EVALUATION OF DIGITAL HEARING AIDS WITH WIRELESS SYNCHRONIZATION IN OLDER ADULTS

Abhijith. M

Register No.: 15AUD001

A Dissertation Submitted in Part Fulfillment

For the Degree of Masters of Science (Audiology)

University of Mysore

Mysuru

ALL INDIA INSTITUTE OF SPEECH AND HEARING

MANASAGANGOTHRI, MYSURU – 570006

May, 2017

CERTIFICATE

This is to certify that this dissertation entitled **"EVALUATION OF DIGITAL HEARING AIDS WITH WIRELESS SYNCHRONIZATION IN OLDER ADULTS"** is a bonafide work submitted in part fulfillment for degree of Master of Science (Audiology) of the student Registration Number: **15AUD001**. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysuru
May, 2017

Prof. S.R. Savithri
Director
All India Institute of Speech and Hearing
Manasagangothri, Mysuru-570006

CERTIFICATE

This is to certify that this dissertation entitled **"EVALUATION OF DIGITAL HEARING AIDS WITH WIRELESS SYNCHRONIZATION IN OLDER ADULTS"** 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.

Mysuru
May, 2017

Guide
Dr. Geetha. C
Lecturer in Audiology
Department of Audiology
All India Institute of Speech and Hearing
Manasagangothri, Mysuru-570006

DECLARATION

This is to certify that this dissertation entitled **"EVALUATION OF DIGITAL HEARING AIDS WITH WIRELESS SYNCHRONIZATION IN OLDER ADULTS"** is the result of my own study under the guidance of Dr. Geetha. C, Lecturer in 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.

Mysuru **Registration No.: 15AUD001**

May, 2017

Acknowledgement

I express my deepest gratitude and heartfelt thanks to my guide ***Dr. Geetha. C*** *for all her inspiration, encouragement, guidance, comments, patient listening and untiring efforts in steering me through every phase of this study.*

I would like to thank ***Prof. S. R. Savithri****, Director, AIISH, and* ***Dr. Sandeep****, HOD, Department of Audiology, for permitting me to utilize the instrument and to carry out the dissertation.*

My sincere thanks to ***Vikas Sir****,* ***Teena akka*** *for helping in calibrating the system and instrument, and* ***vinodini akka*** *for the help in initial stage of the study and for calibration too.*

My sincere thanks to ***Megha mam,*** *and* ***Apeksha mam*** *for sparing there data collection time and subjects for my data collection.*

My heartful thanks to ***Dr.Ashok*** *(baava), who is the main reason for me to join this course and made my opportunity to meet this all beautiful people.*

Thanks to all my teachers and staffs of AIISH who has help me to gain more knowledge about this field and making my journey a fruitful one.

My dear friends – ***Srikanth, Sanjeev, Jagha, Lokesh, Shashank, Anuj, Sumanth, Naveen, Nikhil, Rahul, Shiva, Rajith, Jesnu,*** *and* ***Akshay*** *Thanks, you all for your support and motivativation.*

I thank God Almighty for his blessings, time and strength which is making me to keeping going at all the time.

Heartful thanks to the living gods of my life ***Appa*** *and* ***Amma*** *thank you for all your support, love, trust and motivation and for standing beside me in both and ups of my life…… I know thank you is not just enough for what all you both done for me.*

Thank you to my lovely sister ***Appu*** *for her love and cheering me up all the time and supporting me.*

Thanks to all my dear classmates who have helped in my studies and special mention for my dissertation partners ***robina*** *and* ***sanjeev*** *for all the support during the peak time of submission.*

Thanks to all my dear subjects, for your time and co-operation without which this dissertation would have been incomplete.

I would like to thank ***Mighty Masters****, all those juniors and seniors who were integral part of this journey with lots of smiley and love.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract

The present study aimed to verify the benefit of digital signal processing (DSP) algorithms in binaural WDRC wireless technology hearing aids in speech intelligibility in a noisy environment. The study included 22 participants with bilateral mild to moderate sensorineural hearing loss naive hearing aid users in the age range of 55 -70 years. Two hearing aids with wireless technology were fitted to all the participants in both the ears. SNR-50 was obtained in the aided conditions with and without wireless synchronization and DSP algorithms. The sentences were presented from the present while the noise was presented from one of the five directions (90°, 180°, 270°, 90°&270° and 0°). The results revealed that activation of DSP algorithms (digital noise reduction algorithm+ directionality) with wireless synchronization resulted in the best performance in all the tasks. The hearing aid yielded the best SNR-50 when the background noise was coming from 180° followed by 90°, 270°, 90°&270° and 0° in the decreasing order. It can be concluded from the above findings that wireless hearing aids improve speech perception in noise in older individuals with mild to moderate degree of hearing loss. Addition of DSP algorithms supplement the benefit provided by wireless synchronization. However, these results may be limited to the test conditions and environment of the current study.

CHAPTER 1

INTRODUCTION

Age-related hearing loss (Presbyacusis) is the loss of hearing that gradually occurs as an individual grows older. It is one of the most common conditions affecting older adults (National Institute on Deafness and other Communication Disorders, 2016). Approximately 25% to 40% of individuals between the ages of 65 and 74 years have hearing loss, and about 90% over 80 years of age have difficulty hearing (Cruickshanks, Wiley, Tweed, Klein, Klein, Mares-Perlman & Nondahl, 1998; Logan, 1988; Moscicki, 1985).

Older adults frequently report difficulty understanding speech in background noise (Yueh, Shapiro, MacLean, & Shekelle, 2003). This leads to poor quality of the life (Dalton et al., 2003). Hence, the use of binaural hearing aids in order to improve speech recognition in noise is vital in older adults. Experiments have shown that listeners with hearing impairment wearing two hearing aids (i.e., bilateral amplification) can extract benefits from binaural hearing (Boymans, Goverts, Kramer, Festen, & Dreschler, 2009). Hence, the rate of bilateral fitting has increased in the past few years (Marketrak, 2009). Studies have revealed that the contributions of the two ears are more advantage than the single ear in understanding the information in adverse condition in older adults (Marrone, 2008). Together with advances in digital signal processing (DSP) features such as adaptive directionality and digital noise reduction algorithm (DNR), bilateral amplification continues to contribute to hearing aid fitting success.

Further, it has been reported that time differences and level differences between the two ears play an important role in helping the person to understand speech in the complex listening world. Hence, preservation of binaural cues is said to be crucial for speech understanding (Hawley, Litovsky, & Colburn, 1999; Wightman & Kistler, 1997). In order to achieve this, bilateral hearing aids that coordinate and synchronize their processing through wireless communication have been introduced (Kreisman, Mazevski, Schum, & Sockalingam, 2010).

Binaural wireless hearing aids use a wireless data connection to exchange data between the right and the left hearing aids, process that information, and adjust the settings to the specific auditory situation. This technology, reportedly, significantly improves speech comprehension, particularly in noisy environments (Hamacher, Chalupper, Eggers, Fischer, Kornagel, Puder, & Rass, 2005; Schum, 2008).

There are a few studies evaluating the performance of the hearing aids with wireless communication. Ibrahim, Parsa, Macpherson and Cheesman (2013) studied the effect of wireless synchronization on speech perception using wide dynamic range compression (WDRC) algorithm without any of the DSP algorithms on 20 participants. They used HINT test given by Nilsson, Soli and Sullivan, (1994) in three conditions that is noise from 90^0, 270^0 and simultaneously from 90^0 and 270^0 Azimuth. The results revealed that the wireless synchrony neither improved nor degraded the speech perception scores. Geetha and Kishore (2016) evaluated the effect of DSP features of hearing aids with wireless synchronization. They assessed speech perception in different DSP algorithms and the wireless synchronization by disabling and enabling them. They included 25 participants with mild to moderate hearing impairment. They found that the combination of DSP features along with wireless synchronization resulted in the best performances among other conditions.

Kreisman, Mazevski, Schum and Sockalingam (2010) did a study to evaluate the speech in noise test using the wireless hearing aids on 36 participants with sensorineural hearing loss. They used Quick SIN test under two conditions. Firstly, they presented speech babble from -135^0 and $+135^0$ Azimuths and then it was given from 45^0 and 135^0. HINT test was also done for which the noise was given from eight different speakers and the speech was presented from 0^0 Azimuth. The results showed that there was better performance when they were fitted with the wireless hearing aids.

Ciorba, Loroni, Prosser and Zattara (2014) evaluated the benefits of hearing aids with wireless binaural synchronization using a speech in noise test. There were nine participants who had normal hearing. Stimuli consisted of Italian sentences played through a speaker located at 0°. The noise consisted of cocktail party noise which was presented from 0°, 90°, 180°, and 270°Azimuth. The stimuli were presented in three conditions: 1) wireless synchronization mode on and directionality off; 2) wireless synchronization off and directionality on; and 3) wireless synchronization on and directionality on. The results revealed that the 'wireless on and directionality off' condition resulted in the best performance, followed by 'wireless on with microphone on', then by 'wireless off and microphone on'.

Smith, Davis, Day, Unwin, Day and Chalupper (2008) wanted to see the real world outcome of the hearing aids with the ear to ear synchronization. They included 30 participants of age ranging from 38 to 78 years with bilateral symmetrical sensorineural hearing loss. They used the Speech, Spatial, and Qualities (SSQ) of Hearing Scale given by Gatehouse, (2004). The outcome measure scale consisted of questions related to three domains i.e., Speech, spatial and quality. The testing was carried out in three condition: 1) unilateral fitting, 2) bilateral fitting and 3) bilateral fitting with ear to ear synchronization. Their results revealed that the participants preferred bilateral fitting over the unilateral fitting and the best scores was obtained in the hearing with synchronization.

