HEARING AID USAGE: RELATIONSHIP BETWEEN PLASTICITY AND AUDIOLOGICAL MEASURES

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CERTIFICATE

This is to certify that this dissertation entitled **'Hearing aid usage: relationship between plasticity and audiological measures'** is a bonafide work in part fulfillment for the degree of Master of Science (Audiology) of the student **Registration No.: 09AUD023**. This has been carried under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any diploma or degree.

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This is to certify that this dissertation entitled **'Hearing aid usage: relationship between plasticity and audiological measures'** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.

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DECLARATION

This is to certify that this dissertation entitled **'Hearing aid usage: relationship between plasticity and audiological measures'** is the result of my own study and has not been submitted earlier to any other university for the award of any degree or diploma.

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While journeying east and west -
The only folks we really wound
Are those we love the best.
We flatter those we scarcely know,
We please the fleeting guest,
And deal full many a thourghtless blow
To those who love us best.
~ Ella Wheeler Wilcox

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Chapter 1

Introduction

Hearing devices, such as hearing aids and cochlear implants, help individuals with hearing impairment. Evidence from literature reflects that there is a lot of variability in performance with such devices across individuals (Tremblay, 2003). Kochkin (2003) has reported that over 16% of people receiving hearing aids completely rejected them, and only 60% are satisfied with their aids. Despite much research focusing on the technology used in such devices, research still cannot fully explain the reason for two individuals with the same configuration and degree of hearing loss demonstrating significantly different improvements in speech understanding with similar devices. One possible explanation for performance variability may lie beyond the ear, i.e., central auditory plasticity could be a factor (Tremblay, 2003).

Changes in the sensory environment modify our sensory experience and may result in experience-related or learning-induced re-organization within the central auditory nervous system. An appropriately selected hearing aid amplifies sounds to a degree and in a manner in which a person with hearing impairment is able to use his or her remaining hearing in an effective manner (Staab, 2002). Hearing aids change the sensory environment by stimulating a deprived auditory system; therefore, they may be capable of inducing changes within the central auditory system.

‘Plasticity’ is a term used to describe a variety of physiological changes in the central nervous system in response to sensory experiences. That is, the brain changes as a function of experience and adapts to its environment (Tremblay, 2003). Plasticity is based in part on changes in synaptic function (synaptic plasticity), on change in synchronization in the neuronal networks, and on change in inter-neuronal connection patterns within the neuronal networks. Auditory plasticity is the changes occurring in the auditory system.

The expression of auditory plasticity increases up the way from the cochlea to the cortex (Kamke, Brown, & Irvine, 2003). Thus, the auditory cortex and the thalamus have a higher plasticity than the centrifugal structures such as inferior colliculus or cochlear nucleus. Furthermore, higher-order auditory cortex has a higher capacity for plastic re-organization than primary auditory areas. Mechanisms of neuronal plasticity have been the focus of interest in research for many decades (Reale, Brugge, & Chan, 1987; Willott, 1996; Ponton et al., 2001; Tremblay, 2007).

Plasticity has been documented in hearing aid users as well as in implant users (Purdy, Kelly, & Thorne, 2001). The improvement in speech scores that occurs over an approximately six week period in adults fitted with hearing aids has been referred to as 'acclimatization' (Turner, Humes, Bentler, & Cox, 1996). In adults with bilateral hearing impairment fitted with only one hearing aid, there is a late onset 'auditory deprivation effect' in the unaided ear (Silman, Silverman, Emmer, & Gelfand, 1992). Willott (1996) has opined that plasticity in the auditory system might contribute to acclimatization and/or deprivation effects.

Alterations in the physiological and/or the anatomical properties of the central auditory system, i.e., neural plasticity, can be induced by unilateral or bilateral sensorineural hearing loss, auditory stimulation, and conditioning in which sounds are used as the conditioning stimuli. These types of neural plasticity have implications for hearing aid use, i.e., acclimatization, and deprivation effects. The occurrence of hearing-loss-induced plasticity suggests that the organization of the central auditory system may be altered by the time a hearing aid is fitted. The success of hearing aids may depend, therefore, on how the auditory system responds to the re-introduction of certain sounds by amplification. For example, enhanced auditory stimulation provided by hearing aids may induce 'secondary' plasticity in the auditory system, which might contribute to acclimatization and/or deprivation effects. Such functional changes might be further modulated by reinforcing responses to re-introduced sounds using conditioning techniques. Thus, measuring changes in central auditory system is likely to give an indication of the presumed hearing aid benefit.

Willott (1996) further suggested three ways in which the plasticity of the Central Auditory System (CAS) might be relevant to the aural rehabilitation of adults with acquired hearing loss. First, reduced auditory input may cause functional changes in the CAS and affect auditory perception. Second, provision of amplification may lead to secondary plasticity because of altered input to the auditory system; this might yield secondary changes in auditory perception. Third, learning can cause functional changes in the auditory system and can lead to alterations in auditory perception.

Two forms of plasticity are presumed to take place when a person is fit with a hearing aid. First, when a hearing aid increases the intensity of a signal, aspects of the auditory system that were once deprived of sound now become stimulated. This change in auditory experience probably contributes to additional changes in the CAS. This assumption is based on evidence from multiple unit studies in animals, which demonstrates that electric and acoustic stimulation of a deprived auditory system also modifies the CAS (Javel & Shepherd, 2000; Shepherd, Baxi, & Hardie, 1999; Kral, Hartmann, Tillein, Heid, & Klinke, 2002). Second, hearing aids and cochlear implants deliver a modified signal to an impaired and re-organized auditory system (Stelmachowicz, Kopun, Mace, Lewis, & Nittrouer, 1995; Tyler & Summerfield, 1996). Hearing aids alter the acoustics of a stimulus (e.g., stimulus-rise characteristics, signal-to-noise ratio, and amplitude overshoot caused by circuitry activation). Thus, hearing aids deliver a modified signal to the auditory system. In a sense, this modified signal is a new signal that is likely to stimulate new neural response patterns in the CAS.

Information from electrophysiological measures combined with information from behavioural measures, allows us to re-examine the way in which the aural rehabilitation in adults with acquired hearing loss might affect and be affected by CAS plasticity (Neuman, 2005). Auditory Evoked Potentials (AEPs) are particularly sensitive neural indices to neural activity in response to rapidly changing signals such as speech. Unlike imaging tools, AEPs can be recorded quickly and inexpensively in most clinical settings. This feature makes AEPs suitable tool for assessing central auditory functions in clinical population with hearing disorders. For this reason, identifying AEPs that reveal central auditory dysfunction, as well as central auditory plasticity is a current focus of clinical research.

The auditory brainstem response (ABR) is a non-invasive measure of far-field representation of stimulus-locked, synchronous electrical events. In response to an acoustic signal, a series of potential fluctuations measured at the scalp provides information about the functional integrity of brainstem nuclei along the ascending auditory pathway, making it a widely used clinical measure of auditory function. The P1-N1-P2, a complex of positive, negative, and positive waveform deflections that occurs 50 to 200 ms after stimulus presentation, is an obligatory cortical response that can be evoked with the use of simple stimuli, such as clicks and tones, or more complex stimuli, such as speech. The presence of this complex of waves is associated with detection of a stimulus (Naatanen & Picton, 1987). P1-N1-P2 complex has also been used to study the effects of hearing aid amplification and training on the central auditory system (Tremblay, 2007).

With appropriate prescription and fitting, a hearing aid can significantly improve speech recognition scores for an individual with hearing impairment in quiet and non-reverberant listening environment. The difference between clinically measured aided and unaided speech understanding is often used to predict the hearing aid benefit that can be expected from the fitting. However, it cannot be asserted with confidence that hearing aid benefit (aided versus unaided speech understanding) measured at the time of hearing instrument fitting can be used with accuracy to predict the everyday benefit that will ultimately be obtained from the fitting (Cox & Alexander, 1992).

The benefit from amplification, however, is greatly reduced in presence of noise, especially for individuals with higher degrees of hearing loss (Killion & Niquette, 2000). Individuals with hearing loss of cochlear origin have much greater difficulty in perceiving speech in background of noise than do listeners with conductive or mixed hearing loss. Invariably, individuals with cochlear hearing loss require an increase in the signal relative to the noise (2.5 dB to 7 dB) for understanding the speech material (Plomp, 1994). Therefore, a measure of performance in noise may be a better indicator than traditional speech identification measures to evaluate the changes due to hearing aid usage.

Research has shown that listeners with hearing loss require signal-to-noise ratio (SNR) improvements of 4 to 8 dB, depending on the magnitude of hearing loss, to achieve word recognition scores equal to that of listeners with normal hearing when the signal is presented at 70 dB HL (Killion, 1997 a, b, c).

Evidently, electrophysiological and behavioural measures provide a holistic view of changes associated with hearing aid usage. As such, they may be well-suited to probe the way in which sensorineural hearing loss alters the brain processes and the way in which amplification leads to changes in performance.

