compression ratio of 4:1).

Chapter 2

REVIEW OF LITERATURE

Individuals with cochlear hearing impairment have reduced audibility, poor frequency resolution, and smaller dynamic range (Carney & Nelson, 1983). To overcome these issues, researchers have come up with various technological advancements. Equal amplification is provided irrespective of the input levels in linear hearing aids. However, because of the reduced dynamic range, the listeners suffer from loudness discomfort with linear amplification. Thus, compression was introduced in hearing aids and these hearing aids are called non-linear hearing aids.

The non-linear hearing aids with compression are based on compression parameters. They include compression knee-point or compression threshold (though these two concepts vary slightly, they are being used interchangeably), compression ratio, attack and release time. The compression threshold or knee-point is the lowest level from where gain starts to decrease (Souza, 2002). According to Dillon, 2001, the compression threshold is defined as the point in the input-output function at which the output level deviates by 2 dB on the linear input-output function. The compression knee-point depicts the lowest point where the hearing aid switches from linear to compression mode, with the slope of the I/O function less than one. The ratio of incremental change in input to the resulting incremental change in output is called the compression ratio (ANSI S3.22, 2003). The gain is modified automatically, depending on the intensity of the input signal. More gain is reduced for higher input intensities (Souza, 2002).

Studies indicate that there is an impact of compression ratio on the speech quality and consonant perception (Newman et al., 1998; Hornsby & Ricketts, 2001; Souza & Kitch, 2001). In the presence of noise, there were interaction effects between the compression ratios and the signal to noise ratios (SNR) (Hornsby & Ricketts, 2001). Similarly, the interaction effects were also seen between the compression ratios and presentation levels (Hornsby & Ricketts, 2001). The findings of this study showed that the speech recognition scores deteriorated with higher compression ratios when combined with increased SNR (+ 6 dB). The interaction between the compression ratio and presentation levels was also studied. Consonant recognition was poor with increased compression ratios at lower presentation levels (65 dB SPL). However, increased compression ratios at higher presentation levels (95 dB SPL), did not remarkably impact the speech recognition (Hornsby & Ricketts, 2001).

Another important parameter is the time with which the hearing aid adjusts its gain following the activation of compression. The attack time of compression is defined as the duration between the sudden increment in input intensity from 55 to 90 dB SPL and the point of stabilization of the output level within 3 dB SPL of the stable value for an input of 90 dB SPL (ANSI S3.22, 2003). The attack time should be brief so that it does not cause discomfort because of the overshoot in the output. The duration between the input signal offset which can initiate compression and the following increment in gain to its target value is called the release time. It is defined as the interval between the sudden decrease in input level from 90 to 55 dB SPL and the point of stabilization of the output level within 4 dB of the stable value for an input of 55 dB SPL (ANSI S3.22, 2003). The release time is generally longer than the attack time. If the release time is very prolonged, the speech that follows may get compressed and become less audible or inaudible.

When low compression thresholds and lower compression ratios (less than five: one) are used, it is referred to as wide dynamic range compression (WDRC)(Walker & Dillon, 1982; Souza, 2002). Along with low compression thresholds, fast acting compression systems act on the syllables of the speech sounds to decrease the intensity differences between syllables, resulting in syllabic compression.

Earlier literature suggests that WDRC normalizes the increase in loudness effectively than linear amplification and provides listening comfort to individuals with sensorineural hearing loss (Fortune, 1999; Jenstad et al., 2000). With regard to speech identification, there are a number of equivocal studies (Plomp, 1988; Festen et al., 1990; Verschuure et al., 1996; Boothryod et al., 1998; Souza & Turner, 1998; Humes et al., 1999; Boike & Souza, 2000) on the benefits of WDRC for speech perception and there are several factors which contribute to the transfer of information. It includes the listener's abilities, the listening environment, the amplification strategies and technologies utilized.

2.1. Effect of WDRC on Speech Perception

Research findings suggest that the fast acting WDRC negatively affects the speech perception. Although the audibility of speech sounds is improved, distortion of the temporal characteristics of speech is often seen. This can make the speech perception worse, particularly for those individuals with greater degrees of hearing impairment. These individuals having cochlear hearing impairment depend on the temporal cues, because they have very limited spectral information available (Erber, 1972).

Boothryod et al., (1988) conducted a study in nine individuals with profound sensorineural hearing loss. All of them were with pre-lingual hearing impairment. Out of the nine individuals, one person performed better with compression than without the compression. The rest of the eight performed poorly with compression. This is attributed to the distortions caused by the compression on time-intensity cues. The improvement in speech perception in one subject was reported to be because of the improvement in the audibility.

The deleterious effects of compression in the hearing aids were studied by Plomp (1988). In this study, the author used Modulation Transfer Function (MTF) to see the amount of transfer of information in terms of the frequency and intensity of speech. This information is particularly required for stop consonants. The effects on speech intelligibility is also studied based on the amount of information transmitted. The study discussed the importance of the preservation of the spectro-temporal contrasts, especially for those with hearing impairment. The findings of the study illustrate the deleterious effects of multi-channel amplitude compression on the speech perception.

Similarly, Festen et al., (1990) also used MTF to study the effects on speech perception. The results were also similar to that reported by Plomp (1988), suggesting that the multichannel amplitude compression with short time constants, such as short attack and release times, can reduce the quality of the speech transmission.

Dreschler (1989) studied phoneme perception with and without compression. Participants were 12 individuals with nine of them having sensorineural hearing loss and three of them having conductive hearing loss. The compression ratio and the release time was varied in two presentation levels. One hearing aid setting was had compression ratio of 5:1 with recovery time of less than ten milliseconds. The second hearing aid setting had the compression ratio of 3:1 with recovery time of less than twenty-five milliseconds. The study concluded that perception of temporal cues of CVC syllables are not significantly altered by compression. However, the difference in quality was seen.

Souza and Turner (1996) studied the impact of compression on the temporal speech information. This study had focused on both spectral and temporal information with special emphasis on temporal cues. With the use of natural speech, a stimulus that was compressed digitally, the SIS were obtained for ten individuals having mild to severe sensorineural hearing impairment. The control group consisted of individuals having normal hearing thresholds. The speech stimuli included 16 non-sense syllables in /VCV/ format. The findings of the study showed that single channel syllabic compression did not change the temporal signal sufficiently to result in poor speech identification scores. However, it has to be noted that in this study, VCV syllables were used and Sequential Information Analysis (SINFA) was carried out, which indicates chances of better responses because the participant could guess the token from the confusion matrices.

The compression in hearing aids and its effect on speech stimuli was studied by Verschuure et al. (1996). The study revealed that with smaller compression ratios, i.e., less than 3:1, there is an improvement in the speech score for fast compression, when compared to linear amplification. However, adaptive compression can result in overshoots, that can result in the alteration of the temporal parameters of speech. This can cause deterioration the speech intelligibility.

Souza and Turner (1998) studied multi-channel compression and its effect on temporal cues and audibility. The study had participants with mild to moderate sensorineural hearing impairment. Sixteen non-sense syllables in /VCV/, as well as signal correlated noise (SCN) which has minimum spectral information were used as stimuli. But temporal information was preserved in the stimuli. SINFA was carried out and the results showed that the multichannel compression had no impact on the speech identification scores when both spectral and temporal information is available. But extreme multichannel compression can result in temporal distortions, that was evident with use of SCN stimuli.

Van Tasell and Trine (1996) studied the impact of single band syllabic amplitude compression. The stimuli used were VCV syllables and sentences that were altered in such a way that only the temporal information was retained. The subjects were individuals with normal hearing and they had to listen to /aCa/ stimuli that were subjected to different compression settings. The results revealed that the performance deteriorated only with severe compression. However, this study was done in normal hearing listeners and the stimuli used were not natural. The impact may thus be greater or different for individuals with hearing impairment who depend mostly on temporal information.

Franck et al., (1999) studied the combined effect of spectral enhancements along with phonemic compression on the speech perception. Eight subjects with hearing impairment were selected for this study. The stimulus used was consonant-vowel-consonant words. The study concluded that, when spectral enhancement and single channel compression are used in combination, there is no additional benefit on the top of spectral enhancement. When multichannel compression was used, the SIS were poor because spectral enhancements and multichannel phonemic compression have opposite effects.

Souza, in 2000, conducted a study to compare how the temporal information in speech is utilized by the young and the elderly when processed with compression. The stimuli used were VCV syllables and it was processed with WDRC. The scores obtained were poorer with WDRC than with linear amplification. In addition, the elderly had performed poorer than the younger listeners. The results of the study are indicative of the fact that WDRC impairs consonant perception. And for older adults, reduced availability of temporal information along with altered envelop can cause significant deterioration in the recognition of speech sounds.

Hedrick and Rice (2000) conducted a study to examine the impact of single channel WDRC on perception of place of articulation of stop consonants. Hearing aids with single channel fast acting WDRC can alter the ratio of the consonant to vowel intensities by increasing the consonant energy. Thereby, affecting the natural amplitude balance between the consonant and the vowel in the important frequencies. Thus, the place of articulation cues is severely hampered. Synthetic CV stimuli were modified in such a way that all the place cues were removed except relative amplitudes of the consonant. Acoustical analysis of the stimuli was done prior to and after hearing aid processing and it showed an enhancement in high frequency energy, especially for the consonant bursts. Subjects were 25 individuals having normal hearing sensitivity and five individuals having sensorineural hearing impairment. It was found that the fast acting WDRC can alter the consonant vowel amplitude in discrete frequency regions. This can influence how the place of place of articulation of stops is perceived ultimately resulting in erroneous perception.

Souza and Kitch (2001) examined the significance of amplitude envelop cues for the sentence identification in the elderly and the impact of compression ratios. The results reveal that with higher compression ratios, there is increased distortion of amplitude envelop. Although, older individuals performed poorly, they were not vulnerable to the changes in amplitude envelop alterations caused by fast acting amplitude compression systems. This effect is greater for higher compression ratios and short time constants. In older adults, the deterioration in the performance is attributed to the changes in the functioning associated with aging at central processing level.

Souza (2002) stated that the effect of WDRC on speech sounds will be greatest for those whose critical information is carried by variations in sound amplitude over time. These include stops and affricates. The perception of voicing in stops is based on the onset of voicing relative to the start of the burst. Thus, this information helps the listener to distinguish between voiced and voiceless stops. Also, the temporal cues such as falling or rising burst spectrum can help in the perception of place of articulation of stops. Stops are therefore more susceptible to WDRC induced alterations in the amplitude envelop.

The WDRC in hearing aids could make alterations in the rise pattern of the phoneme. This could adversely affect the perception of affricate, because affricates are differentiated from stops by the rise time and the duration of the frication noise. Affricate perception is deteriorated by the use of in multichannel WDRC, but most common is the erroneous perception of the stop consonants (Souza, 2002).

In the study by Kates (2010), the effects of WDRC and linear amplification on speech intelligibility and speech quality were assessed. The effects of compression channels and the compression time constants were compared across linear amplification and WDRC. The sentences were used as stimuli in the presence of background stationary noise. Subjects included were individuals with various configurations of hearing impairment. For individuals with the mild loss, speech quality and intelligibility are better with linear amplification than with compression. For participants with moderate to severe hearing loss, the compression offers better benefits than linear amplification when speech is presented at reduced intensity. The benefits of compression were based on the hearing loss, signal to noise ratio (SNR), and the listening conditions. In the case of poor signal to noise ratios, longer release time helped in improving the intelligibility and quality. It was concluded that interactions among various compression parameters is important and hence it is hard to make conclusions about the effects of WDRC.

2.2. Effect of WDRC on Speech Quality

Sound quality assessments can give an insight into how appealing the sound is in terms of its clarity, loudness, easiness and several other parameters. These sound quality assessments are quicker and easier to administer. There are various ways in which these qualitative assessments are done. Many studies have utilized qualitative assessments such as rating scales, questionnaires or by interviews.

Newman et al. (1998) conducted experiments to determine the effect of compression ratio and release time of a single band WDRC on the sound quality. In this study, the compression ratios were varied from linear to compression ratio of 10:1. The subjects included were 20 participants with sensorineural hearing impairment. They rated for various parameters of speech quality such as the clarity, pleasantness, background noise, loudness, and overall impression of speech in noise. The listeners rated poor for all of them when the compression ratios were increased.

Kam and Wong (1999) compared between WDRC and linear amplification. Twenty participants having moderate to moderately- severe sensorineural hearing loss were selected for the study. Paired comparison procedure was used. The subjects were asked to do the comparison between WDRC and linear amplification on the loudness, clarity, and pleasantness in quiet and in noise. The HINT sentences were used for sound quality ratings. It was seen that subjects preferred WDRC over linear amplification for loudness to both high- and low-level signals; and for pleasantness to high-level signals, except in the presence of noise.

Hansen (2002) conducted a study to determine the influence of multichannel time constants on subjectively perceived sound quality and speech intelligibility. Subjects included were six individuals with normal hearing sensitivity and six individuals with hearing impairment. Using the paired comparison procedure, the subjects were asked to subjectively assess their preference with regard to speech intelligibility and sound quality. With regard to speech intelligibility and speech quality, subjects with hearing impairment preferred lower compression thresholds. Among the individuals with normal hearing sensitivity, there was no significant difference in the sound quality. However, for speech intelligibility they preferred lower compression thresholds.