Sockalingam, Eneroth, Holmberg & Shulte (2009) found out the benefit of wireless hearing aid on sound quality, on 30 participants having sensorineural hearing loss, The sound quality was assessed in three simulated conditions (cafeteria, garden and street) and the participants were given a rating scale to rate on the neutrality and the clarity of the speech. The results of their study revealed that when the wireless synchronization was enabled the sound quality was better.

1.1. Need of the study

Many communicative situations occur in environments where listening is impaired by the presence of competitive noise. It has been reported that understanding speech against a noisy background is a challenging task for any age group, but more for older adults. Spatial processing ability has been reported to be reduced in an older population in comparison to young adults, leading to poorer speech understanding in noise (Ahlstrom, Horwitz & Dubno, 2009; Glyde & Hickson, 2011; Murphy, Daneman & Schneider, 2006; Warren, Wagener & Herman, 1978).

Fitting binaural hearing aids has been reported to improve speech perception in noise (Boymans et al., 2009). Whereas, fitting wireless synchronization technology (ear to ear synchronization) in hearing aids have been proven to further improve localization and speech perception in noisy situations for adults with sensorineural hearing loss (Geetha & Kishore, 2016; Iman et al., 2013; Kreisman et al., 2010; Sockalingam et al., 2010; Smith et al., 2008). The effect of only the wireless WRDC synchronization on speech perception in noise was studied by Iman et al. (2013).

Whereas the effect of DNR in wireless synchronization hearing aids on speech perception ability was studied by Mueller et al. (2006) while the effect of wireless synchronization with all the DSP features (Directionality and DNR) activated together was evaluated by Kreisman et al. (2010) and the effect of all the above algorithms by Geetha and Kishore (2016) in wireless synchronization hearing aids. All of these studies have included adult participants and they have consistently shown an improvement in speech perception in noise with wireless synchronization technology and activation of the advanced digital signal processing algorithms.

Though there is an evidence of positive results from the use of wireless synchronization all the above studies have been done in adults. The benefits of wireless synchronization in older adults are not well established. This is because, no research studies, to our knowledge have assessed the use of wireless technology in older adults. The results of the studies on adult listeners cannot be generalized to the older adults due to the differences between the two groups in their ability to process and understand the information. There are reports supporting the view that there is a change in the way that the brain processes speech in older adults (Glisky, 2007). Further, the impact of hearing loss is much stronger in older adults (Huang, Dong, Lu, Yue & Liu, 2010; Kelly, Tolson, Day, McColgan, Kroll, & Maclaren, 2013); the reaction time is said to be much slower in older adults; and the cognitive skills important for speech perception in noise have been found to be diminished in older adults (Hultsch, MacDonald, & Dixon, 2002).

Several studies have revealed that aging will lead to the loss and shrinkage of the nerve fibers that leads to less accurate temporal resolution (Schmiedt, 2010). Elderly people exert more effort and cognitive resources than the young adults to understand the speech in noise (Penny et al., 2011). In addition, older adults have been found to have significantly worse temporal resolution scores and significantly greater difficulty understanding sentences in noise than younger adults (Vermeire, Knoop, Boel, Auwers, Schenus, Talaveron-Rodriguez & De Sloovere, 2015).

Similarly, there could be an effect of angle at which the stimuli is presented which is very important when the study is carried out with a directional hearing aid (Nilsson et al., 1994). The difference in angle was considered in the study, as the noise was presented from different angles and the hearing aids used were directional hearing aid. The directionality of the hearing aid tends to change based on the direction of the speech and noise (Geetha and Rajan, 2014).

Hence, it is important that strong evidence be available with reference to the advanced digital signal processing algorithms in wireless hearing aids, in order to justify the selection of wireless hearing aids for individuals with hearing impairment in older adults. Further, it is imperative to know the functioning of these algorithms for appropriate selection of these features based on the listening need of the individuals with hearing impairment. Hence, the present study aimed to check the benefit of binaural WDRC wireless technology hearing aids on speech intelligibility in a noisy environment in older individuals with hearing loss.

1.2. Aim of the study

The present study aimed to investigate the benefit of wireless synchronization and DSP algorithms in hearing aids for speech perception in noise in older adults with mild to moderate bilateral sensorineural hearing loss.

1.3. Objectives of the study

The objectives of the present study were:-

1. To measure signal to noise ratio-50 (SNR-50) in older adults in the following aided conditions (given in Table 1) with the Kannada speech babble as background noise in presence of a) noise from the front (0^o Azimuth), b) noise from the right (90^o Azimuth), c) noise from the back (180^o Azimuth), d) noise from the left (270^o Azimuth) and e) noise from both 90^o and 270^o Azimuths.

Table 1

List of aided conditions

Sl. No.	Conditions	Directionality	DNR	Wireless synchronization
1.	Wireless On DSP On	On	On	On
2.	Wireless On DSP off	Off	Off	On
3.	Wireless Off DSP On	On	On	Off
4.	Wireless Off DSP Off	Off	Off	Off

Note: Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.

2. To compare SNR-50 across different aided conditions, and
3. To compare SNR-50 across different noise (presented from different angles) conditions.

CHAPTER 2

REVIEW OF LITERATURE

Binaural hearing helps an individual in understanding speech in adverse conditions because of various reasons such as interaural time and intensity differences, binaural squelch in normal individuals. Similarly, the individuals with hearing impairment also make use of benefits of binaural hearing aids due to the same reasons (Dillon, 2001).

David and Hawkins (1984) reported that good SNR is necessary for a constant performance of an individual who is finding difficulty to understand speech in noise. It has been shown that advancements in the technology of the hearing aids such as DNR and directionality in binaural hearing aids improve SNR (Bretoli, Bodmer, and Probst, 2010).

The performance of these advanced technologies has been reported to bring about additional benefit in wireless synchronization hearing aids. The wireless synchronization hearing aids in the two ears communicate with each other through wireless connection. The present study aimed to see the effect of noise reduction and directionality in binaural wireless synchronization hearing aids on speech identification scores in the presence of noise using SNR-50 measure. Hence, in the current study, the literature was reviewed and reported under the following domains:

2.1. Effect of noise reduction algorithms on speech perception.

2.2. Effect of directionality on speech perception.

2.3. Effect of both the directionality and the DNR on speech perception.

2.4. Wireless technology in the hearing aids.

2.1. Effect of noise reduction algorithms on speech perception

Digital noise reduction algorithm (DNR) refers to the ability of digital hearing aids to use envelope-detection to determine if the signals are speech-like or noise-like and make gain adjustments accordingly (Sridhar, 2008). Early analog versions of noise reduction method included a tone switch that was designed to switch on low-frequency filter to reduce the low-frequency amplification of background interference. Later, digital processing schemes were marketed as noise reduction methods which included adaptive filtering, adaptive compression and low-frequency compression. However, these techniques did not provide the anticipated improvement in speech-perception ability in the presence of background noise.

Bentler, Anderson, Niebuhr and Getta (1993) introduced digital noise reduction techniques in hearing aids. These techniques were well accepted and most researched since then. There are umpteen number of research articles evaluating the use of DNR algorithms. One such study was conducted by Heintzman et al. (2009). In this study, speech and noise were calibrated to SNRs of 0, -5, and -10 dB. They recorded the output from a hearing aid at different SNRs in the ears of a Knowles Electronic Manikin for Acoustic Research, with and without DNR algorithm. The recorded output was presented to listeners. Speech intelligibility scores and sound quality preferences were evaluated at 85 dB SPL. The results of their study revealed that better speech perception was observed when DNR was activated. Bentler and Chiou (2006) reviewed different noise reduction algorithms and they also concluded that there are many evidences available for the effectiveness of DNR in speech understanding in the presence of noise.

Jaime and Karen (2014) investigated the effect of DNR on speech understanding in noise. Twelve individuals with hearing impairment were provided with a hearing aid with modulation-based DNR algorithm for both the ears. Speech in noise test was administered at two different levels of difficulty. The results revealed that there was no significant change in the scores even with DNR, however, there was reduction in listening effort. Mueller et al. (2006) also found similar results. That is, there was no significant improvement seen in speech perception with DNR, but, most listeners reported improvement with regard to ease of listening for speech in noise. The reason for these results in the above studies could be because both stimuli and the noise were presented from the same loudspeaker which was kept at 0^{o} Azimuth making the task difficult. Nevertheless, there are many evidences that showed the preference for DNR in quiet and in noise (Alcantara et al., 2003; Boymans & Dreschler, 2000; Keidser, Carter, Chalupper, & Dillon, 2007; Marcoux, Yathiraj, Cote, & Logan, 2006; Mueller, Weber, & Hornsby, 2006; Powers, Branda, Hernandez, & Pool, 2006; Ricketts & Hornsby, 2005; Walden, Surr, Cord, Edwards, & Olsen, 2000).

From the above studies, it has been noted that DNR does not improve speech perception in all the noise conditions. However, most studies consistently support that comfort and ease of listening improve with DNR algorithm which in turn may help the individuals to perform better at speech in noise situation.

2.2. Effect of directionality on speech perception

The directional hearing aid is the one that picks up sounds from specific direction or angle. There are several types of microphones which are used in hearing aids. They are omnidirectional (picks information from all the direction), bidirectional (picks signal from and back but poorly from side), adaptive directional microphone (which adapts itself to the signal based on its polar response) (Thompson, 2000) among others.