1.1 Need for the study

1. There are abundant studies in literature that have evaluated the change in subjective measures following hearing aid usage (Gatehouse, 1992, 1993; Arlinger & Billermark, 1999; Cox & Alexander, 1992; Cox, Alexander, Taylor, & Gray, 1996). However, there is a dearth of literature on the changes in electrophysiological measures following hearing aid usage.

2. Most of the existing studies have focused on psychophysical measures (DLI, DLF) to evaluate plasticity following hearing aid usage (Robinson & Gatehouse, 1995, 1996). The present study focuses on electrophysiological measures to evaluate the plasticity following hearing aid use.

3. Several retrospective studies have evaluated physiological changes such as (changes in ABR) in fitting ear of adults (Hamilton, 2007 as cited in Munro, 2008, p. 266; Munro, Pisareva, Parker, & Purdy 2007). The present study is a prospective study to monitor the changes in brainstem and cortical potentials following hearing aid usage.

4. Changes in cortical potentials have been monitored following cochlear implantation (Purdy et al., 2001; Guiraud et al., 2007). There is a paucity of research in evaluating changes in the same following hearing aid usage.

1.2 Aim of the study

The aim of the present study is to document the changes in behavioural and electrophysiological measures in monaural hearing aid users before and after a period of hearing aid usage.

1.3 Objectives of the study

Specific objectives of the study were:

1. To compare the unaided performance for the following measures in the unaided and aided ear:
   (a) The speech identification scores (SIS) at the time of baseline evaluation and after a period of two to three months months.
   (b) Signal-to-Noise Ratio-50 (SNR-50) at the time of baseline evaluation and after a period of two to three months months.
   (c) The Auditory Brainstem Response (ABR) at the time of baseline evaluation and after a period of two to three months months.
   (d) The Auditory Long Latency Responses (ALLR) at the time of baseline evaluation and after a period of two to three months months.
2. To compare, the aided performance on the following measures in the aided ear:
   (a) The speech identification scores (SIS) at the time of baseline evaluation and after a period of two to three months months.
   (b) Signal-to-Noise Ratio-50 (SNR-50) at the time of baseline evaluation and after a period of two to three months months.

Chapter 2

Review of Literature

Changes in performance are noticed when the hearing aid users wear their hearing aids for the first time. These changes in performance may be related to the two effects of plasticity namely- auditory deprivation and auditory acclimatization. The auditory deprivation effect is the "systematic decrease, over time in auditory performance associated with the reduced availability of acoustic information." (Arlinger et al., 1996). While, auditory acclimatization is defined as "a systematic change in auditory performance with time, linked to a change in the acoustic information available to the listener. It involves improvement in performance that cannot be attributed purely to task, procedural, or training effects" (Arlinger et al., 1996). Plasticity implies a physiologic basis for change in auditory function. Auditory learning is defined as a functional change in auditory ability for the better (acclimatization) or for the worse (deprivation). Acclimatization and deprivation can be characterized as components of auditory learning that are going in two different directions (Palmer, Nelson, & Lindley, 1998). Physiological plasticity of the auditory system is examined as the possible underlying mechanism for auditory learning that is measured through functional abilities.

Several areas of research in plasticity suggest that peripheral hearing loss may induce important changes in the response properties of the central auditory system (CAS) neurons, and it is possible that these changes could have an impact on hearing aid use. Potential changes include 1) re-organization of sensory maps caused by damage to a portion of the peripheral receptors, 2) re-organization of the neural responses with respect to the laterality or spatial location of sound, and 3) synaptic or circuit alterations associated with attenuation of peripheral sensory input to the brain (Willott, 1996).

There are many ways to measure auditory learning, (Palmer et al., 1998). One can examine the unaided ears of monaurally aided individuals over time and determine if a decrement in performance is noted and examine if any recovery takes place after a hearing aid is supplied to the non-stimulated ear. Or, one can fit a hearing aid(s) on an individual and measure performance during the weeks/months/years post-fitting to determine if any change occurs. The studies/research in the area of concern are categorized into the following headings:

2.1 Auditory deprivation
    2.1.1 Effect on speech measures
    2.1.2 Time frame for deprivation
2.2 Acclimatization
    2.2.1 Changes in hearing aid benefit
    2.2.2 Time course for acclimatization
    2.2.3 Effect of acclimatization on other psychophysical measures
        2.2.3.1 Changes in tolerance level or loudness perception
        2.2.3.2 Changes in intensity and frequency discrimination
2.3 Hearing loss and plasticity
2.4 Hearing aid usage and plasticity
    2.4.1 Physiololgical measures
    2.4.2 Electrophysiological measures

2.1 Auditory deprivation

2.1.1 Effect on speech measures

Silman, Gelfand, and Silverman (1984) conducted a retrospective study in which 67 individuals with bilateral (moderate, sloping) sensorineural hearing (SN) loss who had received amplification. On follow up testing after 4-5 years of hearing aid usage, 39 of the monaurally aided had reduced word recognition ability over time in the unaided ear.

In a similar study, Gelfand, Silman, and Ross (1987) retrospectively considered 86 subjects in the age range of 21-86 years with symmetrical sensorineural (SN) hearing loss. Out of these, 48 were monaural hearing aid users, 19 binaural hearing aid users and 19 subjects did not use amplification. Decrease in performance was found for the W22 list in the unaided ear as compared to the aided ear in the monaural hearing aid users.. No change in performance was seen in the binaurally aided or the unaided groups.

The above mentioned studies compared the effect of amplification and deprivation in different groups of subjects. In contrast, Burkey and Arkis (1993) retrospectively considered 20 subjects who had used monaural amplification and then switched to binaural amplification. Although the authors report significant decrease in the performance of the unaided ear and then significant improvement after one year of amplification, the word recognition scores changed by only 7%, which is most likely not significant (Thornton & Raffin, 1978). They also reported that the more severe the hearing loss, the more is the decrement. However, these authors did not mention about the duration of monaural hearing aid usage that causes deprivation in the unaided ear.

To document changes due to deprivation in children, Hattori (1993) studied the effect of monaural amplification on children. Participants had hearing loss ranging from moderately severe to profound sensorineural hearing loss. He compared the nonsense syllable recognition scores in two groups of children. The first group (N=17) wore monaural amplification. The second group (N=18) wore either binaural amplification or a monaural hearing aid that was alternated between the ears on a weekly basis. An average of 4 years elapsed between the time of hearing aid fitting and the initial measure reported in the study. A significant inter-aural difference in speech recognition scores was found for the group wearing monaural hearing aids, with the aided ear having a significantly higher score. The group consisting of subjects who alternated a monaural aid or wore binaural hearing aids did not show significant inter-aural difference in their speech recognition scores.

Similarly, Gelfand and Silman (1993) studied the deprivation effect on children speech-reception thresholds and found a significant decrease in performance for the unaided ear of children fitted monaurally with the aided ear showing no significant change.

Gatehouse (1989) highlighted the role of presentation level in measuring the late onset auditory deprivation and acclimatization effect. He considered 24 individuals with symmetrical hearing impairment who were using one hearing aid. Four alternative auditory feature test (FAAF) was administered in noise at different presentation levels (50-90 dB SPL). Performance in the aided ear was better at higher presentation levels while, performance in the unaided ear was better at lower presentation levels. Applied to monaural amplification, the intensity dependence suggest that an ear which is used to receiving a high level of stimulation (and hence the associated pattern of speech cues) will 'adapt' to the pattern of cues presented and be most efficient at analyzing at high presentation levels. Nevertheless it can be inferred from the findings of this study, that the effects of deprivation and acclimatization might be noticed only at higher presentation levels.

2.1.2 Time frame for deprivation

Hurley (1999) investigated whether the auditory function deteriorates in the unaided ear of individuals with sensorineural hearing loss (SNHL) who receive monaural hearing aid fittings. The word recognition scores (WRSs) of 77 monaurally and 65 binaurally fitted subjects with symmetric bilateral SNHL were examined at one, three, and five years post hearing aid fitting. Analyses of the data indicated that 25% of the monaurally fitted subjects experienced a significant change in the WRSs of their unaided ears, whereas only six percent of the binaurally fitted subjects experienced a significant change in the WRSs of either ear. Auditory function does deteriorate in the unaided ears of individuals with SNHL who receive monaural hearing aid fittings. They also found that the decline in auditory function of the unaided ear does not result from a decrease in hearing sensitivity. In most cases, deprivation effect required at least two years of monaural hearing aid usage.

In a similar study by Silman, Silverman, Emmer, and Gelfand (1993), there were no significant differences in the speech recognition performance of either the aided or unaided ear of the monaurally aided group during the follow-up conducted one year after hearing aid fitting. Arkis and Burkey (1994) also reported failure to find a deprivation effect in a similar time frame.

Table 2.1 summarizes the aforementioned studies.