Boike and Souza (2000) conducted the study to see the effect of compression ratio on speech recognition and sound quality. The materials used were sentences from connected speech test. These were digitally processed with linear amplification and WDRC with three compression ratios. These sentences were presented in both noise as well as in quiet conditions. The participants included six listeners each, with mild to moderate sensorineural hearing loss and the control group consisted of individuals with normal hearing sensitivity. The subjects rated each of the condition in terms of clarity, pleasantness, ease of understanding, and overall impression. The participants were also instructed to repeat back the sentences and the correct scores were calculated. It was found that as the compression ratio is increased, the speech quality ratings decreased in both the groups and the increase in the compression ratios did not affect the speech recognition. Significant reduction in speech quality rating was seen when the compression ratio was 10:1. Therefore, speech recognition was not compromised by the selection of compression ratios on the basis of speech quality judgments.

In the simulated hearing losses, similar studies were done by Rosengard et al., (2005) to see the effect of slow acting WDRC on measures of intelligibility and speech quality. The results demonstrated that in case of simulated flat moderate hearing loss, WDRC provided small but significant improvement in speech intelligibility. However, this improvement is not observed in sloping mild to moderate hearing losses. In the speech quality ratings, the rating for pleasantness decreased with the increase in compression ratios.

In conclusion, many of the studies indicate that WDRC can affect the identification of speech sounds. Also, many studies have shown no effect of WDRC on speech identification. Moreover, the studies that assessed sound quality indicate that individuals with hearing impairment prefer simpler processing, i.e., with lower compression ratios and thresholds. Therefore, assessment of sound quality can also provide insight to the selection of appropriate compression amplification strategies for individuals with hearing impairment.

2.3. Acoustical Analysis of Hearing Aid Output

Mohan and Rajashekhar, 2019, studied the temporal processing and speech perception through multichannel and channel-free hearing aids in individuals with hearing impairment. This study was carried out in three phases. In the first phase, subjective estimation of temporal processing skills and speech perception was carried out. In the second phase, the hearing aid output was analyzed acoustically using the KEMAR. In the third phase, subjective preference and quality rating was done. Twenty-one subjects, within fifteen to fifty-five years having sensorineural hearing loss were selected as participants in the study. The findings revealed that in, both multichannel and channel-free hearing aids, the envelop of the signal is altered. The authors concluded by stating that the multichannel compression could have possibly resulted in the deterioration of the signal.

From the literature, based on the previous studies, there are equivocal findings regarding the effects of WDRC on speech identification, acoustics and on speech quality. Therefore, it is difficult to conclude whether there is in fact, any adverse effects of WDRC. Very limited studies are done in the past where the direct output from the hearing aid is analyzed to see the effects of WDRC on the temporal characteristics of speech and thereby on speech identification and quality. Also, there are only minimal studies conducted in the Dravidian languages which differ in terms of its various temporal characteristics. Thus, the present study aims to see the effects of WDRC on a few temporal characteristics of speech, speech identification and speech quality.

Chapter 3

METHODS

The study was done to examine the effect of wide dynamic range compression (WDRC) in hearing aid on a few temporal characteristics of speech, speech identification and speech quality. The study was done in three phases. In Phase I, the effect of WDRC on temporal characteristics was measured through acoustical analysis. In Phase II, the effect of WDRC on speech identification was measured. The speech quality was assessed in the linear setting as well as with WDRC settings in Phase III. The details of the three phases used in this study are described in the following sections.

3.1. Participants

The data were collected from 16 ears of 16 participants who were in the age range from 15 to 60 years. Each of them had bilateral moderate to moderately-severe sensorineural hearing loss (SNHL). All of them were native speakers of Kannada language with education level of V standard and above. AIISH ethical guidelines for bio-behavioural research were followed.

3.1.1. Inclusion Criteria

1. sensorineural hearing loss (SNHL) in the range of moderate to moderately-severe degree (Clark, 1981), with a flat audiogram configuration (Demeester et al., 2009) in the test ear (Table 3.1). In case of symmetrical SNHL, either ear was considered the test ear. In case of asymmetrical SNHL, the better ear falling within the inclusion criteria was considered as the test ear.
2. post-lingually acquired hearing loss, with adequate speech and language.
3. speech identification score of not less than 60%.

4. naïve hearing aid users.

3.1.2. Exclusion Criteria

1. associated complaints on psychological issues and cognitive decline.
2. tinnitus and hyperacusis.

Table 3.1.
Age, Gender, Degree and Type of Hearing Loss of the Participants.

Participant no:	**Age in years / Gender**	**Degree and Type of hearing loss (in R=Right ear, L=left ear)**
1.	17/female	**R: Moderate sensorineural hearing loss** L: Moderately severe sensorineural hearing loss.
2.	22/male	R:Moderate sensorineural hearing loss **L:Moderate sensorineural hearing loss**
3.	42/female	R: Moderate sensorineural hearing loss **L: Moderate sensorineural hearing loss**
4.	31/male	**R: Moderate sensorineural hearing loss** L: Moderate sensorineural hearing loss
5.	43/male	R: Moderate sensorineural hearig loss **L: Moderate sensorineural hearing loss**
6.	60/male	**R:Moderately severe sensorineural hearing loss** L: Moderately severe sensorineural hearing loss
7.	19/female	**R: Moderately severe sensorineural hearing loss** L: Moderately severe sensorineural hearing loss
8.	60/male	**R: Moderately severe sensorineural hearing loss** L: Moderately severe sensorineural hearing loss
9.	42/male	R: Moderate sensorineural hearig loss **L: Moderate sensorineural hearing loss**
10.	15/male	R: Moderately severe sensorineural hearing loss **L: Moderately severe sensorineural hearing loss**
11.	58/female	R: Profound hearing loss **L:Moderately severe sensorineural hearing loss**
12.	50/female	**R: Moderate sensorineural hearing loss** L: Severe sensorineural hearing loss
13	53/male	**R: Moderate sensorineural hearing loss** L: Profound hearing loss
14.	55/male	R: Moderately severe sensorineural hearing loss **L: Moderately severe sensorineural hearing loss**
15.	16/male	**R: Moderately severe sensorineural hearing loss** L: Moderately severe sensorineural hearing loss
16.	51/female	**R: Moderately severe sensorineural hearing loss** L: Severe sensorineural hearing loss

Note. The test ear is in bold letters.

3.2. Instrumentation

1. A calibrated clinical audiometer with facility for pure-tone audiometry, speech audiometry, and sound field measurement was used for selection of participants and data collection.
2. A calibrated middle ear analyser to ensure normal middle ear status.
3. A computer connected to HiPro interface, programming cables, and hearing aid programming software in the computer to program the digital hearing aid.
4. A high power digital behind the ear (BTE) hearing aid with eight signal processing channels and four gain handles, had a fitting range from mild to profound hearing loss. Other features of the hearing aid include four hearing aid programs, option to alter various compression parameters such as the compression knee-point and the compression ratio. The hearing aid had facility to change the compression knee-point from 20 to 86 dB SPL and the compression ratio from 1:1 to 4:1. IN the study the compression kneepoint was set at 50 dB SPL and the hearing aid was set at 1:1, 2:1 and 4:1 compression ratios. The hearing aid also had feedback management, fixed directional microphone, telecoil, and noise management strategies which were disabled. Hardware of the hearing aid consisted of push button, rocker switch, and it used 675 size battery.
5. A high fidelity microphone connected to the computer for recording the speech stimulus. A Dell Inspiron 14 5000 computer installed with Praat software (version 6.0) for accoustical analysis and Adobe Audition software (version 3.0) to record the stimulus.

6. Knowles Electronics Manikin for Acoustic Research (KEMAR) configured with pinnae, ear simulator, and ear canal extension in the right ear for recording the speech stimuli from the hearing aid for acoustic analysis. A loud speaker connected to the audiometer to present the stimulus to the KEMAR. A high fidelity microphone for recording the the output from the hearing aid using KEMAR. A Sound Level Meter connected to the microphone to record the output from the hearing aid mounted on KEMAR.

3.3. Speech Material

1. VCV syllables (in /aCa/ context). The syllables /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/, /asa/, /aʃa/, /aʧa/, /aʤa/ were recorded. The VCV syllables were audio recorded using a high precision microphone when it was spoken with normal vocal effort by an adult female native speaker of Kannada. The microphone was connected to the personal computer and the uttered syllables were recorded using the Adobe Audition (version 3.0) software. The same stimulus/syllable was recorded thrice with normal vocal effort. The recording was done in a sound treated room. The speech sounds /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/, /asa/, /aʃa/, /aʧa/, /aʤa/ recorded had an inter stimulus interval of five milliseconds. The recorded stimuli were presented to a native speaker of Kannada language and the best uttered syllable of the three uttered stimulus was chosen as the test stimulus for the testing. The selected recorded stimulus was later normalised to -5 dB using Adobe Audition (version 3.0) software.

2. Phonemically Balanced (PB) word lists in Kannada for adults (Manjula et al., 2015). Four of the twenty four recorded word lists were used for obtaining the speech identification scorees (SIS) in each aided condition. Each PB list consists of twenty

five bisyllabic words. Each correct word repetition was scored with one and incorrect or no repetition of the word was scored zero. The total number of words correctly repeated was considered as the SIS, and the maximum SIS was 25 per list.

3. Speech quality rating scale (Boike & Souza, 2000) which consists of four parameters of quality such as clarity, pleasantness, loudness, and overall impression, that has been translated and adapted into Kannada. It uses a eleven-point rating scale for each parameter. Definitions of the parameters were taken from those used by Gabrielsson et al. (1988) and given in Appendix. The highest rating ten depicted the most favourable outcome for all the parameters except for loudness. For loudness, the zero rating depicts “not loud at all” and ten represents “very loud” and five depicts the optimum rating. The participants rated for three aided conditions. The explanation (Davies-Venn et al., 2007) of different parameters of quality is provided here.

- CLARITY: How intelligible or understandable is the speech? The opposite of intelligible is extremely hard to understand and unclear.
- PLEASANTNESS: How pleasing is the tonal quality of the sound? The opposite of pleasant is unpleasant.
- LOUDNESS: How loud, strong or forceful is the sound? The opposite of loud is soft, weak or faint?
- OVERALL IMPRESSION: Considering everything that you have heard, what do you think about the sound?

4. Kannada passages, three in number, for the sound quality assessments: Three Kannada passages were audio recorded while being read by a native adult female speaker of Kannada. The Kannada speaker was instructed to read the passages using a

normal vocal effort with natural, clear, and neutral tone. This was recorded using a high fidelity microphone. The microphone was connected to the personal computer installed with Adobe Audition (version 3.0) software. The stimulus was normalised to -5 dB using the Abode Audition (version 3.0) software.

3.4. Test Environment

All the tests were carried out in a double-room sound treated air conditioned test suite with permissible noise levels in the room (ANSI S3.1-1999; R2013).

3.5. Procedure

The pure-tone audiometry, speech audiometry and immittance evaluation were done to ensure that the test ear of the participants met the inclusion criteria. The hearing aids were connected to the HiPro using connecting cables. The HiPro was in turn connected to the computer system with hearing aid programming softwares. The participant details and the diagnostic information were fed into the computer software. The hearing aid was programmed based on the hearing thresholds and NAL-NL1 prescriptive formula, at an acclimatization level of 2. The settings were optimized for audibility of Ling's six sounds (Ling, 1976). All other additional features, such as noise reduction as well as feedback management were turned off or disabled during the programming. The volume control was also disabled. The hearing aid was programmed with linear settings (1:1) in Program 1 (P1), minimum compression ratio (2:1) in Program 2 (P2), and maximum compression ratio (4:1) in Program 3 (P3). Thus, there were three aided conditions. They included testing in linear setting of 1:1 (in P1), compression ratio setting of 2:1 (in P2), and a compression ratio setting of 4:1 (in P3). The compression threshold was kept at 50 dB SPL in P2 and P3. The push button to change the programs was enabled.

The data were collected in three phases. In the Phase I, measurement of the acoustical effect of WDRC on temporal characteristics of speech sounds was done, with hearing aid programmed in P1, P2 and P3 program settings. In the Phase II, speech identification scores (SIS) were measured with the hearing aid programmed in P1, P2, and P3 program settings. In the Phase III, the speech quality rating was measured in P1, P2, and P3 program settings of the hearing aid.