The directionality in hearing aid provides enhancement to the sound coming from one direction (usually front) and tries to suppress the other signals (assuming to be unwanted) coming from back side (Kuk, Keenan, Lau & Ludvigsen, 2006). Hence they found that the recognition of speech would improve if the speech and noise are coming from different direction (Ricketts, 2005).

Ricketts (2005) evaluated the use of directional and omnidirectional microphones in speech perception in noise on 20 participants who are fitted with both monaural and binaural amplification. The study used HINT test to assess the speech perception in noise. The sentences from the HINT test were presented using the cafeteria noise which was spatially separated into five backgrounds. Participants were given a task of repeating sentences. Their results revealed that better advantage for those who fitted with both directional and binaural amplification in noisy environment. Ricketts and Henry (2002) noted that the microphone which changes their polar pattern (the adaptive microphone) resulted in better SNR for understanding of the speech.

Similarly, Walden et al. (2000) conducted a study with the 40 listeners to quantify the difference between the directional and the Omni directional microphone in every day listening conditions. They found that the quality, comfort and the understanding ability improved with the directional microphone.

Mueller, Weber and Bellanova (2011) evaluated 21 participants with sensorineural hearing loss fitted with directional hearing aids and assessed speech perception using the (HINT; Nilsson, Soli, and Sullivan, 1994) hearing-in-noise-test (HINT; Nilsson, Soli, and Sullivan, 1994) in the sound field. The sentences were delivered adaptively from the back (180°) and the standard HINT competing noise from the front (0°; 72 dB SPL). The participants were tested for three different hearing aid conditions: omnidirectional, conventional directional and adaptive directional microphones. They found that adaptive directional with the reverse cardioid pattern improved scores on the HINT by an average of 5.7 dB.

There are several other studies which state that the directional microphone is better than the omnidirectional microphone in the understanding of speech in noise (Boymans and Dreschler, 2000; Gnewikow & Ricketts, 2005; Plamer et al., 2005; Prevees and Conde, 1999; Ricketts et al., 2003; Surr et al., 2002; Yueh, Shapiro, MacLean & Shekelle, 2003).

2.3. Effect of both the directionality and the DNR on speech perception

Hearing aids improve speech in noise performance by applying different noise reduction algorithms in which they tend to select speech and cancel the noise depending on the various acoustic parameters in speech. Similarly, directional microphones were introduced in hearing aids so as to focus on the direction of speech source. The directional hearing aids cancel out the surrounding signal which comes from the side of the listeners and the concentration is more on the signal that are coming from front. These algorithms work together to enhance speech and reduce noise in real life situation.

Boymans and Dreschler (2000) studied the effect of both directionality and DNR algorithms using an experiment of speech identification. Sixteen participants were supposed to identify the speech of male voice and female voice in the presence of cocktail noise and car noise in the background. Participants reported that they were able to perform better when the both the algorithms were activated that is the noise reduction and directionality when compared to the separate algorithms.

Taufik, Iman, Fathy and Hoda (2010) found that the use of DNR along with the directional microphone enhances speech discrimination ability of individuals who had bilateral sensorineural hearing loss. They conducted aided assessment in two conditions, one with DNR and in second with both directionality and DNR. They assessed the speech discrimination in quiet and in noisy situation. They concluded that using both DNR and directional microphone got better scores, than just by using any of the condition. The directional microphone and the digital noise reduction have shown improvement in perception of speech in the real world situation which in turn increases the understanding ability of the speech (Bentler, 2005). Cord et al. (2002) also found similar results in speech perception in noise task and in self reported benefit scale.

The above studies have used hearing aids in two ears that are independent from each other. The beam forming in directional microphones and reduction of noise using DNR algorithm happen separately in two hearing aids. The working of these algorithms is different in wireless synchronization hearing aids.

2.4. Wireless Technology in the Hearing Aids

The auditory system is truly a system that relies on inputs from two different sensors (right and left ears) and a central processor (the brain). Amplification has rarely included considerations of how this system works, especially in terms of the relationships between the signals that enter the system via the two different ears (Kreisman et al., 2010).

Considering the above point they found a hearing aid which would exchange information with each other without any wires. Commonly used approach to wireless communication in hearing aids is near-field magnetic Induction (NFMI). Wireless communication through NFMI uses technology similar to a traditional telecoil. The range of frequencies used in hearing aids for NFMI data transmission typically falls between 3 and 15 MHz (Galster & Jason, 2010).

NFMI in the hearing aid are able to accommodate enough bandwidth and they can carry the high quality signal and the power consumption is very less when compared to Bluetooth or present FM devices (Schum, 2008). The efficient way of NFMI data transmission from audio source to hearing aid and utilize the bandwidth (currently 120 Kbits) effectively.

Similarly, this type of hybrid wireless transmission will combat delay in the transmission of audio Information. These delays have been reported to result from the audio data compression and transcoding of standardized wireless protocol, such as Bluetooth technology (Galster & Jason, 2010). Hence they are considered to be the perfect way to send the high quality signals in the short range for the hearing aids, which would in turn provide understanding of speech in the noisy situation (Schum, 2008).

There are research studies that have evaluated the effect of wireless technology on speech perception, sound quality and localization ability one such studies was carried out by Kreisman et al. (2010).

Kreisman et al. (2010) evaluated speech intelligibility in noise (SIN) using two different models of wireless hearing aids. There were 36 participants (18 naive hearing aid users and the other 18 experienced hearing aid users). Participants were aged from 39 to 79 years and had mild to severe sensorineural hearing loss.

They administered Quick SIN test under two conditions. In the first condition, the speech babble was routed through the loudspeakers at +135° and –135° Azimuth, and in the second condition it was given from loudspeakers at ±45° and ±135°Azimuth. They had activated all the adaptive algorithms. HINT test also administered wherein all 8 loudspeakers had noise and speech was presented from 0° Azimuth.

The results suggested that there was significantly better performance in the Quick SIN test and the HINT test when the participants were fitted with the binaural wireless technology. The newer model of hearing aid was found to be better than the older one and the results also depended on the noise condition. The difference between the two different model hearing aid could be due to technological differences: the two models differed in terms of technology, bandwidth, and signal processing algorithms.

Sockalingam et al. (2009) evaluated the benefit of wireless synchronization hearing aids on sound quality and localization. There were 30, participants in mild to moderate sensorineural hearing loss. 14 were naive hearing aid users and the others were experienced users. For evaluating sound quality, three environments (cafeteria, garden, and street) were simulated. Participants were given a rating scale to gauge naturalness and clarity. For localization task, 8 loudspeakers, kept at 15° apart and arranged from 0° to ±105° were used in a sound treated room.

They reported that when synchronization was activated, participants made 14% less localization errors in noise than when it was deactivated, they also reported that the naturalness was better (only in the cafe environment) when synchronization was activated. There was no mention whether the DSP algorithms were activated along with wireless synchronization or not in article. Information regarding the use of DSP algorithms such as DNR and directionality would have thrown more light on the performance of these devices.

Iman et al. (2013) evaluated the effect of binaural wireless technology on speech intelligibility and localization. They activated only the WDRC algorithm and not any other DSP algorithm. There were 20 participants: 8 listeners with normal hearing sensitivity and 12 listeners with moderate to severe sensorineural hearing loss. The 12 participants with hearing loss were experienced hearing aid users.

They had assessed Speech intelligibility using the HINT procedure under three test conditions: 1) noise presented at 90° Azimuth; 2) noise at 270°Azimuth; and 3) noise presented simultaneously from 90° and 270° Azimuths. They also measured localization errors in both the front/back and left/right dimensions. For the speech intelligibility task, their results showed no statistically significant difference between wireless activated and wireless deactivated, which contradicts the results of Kreisman et al's study.

The explanation for the differences in results between the two studies could be that Kriesman and colleagues activated the advanced DSP algorithms and used hearing aids with a wider bandwidth, whereas in the study by Iman et al. (2013). DSP algorithms were deactivated and in addition, the participants were older and age-related cognitive deficits may have affected the results.

Geetha et al. (2014) evaluated the effect of digital signal processing in the hearing aids with wireless synchronization. The study included 25 participants with bilateral mild to moderate sensorineural hearing loss, first time hearing aid users in the age range of 18 to 55 years. Two hearing aids with wireless technology were used for the present study. The participants were made to sit in center of the loudspeakers which were arranged in circular manner.

Localization experiment was performed and degrees of error in localization were obtained. SNR-50 was obtained in the unaided condition and in the aided conditions with and without wireless option, directionality and DNR algorithms for this stimulus used was Kannada sentence list and speech babble as noise, stimulus was presented from the front speaker and the noise were given from 0°, 90°, 270° and 90° & 270°, and participants were suppose to repeat back what they heard.

The results reflected that wireless synchronization technology in hearing aids did improve localization and better speech perception in noisy situations. Activation of both directionality and DNR together in the wireless hearing aids resulted in the best performance in all the tasks.

Ciorba, Loroni, Prosser and Zattara (2014) evaluated the benefits of hearing aids with wireless binaural synchronization using a speech in noise test. There were nine participants and they had normal hearing sensitivity. Stimuli consisted of Italian meaningful sentences in 13 lists played through a loudspeaker located at 0°. The noise consisted of cocktail party noise delivered from 0°, 90°, 180°and 270°. The stimuli were presented in three conditions: 1) wireless synchronization mode on and directionality off; 2) wireless synchronization off and directionality on; and 3) wireless on and directionality on.

The results revealed that the wireless enabled and directionality disabled condition resulted in the best performance, followed by ‘wireless on with microphone on’, then by ‘wireless off and microphone on’. They concluded that under extremely noisy conditions, the condition of wireless enabled and directionality disabled be recommended.