Table 2.1: *Summary of studies on auditory deprivation*

Author/s, (year)	Participants	Hearing loss	Prospective/ Retrospective	Hearing aid details	Measures	Results
Silman, Gelfand, and Silverman (1984)	2 groups- 59.5 & 57.95 years (N=44)	PTA: >25 dB HL Symmetrical SNHL	Retrospective	Monaural and binaural hearing aid users, 4-5 years	W-22	39 of the monaurally aided had reduced ability in the unaided ear over time.
Gelfand, Silman and Ross (1987)	21-86 years (N=86)	Symmetrical SNHL	Retrospective	48 monaural and 19 binaural hearing aid users; 19 unaided, 4-17 years	W-22	Decrease in performance found only for the unaided ear of monaural users.
Burkey and Arkis (1993)	57.4 years (N=20)	41-51 dB HL PTA Symmetrical SNHL	Retrospective	Monaural hearing aid users who switched to binaural	W-22	Improvement in the previously unaided ear
Hattori (1993)	4.8 years (N=17) 4.9 years (N=18)	Moderate-severe to profound SNHL	Retrospective	Non-alternating monaural amplification; and alternating or binaural amplification, 13-15 years	NST (Japanese)	The non-alternating group showed a decrement between the aided and unaided ear over time.

Author/s, (year)	Participants	Hearing loss	Prospective/ Retrospective	Hearing aid details	Measures	Results
Gelfand and Silman (1993)	2 groups 5.1-7.5 years (N=20)	41-48 dB HL SRT Symmetrical SNHL	Retrospective	Monaurally aided and binaurally aided, 5-7 years	WRS	5/10 monaurally aided children showed a decrement in performance in the unaided ear.
Gatehouse (1989)	59.3 years (N=24)	Symmetrical high frequency SNHL	Prospective	Monaural fitting, mean 4.8 years experience	FAAF	Aided ear performs better at higher presentation levels whereas the unaided ear performs better at lower presentation levels
Hurley (1999)	26-76 years (N=142)	Symmetric bilateral SNHL	Prospective	77 monaurally and 65 binaurally fitted (1, 3, 5 years post-fitting)	WRS	Deprivation requires at least 2 years of monaural hearing aid usage

2.2 Acclimatization

2.2.1 Changes in hearing aid benefit

Bentler, Niebuhr, Getta, and Anderson (1993 a, b) published the results from 39 ‘new’ and 26 individuals who had used hearing aid for a long time. Evaluations were carried out over the course of one year. Objective measures included the Speech Perception in Noise and Non-sense Syllable Test (NST). Subjective measures included the Understanding Speech sub-section of the Hearing Performance Inventory and a qualitative judgment test. Significant improvements over time were not noted for most of the tests, the exception was a subjective measure relating to speech in quiet. However, some of the ‘new’ hearing aid users included those who had worn the hearing aid during the past year or more recently. Therefore, any acclimatization effects that may have occurred would have been over before the initial evaluation.

Similarly, Horwitz and Turner (1997) followed 13 listeners with newly fitted hearing aids and also a control group of 13 long-standing hearing aid users. Both objective Nonsense Syllable Test (NST) and subjective Profile of Hearing Aid Benefit (PHAB) scores were obtained over an 18 week period. For the NST testing, two volume control conditions were taken, the first with volume controls fixed in the same position as the initial test session, the second allowing the subjects to adjust the volume control themselves for each session. Group mean NST scores significantly increased for the new hearing aid users in both the fixed and adjusted volume control settings. In contrast, the NST scores for the long-standing user group only increased for the adjusted volume control condition. Unaided scores remained stable for both groups. The increase in objectively measured benefit observed in the new user group was approximately 6%. The subjective measures of benefit did not show a significant improvement in benefit for the new users. These results suggest that the acclimatization observed for the objective measures was not dependent on increasing the volume control settings. This increase was also not due to procedural learning effects, because as a corresponding increase in word recognition was not observed in the fixed-volume, longstanding (control) group. It also suggests that significant increases in objective benefit may not necessarily be accompanied by a corresponding significant subjective improvement.

Humes, et al. (1995) (as cited in Turner et al. (1996), p.17S) measured speech recognition for 102-item NST syllable lists both in quiet and in noise, and the 100-item Hearing in Noise Test speech test over a 24 week period in 20 individuals, 10 naive and 10 experienced users of hearing aid. In addition, the subjective Hearing Aid Performance Inventory and HHIE scales were also administered. No significant increase over time was noted in any of the measures or groups in this study.

Cox, Alexander, Taylor, and Gray (1996) measured speech recognition on Competing Sentence Test and a Speech Pattern Contrast (SPAC) test in 22 elderly, first-time users fitted with unilateral hearing aids. Statistically significant improvement was seen in speech recognition scores over a 12 week period. This change was absent in the control group or the unaided scores for the test ear.

Arkis and Burkey (1994) reported clinical Consonant Nucleus Consonant (CNC) word-recognition scores for 105 patients. The first measure was taken before a hearing aid fitting and the second was taken a few months later. A 5% increase in word recognition was noted for the aided ear. This study has been criticized as all testing was performed at 30 dB SL under headphones, hence this study did not specifically test the situation for acclimatization occurring under more realistic conditions of listening to newly amplified sound via the participants' hearing aid.

Amorim and Almeida (2007) investigated acclimatization based on the analysis of the speech recognition percent index (SRPI), objective (functional gain) and subjective (self-evaluation questionnaires) procedures before the fitting of the hearing aids and after four and 16/18 weeks of hearing aids use. They evaluated 16 recent hearing aid users between 17 and 89 years, with symmetric moderate or severe sensorineural hearing loss. Results showed statistically significant differences between objective and subjective measures after the use of hearing aids, indicating short-term benefit. However, as time went by, the benefit obtained with the use of hearing aids did not improve significantly, suggesting that benefit does not increase with time. Statistically significant differences were not seen in SRPI and subjective measures. The authors concluded that the phenomenon of acclimatization was not observed through the SRPI.

Gatehouse & Killion (1993) recommend that during the course of fitting hearing aids, the Hearing Aid Brain Rewiring Accommodation Time (HABRAT) should be considered. The auditory system requires time to accommodate the pattern of speech cues available to it. When the individual with high frequency hearing loss is provided with amplification, the previously inaudible signals are now audible. However, the areas that were previously used for coding high frequency, low intensity would have been reallocated to other frequencies and intensities, hence it may take a considerable period of time for the 'rewiring' of the brain. This information will help in selecting adjustments and in rehabilitation support for new hearing aid users.

Table 2.2 summarizes the aforementioned studies on auditory acclimatization.

Table 2.2: Summary of studies on acclimatization

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Bentler, Niebuhr, Getta, and Anderson (1993a,b)	21-84 years (N=65)	Moderately severe flat and sloping SNHL	Prospective	Investigated learning in new (<1 year of hearing aid usage) and experienced hearing aid users	SPIN, NST in quiet and noise, HPI, quality judgements	Individuals chose to be monaural or binaural users. No improvement on any objective measures. The quiet section of the HPI (subjective) showed a significant change.
Horwitz and Turner (1997)	Adults (N=26)	Mild-to-moderate sloping SNHL	Prospective	13 new hearing aid users, 13 long standing monaural hearing aid users	NST, APHAB	Benefit (objective) increased for new users, not for long standing users. No subjective benefit increase
Humes et al., (1995)	63-78 years (N=20)	Mild-to-moderate Sloping SNHL	Prospective	10 new hearing aid users (not used within 2 years) 10 experienced hearing aid users, monaural and binaural	NST in quiet and noise 100-item HINT, HAPI, HHIE	Measured over a 24-week period. No increase for anything in any group.

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Cox, Alexander, Taylor, and Gray (1996)	60-82 years (N=22)	Bilateral SNHL (21 symmetric)	Prospective	Naïve hearing aid users and experienced users	CST, SPAC, Analyze by Speech features	After 12 weeks, 4% improvement in CST (significant) with no increase in the control group. Acclimatization should be mainly in high-frequency speech, but the SPAC data did not support this.
Arkis and Burkey (1994)	60.4 years (N=70) 61.5 years (N=35)	Moderate SNHL	Retrospective	1st group monaural hearing aid users 2nd group: binaural hearing aid users. (Pre-fitting vs few months later)	WRS	5% increase for the aided ears after several months of hearing aid use.
Amorim and Almeida (2007)	17-89 years (N=16)	Symmetric moderate or severe SNHL	Prospective	Naïve hearing aid users, pre-fitting vs. 4 weeks vs. 16/18 weeks of HA use	SRPI, functional gain, questionnaire	Improvement in subjective measures but not in SRPI

2.2.2 Time course for acclimatization

Gatehouse (1992) and Horwitz (1995) (as cited in Turner et al. (1996), p. 23S) both showed that some of the largest changes in benefit occur in the time period between 3 to 18 week post-fitting. Although Cox et al. (1995) did show increasing benefit continuing beyond 12 weeks in some subjects, these increases were due to declining unaided scores. A clear picture of the time course of acclimatization cannot be drawn because of the large variability across subjects and studies (Turner, Humes, Bentler, & Cox, 1996).