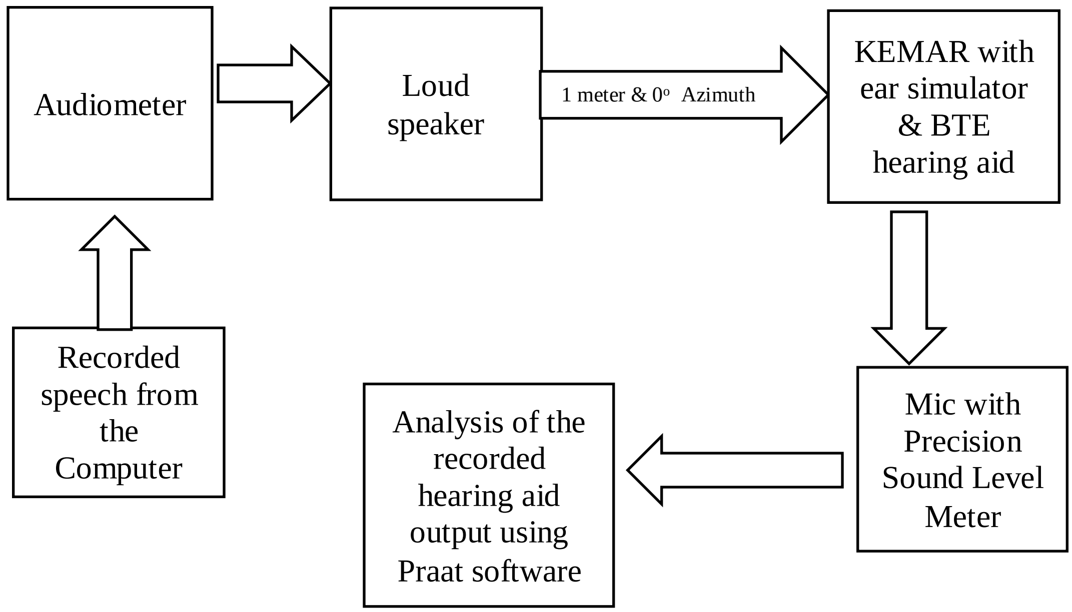
3.5.1. Phase I: Measurement of the Acoustical Effect on Temporal Characteristics of Speech Sounds

In Phase I, measurement of the acoustical effect of WDRC on temporal characteristics of speech sounds was done in three aided conditions. For this, the three hearing aid programs, i.e., programmed in linear settings (P1), minimum compression setting (P2), and maximum compression setting (P3) were used.

For measurement of acoustical effect, the stimulus (VCV syallables) was presented through the loud speaker of the audiometer, placed at a distance of one meter and at 0 degree Azimuth from the KEMAR with ear simulator. The block diagram of the instrumental set-up used for recording the temporal characteristics of speech sounds is depicted in Figure 3.1.

Figure 3.1.

Block Diagram of the Instrumental Set-up for Recording of Speech Output from the Hearing Aid



The programmed digital BTE hearing aid was placed at the ear of the KEMAR using an appropriate ear tip. The stimuli presented to the hearing aid was routed to the ear simulator of the KEMAR. The hearing aid was set in first program, i.e., P1 or the linear setting. The output of the hearing aid was recorded in the ear simulator using a unidirectional microphone connected to the high precision Sound Level Meter. The output was later stored in the Praat software. The temporal characteristics such as the voice onset time (VOT), burst duration (BD), closure duration (CD), frication duration (FD) and transition duration (TD), for relevant speech sounds, were measured using the Praat software in the laptop computer. The acoustic parameters measured for each speech syllable in each of the three program settings of the hearing aid are provided in Table 3.2.

Table 3.2.

Temporal Parameters Measured for Different Speech Sounds

Temporal Parameters / VCV Syllables	VOT	BD	CD	TD	FD
/apa/	✓	✓	✓	✓	
/aṭa/	✓	✓	✓	✓	
/aka/	✓	✓	✓	✓	
/aba/	✓	✓		✓	
/aḍa/	✓	✓		✓	
/aga/	✓	✓		✓	
/asa/					✓
/aʃa/					✓
/aʧa/					✓
/aʤa/					✓

Note. VOT = voice onset time; BD = burst duration; CD = closure duration; FD = frication duration; TD = transition duration.

The voice onset time (VOT) is the duration between the release of the consonant and the onset of vocal fold vibration. The duration of the burst of energy when the consonant is released is called the burst duration (BD). The interval of occlusion prior to the articulatory release is the closure duration (CD). The frication duration (FD) is the extended duration of aperiodicity or frication that is a characteristic of the fricatives. The articulatory transition from stop to vowel is associated with an acoustic transition in the form of shifting formants and the duration required for this transition is called the transition duration (TD) (Kent & Reed, 2002). For the purpose of the current study, the F2 transition was considered.

The temporal characteristics of speech in the intervocalic position (aCa) are represented in the figures 3.2., 3.3., 3.4., 3.5., 3.6. These figures depict the waveforms of the speech sounds without being processed by the hearing aid.

Figure 3.2.

Frication Duration (FD) Measured in /asa/ Context

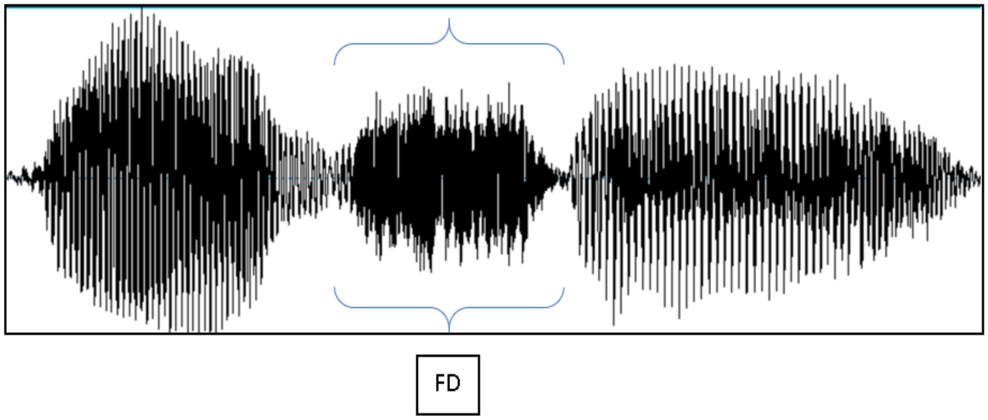


Figure 3.3.

Frication Duration (FD) Measured in /aʧa/ Context

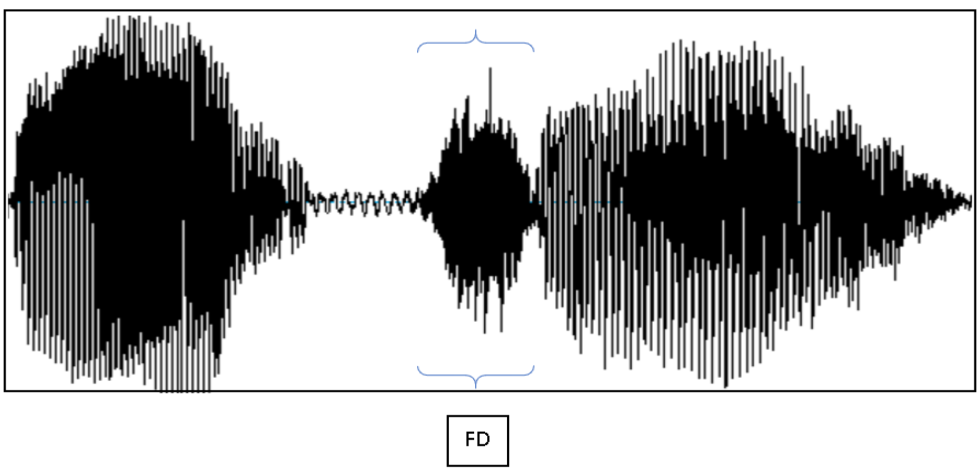


Figure 3.4.

Voice Onset Time (VOT) and Burst Duration (BD) Measured in /aba/ Context.

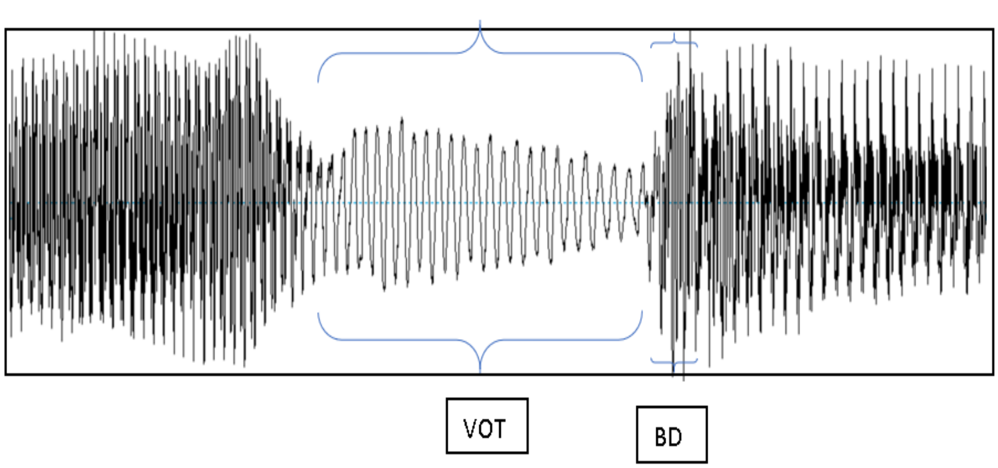


Figure 3.5.

Voice Onset Time (VOT),Burst Duration (BD) and Closure Duration (CD) Measured in /apa/ Context.

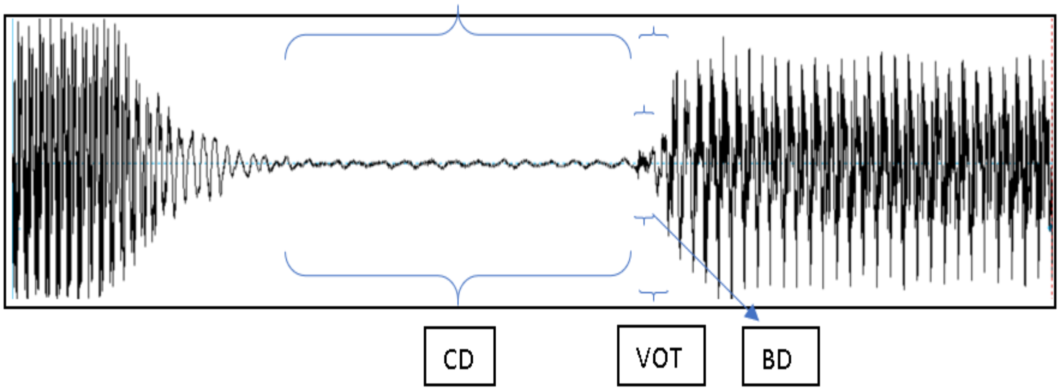
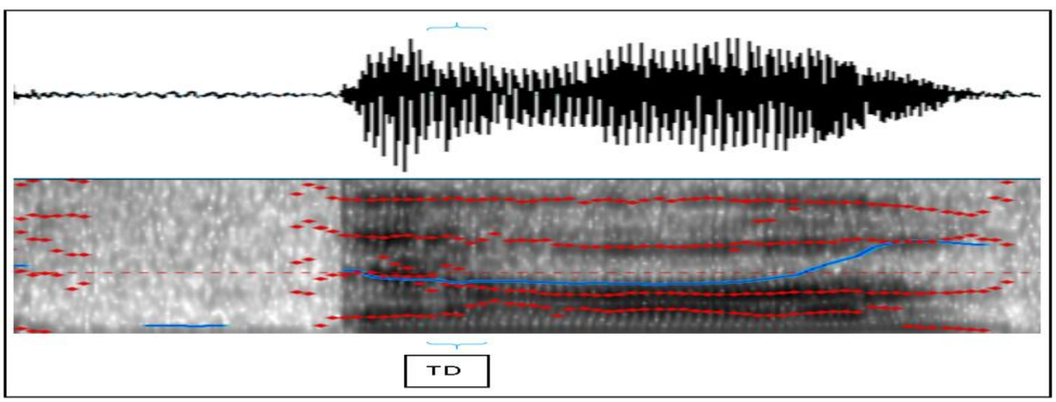


Figure 3.6.

Transition Duration for Second Formant (TD) Measured in /aʈa/ Context.



The hearing aid was then changed to program settings of minimum (P2) and maximum (P3) compression ratios. In each program setting, the output from the hearing aid was recorded through the KEMAR. This recorded output was analysed using the Praat software to measure the VOT, BD, CD, FD, and TD for relevant speech sounds as mentioned earlier (Table 3.2).

3.5.2. Phase II: Measurement of Speech Identification Scores

The speech identification scores for syllables and PB word lists were measured with hearing aid programmed with P1 having the linear settings, P2 having the minimal compression ratio, and P3 having the maximal compression ratio**.** The VCV syllables and PB word list (Manjula et al., 2015) were presented through the loud speaker of the calibrated audiometer located at zero degree Azimuth and one meter distance from the participant, in a two room sound treated test suite. The presentation level was 45 dB HL. The participant was instructed to repeat the syllables / words presented. Ten VCV syllables and 25 PB words were presented in each of the three aided conditions. The same ten VCV syllables, in different order to avoide practce effect, were presented for obtaining the SIS for syllables. Different PB word lists were used for obtaining the SIS for words to avoid familiarity effect. The number of VCV syllables or words correctly repeated was noted as the SIS for syllables and SIS for words, in each aided condition. In this way, the SIS was obtained separately for VCV syllables and PB word list in each aided condition, for each test ear of the participants. This was done with linear (1:1), minimum (2:1), and maximum (4:1) compression settings. The maximum compression settings was used first, then the minimum compression followed by the linear aided condition. The responses were audio recorded for each of the program settings, for each participant. After listening to the recorded responses of the participants, the number of correctly repeated VCV syllables and words, in each test condition, for each participant was tabulated as SIS for syllables and SIS for words. The responses were scored by an audiologist while listening to the audio recorded responses. Each correct word or syllable repetition was awarded a score of one and incorrect or no repetition was scored zero.