The results of the above studies showed that there is a better performance by the hearing aid when there is wireless synchronization at least in some of tasks. They have not studied the effect of each of the aspects such as DNR and other aspects in the wireless hearing aid are not known. Studies have reported that the directionality of the microphone and the noise reduction algorithms help in the understanding of speech in the noisy condition (Kuk et al., 2005). Hence, the present study aimed to find out the benefit of the wireless synchronizing hearing aid on speech intelligibility in noisy condition in older adults with hearing impairment.

CHAPTER 3

METHODS

3.1. Selection of participants

Twenty participants with bilateral sensorineural hearing loss, within the age range of 55 to 70 years (mean age = 62.5; SD = 4.6) were taken for the present study. All the participants fulfilled the following criteria.

Inclusion criteria

- Bilateral post-lingual mild to moderate flat or gradual slopping sensorineural hearing loss,
- Speech identification scores in each ear not less than 65% (Meyer, Dentel & Meunier, 2003),
- Good working memory as reflected in the work memory test developed by Pershad and Verma (1989)
- No history/indication of middle ear pathology,
- ‘A ‘or ‘As’ type of tympanogram on Immittance evaluation with acoustic reflex thresholds.
- No experience of using amplification devices, and
- Native speakers of Kannada Language.

Exclusion criteria

Participants who were having one or more of the following were excluded from the study:

- Any history or indication of middle ear disorders,
- Any associated neurological problem and
- Any history or presence of psychological problems.

Instrumentation

- A calibrated dual channel diagnostic audiometer was connected to TDH 39 head phones housed in MX-41 AR cushion, Radio Ear B-71 Bone vibrator and two loudspeakers located at ±45° angle to assess the air conduction, bone conduction and speech identification scores, respectively.
- The status of middle ear was found out using GSI-Tympstar middle ear analyzer.
- Two 16-channel digital WDRC hearing aids of same model with the following features was used:
    - Facility of NFMI facilitating wireless transmission,
    - Fitting range of mild to moderately-severe degree of hearing loss,
    - Facility for DNR and directionality algorithms, and
    - Option of disabling/enabling the above features individually.
- The computer incorporating Intel Core 2 Duo processor and running windows 7 operating system was used to program the hearing aids. Programming was carried out through NOAH Link using proper cables and appropriate software.
- Bruel and Kjaer sound level meter (model no. 2270) with a ½ inch free-field microphone was used to calibrate the stimuli.
- Maico MA52 audiometer with a laptop running windows 7 with auxiliary input to present stimuli was utilized to perform speech intelligibility in noise experiment.

- For the speech intelligibility in noise experimental task, four Genelec 8020B speakers mounted on Iso-PodTM (Isolation position/decouplerTM) vibration insulating stand were located at 0°, 90°, 180° and 270° azimuth. Speakers were arranged in a circular array with one meter radial diameter from the centre. All the speakers were placed at 90^o apart from each other.
- Cubase 6 software, HP work station desktop, Lynx Aurora Sound card and Signal router hardware were utilised for presenting the stimuli in the experimental task.

Test environment

All the testing was carried out in an acoustically and electrically shielded room. The noise levels were within the permissible limits according to ANSI 3.1 (1999) in this room.

Stimuli

- Kannada paired words developed at the Department of Audiology, All India Institute of Speech and Hearing, Mysuru, was used to find out speech recognition threshold (SRT).
- Phonemically Balanced (PB) Kannada word test developed by Yathiraj and Vijayalakshmi (2005) was used to find out speech identification scores (SIS). This test has four lists of 25 phonemically balanced words.
- Digit span test from Post-Graduation Institute (PGI) battery of brain dysfunction developed by Pershad and Verma (1989) to assess the working memory of the participants.

- The sentence test in Kannada language developed by Geetha, Manjula, Sharath and Pawan (2014) was used to assess speech intelligibility in noise. This test has twenty five equivalent lists with ten sentences each.

3.2. Basic Audiological assessment

Routine Audiological evaluation included pure-tone audiometry, speech audiometry and immittance evaluation. In the pure tone audiometry, the pure-tone thresholds (air conduction thresholds for frequencies from 250 Hz to 8000 Hz and bone conduction thresholds from 250 Hz to 4000 Hz) were obtained by using the modified Hughson and Westlake procedure (Carhart and Jerger, 1959). The air conduction thresholds at 500 Hz, 1 kHz, 2 kHz and 4 kHz were used to calculate the pure-tone average (PTA). The SRT and SIS were also obtained and used to correlate with the PTA.

In order to check the middle ear function, immittance evaluation was done on all the participants. Tympanometry and acoustic reflex assessments were carried out using GSI-Tympstar middle ear analyzer using the standard parameters and procedures. Based on the results of the above tests, participants who fulfilled the selection criteria were considered for further evaluations. Informed consent was taken from all the participants.

3.3. Hearing aid programming and routine hearing aid evaluation

The digital BTE hearing aids were programmed using NOAH software, Based on the prescriptive formula NAL–NL2. The participants were asked to identify the ling's six sounds after the initial fitting. Optimization of gain was done till they were able to identify all the six sounds. A routine hearing aid evaluation was carried out by asking five questions and finding out SIS for words at 40 dB HL. This was done for individual ears and for binaural fitting. The WDRC setting was as prescribed by NAL-NL2 prescriptive formula.

3.4. Assessment of working memory

The present study made use of digit span test from Post-Graduation Institute (PGI) battery of brain dysfunction by Pershad and Verma (1989) to assess the working memory of the participants. The test consists of two parts: digit forward test and digit reverse test. The test has normative values for individuals in the age range of 20 to 70 years. The test was carried out at the most comfortable level of the participants. The participants were instructed to repeat the digits in the same order as the clinician instructed. Individuals were considered to have good working memory if their scores were greater than the mean minus standard deviation of the test norms (Gulvadi and Geetha, 2011). The participants in the present study had good working memory as per the normative values for age matched and different education level, which is given by the developers.

3.5. Experiment to assess speech intelligibility in noise

Speech intelligibility in noise was assessed using the sentence test in Kannada language developed by Geetha et al. (2014). This test has twenty five equivalent lists with ten sentences each. The stimuli were calibrated using Bruel and Kjaer hand held analyzer (model no. 2270) sound level meter (SLM) placed at centre with a ½ inch free-field microphone. The microphone of the SLM was placed at a position corresponding to the centre of the head at a height of one meter. Sound pressure readings was taken by presenting the stimuli through loudspeaker one at a time, and the level of the stimulus was calibrated to deliver 70 dB SPL from each speaker. The 4-talker Kannada speech babble was presented as background noise in a) noise from the front (0°Azimuth), b) noise from the right (90°Azimuth), c) noise from back (180° Azimuth), d)noise from the left (270°Azimuth) and e) noise from both 90°and 270°Azimuth.

The sentence list was presented from 0^{o}Azimuth in all the aided conditions given in Table 1. The participants were made to sit in the centre of the circular loudspeaker array. The speech babble was presented at a constant noise level of 70 dB SPL and the intensity of the speech stimuli was varied to find out SNR-50. The listeners were instructed to repeat what they hear. The tester noted down the responses given by the participants. The SNR that results in 50% speech recognition scores was obtained. The difference in the level of noise and speech was noted down as the SNR-50. Before the actual test started, a practice session was given. The test conditions were randomized and counterbalanced to reduce order effects. Each sentence list was used only once in order to avoid practice effect.

3.6. Statistical Analysis

The data obtained from the above experiment were subjected to statistical analysis using Statistical Package for Social Sciences (SPSS) Version 21 software. Shiparo-Wilk test of normality was performed along with Friedman test and Wilcoxon singed -rank tests to find out the differences in SNR-50 between different aided and noise conditions.

CHAPTER 4

RESULTS

The aim of the present study was to evaluate the effect of wireless synchronization and DSP algorithms on speech perception in noise using SNR-50 measure in different noise conditions. The noise conditions include- a) noise from the front (0^o Azimuth), b) noise from the right (90^o Azimuth), c) noise from the back (180^o Azimuth), d) noise from the left (270^o Azimuth) and e) noise from both 90^o and 270^o Azimuths (90^o & 270^o). The SNR-50 scores obtained at several aided conditions (given Table 1) were tabulated and statistically analyzed using SPSS (version 21.0).

The data were analyzed for normality using Shapiro-Wilk's test. The results of scores obtained in different aided conditions did not follow the normal distribution ($p < 0.05$). Hence, the data were subjected to non-parametric tests.

4.1. Effect of wireless technology and DSP algorithms on SNR-50 across different noise conditions

The mean, median and standard deviation (SD) of SNR-50 across different aided conditions are given in Table 4.1. A lesser SNR-50 value indicates better performance and a higher SNR-50 indicates poorer performance.

Table 4.1.

Mean, median and SD of SNR-50 in all the aided conditions (N = 22).

Direction of noise source	Aided conditions	Mean	Median	SD
90°	Wireless on DSP on	2.36	2.00	0.72
	Wireless on DSP off	2.77	3.00	0.61
	Wireless off DSP on	3.63	4.00	0.58
	Wireless off DSP off	4.81	5.00	0.66
180°	Wireless on DSP on	1.95	2.00	0.65
	Wireless on DSP off	2.59	2.00	0.73
	Wireless off DSP on	3.40	3.00	0.66
	Wireless off DSP off	4.40	4.00	0.73
270°	Wireless on DSP on	2.77	3.00	0.68
	Wireless on DSP off	2.86	3.00	0.63
	Wireless off DSP on	3.81	4.00	0.73
	Wireless off DSP off	4.77	5.00	0.92
90° & 270°	Wireless on DSP on	3.31	3.00	0.71
	Wireless on DSP off	3.63	3.50	0.84
	Wireless off DSP on	4.68	5.00	0.71
	Wireless off DSP off	6.72	7.00	1.03
0°	Wireless on DSP on	3.45	4.00	0.80
	Wireless on DSP off	3.54	4.00	0.80
	Wireless off DSP on	4.45	5.00	0.80
	Wireless off DSP off	5.95	6.00	0.84

Note: Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.