2.2.3 Effect of acclimatization on other psychophysical measures

2.2.3.1 Changes in tolerance level or loudness perception.

Munro and Trotter (2006) compared uncomfortable loudness levels (ULLs) in a group of adults before and after unilateral hearing aid experience. Twelve participants with symmetrical hearing loss were taken. The post-fitting ULLs were typically measured three years after fitting. Hearing thresholds were symmetrical and remained unchanged after fitting. Mean ULL values were symmetrical before fitting. The mean ULL values increased (i.e., greater tolerance) in both ears after fitting; however, the increase was greatest in the fitted ear, i.e., 14.5 and 7 dB from 2000 to 4000 Hz in the fitted and not-fitted ear, respectively.There was no statistically significant difference for ear when comparing the pre-fitting ULLs. However, there was a statistically significant difference for ear when comparing post-fitting ULLs. The authors concluded that the underlying mechanism for the asymmetry is unknown but it is consistent with learning induced re-organization within the auditory system.

Hamilton and Munro (2007) (as cited in Munro, 2008, p. 264) retrospectively considered individuals with symmetrical high frequency hearing loss who had a minimum two years of hearing aid experience. They were divided into three groups of participants: unilateral users, bilateral users, and a control group with no previous hearing aid experience. The number of participants in the unilateral and bilateral group was 50 and 48, respectively. The control group consisted of 54 participants who were about to be fitted with their first hearing aid. The ULLs were measured using the same procedure as the earlier study by Munro and Trotter (2006). There was a statistically significant difference in ULL between the fitted and not-fitted ears. The mean ULL was around 4 dB higher in the fitted ears. The ULL in the bilateral users was higher than the control group, and there was an asymmetry in the ULL in the unilateral hearing aid users. Therefore, ULLs are higher in fitted ears irrespective of unilateral or bilateral fitting. However, it was not certain that all participants were making regular use of their hearing aids. Thus, it is likely that 4 dB was an underestimate of the potential maximum effect. These findings are consistent with the contention that a change in perceptual abilities after hearing aid fitting is a characteristic of a dynamic auditory system and is not restricted solely to unilateral hearing aid experience.

Philibert, Collet, Vesson, and Veuillet (2002) compared performance on a loudness-scaling task between two groups of subjects paired for age, gender and absolute thresholds in both ears. One group comprised of individuals who had used binaural hearing aids (HA) for a long time and the other who had not used hearing aids. Results indicated that significant differences exist in loudness perception between long-term HA users and non-HA users, the latter rating intensity as louder than the former. Moreover, significant differences between ears were observed in the loudness-scaling task, with the right ear showing greater inter-group difference than the left ear. This additional result points to a lateralization of the acclimatization effect.

Philibert, Collet, Vesson, and Veuillet (2005) administered a loudness scaling task on eight elderly individuals who presented with symmetrical hearing loss and were fitted with binaural hearing aids. Loudness scaling was done using the Aurical software without hearing aids, before HA fitting, and one month, three months and six months after the hearing aid fitting. Changes in loudness scaling were significant for the high frequencies after three and six months of hearing aid usage. However, there was no control group so it is not possible to rule out changes due to the practice from repeated test exposure.

Table 2.3 summarizes the above mentioned studies.

Table 2.3: Summary of studies on changes in tolerance level or loudness perception due to acclimatization

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Munro and Trotter (2006)	47-89 years (N=12)	Symmetrical high frequency loss	Retrospective	Monaural fitting, 1-5 years experience	ULL	ULL higher in fitted ear
Hamilton and Munro (2007)	26-97 years (N=16)	Symmetrical high frequency loss	Retrospective	1-16 years experience monaural and binaural hearing aid users	ULL	ULL higher in fitted ears
Philibert, Collet, Vesson, and Veuillet (2002)	Group I: 64-82 years (N=9) Group II: 73-90 years (N=9)	Moderate to severe symmetrical hearing loss	Prospective	Long-term binaural (1-5 years) Non HA group	Loudness scaling	Difference between 2 groups, right ear showing more difference.
Philibert, Collet, Vesson and Veuillet (2005)	69-78 years (N=8)	Symmetrical, sloping SNHL	Prospective	Naïve, binaural (pre-fitting, 1,3, 6 months after fitting)	Loudness scaling	Changes in loudness scaling were significant for the high frequencies after three and six months of hearing aid usage

2.2.3.2 Changes in intensity and frequency discrimination

Robinson and Gatehouse (1995) retrospectively investigated the difference limen for intensity (DLI) in four participants with bilateral symmetric hearing impairment. The control group consisted of five individuals with normal hearing in the age range of 18 to 35 years. The DLI was measured with tone complexes of 0.25 and 3 kHz at 65, 80, and 95 dB SPL. Difference limens were measured using the gated pedestal method with an adaptive, three alternative, forced-choice procedure for a criterion performance of 71% correct. The results showed that the fitted ear behaved differently from the not-fitted ear. At 3 kHz, DLI was poorer at low presentation levels but better at high presentation levels in the fitted ear. The changes in intensity discrimination in the aided ear are as a result of exposure to amplified sound and consistent with the frequency-gain characteristics of the hearing aid. The level-dependent effects parallel the findings of Gatehouse (1989) for speech identification in noise.

Robinson and Gatehouse (1996) carried out a prospective study of intensity discrimination in five individuals (age range 38 to 83 years) who were fitted with a monaural hearing aid with linear and peak-clipping features. The participants had bilateral sensorineural hearing impairment. The hearing aids were fitted according to the NAL-R target for REIG. Measurements were carried out at 0 to 4, 6 to 12, and 15 to 18 weeks post-fitting. The results showed that immediately after fitting, there was no difference between the two ears for either stimulus. Also, there was no difference between the aided and unaided ear 0-4 weeks post-fitting. At 0.25 kHz, there was no difference between the ears when the study terminated at 18 weeks post-fitting. However, at 3 kHz, there was a progressive influence of hearing aid experience with the difference limen being significantly smaller in the fitted ear at high presentation levels when the study terminated at 18 weeks post-fitting. This shows that the fitted ear becomes progressively better able to discriminate intensity at the highest sound pressure level for frequencies that are normally amplified by the hearing aid. Use of hearing aid for 15 to 18 weeks was required before this was observed. There was little or no change over time at lower sound pressure levels, at frequencies not amplified by the hearing aid, or in the not-fitted ear.

Philibert et al. (2002) compared intensity-related performance between two groups of subjects matched in terms of age, gender and absolute thresholds in both ears. One group comprised of long-term binaural hearing aid (HA) users and the other of individuals who did not wear a hearing aid (non-HA users). Better DLIs were noted in the long-term users than in the non-HA users. This study suggests significant perceptual modification and thus a possible functional plasticity entailed by hearing aid use.

Philibert et al. (2005) considered eight subjects with symmetrical sloping sensorineural hearing loss fitted with monaural hearing aid. DLIs were measured using a maximum-likelihood procedure. This was done for both ears of each listener, at two intensities (75 and 95 dB SPL), at two frequencies (0.5 and 2 kHz) and at four times during HA fitting (before HA fitting, and one month, three months and six months after). Smaller DLI values were obtained at 95 dB SPL than at 75 dB SPL. Greater differences were found between both intensities in right ear than in left ear. Results showed improvements in performance over hearing aid fitting time-course particularly at loud intensity levels and at 2 kHz. No statistically significant change in DLI was found at 75 dB SPL, an intensity level perceived as soft by the listeners with sensorineural hearing loss. Intensity discrimination performance improved mostly for loud auditory cues, newly available to the subject indicating that hearing aid fitting induces functional plasticity at the peripheral level of the auditory system.

Gabriel, Veuillet, Vesson, and Collet (2006) investigated the occurrence of rehabilitation plasticity associated with hearing aid fitting. Nine subjects with steeply sloping hearing loss and who were candidates for auditory rehabilitation were tested. Six subjects had binaural and three had monaural HA fitting. Discrimination-limen-for-frequency (DLF) enhancement was investigated at the frequency with the best DLF (bDLF) for each individual subject before and during auditory rehabilitation (at one month, three months and six months). From one month after hearing aid fitting, as time progressed, frequency discrimination performance decreased significantly at the bDLF frequency, while remaining stable at other frequencies. This normalization may reflect a new central re-organization reversing the initial injury-induced changes in the cortical map. A correlation between subject's age and alteration in DLF at one month was also found, suggesting that plasticity operates faster in younger patients. The authors rule out acclimatization effect and suggest the mechanism of central auditory plasticity responsible for it.

In individuals with steeply sloping hearing loss, McDermott, Lech, Kornblum, and Irvine (1998) found that DLFs showed a local reduction near the cutoff frequency in most participants. They interpreted the DLF data based on animal experiments that have shown that cortical re-organization occurs resulting in an increase in the spatial representation of lesion-edge frequencies. Therefore, the local reduction in DLFs may reflect neural plasticity.

Table 2.4 summarizes the aforementioned studies on changes in intensity and frequency discrimination.