Thus, for each test ear and each aided condition, SIS for PB word and SIS for syllables were tabulated.

3.5.3. Phase III: Measurement of Speech Quality

The recorded Kannada passages were presented to the participant through the loud speaker of the audiometer placed at one meter distance and 0^o Azimuth from the participant. The participant was instructed to rate the quality of the passage on four different parameters or attributes of quality, using a rating scale of 0 to 10. The parameters of the quality were defined (Appendix) to the participant before the testing and they were also given the print out, in which the terms were explained, for them to read.

The participant was instructed to listen to the entire passage and then make judgments about the sound quality in terms of its various parameters that was explained beforehand. For clarity, they had to judge on a scale of 0 to 10; where 0 represents ‘not at all clear’ and 10 represents ‘very clear’. For pleasantness, 0 for the ‘least pleasant’ to 10 for ‘very pleasant’. The loudness scale had to be judged as 0 if its inaudible and 10 represents very loud. Taking into account all the other parameters including the loudness, clarity, pleasantness, intelligibility and easiness, the participant had to give the rating for overall impression from 0 to 10, with 0 representing the least and 10 representing the best.

The participants were instructed not to repeat the sentences, instead they were asked to listen to the passage and rate the sentences on four parameters of speech quality. Thus, the participants made these ratings while listening to the first passage in P1 program setting, second passage in P2 program setting of the hearing aid; and while listening to the third passage in P3 program sretting of the hearing aid. The participants rated the four parameters of speech quality, using a eleven-point scale.

Three different passages, one for each of the three aided conditions, were presented in the order of maximum compression settings (4:1), minimum compression settings (2:1), and in the linear settings of the hearing aid. The speech quality rating was done on four parameters i.e., clarity, pleasantness, loudness, and overall impression. The scores or ratings were tabulated for each parameter, in each aided condition, for each test ear of the participant.

The parameters on which the data were collected for each aided condition under each of the three Phase of the study, for each test ear, are given in Table 3.3.

Table 3.3

Parameters of Acoustical Measures, Speech Identification Scores and Speech Quality measures.

Phase I: Acoustical measures			
Aided conditions → / **Parameters** ↓	**P1**	**P2**	**P3**
VOT, BD, TD	/apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/	/apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/	/apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/
CD	/apa/, /aʈa/, /aka/	/apa/, /aʈa/, /aka/	/apa/, /aʈa/, /aka/
FD	/asa/, /aʃa/, /aʧa/, /aʤa/	/asa/, /aʃa/, /aʧa/, /aʤa/	/asa/, /aʃa/, /aʧa/, /aʤa/

Phase II: SIS			
Aided conditions → / Parameters	**P1**	**P2**	**P3**
SIS for PB words (Max score: 25)			
SIS for Syllables (Max. score: 10)			
Phase III: Quality of speech			
Aided conditions → / Parameters	**P1**	**P2**	**P3**
Clarity (0-10)			
Pleasantness (0-10)			
Loudness (0-10)			
Overall impression (0-10)			

The data collected in the Phase I, Phase II, and Phase III were tabulated as described above for each aided condition for each test ear for each participant. In the Phase II, and Phase III, the scores obtained for the identification of PB words, VCV syllables, and speech quality ratings are compared across three settings i.e., in the linear setting, with minimum compression setting (2:1), and with maximum compression setting (4:1) using statistical package for social science (SPSS) software (version 21). Shapiro Wilk test was carried out as test of normality. Since the data were not normally distributed (p<0.05), non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) were carried out to find if there are any significant differences between the three aided conditions.

Chapter 4

RESULTS

This study evaluated the effect of wide dynamic range compression in hearing aid on a few temporal characteristics of speech, speech identification, and speech quality in three hearing aid settings. The hearing aided conditions included hearing aid in the linear mode, in WDRC with a compression ratio of 2:1, and in WDRC with a compression ratio of 4:1. In the Phase I, the hearing aid output for ten speech sounds were recorded in three aided conditions and the data were collected and acoustically analysed. In the Phase II, the speech identification scores were obtained in three aided settings. In the Phase III, the speech quality was measured on various parameters of quality such as clarity, pleasantness, loudness and overall impression in these three aided conditions. The data obtained in the Phase II and Phase III were tabulated and were subjected to statistical analysis using Statistical Package for the Social Sciences (SPSS, version 21) software.

The mean, median, standard deviation (SD), and range of the data on speech identification scores (SIS) for VCV syllables, SIS for PB words and four attributes of speech quality were computed. The mean, median, standard deviation, minimum value, and maximum value of the SIS using VCV syllables, PB words, and speech quality measures on clarity, pleasantness, loudness, and overall impression are given in the Table 4.1.

Table 4.1.

Mean, Median, Standard Deviation, Minimum Value and Maximum Value of Speech Identification Scores for (VCV Syllables, PB Words), and Speech Quality Measures.

Measures		Aided conditions	Mean	Median	Std. Deviation	Minimum value	Maximum value
SIS	for VCV	4:1	7.44	7.50	1.71	4	10
		2:1	8.13	8.00	1.45	5	10
		1:1	8.63	9.00	1.08	7	10
	for PB words	4:1	20.44	20.00	3.30	13	25
		2:1	21.38	22.50	3.16	14	25
		1:1	21.88	22.50	2.75	15	25
Speech Quality	Clarity	4:1	6.87	7.00	1.99	3	10
		2:1	8.03	8.00	1.27	6	10
		1:1	8.65	9.00	1.30	6	10
	Pleasantness	4:1	7.18	7.00	1.51	5	9
		2:1	8.31	8.00	1.30	6	10
		1:1	8.75	9.00	1.12	7	10
	Loudness	4:1	7.43	7.00	1.45	4	9
		2:1	8.12	8.00	1.31	6	10
		1:1	8.56	8.75	1.40	6	10
	Overall Impression	4:1	7.50	7.00	1.36	5	10
		2:1	8.37	8.50	1.14	7	10
		1:1	8.75	9.00	1.23	7	10

Note: VCV represents vowel-consonant-vowel, PB represents phonemically balanced.

The data obtained in the Phase II and Phase III were subjected to tests of normality. The Shapiro Wilk test results showed that the data from Phase II and Phase III were not normally distributed (p<0.05). Therefore, non-parametric tests such as Friedman test and Wilcoxon signed ranks test (if indicated) were carried out. The Friedman test was done to see if there were significant overall differences between the three aided conditions and Wilcoxon signed ranks test was done on different combinations of conditions to find out the statistical significance between pairs of data, when indicated on Friedman test.

The data from Phase II and Phase III were not normally distributed, as revealed through Shapiro Wilk test. Hence, non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) were administered. Bonferroni adjustment was done to interpret the results obtained in Wilcoxon signed rank test, because multiple comparisons are made. The new significance level after applying Bonferroni adjustment is 0.05/3, that is 0.017. That is, the p value has to be <0.017 if the difference has to be significant. The results of the study are detailed under the following headings:

4.1. Effect of WDRC on a few temporal characteristics of speech.

4.1.1. Effect of WDRC on voice onset time.

4.1.2. Effect of WDRC on closure duration.

4.1.3. Effect of WDRC on burst duration.

4.1.4. Effect of WDRC on transition duration.

4.1.5. Effect of WDRC on frication duration.

4.2. Effect of WDRC on speech identification.

4.2.1. Effect of WDRC on the identification of VCV syllables.

4.2.2. Effect of WDRC on the SIS using PB words.

4.3. Effect of WDRC on speech quality.

4.3.1. Effect of WDRC on clarity of speech.

4.3.2. Effect of WDRC on pleasantness of speech.

4.3.3. Effect of WDRC on loudness of speech.

4.3.4. Effect of WDRC on the overall impression of speech quality.

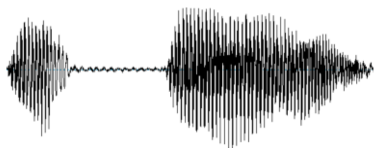
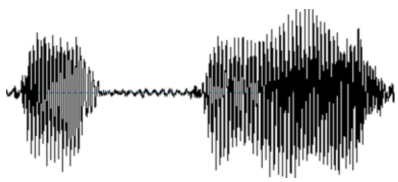
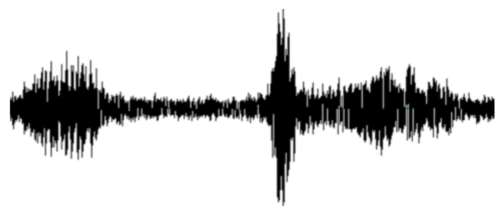
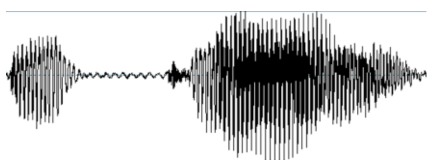
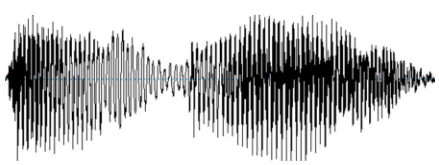
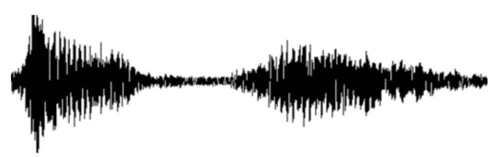
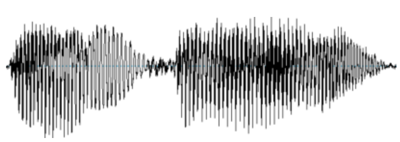
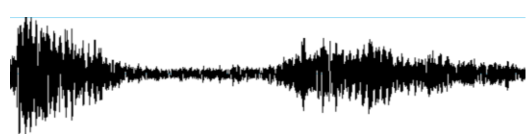
4.1. Effect of WDRC on a Few Temporal Characteristics of Speech

To evaluate the effect of WDRC on acoustic measures, the hearing aid output in three aided settings, was recorded and analyzed acoustically using the Praat software. The acoustic measures of voice onset time (VOT), closure duration (CD), burst duration (BD), transition duration (TD), and frication duration (FD) were measured for relevant speech sounds, in three aided conditions. The aided conditions were linear setting, WDRC with compression ratio of 2:1, and WDRC with compression ratio of 4:1. This is a single value of acoustic measures, as the measurement was done for single speech sound in VCV context. Hence statistics was not applicable for these acoustic measures for making inferences.

A comparison of the waveforms of ten different speech sounds without being processed by the hearing aid and when being processed by three (1:1, 2:1, 4:1) hearing aid settings are provided in Figures 4.1. and Figure 4.2.

Figure 4.1.

A Comparison of Unprocessed VCV Syllables to Linear-Amplified VCV Syllables.

VCV syllables	Waveforms without being processed by the hearing aid.	Waveforms processed using linear amplification(1:1)
/apa/		
/at̪a/		
/aka/		
/aba/		
/ad̪a/		
/aga/		