It can be observed from the Table 4.1 that, overall, the mean SNR-50 ranged from + 1.95 to + 6.72. The conditions where the DSP algorithms and the wireless synchronization were enabled resulted in the best scores in all noise conditions.

In order to check if the above observations were statistically significant or not, Friedman test and Wilcoxson signed-rank test were done comparing SNR-50 across different hearing aid conditions at different Azimuth angles. The results of the same are given below for each angle of loudspeaker separately.

4.1.1. Effect of DSP algorithms and wireless synchronization on SNR-50 at 90° Azimuth

The results of the Friedman test showed a significant difference ($\chi^2 = 56.238$; $p < 0.001$) across different aided conditions at 90°Azimuth. Hence, Wilcoxon signed-rank test was used for pair-wise comparison of different aided conditions at 90° Azimuth (given in Table 4.2).

Table 4.2

Comparison of SNR-50 in the presence of noise from 90°Azimuth across different aided conditions using Wilcoxon signed-rank test

Aided conditions	Wireless on DSP on	Wireless on DSP off	Wireless off DSP on	Wireless off DSP off
	Z value			
Wireless on DSP on	-	-4.053*	-3.000***	-4.185***
Wireless on DSP off	-4.053*	-	-3.945***	-3.729***
Wireless off DSP on	-3.000***	-3.945***	-	-4.218***
Wireless off DSP off	-4.185***	-3.729***	-4.218***	-

Note:$p < 0.05$*;***$p < 0.001$*; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

It can be observed from the Table 4.2 that there was a significant difference among all the pairs tested. That is, at 90° Azimuth noise condition, the presence of wireless synchronization lead to significantly better SNR-50 ($p < 0.05$) when compared to the conditions where the wireless synchronization was deactivated. Further, activation of DSP algorithms resulted in significantly better SNR-50 ($p < 0.001$) than deactivation of DSP algorithms.

4.1.2. Effect of DSP algorithms and wireless synchronization on SNR-50 at 180° Azimuth

Comparison of SNR-50 across different aided conditions at 180° Azimuth was also done using Friedman test. The results of the Friedman test of SNR-50 for loudspeaker angle of 180° Azimuth showed a significant difference (χ^2 = 60.965; $p < 0.001$) across different aided conditions at 0.001 level of significance. Hence, Wilcoxon signed-rank test was used for pair-wise comparison across different aided condition at 180° Azimuth. The results of the same are given in Table 4.3.

Table 4.3

Comparison of SNR-50 in the presence of noise from 180°Azimuth across different aided conditions using Wilcoxon signed-rank test

Aided conditions	Wireless on DSP on	Wireless on DSP off	Wireless off DSP on	Wireless off DSP off
		Z value		
Wireless on DSP on	-	-3.500***	-4.235***	-4.187***
Wireless on DSP off	-3.500***	-	-4.025***	-4.247***
Wireless off DSP on	-4.235***	-4.025***	-	-3.999***
Wireless off DSP off	-4.187***	-4.247***	-3.999***	-

*Note: ***$p < 0.001$; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

The results of Wilcoxon signed-rank test (Table 4.3) showed that there was a significant difference among all the pairs of aided conditions tested. That is, at 180° Azimuth noise condition, the presence of wireless synchronization lead to significantly better SNR-50 ($p < 0.001$) when compared to the conditions where the wireless synchronization was deactivated. Further, activation of DSP algorithms resulted in significantly better SNR-50 ($p < 0.001$) than deactivation of DSP algorithms.

4.1.3. Effect of DSP algorithms and wireless synchronization on SNR-50 at 270° Azimuth

Similar to the analysis of SNR-50 at 180° Azimuth, Friedman test was done to compare SNR-50 across different aided conditions at 270° Azimuth as the data did not follow normality. The results of Friedman test showed a statistically significant difference (χ^2 = 58.354; $p < 0.001$) across different aided conditions at 0.001 level of significance. Hence, Wilcoxon signed-rank test was used for pair-wise comparison across different aided conditions at 270° Azimuth and the results are given in Table 4.4.

Table 4.4

Comparison of SNR-50 in the presence of noise from 270°Azimuth across different aided conditions using Wilcoxon signed-rank test

Aided conditions	Wireless on DSP on	Wireless on DSP off	Wireless off DSP on	Wireless off DSP off
	Z value			
Wireless on DSP on	-	-0.816	-4.104***	-4.242***
Wireless on DSP off	-0.816	-	-4.185***	-4.174***
Wireless off DSP on	-4.104***	-4.185***	-	-3.700***
Wireless off DSP off	-4.242***	-4.174***	-3.700***	-

*Note: ***p < 0.001; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

Table 4.4 shows that there was a significant difference among all the pairs tested except between the two conditions where wireless synchronization was activated. That is, at 270°Azimuth noise condition, the presence of wireless synchronization lead to significantly better SNR-50 ($p < 0.001$) when compared to the conditions where the wireless synchronization was deactivated. In addition, activation of DSP algorithms resulted in no significant change in SNR-50 when the wireless synchronization was activated and, however, activation of DSP algorithms resulted in better SNR-50 when the wireless synchronization was deactivated.

4.1.4. Effect of DSP algorithms and wireless synchronization on SNR-50 in the presence of noise at 90° & 270°Azimuth and in the presence of noise & 0°Azimuth

Comparison of SNR-50 across different aided conditions at 90° & 270° and 0° Azimuths was also done using Friedman test. The results of the Friedman test of SNR-50 for loudspeaker angles of 90° & 270°,and 0° Azimuths showed a significant difference ($\chi^2 = 60.965$; $p < 0.001$) and ($\chi^2 = 59.242$; $p < 0.001$) respectively across different aided conditions at 0.001 level of significance. Hence, Wilcoxon signed-rank test was used for pair-wise comparison across aided condition at 90° & 270°, and 0° Azimuths. The results of the same are given in Table 4.5 and Table 4.6.

Table 4.5

Comparison of SNR-50 in the presence of noise from 90°&270° Azimuths across different aided conditions using Wilcoxon signed-rank test

Aided conditions	Wireless on DSP on	Wireless on DSP off	Wireless off DSP on	Wireless off DSP off
	Z value			
Wireless on DSP on	-	-2.333	-4.261***	-4.194***
Wireless on DSP off	-2.333	-	-3.758***	-4.151***
Wireless off DSP on	-4.261***	-3.758***	-	-4.272***
Wireless off DSP off	-4.194***	-4.151***	-4.272***	-

*Note: ***p < 0.001; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

Table 4.6

Comparison of SNR-50 in the presence of noise from 0°Azimuth across different aided conditions using Wilcoxon signed-rank test

Aided conditions	Wireless on DSP on	Wireless on DSP off	Wireless off DSP on	Wireless off DSP off
	Z value			
Wireless on DSP on	-	-1.000	-3.787***	-4.221***
Wireless on DSP off	-1.000	-	-3.704***	-4.215***
Wireless off DSP on	-3.787***	-3.704***	-	-4.118***
Wireless off DSP off	-4.221***	-4.215***	-4.118***	-

*Note: ***p < 0.001; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

It can be observed from the Table 4.5 and 4.6 that the results of Wilcoxson signed-rank test comparing SNR-50 in the presence of noise at 90°& 270° Azimuth, and at 0°Azimuth was same as that of 270°Azimuth noise condition. That is, the presence of wireless synchronization lead to significantly better SNR-50 ($p < 0.001$) when compared to the conditions where the wireless synchronization was deactivated. In addition, activation of DSP algorithms resulted in no significant change in SNR-50 when the wireless synchronization was activated and, however, activation of DSP algorithms resulted in better SNR-50 when the wireless synchronization was deactivated.

4.2. Effect of direction of noise source on SNR-50 across different aided conditions.

Another objective of the study was to evaluate the effect of the angle from which the noise was presented on SNR-50. There were five conditions which had five different angles (viz. 90°, 180°, 270°, 90° & 270° and 0°) of presentation of noise. The mean and SD of SNR-50 across different angles are given in Figure 4.1.