Table 2.4: Summary of studies on changes in intensity and frequency discrimination

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Restrospective**	**Hearing aid details**	**Measures**	**Results**
Robinson and Gatehouse (1995)	54-82 years (N=4)	Bilateral symmetric SNHL	Retrospective	Monaural hearing aid users for an average of 2 years	Gated pedestal method with an adaptive, three interval, forced-choice procedure	DLI was poorer at low presentation levels but better at high presentation levels in the fitted ear
Robinson and Gatehouse (1996)	38-83 years (N=5)	Bilateral, sloping SNHL	Prospective	Naïve monaural hearing aid users; follow-up till 18 weeks post-fitting	Gated pedestal method with an adaptive, three interval, forced-choice procedure	DLI better at high presentation levels in the aided ear only at 3 kHz.
Philibert, Collet, Vesson, and Veuillet (2002)	64-82 years (N=9), 73-90 years (N=9)	Moderate to severe symmetrical hearing loss	Prospective	Long-term binaural (1-5 years) Non HA group	Maximum-likelihood procedure for estimating DLI	Left Ear displayed a greater difference in DLI between low and high intensities than did the right ear. There was a tendency of better DLI in the long- term users than non-HA group

Author/s, (year)	Participants	Hearing loss	Prospective/ Retrospective	Hearing aid details	Measures	Results
Philibert, Collet, Vesson and Veuillet (2005)	69-78 years (N=8)	Symmetrical, sloping SNHL	Prospective	Naïve, binaural (pre-fitting, 1,3 6 months after fitting)	DLI were measured in both ears at two intensities (75 and 95 dB SPL), at two frequencies (0.5 and 2 kHz)	Smaller DLI values were obtained at 95 dB SPL than at 75 dB SPL. Greater differences were found between both intensities in right ear than in left ear
Gabriel, Veuillet, Vesson, and Collet (2006)	35-73 years (N=9)	Steeply sloping SNHL	Prospective	Naïve HA users. (before HA fitting, 1, 3, 6 months post fittings). 6 binaural and 3 monaural HA users	Three-interval, two-alternative forced-choice procedure with a two-down, one-up decision rule	Frequency discrimination performance decreased significantly at the best DLF frequency, while remaining stable at other frequencies

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Mcdermott, Lech, Kornblum and Irvine (1998)	37-55 years (N=5)	Steeply sloping SNHL	Prospective	Not a factor as only one participant wore hearing aid	DLF for pure tones using adaptive, three-interval, forced-choice procedure.	DLFs were elevated, on average, relative to DLFs measured using the same procedure in five individuals with normal hearing, but showed a local reduction near the cut-off frequency in most subjects with high-frequency loss.

2.3 Hearing loss and plasticity

Vasama and Makela (1995) used whole scalp Magnetoencephalography (MEG) to study possible cortical plasticity in persons with sudden unilateral sensorineural hearing loss. Auditory evoked magnetic fields (AEFs) were recorded 2 to 5 years after hearing loss onset from eight adults with sudden unilateral hearing loss (presumably of cochlear origin). All subjects had normal hearing through 4 kHz in the unaffected ear. The degree of hearing loss in the affected ear differed among subjects. Eight adults with normal bilateral hearing were also tested as control subjects. The N1m response was measured with a series of 1 kHz tones. Five of the persons with unilateral hearing loss showed shorter latencies and/or stronger dipole moments in the cortical hemisphere ipsilateral to the stimulated ear (the better ear). This pattern of performance (shorter latency/stronger activity in the ipsilateral rather than contralateral hemisphere) was interpreted as evidence of re-organization of the auditory system as a result of the hearing loss. Three of the persons with unilateral hearing loss also showed a very different spatial and temporal response in the MEG than did the control subjects, which indicated additional sources of cortical activity. Thus, parts of the brain that are not active in persons with normal hearing appear to be active in those with unilateral hearing loss. The results of this study are mixed in that some subjects with unilateral hearing loss had AEF patterns similar to those with normal hearing while others did not. Subjects with profound and lesser degrees of hearing loss exhibited a pattern of activity that differed from that seen in the individuals with normal hearing.

Ponton et al. (2001) investigated the effects of unilateral hearing loss on representation of the signal at the cortex by evaluating the N1-P2 complex, AEPs were measured in 15 persons with profound, adult-onset unilateral hearing loss (12 from otologic surgery, 3 from sudden hearing loss). The subjects with unilateral hearing loss were divided into two subgroups: eight with hearing loss less than two years, seven with hearing loss greater than two years. All the subjects had normal hearing at frequencies up to 4 kHz in the better ear. Nine subjects with normal bilateral hearing served as controls. Compared to monaurally stimulated normal-hearing subjects, the

AEPs recorded from central electrode sites located over auditory cortical areas showed significant increases in inter-hemispheric waveform cross-correlation coefficients, and in inter-hemispheric AEP peak amplitude correlations. These increases provide evidence of substantial changes from the normal pattern of asymmetrical (contralateral > ipsilateral amplitude) and asynchronous (contralateral earlier than ipsilateral) central auditory system activation in the normal hearing population to a much more symmetrical and synchronous activation in individuals with unilateral hearing impairment. These cross-sectional analyses of AEP data recorded from the individuals with unilateral hearing impairment also suggested that the changes in cortical activity occur gradually and continue for at least two years after the onset of hearing loss. Analyses of peak amplitude correlations suggested that the increased inter-hemispheric symmetry may be a consequence of changes in the generators producing the N1 (approximately 100 ms peak latency) potential. These experience-related changes in central auditory system activity following late-onset profound unilateral impairment thus provide evidence of the presence and the time course of auditory system plasticity in the adult brain.

One confounding factor identified by the researchers is the age difference between the two groups of subjects with hearing loss. The group with shorter duration hearing loss was older than the group with longer duration hearing loss. Thus, the possibility exists that the difference between the two hearing loss groups may be attributable to a smaller capacity for plasticity in older persons rather than the duration of hearing loss. An additional issue in this and many other studies is the use of younger subjects in the control group.

Khosla et al. (2003) also measured long-latency AEPs (70-210 ms) in 19 listeners with profound unilateral hearing loss (average duration of hearing loss 2.4 years) and eight with normal hearing in both ears using click stimuli. Better ear was tested in the hearing impaired group whereas both ears were tested in the normal hearing group In the individuals with unilateral hearing loss, inter-hemispheric amplitude differences were reduced. Central auditory plasticity also depends on which ear has hearing loss. For individuals with left ear unilateral hearing loss (right ear stimulation), there was equal cortical activation in the right and left hemispheres for clicks. Whereas, in individuals with right ear unilateral hearing loss (left ear stimulation) produced normal asymmetry, i.e., contralateral right hemisphere larger than ipsilateral left hemisphere activation. This suggests that compensatory plasticity does not take place for a right ear hearing loss. They concluded that unilateral hearing loss can disrupt the normal inter-hemispheric pattern of cortical response.

Table 2.5 summarizes the aforementioned studies on hearing loss and plasticity.

Table 2.5: Summary of studies on hearing loss and plasticity

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Vasama and Makela (1995)	35-48 years (N=8)	Sudden unilateral SNHL	Prospective	2 to 5 years	Magnetoencephalography (MEG)	Five out of eight of the persons with unilateral hearing loss showed shorter latencies and/or stronger dipole moments in the cortical hemisphere ipsilateral to the stimulated ear (the better ear)
Ponton, Vasama, Tremblay, Khosla, Kwong, and Don (2001)	17-67 years (N=15)	Profound, adult-onset unilateral	Prospective	1 year (for three subjects) to 13.7 years.	Long-latency auditory evoked potentials	Symmetrical and synchronous activation in those with unilateral hearing impairment

Author/s, (year)	Participants	Hearing loss	Prospective/ Retrospective	Hearing aid details	Measures	Results
Khosla, Ponton, Eggermont, Kwong, Don, and Vasama (2003)	16-68 years (N=19)	Profound unilateral hearing loss	Prospective	Average duration of hearing loss= 2.4 years	Long-latency auditory evoked potentials	Differences between the ipsilateral and contralateral responses in adults with unilateral hearing impairment were significantly altered from the individual with normal hearing Inter-hemispheric differences depended on which ear was being stimulated and which ear had hearing loss

2.4 Hearing aid usage and plasticity

2.4.1 Physiololgical measures

Munro, Pisareva, Parker, and Purdy (2007) investigated both perceptual and physiological asymmetry in unilateral hearing aid users. They investigated ear asymmetry in uncomfortable loudness level (ULL) and the acoustic reflex threshold (ART) in adult humans following long-term use of a monaural hearing aid who had symmetrical hearing loss. The median duration of use was three years (ranging from 1 to 25 years), and the median self-reported daily use was 10 hours (range 4 to 16 hours). The asymmetry was greatest at the high frequencies, and this was almost certainly underestimated at 4 kHz because it was not always possible to measure a reflex in the fitted ear. Elevation of the ART occurred in the ear with hearing aid experience irrespective of the ear of stimulation. These findings suggest that hearing aids can induce physiological changes in the adult auditory brainstem.

2.4.2 Electrophysiological measures

Philibert et al. (2005) administered click evoked ABR on five elderly individuals who presented with symmetrical hearing loss and were fitted with binaural hearing aids. ABR for clicks was measured before HA fitting, and one month, three months and six months after the hearing aid fitting. There was shortening of wave V latency in the right ear of the subjects and greatest change was found for subject who performed best in the behavioural task such as intensity discrimination. No ABR modification was found in the left ear. The authors hypothesized the inter-ear differences observed in this study were due to functional auditory pathway asymmetry (Hugdahl, 2000). It is well known that the auditory system is asymmetrically organized in right-handed subjects, at both central and peripheral levels. They also suggested the influence of the medial olivocochlear efferent system, which is thought to have more effect on right ears than on left ears in right-handed listeners.