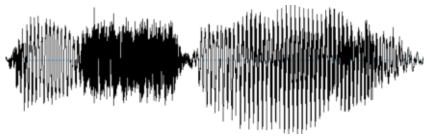
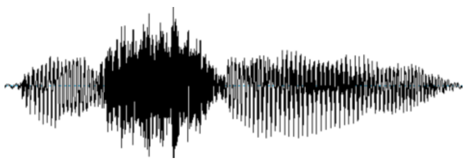
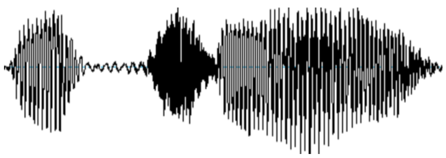
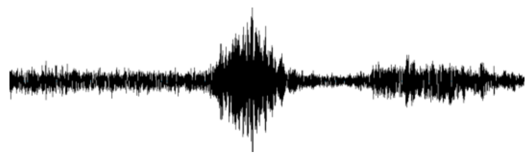
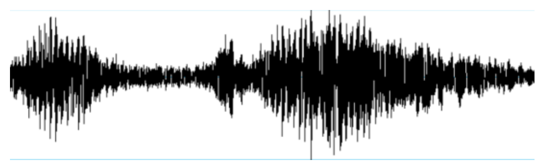
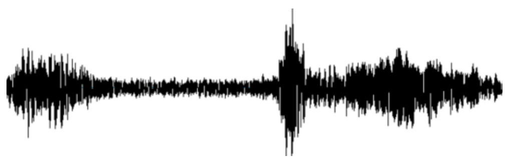
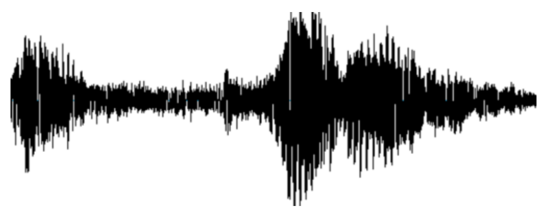
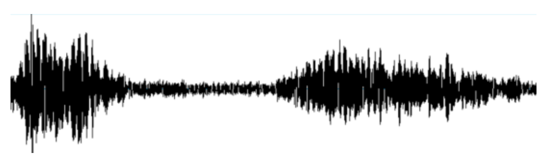
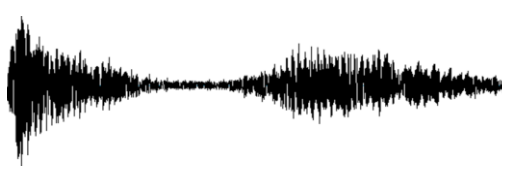
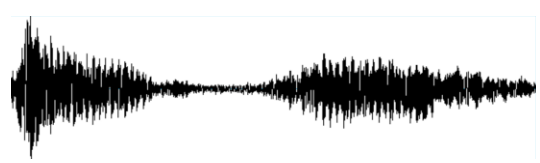
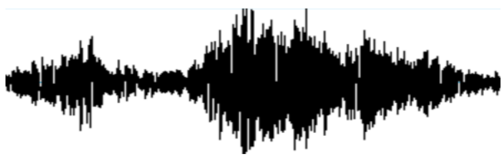
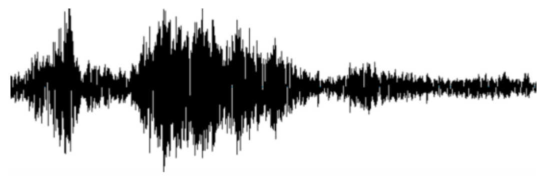
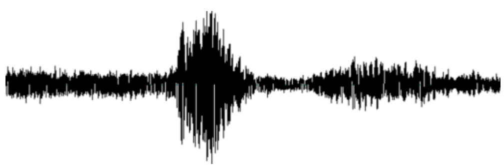
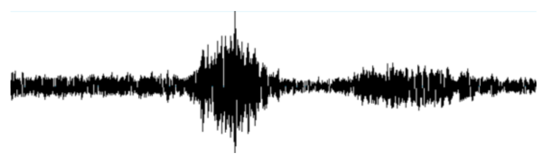
VCV syllables	Waveforms without being processed by the hearing aid.	Waveforms processed using linear amplification(1:1)
/asa/		
/aʃa/		
/aʧa/		
/aʤa/		

Figure 4.2.

A Comparison of WDRC Amplified Speech with Compression Ratio of 4:1 to 2:1

VCV syllables	**Waveforms processed using WDRC(4:1)**	**Waveforms processed using WDRC(2:1)**
/apa/		
/aʈa/		
/aka/		
/aba/		
/aɖa/		
/aga/		

VCV syllables	Waveforms processed using WDRC(4:1)	Waveforms processed using WDRC(2:1)
/asa/		
/aʃa/		
/aʧa/		
/aʤa/		

The measurement values of the effect of WDRC on these acoustic measures are being provided in the sections that follow.

4.1.1. Effect of WDRC on Voice Onset Time

The voice onset time for the VCV syllables such as /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/ was measured. The results depicted in Table 4.2.

Table 4.2.

Voice Onset Time (in milliseconds) of the Stop Consonants in the VCV Context, for Three Aided Conditions.

VCV Syllables	VOT (in ms) in three aided conditions		
	4:1	2:1	1:1
/apa/	12.31	14.73	15.00
/aʈa/	11.00	10.00	6.37
/aka/	9.74	9.00	9.84
/aba/	166.68	117.22	142.14
/aɖa/	107.97	113.78	97.51
/aga/	139.99	141.77	116.03

4.1.2. Effect of WDRC on Closure Duration

The effect of WDRC on the closure duration was measured in the medial position for unvoiced stop consonants in VCV syllables such as /apa/, /aʈa/, and /aka/. The closure duration for these speech sounds is given in the Table 4.3.

Table 4.3.

Closure Duration (CD) (in milliseconds) of the Unvoiced Stop Consonants in VCV Syllables for Three Aided Conditions

VCV syllables	CD (in ms) in three aided conditions		
	4:1	2:1	1:1
/apa/	124.62	135.84	120.86
/aʈa/	125.32	161.36	151.18
/aka/	142.70	166.35	140.57

4.1.3. Effect of WDRC on Burst Duration

The burst duration of the hearing aid output in three aided settings were measured to examine the effect of WDRC on burst duration of the VCV syllables such as /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/. Since burst duration is one of the shortest acoustic events that is commonly analyzed in speech, it is severely affected by compression as well as the internal noise of the hearing aid. Because of this reason, the burst duration could not be measured.

4.1.4. Effect of WDRC on transition duration

The effect of WDRC on transition duration was examined by measuring the transition duration in three aided conditions for the VCV syllables such as /apa/, /aʈa/, /aka/, /aba/, /aɖa/, /aga/. The results obtained are tabulated in the Table 4.4.

Table 4.4.

Transition Duration of the Stop Consonants (milliseconds) in VCV context, for Three Aided Conditions

VCV syllables	Transition duration (in ms) in three aided conditions		
	4:1	**2:1**	**1:1**
/apa/	20.00	13.00	16.00
/aʈa/	20.00	19.44	16.81
/aka/	20.25	18.31	16.70
/aba/	19.88	19.35	17.34
/aɖa/	26.14	20.18	22.4
/aga/	21.74	22.11	18.68

4.1.5. Effect of WDRC on Frication Duration

The frication duration was analyzed for fricatives and affricates in VCV syllables such as /asa/, /aʃa/, /aʧa/, /aʤa/ in three aided conditions.The findings are given in Table 4.5.

Table 4.5.

Frication Duration of the Fricatives and Affricates (in milliseconds) in VCV context, for Three Aided Conditions

VCV syllables	Frication duration (in ms) in three aided conditions		
	4:1	**2:1**	**1:1**
/asa/	193.31	211.21	208.81
/aʃa/	182.25	183.52	190.85
/aʧa/	84.23	99.00	115.32
/aʤa/	43.67	62.76	48.95

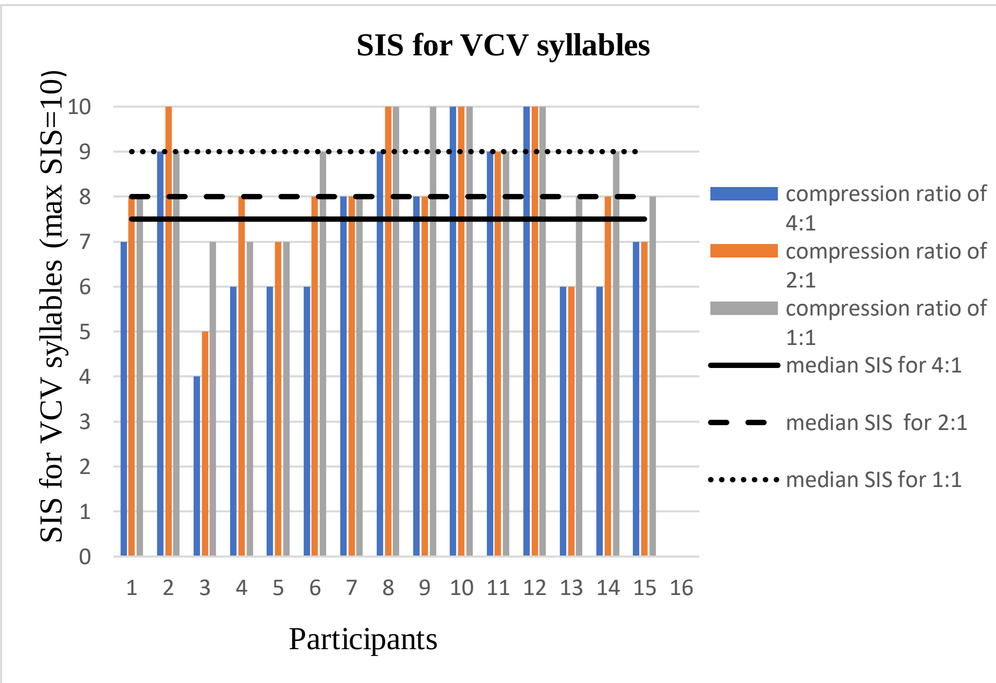
4.2. Effect of WDRC on Speech Identification

4.2.1. Effect of WDRC on the Identification of VCV Syllables

To investigate the effect of WDRC on the SIS for VCV syllables, the scores obtained in three aided conditions i.e., in the linear mode, with minimum compression (with the compression ratio of 2:1) and with maximum compression (with the compression ratio of 4:1) were compared. The scores obtained by each of the sixteen participants are shown in the Figure 4.3.

Figure 4.3.

SIS for VCV Syllables (maximum score of 10) in Three Aided Conditions, for 16 Participants.



Friedman test was administered on the SIS for VCV syllables data and it indicated that there were overall significant differences between the groups ($p<0.05$). Wilcoxon signed ranks test was administered to make multiple comparisons between the pairs of data. The test results revealed that the SIS for VCV syllables was significantly better with minimum compression (compression ratio of 2:1) than with maximum compression (compression ratio of 4:1) ($p<0.017$). The SIS for VCV syllables was significantly better with linear setting than with maximum compression (compression ratio of 4:1) ($p<0.017$).

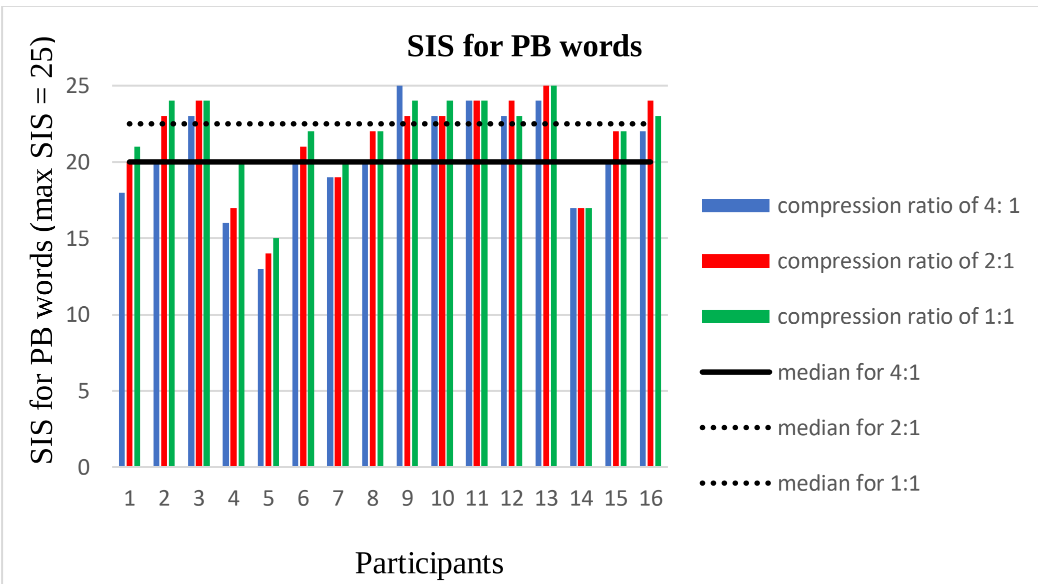
However, no significant difference was found between linear settings and with minimum compression (with a compression ratio of 2:1) (p>0.017).

4.2.2. Effect of WDRC on the SIS using PB words

The scores obtained for the SIS of PB words across three aided settings were compared to see the effect of WDRC on SIS. The scores obtained for each of the 16 participants are represented below in the Figure 4.4. The maximum SIS that could be obtained was twenty-five.

Figure 4.4.

SIS for PB words (Maximum Score of 25) in Three Aided Conditions, for 16 Participants.



Non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) were administered. The Friedman test indicated that there is overall significant difference between the groups in SIS (p<0.05). Wilcoxon signed ranks test was administered to make pair-wise comparison between the SIS in aided conditions. There were three pairs of data and the comparison between these pairs revealed that there was a significant difference between two pairs of data ($p<0.017$). The overall significant differences in the SIS of PB words and VCV syllables between the aided conditions based on the Friedman test are represented in the Table 4.6.

Table 4.6.

Chi Square Values, Degrees of Freedom, and Significance Level for the SIS of VCV Syllables and PB Words.

Measures	Chi Square	df	Significance level (*p*)
SIS for VCV syllables	15.65	2	0.00**
SIS for PB words	15.22	2	0.00**

Note: ***p*<0.01.

The significant differences for each pair of three aided conditions in the SIS for PB words and VCV syllables based on Wilcoxon signed rank test are given in the Table 4.7.

Table 4.7.

The Z Value and p Value for Different Aided Conditions of SIS for VCV Syllables and PB Words

Measures	Comparison between the aided conditions.	Z	Asymp. Sig.(2-tailed) (*p* value)
SIS for VCV syllables	1:1 - 2:1	-1.90	0.057
	1:1 - 4:1	-2.99	0.003*
	2:1 - 4:1	-2.60	0.009*
SIS for PB words	1:1 - 2:1	-1.94	0.052
	1:1 - 4:1	-2.98	0.003*
	2:1 - 4:1	-2.41	0.016*

Note: **p*<0.017; VCV = vowel-consonant-vowel syllables; PB = Phonemically Balanced words.