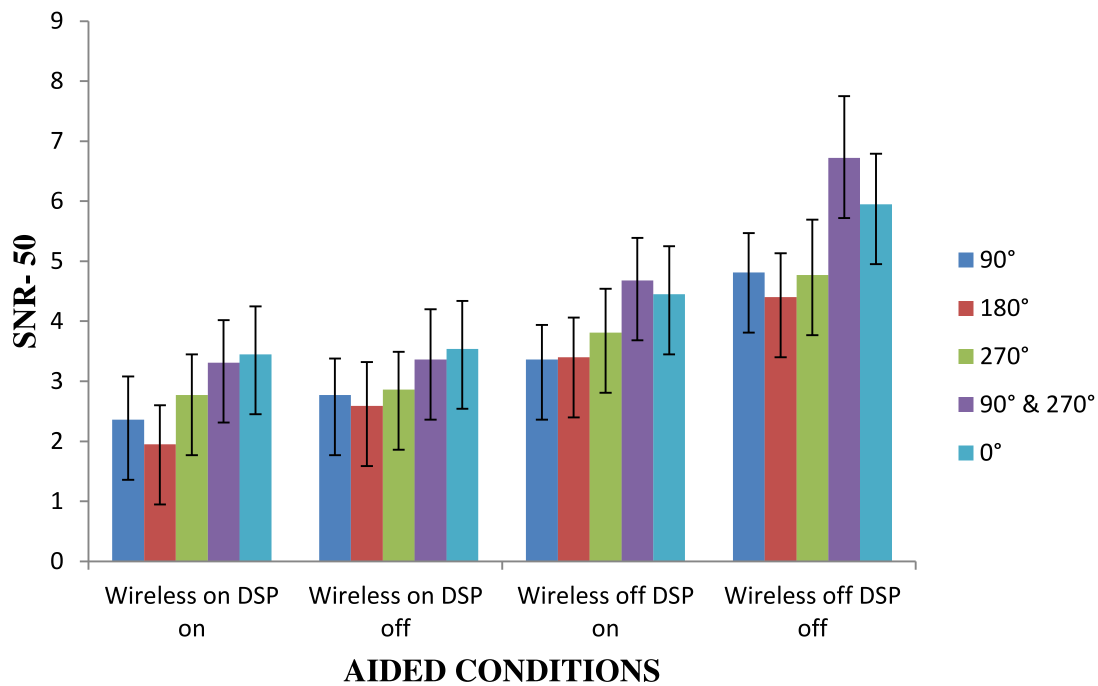

Figure 4.1: Comparison of SNR-50 in the presence of noise from different angles across different aided conditions. *Note: Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

As it can be seen from the Figure 4.1, among different noise sources, 180° yielded best SNR-50 followed by presentation of noise from 90° and 270° angle. The highest (poorer) SNR-50 was obtained for presentation of noise from 90° & 270° and 0°. The trend was similar in all the aided conditions.

In order to check if the above observations were statistically significant or not, Friedman test was done comparing SNR-50 across different hearing aid conditions at different Azimuth angles. The results showed that there was a significant difference seen ($\chi2 = 458.97$; $p < 0.001$) at 0.001 level of significance. Pair-wise comparison of SNR-50 across different directions of noise source was done using Wilcoxon signed-rank test. The results of Wilcoxon signed-rank test are given Table 4.7.

Table 4.7

Comparison of different direction of noise source on SNR-50 across different aided conditions using Wilcoxon signed-rank test

Direction of noise source	**Aided conditions**			
	Wireless on DSP on	**Wireless on DSP off**	**Wireless off DSP on**	**Wireless off DSP off**
	Z value			
90° vs. 180°	-3.000*	-1.414	-1.667	-2.714*
90° vs. 270°	-3.000*	-0.816	-1.265	-0.277
90° vs. 90°&270°	-3.877***	-3.578***	-4.117***	-4.064***
90° vs. 0°	-4.179***	-3.900***	-3.499***	-3.852***
180° vs. 270°	-4.243***	-1.604	-2.714*	-2.000
180° vs. 90°&270°	-4.278***	-3.782***	-4.053***	-4.158***
180° vs. 0°	-4.144***	-4.164***	-3.966***	-4.122***
270° vs. 90°&270°	-2.972*	-3.368**	-3.624***	-4.813***
270° vs. 0°	-3.873***	-0.707	-3.116*	-4.099***
90°&270° vs. 0°	-0.832	-0.765**	-1.291	-3.532***

*Note:*p < 0.05;**p < 0.01; ***p < 0.001; Wireless = Synchronous exchange of information from one hearing aid to other; DSP = Digital signal processing algorithms, i.e., Directionality and Digital noise reduction; on = enabled; off = disabled.*

It can be observed from the Table 4.7 that the SNR-50 obtained in the presence of noise from 180° Azimuth was significantly better in two of the aided conditions when compared to 90° Azimuth. Whereas, the SNR-50 obtained in the presence of noise from 90° angle was similar to that of 270° in most of the aided conditions. The SNR-50 obtained with the direction of noise source at 90° Azimuth, 180°Azimuth as well as

270°Azimuth were significantly better than that obtained at 90° & 270° Azimuth and 0° Azimuth. Further, SNR-50 for the noise arriving from 90° & 270° Azimuth and 0° Azimuth were not significantly different from each other in most conditions. In addition to the above results, it can be observed from the Table 4.7 that, with reference to different aided conditions, there was no specific trend seen on the effect of direction of noise source on SNR-50.

To summarize the results, activation of both wireless synchronization and DSP algorithms together yielded best SNR-50 scores and deactivation of both the algorithms resulted in the worst SNR-50 scores. The hearing aid yielded the best SNR-50 when the background noise was coming from 180° followed by 90°, 270°, 90°&270° and 0° in the descending order.

CHAPTER 5

DISCUSSION

The aim of the present study was to investigate the benefit of wireless synchronization hearing aids in speech perception in noise in older adults with mild to moderate bilateral sensorineural hearing loss. The results of analysis on the effect of wireless technology and DSP algorithms on SNR-50, and the effect of direction of noise source on SNR-50 are discussed below.

5.1. Effect of wireless technology and DSP algorithms on SNR-50 across different noise conditions.

In the present study, the wireless synchronization was found to significantly help older individuals to understand speech better in competing noisy situations compared to the conditions without it. These results are in agreement with the results of Geetha et al's study done in 2014. In their study, adults with mild to moderate sensorineural hearing loss performed better in SNR-50 task when both DSP and wireless synchronization were activated.

The reason for this has been attributed to the fact that hearing aids without synchronization works independently in both ears and hence, there is a lack of spatial cues resulting in poorer scores when the wireless synchronization is not activated. In hearing aids with wireless synchronization, there is an exchange of information between two hearing aids in two ears and hence, binaural cues are maintained along with spatial cues which would have lead to better speech perception (Geetha et al., 2014; Iman et al., 2014; Kreisman et al., 2010; Smith et al., 2008).

These results are in accordance with Kreisman et al's study, wherein they found a significantly higher performance with the wireless synchronization when tested with Quick SIN test and HINT test. Nevertheless, Iman et al. (2014) reported no significant difference in Quick SIN test. The reason could be that, in Iman et al's study, they did not use DNR and directionality algorithms in any of the conditions and only WDRC was activated along with wireless transmission.

In addition, the average SNR-50 ranged between 2.36 to 3.45 across different loudspeaker Azimuths in the current study for older adults. This is similar to the SNR-50 scores obtained in the study done by Geetha et al. (2014) for adults. This suggests that the older individuals with hearing impairment performed similar to that of adults with wireless synchronization hearing aids in spite of their age related physiological and neuronal changes (Schmiedt, 2010). This provides us a proof that the wireless synchronization digital hearing aids for the older individuals with hearing impairment are very much beneficial.

However, when both DSP and wireless synchronization were deactivated, the SNR-50 scores were slightly better for the older adults in the present study when compared to adult listeners in the study done by Geetha et al. (2014). This could be because of the following three reasons: 1) Older adults must have found the sentence much easy, as they are linguistically more exposed and experienced (Blasi & Bjorklund, 2011); 2) Older individuals had good working memory in the current study (Bopp &

Verhaeghen, 2009); and 3) most of the individuals in the current study had mild hearing loss and they do not be much difficulty in speech perception in noise when compared to the moderate degree of hearing loss (Lewis, 2015; Jane, 2014).

5.2. Effect of direction of noise source on SNR- 50 across different aided conditions.

It was found in the current study that the hearing aid yielded best SNR-50 when noise was coming from 180°, better SNR-50 was obtained when noise was coming from 90° and 270°, whereas the poor SNR-50 was obtained when noise was coming from 90° & 270°, and 0° Azimuth.

The best scores obtained when noise is coming from 180° Azimuth may be due to the working nature of the directional hearing aid (Muller et al., 2011). That is, the directional microphone is most sensitive to the sounds from front (0°) and least sensitive to sounds from the backside (180°) (Ricketts, 2001). When the noise is coming from 180°, the microphone sensitivity is expected to be the minimum helping in reduction of noise. In the current study, the directionality was fixed. In addition, DNR also has been found to be most effective when there is special separation between speech and noise (Geetha et al., 2014; Simth et al., 2008).

Similarly, when the noise comes from the side (i.e., either 90° or 270° Azimuth) there is again spatial separation between the speech and the background noise, thus resulting in better SNR than 90° & 270° and 0° noise conditions. However, the spatial separation is lesser in 90° or 270° noise condition when compared to 180° noise condition. The above results are in agreement with the results of Geetha et al. (2014).

Compared to other noise source conditions, the performance of the hearing aid was poorer when the noise was coming from the 90° & 270°, and 0° Azimuths. Similar findings were also obtained in the study done by Geetha et al. (2014) on adults and Ciorba et al. (2014) also reported similar results with use of hearing aid with wireless synchronization. The reason for this could be that, as mentioned earlier, a directional microphone works on spatial separation between speech and noise, and DNR works on spectral separation. When the two signals are coming from the same direction i.e., 0°, it may be difficult for the devices to separate the signals considering the spectral cues (Hawley et al., 1999). This is true even when wireless synchronization is activated.

CHAPTER 6

SUMMARY AND CONCLUSION

The hearing aids with wireless technology communicate and transmit their signal processing between the hearing aids and this in turn is said to improve SNR by preserving the binaural cues (Geetha et al., 2014; Kreisman et al., 2010). There are a few published reports evaluating the performance of wireless synchronization on adults, however, there are no studies on older adults, to our knowledge, evaluating systemically each of the advanced features, that is, the directionality and noise reduction algorithms in the WDRC binaural wireless hearing aids in comparison with non-wireless hearing aids.