Munro et al. (2007) investigated ear asymmetry in ABR following monaural hearing aid usage. Individuals with bilateral symmetrical high frequency hearing loss were taken and divided into two groups, first group was yet to be fitted with a hearing aid and the second group consisted of long-term monaural hearing aid users. Statistically significant difference was not present between the right and left ears of either group. In participants with symmetrical hearing loss who had no hearing aid experience, the click-ABR was similar in both ears. However, in individuals with symmetrical hearing loss and monaural hearing aid experience, the mean peak-to-peak amplitude of wave V to SN10 was larger on the fitted side. The authors reasoned that the increase in the mean wave V to SN10 peak-to-peak amplitude for the fitted ear may be due to more fibres being activated and/or better neural synchronization.

Sakhuja, Munjal, and Panda (2010) examined whether any significant changes occur following restoration of hearing by a hearing aid in patients with hearing deprivation. Participants consisted of 17 patients (10 males and 7 females) in the age range of 10 to 40 years with mild to moderately severe sensorineural hearing loss (unilateral or bilateral). Brain Stem Evoked responses (BSER) and Middle Latency Responses (MLR) studies were conducted on first visit of the patient and hearing thresholds were estimated with the help of pure tone audiometry. A follow up was done two months after hearing aid fitting. After fitting with a hearing aid, repeated BSER and MLR studies showed significant decrement in the latencies and improvement in the amplitudes of the waves in all the subjects. The authors suggested that after the restoration of hearing in auditory deprived individuals points to the capacity of the central auditory system to re-organize itself. This neural plasticity has implications for hearing aid use, acclimatization, and deprivation effects.

McCullagh (2009) also examined the extent to which AEPs might reveal physiological changes in the central auditory nervous system related to hearing aid use and acclimatization. Individuals with hearing impairment between the ages of 49 and 71 years participated in the study. The experimental group consisted of ten first-time hearing aid wearers who were evaluated on the day of the initial hearing aid fitting and then again six to eight weeks later. The control group consisted of ten individuals who were matched for age and hearing loss but did not wear amplification. The measures used to assess plasticity were the Abbreviated Profile of Hearing Aid Benefit (APHAB), the nonsense syllable test (NST), and the late auditory evoked potentials (N1 and P2). The NST and late auditory evoked potentials were completed during the pre-test session and the post-test session. Results indicated no significant differences between pre- and post- test sessions for the NST, N1 amplitude, P2 amplitude, and P2 latency between the control and experimental group. However, statistically significant differences did exist for the change in N1 latency measure between the two groups. The change in N1 latency was significantly greater for the experimental group compared to the control group. Due to good test-retest reliability for N1 latency and evidence of plastic changes in animals, as well as humans, following alterations in the acoustic environment, the author suggested that the changes seen in the N1 latency were due to plasticity in the CANS following amplification.

Table 2.6 summarizes the aforementioned studies on effects of acclimatization on hearing aid usage and plasticity.

Table 2.6: Summary of studies on hearing aid usage and plasticity

Author/s, (year)	**Participants**	**Hearing loss**	**Prospective/ Retrospective**	**Hearing aid details**	**Measures**	**Results**
Munro, Walker, and Purdy (2007)	68-87 years (N=16)	Symmetrical sloping hearing loss	Prospective	Monaural hearing aid users (from 1-25 years)	Acoustic reflex threshold	The elevation of the acoustic reflex threshold occurs in the ear with hearing aid experience, irrespective of the ear of stimulation
Philibert, Collet, Vesson, and Veuillet (2005)	69-78 years (N=5)	Symmetrical, sloping SNHL	Prospective	Naïve, binaural fitting (pre-fitting, 1,3 6 months after fitting)	Click evoked ABR	Shortening of wave V latency in the right ear of the subjects probably due to functional auditory pathway asymmetry
Munro, Pisareva, Parker, and Purdy (2007)	69 (SD=9.0) years (N=9) and 64 years (SD=7.6) (N=8)	Bilateral symmetrical high frequency SNHL	Prospective	1st group: naïve hearing aid users 2nd group: long term monaural hearing aid users (2 years of use)	Click evoked ABR	In monaural hearing aid users, the mean peak-to-peak amplitude of wave V to SN10 was larger on the fitted side

Sakhuja, Munjal and Panda (2010)	10 to 40 years (N=17)	Mild to moderately severe sensorineural hearing loss (unilateral or bilateral).	Prospective	Monaural hearing aid users (before and 2 months post-fitting)	ABR and MLR	Follow-up BSER and MLR studies showed significant decrement in the latencies and improvement in the amplitudes of the waves in all the subjects
McCullagh (2009)	49-71 years (N=10) 51-71 years (N=10)	Bilateral symmetrical hearing loss	Prospective	1st group naïve hearing aid users (before fitting and 6-8 weeks post fitting) 2nd group (non hearing aid users)	APHAB, NST, LLR	No significant differences between pre- and post-test sessions for the NST, N1 amplitude, P2 amplitude, and P2 latency between the control and experimental group. However, statistically significant differences did exist for the change in N1 latency measure between the two groups.

2.5 Summary

To recapitulate, most of the literature on plasticity in hearing aid users focuses on assessing either one of the two effects of plasticity, namely deprivation or acclimatization. As evidenced in the studies of Silman et al. (1993) and Arkis and Burkey (1994), a minimum of 2 years of monaural hearing aid usage is required before the effects of deprivation can be noted in the unaided ear. Most studies on acclimatization have focused on assessing the change in behavioural measures to ascertain the amount of benefit due to amplification. Fewer studies have focused on other psychophysical and physiological measures to assess plasticity. There are abundant animal studies investigating the mechanism of plasticity using invasive measures. However in humans, Auditory evoked potentials (AEPs) can be used as an objective, non-invasive tool to investigate auditory processing and plasticity of auditory function (Purdy et al., 2001). There have been mixed results in limited number of studies documenting effects of plasticity on electrophysiological measures in hearing aid users. The present study aims to further investigate the effects of plasticity and hearing aid usage on behavioural and electrophysiological measures.

Chapter 3

Method

To evaluate auditory plasticity, electrophysiological testing at brainstem and cortical levels, and behavioural testing were carried out in two phases. They were:

1. At the time of hearing aid fitting (baseline)
2. Two to three months after the hearing aid fitting (follow-up)

The following method was followed.

3.1 Participants

Phase I: In total, 10 individuals between the age of 18 and 65 years (Mean= 53.40 years, SD=14.62 years) participated in the study. The participants had bilateral moderate sensorineural hearing loss. The hearing loss was symmetrical with a difference in pure tone average between the ears being less than or equal to 15 dB. Tympanometric findings fell within normal limits i.e., static compliance between 0.4 and 1.6 cc (Jerger, 1970) and peak pressure between -100 and 50 daPa (Jerger, 1970). The participants were fitted with an appropriate hearing aid and optimized such that the aided thresholds of all participants were within the speech spectrum from 500 Hz to 4000 Hz. Naïve hearing aid users were taken for the study. Aided speech identification scores were at least 80%. The participants did not have any history of any neurological, cognitive, speech and language problems.

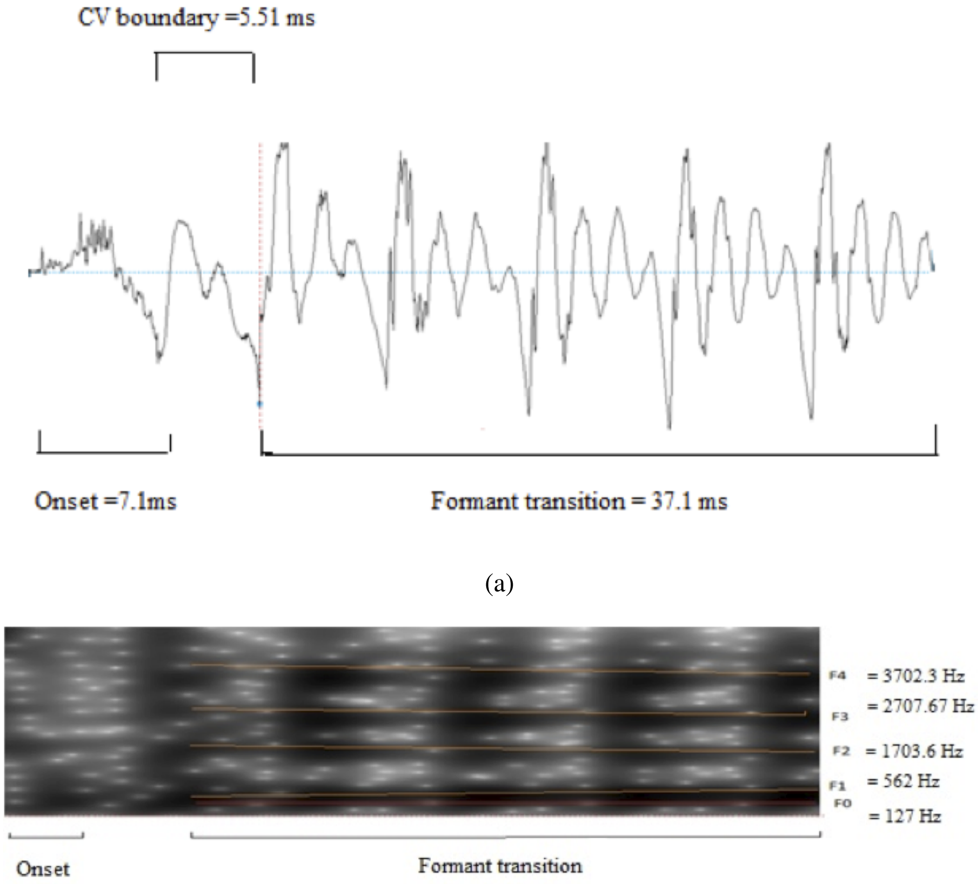
Phase II: Individuals who were evaluated in Phase I, were evaluated again in Phase II after two to three months of hearing aid usage. However, out of the ten individuals who participated in Phase I, eight individuals participated in Phase II. Attrition and lack of consistent hearing aid use were the major reasons for decreased number of participants in Phase II.