The SIS for words obtained with minimum compression (compression ratio of 2:1) was significantly better than with the maximum compression (compression ratio of 4:1). The SIS for words obtained with linear (1:1) amplification was significantly better than with the maximum compression (compression ratio of 4:1). When the SIS for words were compared between linear settings and with minimum compression (2:1), there was no significant difference between the scores ($p>0.017$).

4.3. Effect of WDRC on Speech Quality

To determine the effects of WDRC on the speech quality, a rating scale (0 -10) was used. The participants were instructed to rate the clarity of speech when three standardized passages were presented to them in the Kannada language. These three passages were presented to them in three different aided conditions i.e., two settings using WDRC – one with minimum compression ratio (2:1) and the other with maximum compression ratio (4:1) compression ratios, and linear (1:1) setting. The results of four different attributes of speech quality are given in the following sections. Since the rating data were not normally distributed on Shapiro-Wilk test ($p<0.05$), non-parametric tests such as Friedman test and Wilcoxon signed ranks (if indicated) test were done. Overall significant differences between aided conditions for the speech quality ratings of clarity, pleasantness, loudness, and overall impression based on the Friedman test are given in Table 4.8.

Table 4.8.

Chi Square Values, Degrees of Freedom, and Significance Level, on Friedman Test, for Various Parameters of Speech Quality Such as Clarity, Pleasantness, Loudness, and Overall Impression.

Measures	Chi Square	Df	Significance level (*p* value)
Clarity	19.51	2	0.00**
Pleasantness	16.17	2	0.00**
Loudness	9.17	2	0.01*
Overall impression	15.77	2	0.00**

Note: * $p<0.05$, **$p<0.01$.

Significant differences between pairs of aided conditions in terms of different parameters of quality such as clarity, pleasantness, loudness and overall impression was measured based on Wilcoxon signed rank test. The results are given in the Table 4.9.

Table 4.9.

The Z Value and p Value for Various Parameters of Speech Quality in Different Pairs of Aided Conditions.

Parameters of speech quality	Comparison between aided conditions	Z	Asymp. Sig. (2-tailed) (*p* value)
Clarity	1:1 - 2:1	-2.06	0.039
	1:1 - 4:1	-2.95	0.003*
	2:1 - 4:1	-2.83	0.005*
Pleasantness	1:1 - 2:1	-1.63	0.102
	1:1 - 4:1	-2.82	0.005*
	2:1 - 4:1	-2.69	0.007*
Loudness	1:1 - 2:1	-1.56	0.119
	1:1 - 4:1	-2.66	0.008*
	2:1 - 4:1	1.61	0.108
Overall impression	1:1 - 2:1	-1.67	0.096
	1:1 - 4:1	-2.83	0.005*
	2:1 - 4:1	-2.56	0.011*

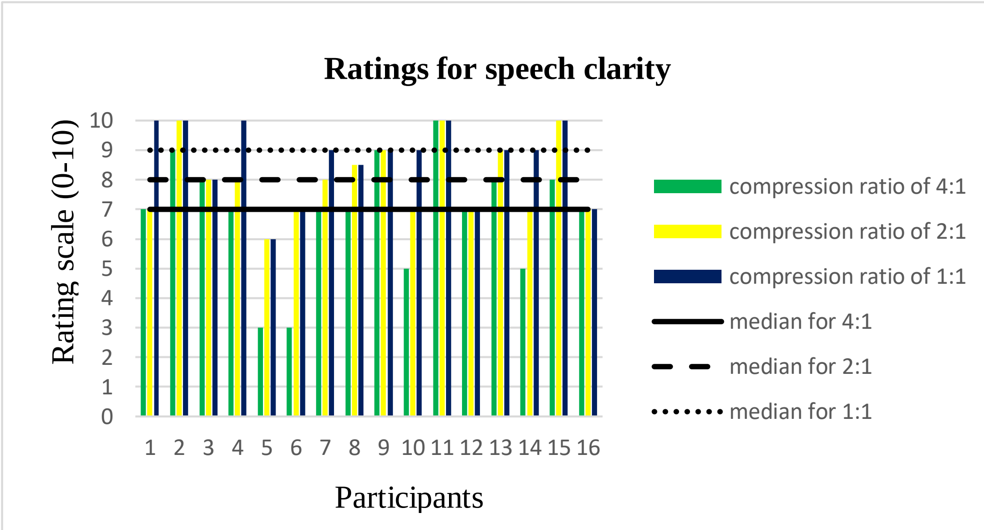
Note: $*p<0.017$.

4.3.1. *Effect of WDRC on Speech Clarity*

The ratings for the speech clarity given by sixteen participants are depicted in the Figure 4.5. The maximum rating that could be given was ten and the minimum rating that could be given was zero.

Figure 4.5.

Speech Quality Ratings (0-10) for Clarity in Three Aided Conditions, for 16 Participants.



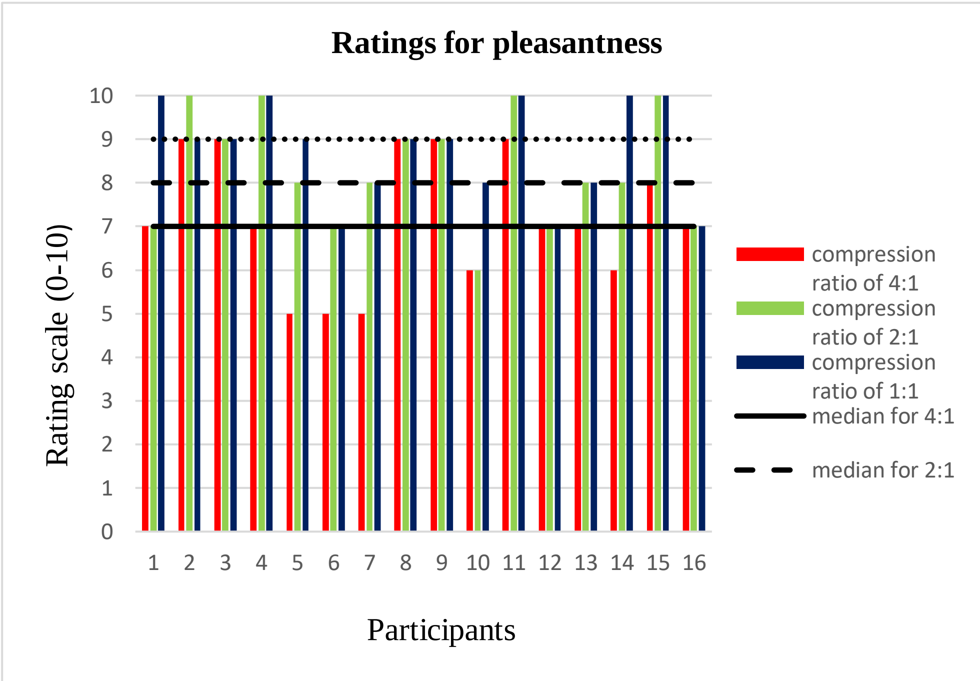
The results showed the similar trend as seen with the speech identification scores for PB words as well as for VCV syllables. On pair-wise comparison, of Wilcoxon signed rank test, between the ratings on clarity, the rating was significantly better with 2:1 than with 4:1 compression ratio of the hearing aid (p<0.017). The rating for clarity was significantly better with linear hearing aid setting than with 4:1 compression ratio of the hearing aid (p<0.017). Further, it can be seen from the Figure 4.5, that ten out of the sixteen participants rated similarly for the linear setting and WDRC with the compression ratio of 2:1, and there was no significant difference between these two settings (p>0.017).

4.3.2. Effect of WDRC on Pleasantness of Speech

The participants rated on a scale of zero to ten for the pleasantness of speech presented to the participants in the three aided conditions. The ratings given by sixteen participants are represented in the Figure 4.6. below.

Figure 4.6.

Speech Quality Ratings for Pleasantness (0-10) in Three Aided Conditions, for 16 Participants.



Five out of the sixteen participants rated the same for the pleasantness of speech in all the three aided settings. Ten of them had rated linear settings to be better than WDRC with the compression ratio of 4:1. Four of them rated linear setting to be better than WDRC with the compression ratio of 2:1. Only one person rated WDRC with compression ratio of 2:1 to be better than that of linear setting. Nine out of the sixteen participants rated WDRC with the compression ratio of 2:1 to be better than WDRC with the compression ratio of 4:1.

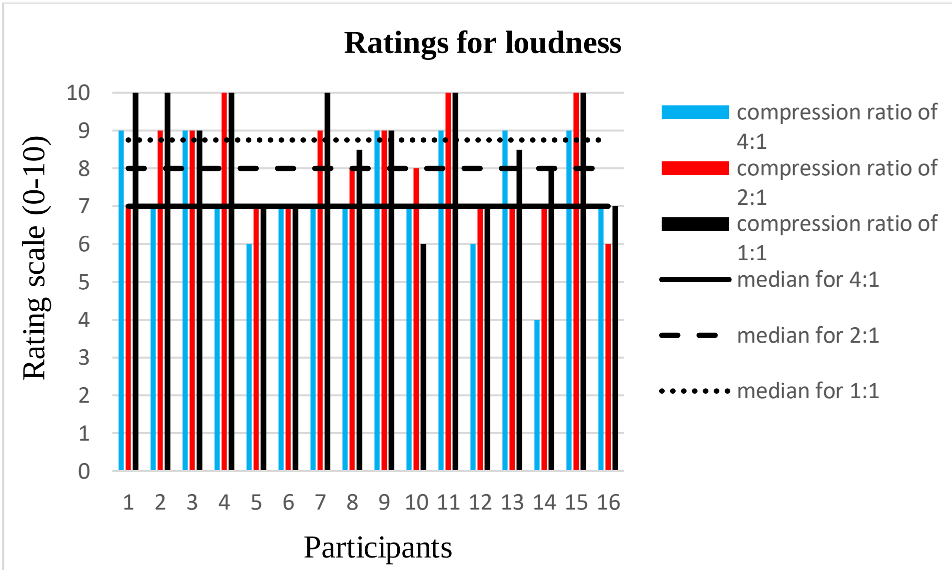
Non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) was done. The Friedman test revealed an overall significant difference in the SIS between the aided conditions (p<0.05). In order to know the pair or pairs of aided conditions that were significantly different in pleasantness, pair-wise comparison through Wilcoxon signed rank test was done. Among the three pairs of data, significant difference was found in two pairs of data. The test results revealed that the rating for pleasantness was significantly with a compression ratio of 2:1 than with 4:1 ($p<0.017$). The rating for pleasantness was significantly better with linear setting than with the compression ratio of 4:1 ($p<0.017$). There was no significant difference in the ratings for pleasantness between the linear setting and WDRC with the compression ratio of 2:1 ($p>0.017$). These results are similar to those obtained for the ratings of speech clarity.

4.3.3. Effect of WDRC on loudness of speech

To investigate the impacts of WDRC on the loudness of speech, the participants were instructed to rate the loudness on a scale of zero to ten, with zero representing the “not at all loud” to ten representing “very loud”. The ratings given by sixteen participants are depicted in the Figure 4.7. Non-parametric tests such as the Friedman test and Wilcoxon signed rank (if indicated) test were administered on these data. Friedman test indicated that there is overall significant difference in the loudness ratings between the aided conditions ($p<0.05$). However, the results from the Wilcoxon signed rank test showed a slightly different pattern when compared to that obtained for other parameters of speech quality such as clarity, and pleasantness. Between the loudness ratings obtained with the linear settings and WDRC with minimum compression ratio (2:1), there was no significant difference ($p>0.017$). There was no significant difference between the loudness ratings of WDRC with the maximum compression ratio (4:1) and WDRC with the minimum compression ratio (2:1) ($p>0.017$). However, the loudness rating was significantly higher for linear setting than with WDRC with a compression ratio of 4:1.

Figure 4.7.

Speech Quality Ratings for Loudness (0-10) in Three Aided Conditions, for 16 Participants.