Hence, the aim of the present study was to check the benefit of wireless synchronization hearing aids for speech perception in noise in older adults. Twenty two individuals with mild to moderate sensorineural hearing loss in the age range of 55 to 70 years had been included in the study. Speech intelligibility was assessed using the sentence test in Kannada language (Geetha et al., 2014) in the presence of noise and SNR-50 was traced. Five loudspeakers (Genelec 8020B) arranged in a circle covering 0^0 to 360^0 angles were used for presenting noise from different angles and the speech was always presented from the front. The SNR-50 measurements were carried out with and without wireless synchronization and DSP algorithms.

The results revealed that there was a significant improvement in understanding of speech in noise by using the wireless synchronization hearing aids when compared to deactivation of wireless synchronization. Further, activation of both the algorithms resulted in better performance. The hearing aid yielded the best SNR-50 when the background noise was coming from 180° followed by 90°, 270°, 90°&270° and 0° in the descending order. The findings of the present study were supported by several other researches which are done under the similar domains.

It can be concluded from the above findings that wireless hearing aids improves speech perception in noise in the older individuals with mild to moderate degree of hearing loss. Addition of DSP algorithms supplement the benefit provided by wireless synchronization. There is an effect of the direction of noise source irrespective of whether wireless synchronization is activated or not. However, the experiment was carried out in the controlled environment and hence, the performance might vary in real life situation.

Implications

- The result of present study provides a strong support to the benefit of binaural wireless hearing aids in older adults.
- The results of the study could be used to counsel the use and selection of digital processing algorithms in wireless hearing aids in older adults.

Future direction

- Further studies can be carried out using various kinds of noises that are present in natural environment.
- The usefulness of wireless synchronization can be assessed in real life environment.

REFERENCES

Ahlstrom, J. B., Horwitz, A. R., & Dubno, J. R. (2009). Spatial benefit of bilateral hearing aids. *Ear and hearing*, *30*(2), 203-209.

Alcantara, J.I., Moore, B.C.J., Kuhnel, V., & Launer, S. (2003). Evaluation of the noise reduction system in a commercial digital hearing aid. International Journal of Audiology, 42, 34-42.

ANSI S-3.1. (1999). Maximum permissible ambient noise levels for audiometric test rooms. New York, American National Standard Institute.

Bentler, R. A. (2005). Effectiveness of directional microphones and noise reduction schemes in hearing aids: A systematic review of the evidence. Journal of the American Academy of Audiology, 16(7), 473-484.

Bentler, R., & Chiou, L. K. (2006). Digital noise reduction: An overview. *Trends in Amplification*, *10*(2), 67-82.

Bess, F. H., Lichtenstein, M. J., Logan, S. A., Burger, M. C., & Nelson, E. (1989). Hearing impairment as a determinant of function in the elderly. *Journal of the American Geriatrics Society*, *37*(2), 123-128.

Boman, E., Enmarker, I., & Hygge, S. (2005). Strength of noise effects on memory as a function of noise source and age. *Noise and Health*, *7*(27), 11.

Bopp, K. L., & Verhaeghen, P. (2009). Working memory and aging: separating the effects of content and context. *Psychology and aging*, *24*(4), 968.

Boymans, M. & Dreschler, W.A. (2000). Field trials using a digital hearing aid with active noise reduction and dual-microphone directionality. Audiology, 39(5), 260-268.

Boymans, M., Goverts, S. T., Kramer, S. E., Festen, J. M., & Dreschler, W. A. (2009). Candidacy for bilateral hearing aids: a retrospective multicenter study. *Journal of Speech, Language, and Hearing Research*, *52*(1), 130-140.

Bretoli, S., Bodmer, D., & Probst, R. (2010). Survey on hearing aid outcome in Switzerland: Associations with type of fitting (bilateral/unilateral), level of hearing aid signal processing, and hearing loss. *International Journal of Audiology, 49,* 333-46.

Carhart, R., & Jerger, J. (1959). Preferred method for clinical determination of pure tone thresholds. *Journal of Speech and Hearing Disorders*, *24*(4), 330-345.

Ciorba, A., Loroni, G., Prosser, S., & Zattara, S. (2014). Quantitative enhancement of speech in noise through a equipped hearing aid. *Acta Otorhinolaryngologica Italica, 34,* 50-53.

Cord, M. T., Surr, R. K., Walden, B. E., & Olson, L. (2002). Performance of directional microphone hearing aids in everyday life. Journal of the American Academy of Audiology, 13(6), 295-307.

Cruickshanks, K. J., Wiley, T. L., Tweed, T. S., Klein, B. E., Klein, R., Mares-Perlman, J. A., & Nondahl, D. M. (1998). Prevalence of hearing loss in older adults in Beaver Dam, Wisconsin the epidemiology of hearing loss study. *American Journal of Epidemiology*, *148*(9), 879-886.

Dalton, D. S., Cruickshanks, K. J., Klein, B. E., Klein, R., Wiley, T. L., & Nondahl, D. M.(2003).The impact of hearing loss on quality of life in older adults. *The Gerontologist*, *43*(5), 661-668.

Dillon, H. (2001). Binaural and bilateral considerations in hearing aid fitting. *Hearing aids.* New York, 370-403.

Dubno, J. R., Dirks, D. D., & Morgan, D. E. (1984). Effects of age and mild hearing loss on speech recognition in noise. *The Journal of the Acoustical Society of America*, *76*(1), 87-96.

Galster, J. A. (2010). A new method for wireless connectivity in hearing aids. *The Hearing Journal*, 63(10), 36-38.

Gatehouse, S., & Noble, W. (2004). The speech, spatial and qualities of hearing scale (SSQ). *International journal of audiology*, *43*(2), 85-99.

Gates, G. A., & Mills, J. H. (2005). Presbycusis. *The Lancet*, *366*(9491), 1111-1120.

Geetha, C., Kumar, K. S. S., Manjula, P., & Pavan, M. (2014). Development and standardisation of the sentence identification test in the Kannada language. *Journal of Hearing Science*, *4*(1), 18-26.

Geetha,C., & Kishore,T, (2016). Evaluation of digital signal processing features in hearing aids with ear to ear synchronization. AIISH Research Funded Project, Department of Audiology, AIISH, Mysuru.

Giuliano, A. R., Palefsky, J. M., Goldstone, S., Moreira Jr, E. D., Penny, M. E., Aranda, C., & Chang, Y. H. (2011). Efficacy of quadrivalent HPV vaccine against HPV Infection and disease in males. *New England Journal of Medicine*, *364*(5), 401-411.

Glisky, E. L. (2007). Changes in cognitive function in human aging. *Brain aging: models, methods, and mechanisms*, 3-20.

Glyde, H., Hickson, L., Cameron, S., & Dillon, H. (2011). Problems Hearing in Noise in Older Adults A Review of Spatial Processing Disorder. *Trends in amplification*, *15*(3),116-126.

Gordon-Salant, S., & Fitzgibbons, P. J. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech, Language, and Hearing Research*, *36*(6), 1276-1285.

Gosselin, P. A., & Gagné, J. P. (2011). Older adults expend more listening effort than young adults recognizing audiovisual speech in noise. *International journal of audiology*, *50*(11), 786-792.

Hamacher, V., Chalupper, J., Eggers, J., Fischer, E., Kornagel, U., Puder, H., & Rass, U. (2005). Signal processing in high-end hearing aids: state of the art, challenges, and future trends. *EURASIP Journal on Applied Signal Processing*, *2005*, 2915-2929.

Heintzman, N. D., Hon, G. C., Hawkins, R. D., Kheradpour, P., Stark, A., Harp, L. F., ... & Ching, K. A. (2009). Effects of digital noise reduction on mild hearing loss on speech recognition in noise. *Nature*, *459*(7243), 108-112.

Hargus, S. E., & Gordon-Salant, S. (1995). Accuracy of speech intelligibility index predictions for noise-masked young listeners with normal hearing and for elderly listeners with hearing impairment. *Journal of Speech, Language, and Hearing Research*, *38*(1), 234-243.

Hawkins, D. B., & Yacullo, W. S. (1984). Signal-to-noise ratio advantage of binaural hearing aids and directional microphones under different levels of reverberation. *Journal of Speech and Hearing Disorders*, *49*(3), 278-286.

Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. (1999). Binaural hearing by listeners with hearing impairments. *The Journal of the Acoustical Society of America*, *105*(2), 1150-1150.

Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. (1999). Speech Intelligibility and localization in a multi- source environment. *Journal of Acoustic Society of America, 105*(6), 3436- 48.

Huang, C. Q., Dong, B. R., Lu, Z. C., Yue, J. R., & Liu, Q. X. (2010). Chronic diseases and risk for depression in old age: a meta-analysis of published literature. *Ageing research reviews*, *9*(2), 131-141.

Hultsch, D. F., MacDonald, S. W., & Dixon, R. A. (2002). Variability in reaction time performance of younger and older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *57*(2), 101-115.

Husain, F. T., Carpenter-Thompson, J. R., & Schmidt, S. A. (2014). The effect of mild-to-moderate hearing loss on auditory and emotion processing networks. *Frontiers in Systems Neuroscience*, *8*, 10.

Ibrahim, I. E. (2013). *Effects of Coordinated Bilaterial Hearing Aids and Auditory Training on Sound Localization* (Doctoral dissertation, The University of Western Ontario), 543- 569.

Ibrahim, I., Parsa, V., Macpherson, E., & Cheesman, M. (2013). Evaluation of speech intelligibility and sound localization abilities with hearing aids using binaural wireless technology. *Audiology research*, *3*(1), 35-40.