3.2 Instrumentation

All the tests were carried out in an air-conditioned sound treated double room set-up. Behavioural thresholds were determined using a calibrated clinical audiometer OB922 (version-2). TDH 39 headphone encased in MX-41/AR supra aural ear cushion was used to estimate the air-conduction thresholds and Radio ear B-71 bone vibrator was used to estimate the bone-conduction thresholds. For evaluating the middle ear status, a calibrated Grason-Stadler TympStar (GSI) (version-2) middle ear analyzer was used. Adobe Audition (version-3) software was used for recording, editing and normalizing the naturally produced speech syllable intended to record the speech-evoked ABR and LLR. The Praat software (Version-5.1.29) installed in a personal computer, was used to analyze the acoustic waveforms and spectrograms of the stimuli. The Bio-Logic Navigator Pro with Biomark Software (Version 7.0) was used to present the stimuli and record the speech-evoked ABR and LLR. The stimulus was presented through the ER 3A insert receiver to record the response. The calibration of the equipment used in the study was ensured before and at regular intervals during data collection.

3.3 Stimulus Recording and Preparation

Three adult male speakers with normal voice whose mother tongue was Kannada (Dravidian language widely spoken in Karnataka, South India) were chosen to utter the Consonant Vowel (CV) token /da/ using normal vocal effort. The CV tokens were recorded on the Adobe Audition (V-3) software, installed in a personal computer, via a microphone (Ahuja, AUD-101XLR) placed at a distance of 10 cm from the lips of the speaker (Winholtz & Titze, 1997). The test stimulus /da/ was a naturally produced voiced alveolar stop speech sound, in consonant vowel combination. The total duration of /da/ was 49.71 ms with an onset duration of 7.1 ms, CV boundary of 5.51 ms and the formant transition of 37.1 ms. The acoustic waveforms and spectrograms of the stimuli were analyzed using Praat software (Version -5.1.29) and are as shown in Figure 3.1.



(a)

(b)

Figure 3.1: (a) Waveform of /da/ stimulus with the onset duration being 7.1 ms, CV boundary being 5.51 ms and formant transition being 37.1 ms. (b) Spectrogram of /da/ stimulus depicting the fundamental frequency and the first four formants.

The recorded stimulus was digitized using a 32-bit processor at 44,100 Hz sampling frequency. A total of 3 CV (/da/ stimulus uttered from three speakers) tokens obtained were subjected to rating for naturalness and quality from 10 listeners with normal hearing. Stimulus with the highest rating for goodness was selected.

The stimulus /da/ is an acoustically complex sound, which begins with a stop burst, characterized by aharmonic and broadband frication, followed by a harmonically rich and spectrally dynamic formant transition. This CV syllable was chosen for a number of reasons. First, /da/ is a relatively universal syllable that is included in the phonetic inventories of most languages. Second, the syllable consists of a transient segment followed by a sustained periodic segment. It is, in a sense, much like a click followed by a tone - two acoustic signals whose brain stem response properties have been extensively characterized. Because of these acoustic similarities, the transient onset response to the stop burst is similar to the click evoked ABR, and the sustained response to the vowel is similar to tone-evoked frequency following response (FFR). Third, the stop consonants pose great perceptual challenges to clinical population such as individuals with hearing impairment and learning problems (Tallal & Stark (1981); Turner, Fabry, Barrett, & Horwitz (1992); Kraus et al. (1996)). In fact, since stop bursts are rapid and low in amplitude compared to vowels, even adults and children with normal hearing can find it difficult to discriminate between contrastive stop consonants (e.g., '*d*are' versus '*b*are') in a noisy environment. Finally, this is continued to be used as a primary stimulus because it elicits clear and replicable ABRs (Skoe & Kraus, 2010).

3.4 Procedure

To document the changes in behavioural and electrophysiological measures in monaural hearing aid users following a period of hearing aid usage, the testing was conducted in two Phases. In Phase I, speech-evoked ABR and LLR measures were obtained in the unaided condition for the participants. In addition, behavioural measures such as speech identification scores (SIS) and the Signal-to-Noise Ratio-50 (SNR-50) i.e., the difference in intensity between speech and speech shaped noise needed for correct repetition of at least 50% of the phonetically balanced words, were also obtained.

To evaluate the change in performance, the measures obtained in Phase I (speech-evoked ABR, LLR, SIS & SNR-50) were repeated in Phase II. At the time of testing for Phase II, the participants had used the hearing aid for at least two to three months and had a self-reported hearing aid usage of at least 5-6 hours per day (range 5- 9 hours per day) .

For the purpose of selection of participants, pure tone audiometry, speech audiometry and immittance evaluation were carried out. Air-conduction and bone-conduction thresholds were determined using modified Hughson-Westlake procedure, ANSI S3.21-1978 (R-1992), using + 5 and -10 dB step size. To obtain speech identification scores (SIS), the Kannada phonetically balanced list (Yathiraj & Vijayalakshmi, 2005) was administered through monitored live voice, at a level of 40 dB SL (ref: SRT). The participant was instructed to repeat the word heard. The total number of correctly identified words was noted down to represent the SIS. For assessing the middle ear status, tympanometry was obtained using a 226 Hz probe tone (Brooks, 1968; Holte, Margolis, & Cavanaugh, 1991) with a pump rate of 50 daPa/unit time (Feldman, Fria, Palfrey, & Dellecker, 1984). Ipsilateral and contralateral reflexes were obtained for both ears using 226 Hz probe tone.

3.4.1 Phase I: Baseline evaluation.

Baseline evaluation was performed at the time when the participant came to collect his/her hearing aid. Electrophysiological measures and behavioural measures were obtained.

3.4.1.1 Electrophysiological measures - ABR and LLR.

A new session for each participant was created by entering and saving the details of the participant in the patient's demographics of the Bio-Logic Navigator Pro. The participant was seated comfortably on a reclining chair with armrest. The skin surface at the two mastoids (M1, M2) and the high forehead (Fz) were cleaned with a skin preparing gel with a mild abrasive to obtain the required skin impedance. The impedance was less than 5 kΩ at each of the electrode sites and the inter-electrode impedance was less than 2 kΩ. Disc type silver electrodes coated with conduction gel were placed in vertical montage.

The stimulus /da/ was presented through the insert receiver to the participant, who was seated in an air-conditioned sound-treated room. While recording speech-evoked ABR and LLR, the non-inverting electrode (+) was placed on the high forehead (Fz), the ground electrode was on mastoid of the non-test ear and the inverting electrode (-) on the mastoid of test ear (M1 or M2). The participant was instructed to relax and not to move during the testing. The ABR recording was initiated once a stable EEG was obtained. The stimulus and recording parameters for speech-evoked ABR and LLR are given in Table 3.1. At least two recordings were obtained for both ABR and LLR. Weighted average of the recordings was taken. The latency of wave V, P1, N1, P2 and amplitude of wave V and the N1-P2 complex in the two recordings were identified, and marked visually by three experienced audiologists. The latencies of the peaks, as identified by the three audiologists were tabulated for wave V, P1, N1, and P2. In addition, the amplitudes of wave V and N1-P2 complex were also tabulated.