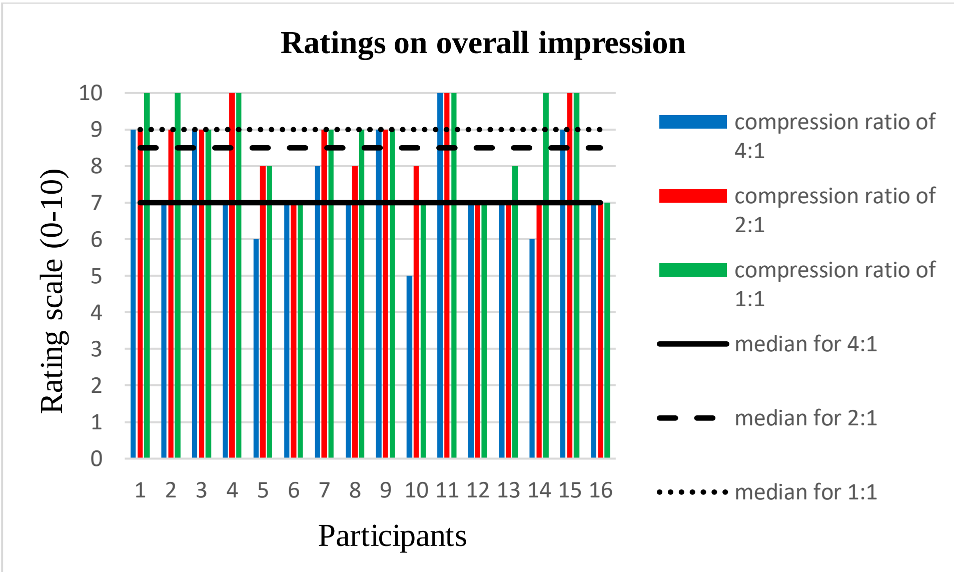
4.3.4. Effect of WDRC on the overall impression of speech quality

Considering all the parameters of speech quality, each of the sixteen participants were instructed to rate their overall impression of quality of speech, on a rating scale (0-10). Three standardized passages in three aided conditions settings in the Kannada language were presented to the participants and the ratings given by the participants are represented in the Figure 4.8. As depicted in the Figure 4.8, six out of the sixteen participants rated same for three different aided conditions. Five participants rated linear settings to be better than the other two aided conditions of WDRC. Seven participants rated the overall quality of speech to be the poorest when WDRC with the compression ratio of 4:1 was used.

Non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) were administered on the data.

Figure 4.8.

Ratings on the Overall Impression of Speech Quality (0-10) in Three Aided Conditions, for 16 Participants.



Friedman test revealed that there is overall significant difference between the aided conditions in terms of the overall impression. Wilcoxon signed rank test compared three pairs to know which aided condition gave a significantly better overall impression. The overall impression in terms of quality was significantly better with linear settings than with the compression ratio of 4:1 (p<0.017). The overall impression was significantly better with compression ratio of 2:1 than with 4:1 ratio (p<0.017). However, there was no significant difference in overall impression between the linear setting and WDRC with minimum compression ratio of 2:1 (p>0.017).

A summary of key findings of the effect of WDRC in hearing aids on speech identification and speech quality is provided in the following section. The aided conditions in which significant differences were noted are provided in Table 4.10.

Table 4.10.

Summary of the Significant Effect ($p<0.017$) of WDRC on Speech Identification Scores (SIS) and Speech Quality Measures

	Measures	**1:1 vs. 2:1**	**1:1 vs. 4:1**	**2:1 vs. 4:1**
SIS	For VCV syllables	-	1:1 > 4:1	2:1 > 4:1
	For PB words	-	1:1 > 4:1	2:1 > 4:1
	SIS in 1:1 > 2:1 > 4:1			
Speech Quality	Clarity	-	1:1 > 4:1	2:1 > 4:1
	Pleasantness		1:1 > 4:1	2:1 > 4:1
	Loudness	-	1:1 > 4:1	-
	Overall impression	-	1:1 > 4:1	2:1 > 4:1
	Speech quality in 1:1 > 2:1 > 4:1			

- The SIS is best with 1:1 or linear aided condition followed by 2:1 and then by 4:1 aided condition, for VCV syllables and PB words. That is the SIS is better in the linear than with WDRC settings.
- The speech quality is best with 1:1 or linear aided condition followed by 2:1 and then by 4:1 aided condition, for clarity, pleasantness and overall impression. The speech quality was rated better in the linear than with WDRC settings.
- The temporal characteristics of speech are altered by the WDRC, especially for short duration transients such as the burst duration.

Chapter 5

DISCUSSION

The aim of the present study was to examine the effect of wide dynamic range compression (WDRC) in hearing aid on a few temporal characteristics of speech, speech identification, and speech quality. The results of the study are discussed under the following subheadings:

5.1. Effect of WDRC on a few temporal characteristics of speech.

5.2. Effect of WDRC on speech identification.

5.3. Effect of WDRC on speech quality.

5.4. Impact of the alterations in the temporal characteristics on speech identification and quality

5.1. Effect of WDRC on a Few Temporal Characteristics of Speech

The effects of WDRC on the temporal characteristics of speech was determined by the acoustical analysis of the hearing aid output for different speech sounds. The hearing aid output was recorded in three different settings, i.e., linear settings, WDRC with a compression ratio of 2:1, WDRC with a compression ratio of 4:1. The temporal characteristics such as voice onset time (VOT), closure duration (CD), burst duration (BD), frication duration (FD), and transition duration (TD) was analyzed using Praat software.

The results of the present study revealed that the temporal characteristics of speech are altered by WDRC. There are differences in the VOT, CD, FD, and TD with three different settings, thereby confirming this hypothesis. Since burst is a short duration event, it is more significantly affected with compression and also due to the internal noise of the hearing aid. These cues are essential for the speech intelligibility, manner distinctions and voicing distinctions. This is evident from the results of the perceptual measures that with the use of WDRC and with higher compression ratios, there is deterioration in the speech identification, for both VCV syllables and PB words.

These results are substantiated by the findings of studies by Stelmachowicz et al. (1995). The results of this study show that with WDRC, there can be loss or aperiodicity in voicing, marked changes in the consonant to vowel ratio, and loss of burst. Their study also conveys the complex interaction between the dynamic characteristics of the hearing aid and the dynamic characteristics of the speech sounds.

Hederick and Younger (2001) supported the finding that WDRC alters the relative amplitude between the consonant burst amplitude and following vowel, a cue that is very important for listeners with hearing impairment. This cue is essential for discrimination of the stop consonants from other manners of speech sounds. The study by Hederick and Rice (2000) put forth similar results. The place of articulation in stop consonants is significantly affected by the alteration in the consonant to vowel ratio, altered by single channel WDRC. Erroneous perception of stop consonants and affricates due to WDRC induced alterations is also expressed by Souza (2002).

5.1. Effect of WDRC on Speech Identification

The speech identification scores (SIS) were obtained for both VCV syllables (represented in the figure 4.3) and Phonemically Balanced (PB) words (represented in the figure 4.4) in three hearing aid settings, i.e., linear setting, WDRC with a compression ratio of 2:1, and WDRC with a compression ratio of 4:1. The mean SIS score was highest, for both VCV syllables and PB words, in the linear setting than with WDRC. The mean SIS, for both VCV syllables and PB words, was highest with linear setting, followed by WDRC in 2:1

compression ratio, and then by WDRC in 4:1 compression ratio setting. The difference in SIS was significant between linear amplification and WDRC with compression ratio of 4:1, for both VCV syllables and PB words. The hypothesis stating that there is no significant difference in SIS between linear and compression setting of 4:1 is thus rejected. On the contrary, though linear amplification gave better mean scores, there was no significant difference between linear amplification and WDRC with the compression ratio of 2:1. Therefore, the hypothesis that stated that there is no significant difference in SIS obtained with linear and compression setting of 2:1 was accepted. The performance with linear hearing aid setting was better. This could be due to the preservation of spectro-temporal characteristics with linear amplification than with compression (Plomp, 1988). Better performance with linear hearing aid setting could also be due to increased distortion of the amplitude envelop with the increased compression ratios (Souza & Kitch, 2001).

The results of this study are in agreement with that reported by Boothroyd et al., (1998), wherein the participants performed poorly with compression than without the compression. The study done by Souza (2000) also revealed poorer perception of VCV syllables processed by WDRC than with the linear amplification.

The adverse effects of WDRC on consonant perception was also reported by Hedrick and Rice (2000). The findings of their study revealed that WDRC can alter the intensity ratio of consonant to vowel. The place of articulation cues was significantly hampered resulting in the poor perception of consonants processed with WDRC. The mean speech identification scores for the sentences were poorer with higher compression ratios. Souza (2002) stated that the greatest effects of WDRC were on stops and affricates, because they are distinguished by the amplitude rise time.

However, there are studies with results that differ from the findings of the present study. Dreschler (1989) studied the phoneme perception with and without compression. He varied the release time and the compression ratio to see the effect of compression. The results revealed that there were no significant detrimental effects of compression, although the participants included were individuals with conductive and sensorineural hearing losses. The results of the study by Souza and Turner (1996) also indicated that single channel syllabic compression does not cause poor speech recognition scores.

Verschuure et al. (1996) stated that there is an improvement in speech recognition with smaller compression ratios such as 3:1, when compared to the linear amplification. However, he also added that adaptive compression can result in overshoots which can alter the temporal cues, which in turn may affect the speech intelligibility. Nevertheless, when both spectral and temporal information were available, Souza and Turner (1998) articulated that there was no effect of multichannel compression on speech recognition scores. In a study by Kates (2010), benefits of WDRC over linear amplification was seen for sentence intelligibility in the listeners with moderate to severe hearing loss.

The varied findings in these studies could be due to procedural differences such as type of hearing loss, degree of hearing loss, type of stimuli (syllables, words, sentences), type of compression, and parameters of compression.

5.2. Effect of WDRC on Speech Quality

The effect of WDRC on four attributes or parameters of speech quality was measured by using a subjective rating scale from 0 to 10. The hearing aid was programmed in three different settings as mentioned earlier i.e., linear setting, WDRC with a compression ratio of 2:1, and WDRC with a compression ratio of 4:1. The participants were instructed to rate on four parameters of speech quality such as clarity, pleasantness, loudness, and overall impression.

The ratings for speech clarity by 16 participants in the three aided settings were represented in the figure 4.5. Five participants rated the same for speech clarity in all the three settings. Eleven participants rated linear setting to be better than the WDRC setting with the compression ratio of 4:1. Ten participants rated the same for the linear settings and the WDRC with the compression ratio of 2:1. From the statistical analysis, it can be noted that the ratings for speech clarity is significantly better in the linear setting than WDRC with the compression ratio of 4:1. Therefore, the hypothesis that stated that there is no significant difference in quality measures between the linear and compression of 4:1 is rejected. Also, the clarity ratings for WDRC with the compression ratio of 2:1 is significantly better than that obtained with the WDRC setting with compression ratio of 4:1. However, no significant difference was found between the linear settings and WDRC with the compression ratio of 2:1 for the speech clarity ratings. Hence, the hypothesis that stated that there is no significant difference in quality measures between linear and 2:1 compression ratio is accepted. Thus, the rating for clarity of speech decreased with increase in the compression ratio.

Similar findings were seen for the ratings given for pleasantness and the overall impression as represented in the Figure 4.6. and Figure 4.8. Among the two settings with WDRC, ratings were significantly better for the compression ratio of 2:1 than for 4:1. The ratings for linear settings is significantly better than WDRC with the compression ratio of 4:1. Thus the hypothesis, which stated that there is no significant difference in quality between linear and compression setting of 4:1, is rejected. The participants rated loudness (as represented in the Figure 4.7) for three different settings after listening to three standardized

Kannada passages. Three participants rated the same for three settings. The ratings for loudness did not follow the same trend as seen for other three parameters of speech quality. This may be because the loudness was defined differently than the others. The optimum rating was represented by five whereas ten represented “very loud”. The ratings for loudness were significantly greater for the linear settings than the WDRC setting with the compression ratio of 4:1. Accordingly this hypothesis is rejected.

The findings of the present study are consonance with the findings of the Newman et al. (1998). The participants of their study rated poor for various parameters such as clarity, pleasantness, background noise, and overall impression of speech in noise when the compression ratios were increased. Similar findings were reported by Boike and Souza (2000), that is with the increase in the compression ratio, the speech quality deteriorated in terms of clarity, pleasantness, loudness, and overall impression. Rosengard et al., (2005) stated that the participants rated poor for the pleasantness of sound when the compression ratios were increased.

The findings of the present study were conclusive of the fact that the individuals with hearing impairment prefer linear setting than WDRC. Further, the increase in compression ratios has detrimental effects on speech quality measures such as clarity, pleasantness, loudness, and overall impression.

5.4. Impact of Alterations in the Temporal Characteristics on Speech Identification and Quality

It is evident from the results of the present study that there are changes in the temporal characteristics of speech sounds. These modifications might have resulted in the deterioration of the speech quality as well as the speech identification, as observable from the findings of this study. These temporal characteristics are essential cues for place, manner, and voicing distinctions. Hence, the speech identification could be affected at both syllable and word level. Also, because of these alterations in the temporal characteristics, speech quality in terms of clarity, pleasantness, loudness and overall impression is deteriorated.

This association of alteration in the temporal characteristics to the speech identification was discussed earlier in the literature. This is substantiated by the findings of Stelmachowicz et al. (1995), Hederick and Rice (2000), Hederick and Younger (2001), and Souza (2002).

The findings of the present study provide more evidence to the effect of WDRC on the speech identification, speech quality and a few temporal characteristics of speech. The study revealed that the speech identification and speech quality deteriorated with WDRC, especially with higher compression ratios. There are also WDRC induced alterations on the temporal characteristics of speech sounds. Though, there are multiple benefits of WDRC for the individuals with hearing loss, the deleterious effects are evident from the findings of this study. In spite of these effects of compression on speech identification and quality, there is a need to incorporate compression in the hearing aids as it helps in making the loud sounds comfortable. In addition, the interaction between the various parameters such as the type and degree of hearing loss, audiogram configuration, age, cognitive abilities, characteristics of the hearing aid, compression parameters such as the compression threshold, attack time, release time, compression ratios etc., along with other strategies for appropriate amplification such as the noise reduction, signal to noise ratio and feedback management, play an important role in the speech identification and speech quality.