Keidser, G., Carter, L., Chalupper, J., & Dillon, H. (2007). Effect of low-frequency gain and venting effects on the benefit derived from directionality and noise reduction in hearing aids. International Journal of Audiology, 46(10), 554-568.

Kelly, T. B., Tolson, D., Day, T., McColgan, G., Kroll, T., & Maclaren, W. (2013). Older people's views on what they need to successfully adjust to life with a hearing aid. *Health & Social Care in the Community*, *21*(3), 293–302.

Killion, M. C., & Niquette, P. A. (2000). What can the pure-tone audiogram tell us about a patient's SNR loss? *The Hearing Journal*, *53*(3), 46-48.

Kim, S., Frisina, R. D., Mapes, F. M., Hickman, E. D., & Frisina, D. R. (2006). Effect of age on binaural speech intelligibility in normal hearing adults. *Speech Communication*, *48*(6), 591-597.

Kochkin, S. (2009). MarkeTrak VIII: 25-year trends in the hearing health market. *Hearing Review*, *16*(11), 12-31.

Kreisman, B. M., Mazevski, A. G., Schum, D. J., & Sockalingam, R. (2010). Improvements in speech understanding with wireless binaural broadband digital hearing instruments in adults with sensorineural hearing loss. *Trends in amplification*, *14*(1), 3-11.

Kuk, F., Keenan, D., Lau, C., & Ludvigsen, C. (2006). Performance of a Fully Adaptive Directional Microphone to Signals Presented from Various Azimuths. *Journal of American Academy of Audiology, 16:* 333–347.

Lichtenstein, M. J., Bess, F. H., & Logan, S. A. (1988). Diagnostic performance of the hearing handicap inventory for the elderly (screening version) against differing definitions of hearing loss. *Ear and hearing*, *9*(4), 208-211.

Lundh, P., & Schum, D. (2008). *U.S. Patent No. 7,321,662*. Washington, DC: U.S. Patent and Trademark Office.

Marcoux, A.M., Yathiraj, A., Cote, I., & Logan, J. (2006). The effect of a hearing aid noise reduction algorithm on the acquisition of novel speech contrasts. International Journal of Audiology, 45(12), 707-714.

Marrone, N., Mason, C. R., & Kidd, G. (2008). The effects of hearing loss and age on the benefit of spatial separation between multiple talkers in reverberant rooms. *The Journal of the Acoustical Society of America*, *124*(5), 3064–3075.

Mc Cormack, A., & Fortnum, H. (2013). Why do people fitted with hearing aids not wear them? *International Journal of Audiology*, *52*(5), 360–368.

Meyer, J., Dentel, L., & Meunier, F. (2013). Speech recognition in natural background noise. *PloS one*, *8*(11), 72-79.

Moscicki, E. K., Elkins, E. F., Baurn, H. M., & McNarnara, P. M. (1985). Hearing loss in the elderly: an epidemiologic study of the Framingham Heart Study Cohort. *Ear and hearing*, *6*(4), 184-190.

Mueller, H. G., Weber, J., & Bellanova, M. (2011). Clinical evaluation of a new hearing aid anti-cardioid directivity pattern. *International journal of audiology*, *50*(4), 249-254.

Mueller, H.G., Weber, J., & Hornsby, B.W.Y. (2006). The effects of digital noise reduction on the acceptance of background noise. Trends in Amplification, 10(2), 83-93.

Mukari, S. Z. M. S., Wahat, N. H. A., & Mazlan, R. (2014). Effects of ageing and hearing thresholds on speech perception in quiet and in noise perceived in different locations. *Korean Journal of Audiology*, *18*(3), 112-118.

Murphy, D. R., Daneman, M., & Schneider, B. A. (2006). Why do older adults have difficulty following conversations?. *Psychology and aging*, *21*(1), 49.

National Institute on Deafness and other Communication Disorders. (2016, May 18). *Age-Related Hearing Loss.* Retrieved from https://www.nidcd.nih.gov/

Nehra, A., & Chopra, S. (2014). Beating the Odds: Intact Neuropsychological Functioning despite TLE. *Annals of Neurosciences*, *21*(4), 155–159.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, *95*(2), 1085-1099.

Nordrum, S., Erler, S., Garstecki, D. & Dhar, S. (2006). Comparison of Performance on the Hearing in Noise Test Using Directional Microphones and Digital Noise Reduction Algorithms. American Journal of Audiology, *15*, 81-91.

Pershad, D., & Verma, S. K. (1989). Handbook of PGI Battery of Brain Dysfunction (PGI- BBD), Agra: National Psychological Corporation.

Petry, N. M. (2002). A comparison of young, middle-aged, and older adult treatment-seeking pathological gamblers. *The Gerontologist*, *42*(1), 92-99.

Powers, T., Branda, E., Hernandez, A. & Pool, A. (2006). Study finds real-world benefit from digital noise reduction. The Hearing Journal, 59(20), 26-30.

Prevees & Conde, C.(1999). A comparison of young, middle-aged, and older adult treatment-seeking pathological gamblers. , 8(29), 3-16.

Raja Rajan. R., & Geetha.C, (2014) Acoustical and Perceptual Assessment of Benefit of Directionality and Noise Reduction Algorithm of Hearing Aids with Ear to Ear Synchronization**.** *Unpublished Dissertation*, Department of Audiology, AIISH, Mysore.

Ricketts, T. (2001). Directional hearing aids. *Trends in Amplification*, *5*(4), 139-176.

Ricketts, T., & Henry, P. (2002). Low-frequency gain compensation in directional hearing aids. *American Journal of Audiology, 11*, 29–41.

Ricketts, T.A., & Hornsby, B.W. (2005). Sound quality measures for speech in noise through a commercial hearing aid implementing digital noise reduction. Journal of the American Academy of Audiology, 16(5), 270-277.

Sbompato, A. F., Corteletti, L. C. B. J., Moret, A. D. L. M., & de Souza Jacob, R. T. (2015). Hearing in Noise Test Brazil: standardization for young adults with normal hearing. *Brazilian journal of otorhinolaryngology*, *81*(4), 384-388.

Schmiedt, R. A. (2010). The physiology of cochlear presbycusis. In *The aging auditory system*, 6, 9-38.

Schum, D. J. (2008).Communication between hearing aids. *Advances for Audiologists*, *10*, 44 – 49.

Schwartz, S. R., Yueh, B., McDougall, J. K., Daling, J. R., & Schwartz, S. M. (2001). Human papillomavirus infection and survival in oral squamous cell cancer: a population-based study. Otolaryngology—Head and Neck Surgery, 125(1), 1-9.

Smith, P., Davis, A., Day, J., Unwin, S., Day, G., & Chalupper, J. (2008). Real-world preferences for linked bilateral processing. The Hearing Journal, 61(7), 33-38.

Sockalingam, R., Eneroth, K., Holmberg, M., & Shulte, M. (2009). Binaural hearing aid communication shown to improve sound quality and localization. *Hearing Journal, 62*, 46-7.

Souza, P. E., Boike, K. T., Witherell, K., & Tremblay, K. (2007). Prediction of speech recognition from audibility in older listeners with hearing loss: effects of age, amplification, and background noise. *Journal of the American Academy of Audiology*, *18*(1), 54-65.

Sruhthi, D., & Geetha.C, (2011) Role of Auditory Working Memory in Prescribing Hearing Aid Gain and Type of Compression in Geriatrics. *Articles based on dissertations done at Aiish*, *9*, 276-283.

Sweetow, R., & Palmer, C. V. (2005). Efficacy of individual auditory training in adults: A systematic review of the evidence. Journal of the American Academy of Audiology, 16(7), 494-504.

Szklarczyk, D., Franceschini, A., Kuhn, M., Simonovic, M., Roth, A., Minguez, P., & Jensen, L. J. (2011). The STRING database in 2011: functional interaction networks of proteins, globally integrated and scored. *Nucleic acids research*, *39*(suppl 1), 561-568.

Taufik, S., Iman, M., Fathy, N. M., & Hoda, A., (2010). Enhancement of Speech Intelligibility in Digital Hearing Aids Using Directional Microphone/Noise Reduction Algorithm. *International journal of Advanced Otology, 6*(1), 74-82.

Thompson, S. C. (2000). Directional microphone patterns: They also have disadvantages. *Audiology Online*,8,54-64.

Vermeire, K., Knoop, A., Boel, C., Auwers, S., Schenus, L., Talaveron-Rodriguez, M., & De Sloovere, M. (2016). Speech Recognition in Noise by Younger and Older Adults: Effects of Age, Hearing Loss, and Temporal Resolution. *Annals of Otology, Rhinology & Laryngology*, *125*(4), 297-302.

Walden, B., Surr, R., Cord, M., Edwards, B., & Olson, L. (2000). Comparison of benefits provided by different hearing aid technologies. Journal of the American Academy of Audiology, 11(10), 540-560.

Warren, L. R., Wagener, J. W., & Herman, G. E. (1978). Binaural analysis in the aging auditory system. *Journal of gerontology*, *33*(5), 731-736.

Wightman, F. L., & Kistler, D. J. (1997). Factors affecting the relative salience of sound localization cues. *Binaural and spatial hearing in real and virtual environments*, *1*, 1-23.

Yathiraj, A. & Vijayalakshmi, C. S. (2005). Phonemically Balanced Word list in Kannada. Departmental project, Developed at the Department of Audiology, AIISH, Mysuru.

Yueh, B., Shapiro, N., MacLean, C. H., & Shekelle, P. G. (2003). Screening and management of adult hearing loss in primary care: scientific review. *Jama*, *289*(15), 1976-1985.