Chapter 6

SUMMARY AND CONCLUSIONS

The aim of the study was to examine the effect of wide dynamic range compression (WDRC) in hearing aid on the temporal parameters of speech and its impact on the speech identification and speech quality, in individuals with sensorinerual hearing loss. The specific objectives of the study were:

1. To examine the effect of WDRC in hearing aid on the temporal parameters of speech, such as voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD).
2. To determine the effect of WDRC in hearing aid on speech identification.
3. To determine the effect of WDRC on the speech quality.

The study was conducted on a total of 16 participants (16 test ears) in the age range from 15 to 60 years. They were native speakers of Kannada language and had bilateral moderate to moderately-severe sensorineural hearing loss with a flat audiogram configuration. All the participants were with post-lingually acquired hearing loss having speech identification scores of more than 60%.

The basic audiological tests such as the pure-tone audiometry, speech audiometry, and immittance evaluation were administered for the selection of the participants. The test hearing aid was programmed with NAL-NL1 prescriptive formula in three different aided settings, i.e., linear setting, WDRC with compression ratio of 2:1, and WDRC with a compression ratio of 4:1. The speech identification scores (SIS) for VCV syllables and PB words in these three hearing aid settings were obtained. The four attributes or parameters of speech quality such as clarity, pleasantness, loudness, and overall impression were rated by these participants on a scale of one to ten in these three aided conditions.

The temporal characteristics of speech such as the voice onset time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD) were measured. The hearing aid was placed on the KEMAR with the ear simulator. The stimulus (VCV syllables) were presented through the loud speaker placed at a distance of one meter and zero-degree azimuth. The output from the hearing aid was analyzed acoustically using the Praat software.

The data obtained were analyzed using statistical package for social science (SPSS) software (version 21). Shapiro Wilk test was carried out as test of normality. Since all the data were not normally distributed ($p<0.05$), non-parametric tests such as Friedman test and Wilcoxon signed rank test (if indicated) were carried out to find if there were any significant differences between the three aided conditions. Wilcoxon signed ranks test was carried out to make pair-wise comparisons between the groups of data. The results of the study are as follows:

1. The mean SIS for both VCV syllables and PB words were greater in the linear setting than with WDRC.
2. The SIS obtained for the VCV syllables were significantly better in the linear settings than the WDRC setting with the compression ratio of 4:1. The SIS obtained for VCV syllables were significantly better in the WDRC setting with the compression ratio of 2:1 than with the compression ratio of 4:1.

3. Similar results were obtained for the SIS of PB words. The scores were significantly better in the linear settings than with WDRC set at a compression ratio of 4:1. Among the WDRC settings, significantly better scores were obtained with a minimum compression ratio of 2:1 than with maximum compression ratio of 4:1.
4. For the speech quality ratings on clarity, pleasantness and overall impression, significantly better ratings were obtained for linear setting than for WDRC with the compression ratio of 4:1. Significantly better ratings were given for the speech clarity with the minimum compression ratio of 2:1 than with maximum compression ratio of 4:1.
5. For the speech quality ratings on loudness, the rating obtained was significantly better in the linear setting than WDRC with the compression ratio of 4:1.
6. Temporal characteristics of speech such as voice Onset Time (VOT), burst duration (BD), closure duration (CD), frication duration (FD), and transition duration (TD) are altered by the changes induced by WDRC.

6.1. Clinical Implications of the Study

1. The study noted a deleterious effect of WDRC on the speech identification especially at higher compression ratios. This information could provide clarity for the clinicians on the prescription of compression parameters.
2. The results of the current study depict the preference of the individuals with hearing loss for linear amplification in terms of various parameters of speech quality. This information would be useful for the clinicians while programming the hearing aid and for counselling.

3. The study also showed that the temporal characteristics of speech are altered by WDRC. This information could provide understanding about the utilization of temporal characteristics for speech perception and also that could be utilized by the clinicians during the fine tuning of the hearing aid.

6.2. Recommendations for Future Research:

1. Further research needs to be done in different hearing aids and multiple samples from different speakers has to be analyzed to substantiate the effect of WDRC on all the temporal characteristics of speech.
2. The study can be extended to see the effect of WDRC on spectrally modified stimulus.
3. Further research is required to understand the interaction effects (if any) between various compression parameters such as the compression threshold, compression ratio, release time and other parameters such as noise reduction strategies, advanced signal processing strategies.
4. The effect of WDRC on the spectral characteristics of speech can also be investigated.

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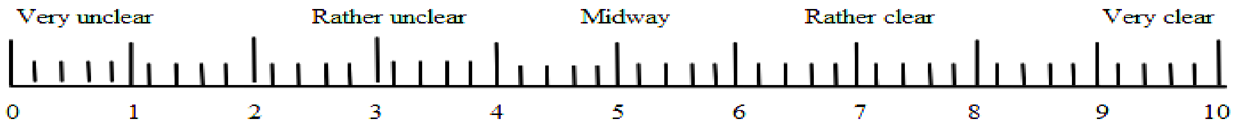
APPENDIX

Appendix: Speech Quality Rating

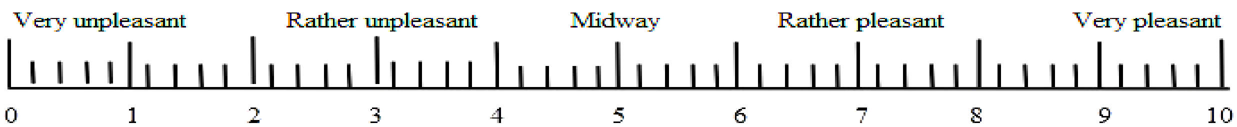
Speech Quality Rating Scale

Instruction for rating the parameter of quality of speech: Circle the number that, in your judgment, best correlates with the corresponding speech quality characteristic:

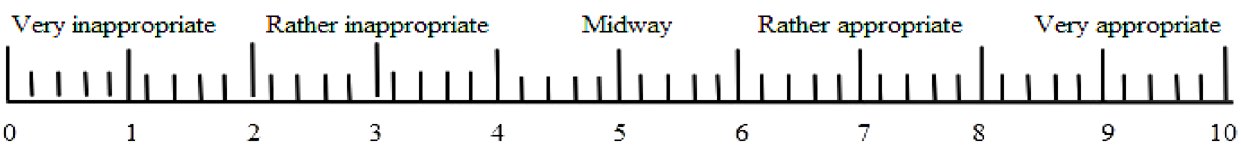
a. *Speech clarity:* How clear, distinct, and sharp is the sound? The opposite of clarity is blurred, fuzzy, and obscure.



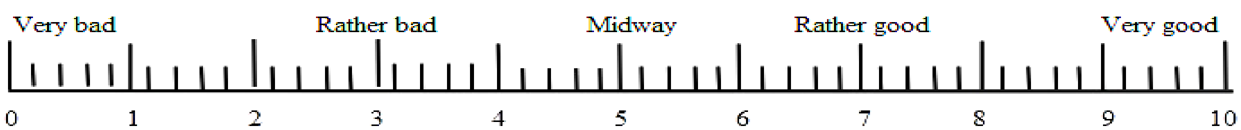
b. *Sound pleasantness:* How agreeable, comfortable, and bright is the sound? The opposite of pleasant is disagreeable, uncomfortable, and dark.



c. *Loudness appropriateness:* How adequate, comfortable and tolerable is the loudness of the sound? The opposite of the loudness appropriateness is inadequate, uncomfortable and intolerable.



d. *Overall impression:* Considering everything you have heard, what do you think about the sound?



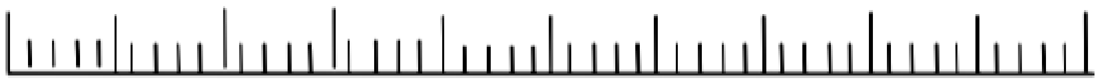
Speech Quality Rating Scale

ಮಾತಿನ ಗುಣಮಟ್ಟದ ಅಳತೆ

<u>ಸೂಚನೆ:</u> ಮಾತಿನ ವಿಶಿಷ್ಟತೆಯನ್ನು ಹೋಲುವ ಸಂಖ್ಯೆಯನ್ನು ಗುರುತು ಮಾಡಿ.

1. **<u>ಮಾತಿನ ಸ್ಪಷ್ಟತೆ:</u>** ಶಬ್ದವು ಎಷ್ಟು ಸ್ಪಷ್ಟವಾಗಿದೆ, ನಿಖರವಾಗಿದೆ, ಹಾಗೂ ಸ್ಫುಟವಾಗಿದೆ? ಸ್ಪಷ್ಟತೆಯ ವಿರುದ್ಧ ಪದ ಮಸುಕಾಗಿ, ಮಂಕಾಗಿ, ಅಸ್ಪಷ್ಟವಾಗಿ.

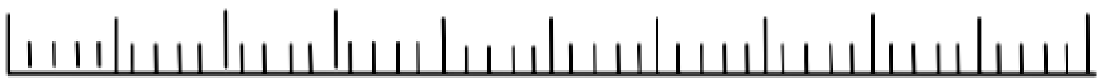
ತುಂಬಾ ಅಸ್ಪಷ್ಟವಾಗಿದೆ	ಸಾಕಷ್ಟು ಅಸ್ಪಷ್ಟವಾಗಿದೆ	ಸುಮಾರಾಗಿದೆ	ಸಾಕಷ್ಟು ಸ್ಪಷ್ಟವಾಗಿದೆ	ತುಂಬಾ ಸ್ಪಷ್ಟವಾಗಿದೆ



0 1 2 3 4 5 6 7 8 9 10

2. **<u>ಶಬ್ದದ ಹಿತ:</u>** ಶಬ್ದವು ಎಷ್ಟು ಸರಿಯಾಗಿದೆ/ಸಮ್ಮತವಾಗಿದೆ? ಹಿತ ಶಬ್ದದ ವಿರುದ್ಧ ಪದ ಹಿತವಲ್ಲದ, ಅಸಮ್ಮತ, ಕೇಳಲಾಗದ.

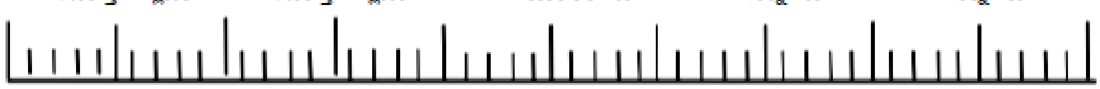
ತುಂಬಾ ಅಹಿತವಾಗಿದೆ	ಸುಮಾರು ಅಹಿತವಾಗಿದೆ	ಸುಮಾರಾಗಿದೆ	ಸುಮಾರು ಹಿತವಾಗಿದೆ	ತುಂಬಾ ಹಿತವಾಗಿದೆ



0 1 2 3 4 5 6 7 8 9 10

3. **<u>ಶಬ್ದದ ಮಟ್ಟ:</u>** ಶಬ್ದವು ಎಷ್ಟು ಸರಿಯಾಗಿದೆ/ಹಿತವಾಗಿದೆ/ಸಹಿಸಿಕೊಳ್ಳಬಹುದಾಗಿದೆ? ಈಪದದ ವಿರುದ್ಧ ಪದ ಶಬ್ದದ ಮಟ್ಟ ಸಾಕಷ್ಟು ಇಲ್ಲ, ಅಹಿತಕರವಾಗಿದೆ, ಸಹಿಸಿಕೊಳ್ಳಲಾಗದು.

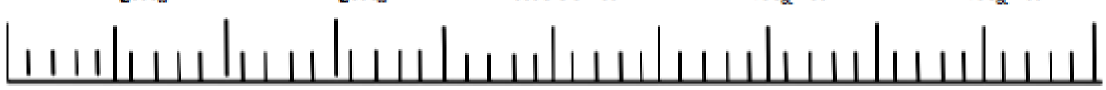
ತುಂಬಾ ಸೂಕ್ತವಲ್ಲದು	ಸಾಕಷ್ಟು ಸೂಕ್ತವಲ್ಲದು	ಸುಮಾರಾಗಿದೆ	ಸಾಕಷ್ಟು ಚೆನ್ನಾಗಿದೆ	ತುಂಬಾ ಚೆನ್ನಾಗಿದೆ



0 1 2 3 4 5 6 7 8 9 10

4. **<u>ಒಟ್ಟಾರೆ ಅಭಿಪ್ರಾಯ:</u>** ಕೇಳಿದ ಶಬ್ದಗಳನ್ನು ಪರಿಗಣಿಸಿ, ಶಬ್ದದ ಬಗ್ಗೆ ನಿಮ್ಮ ಆಲೋಚನೆ ಏನು?

ಬಹಳ ಕೆಟ್ಟದ್ದು	ಸಾಕಷ್ಟು ಕೆಟ್ಟದ್ದು	ಸುಮಾರಾಗಿದೆ	ಸಾಕಷ್ಟು ಚೆನ್ನಾಗಿದೆ	ತುಂಬಾ ಚೆನ್ನಾಗಿದೆ



0 1 2 3 4 5 6 7 8 9 10