Table 3.1: Stimulus and recording parameters for ABR & LLR

Stimulus parameters		
	ABR	*LLR*
Stimulus	Speech stimulus /da/ of 49.71 ms	Speech stimulus /da/ of 49.71 ms
Polarity	Alternate	Alternate
Number of sweeps	2000	200
Stimulus rate	5.1/second	1.1/second
Intensity	80 dB nHL	80 dB nHL
Transducer	ER 3A insert receiver	ER 3A insert receiver

Recording parameters		
	ABR	*LLR*
Mode of stimulation	Monoaural	Monoaural
No. of channel	One channel	One channel
Electrode montage	Vertical Montage Fz: Non-inverting electrode Non test ear: Ground electrode Test ear: Inverting electrode	Vertical Montage Fz: Non-inverting electrode Non test ear: Ground electrode Test ear: Inverting electrode
Filter setting	100 to 3000 Hz	0.1 to 30 Hz
Amplification	1,00,000	50,000
Notch filter	On	-
Recording time window	-15 to +83.3 msec	-30 to +533 msec
Replicability	Twice	Twice

Analysis of frequency following response (FFR) waveforms:

Additionally, to know the different aspects of speech i.e., the coding of fundamental frequency, first formant frequency and higher harmonics, an FFT analysis of the sustained response of the speech-evoked ABR was done. This was executed using the MATLAB R 2009a platform and software (Brainstem toolbox) developed by Kraus (2004) at Northwestern University. Fourier analysis was performed on the 12 to 53 ms epoch of the frequency following response (FFR). Information regarding the coding of fundamental frequency, first formant frequency and higher harmonics was extracted in order to assess the amount of activity occurring over all these three frequencies. Activity occurring in the frequency range of the response corresponding to the fundamental frequency of the speech stimulus (103-130 Hz), first formant frequencies of the stimulus (455-580 Hz) and for the higher harmonics (585-1200 Hz) was measured for all the participants. This was done as per the guidelines given in earlier studies (Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; Russo, Nicol, Musacchia, & Kraus, 2004; Hornickel, Skoe, & Kraus, 2009; Johnson, Nicol, Zecker, Bradlow, Skoe, & Kraus, 2008). To avoid the spectral splatter, a 2 ms 'on' and a 2 ms 'off' Hanning ramp was applied to all the waveforms. Zero-padding was employed to increase the number of frequency points where spectral estimates were obtained.

An auditory evoked response from the participants is required to be above the noise floor in order to be included in the analyses (Russo et al., 2004). This calculation is performed by comparing the spectral magnitude of the pre-stimulus period to that of the response (Russo et al., 2004). If the quotient of the magnitude of the F0, F1 and higher harmonics frequency component of the FFR divided by that of the pre-stimulus period was greater than or equal to one, the response was deemed to be above the noise floor (Russo et al., 2004). If, the response amplitude was above the noise floor, the raw amplitude values of the F0, F1 frequency and higher frequency component of the FFR were then measured and noted. The same procedure was followed for each participant.

3.4.1.2 Behavioural measures.

Speech identification scores and the Signal-to-Noise Ratio-50 were obtained from each of the participants in the aided and the unaided condition.

3.4.1.2.1 Speech identification scores

In the unaided and aided conditions, speech identification scores were obtained in sound field using the PB bisyllabic word lists in Kannada (Yathiraj & Vijayalakshmi, 2005). The presentation level was 40 dB SL (re: SRT) in the unaided condition and at 45 dB HL in the aided condition. Speech stimuli were presented using monitored live voice and routed through the loudspeaker of the audiometer. The loudspeaker was situated one meter and at an azimuth of 45° from the test ear. The number of words repeated correctly, out of 25 words in the list, was noted as the speech identification scores in the unaided and aided condition.

3.4.1.2.2 Speech recognition threshold in noise to obtain Signal-to-Noise ratio-50 (SNR-50).

For the purpose of this step, Signal-to-Noise Ratio-50 (SNR-50) was obtained by determining the difference in intensity of the speech and the intensity of speech noise, in dB, when the participant correctly repeated at least two out of four words presented.

The participant was seated in an air-conditioned sound-treated room. Both speech and speech noise were presented through the same loudspeaker at 45° azimuth from the test ear. An adaptive procedure was used to obtain SNR-50 for each participant in the unaided and aided conditions. The unaided and aided SNR-50 was obtained with the monitored live speech signal presented at a constant level of 45 dB HL. The level of the noise was varied, with the initial level being 30 dB HL, i.e., 15 dB less than the level of speech. The participant was instructed to repeat the words heard. The noise level was increased in 5 dB steps until the participant obtained a score of 50%. From this point, the noise was varied, either increased or reduced in 2 dB steps so as to obtain a 50% correct word recognition score for determining SNR-50. The difference between the level of the speech and the speech noise, at this stage, was noted as the SNR-50.

3.4.2 Phase II: Testing after a period of hearing aid usage

Follow-up assessment of participants of Phase 1 was carried out. The participants had a self reported hearing aid usage of at least 5-6 hours per day. Electrophysiological (3.4.1.1) and behavioural measures (3.4.1.2) were assessed using a similar procedure as in Phase I.

Thus, in Phase I and II the following data were collected for each participant in the unaided condition:

1. Speech identification scores
2. Signal-to-Noise Ratio-50 (SNR-50)
3. Speech-evoked ABR and LLR

Whereas, in the aided condition the following data were collected from each participant:

1. Speech identification scores
2. Signal-to-Noise Ratio-50 (SNR-50)

In order to evaluate the presence or absence of auditory plasticity, the collected data were subjected to appropriate statistical analyses.

Chapter 4

Results and Discussion

The present study aimed to assess auditory plasticity through behavioural and electrophysiological measures in monaural hearing aid users, before and after a period of hearing aid usage. To this end, data were collected from eight participants in two phases, at the time of hearing aid fitting (baseline) and two to three months after hearing aid usage (follow-up). Data for behavioural measures included:

1. Speech identification scores (SIS) and signal-to noise ratio-50 (SNR-50) for the unaided ear in the unaided condition.
2. Speech identification scores (SIS) and signal-to noise ratio-50 (SNR-50) for the aided ear in the unaided condition.

Data for electrophysiological measures included:

1. Speech-evoked ABR for both ears in the unaided condition.
2. Speech-evoked LLR for both ears in the unaided condition.

Descriptive statistics was obtained for each of the data collected. The data were then subjected to two-way repeated measures analysis of variance (ANOVA) to determine if there were significant changes seen in behavioural and electrophysiological measures following hearing aid usage.

4.1 Behavioural measures

4.1.1 Speech Identification Scores (SIS)

Descriptive statistics was done to find out the mean and standard deviation. Table 4.1 depicts the mean and standard deviation for unaided SIS at the time of baseline and follow-up. Table 4.2 shows the mean and standard deviation (SD) of SIS in the aided condition.

Table 4.1: Mean and Standard Deviation (SD) for unaided speech identification scores in the aided and unaided ear during the baseline and follow-up evaluations

Unaided SIS					
Unaided Ear			*Aided Ear*		
Baseline	*Follow-up*	*p*	*Baseline*	*Follow-up*	*p*
21.00 (1.93)	21.13 (2.17)	0.69	21.63 (1.85)	22.38 (1.85)	0.02

Table 4.2: Mean and Standard Deviation (SD) for aided speech identification scores in the aided ear during the baseline and follow-up evaluations

Aided SIS		
Aided Ear		
Baseline	*Follow-up*	*p*
22.6 (1.60)	23.5 (1.39	0.03

Two-way repeated measures ANOVA was done to compare the unaided performance in the unaided and aided ear for the speech identification scores (SIS) at the time of baseline evaluation and after a period of two to three months (follow-up). Interaction between the evaluations (baseline & follow-up) and conditions (aided & unaided ear) was statistically significant ($p<0.01$). Hence, the data were subjected to paired t-test. Statistically significant difference was not present between the two evaluations for the unaided ear. However, in the aided ear, the follow-up evaluation revealed a significant improvement in speech identification scores ($p<0.05$). This finding is in consonance with that reported by Gatehouse (1992) and Arkis and Burkey (1994) who reported that the mean word recognition scores remained stable in the unaided ears but improved for the aided ears.

The speech identification scores are measured at supra-threshold level. It can be postulated that aided ears acclimatize to the higher sound levels due to amplification and hence perform better on the supra-threshold task. Gatehouse (1989) also found that at higher presentation levels, the aided ear performs better than the unaided ear.

To compare, the aided performance in the aided ear for the speech identification scores (SIS) at the time of baseline and follow-up evaluation, paired t-test was done. Statistically significant difference was noted between the two evaluations ($p<0.05$), with the SIS after a period of hearing aid usage being better than at the baseline. This finding is supported by Cox, Alexander, Taylor, and Gray (1996) who have also reported improvement in speech intelligibility measures for the aided condition over time.

4.1.2 Signal-to-Noise Ratio-50 (SNR-50)

Descriptive statistics was done to find out the mean and standard deviation of SNR-50 during baseline and follow-up evaluations. Table 4.3 depicts mean, standard deviation (SD) and p values (two-tailed) for unaided SNR-50 scores in aided and unaided ear during the baseline and follow-up evaluations.

Table 4.3: Mean and Standard Deviation (SD) for unaided SNR-50 scores in aided and unaided ear during the baseline and follow-up evaluations

Unaided SNR-50					
Unaided Ear			*Aided Ear*		
Baseline	*Follow-up*	*p*	*Baseline*	*Follow-up*	*p*
5.40 (5.56)	2.75 (5.18)	0.67	4.20 (5.83)	-0.25 (5.65)	0.13

To compare the unaided performance in the unaided and aided ear for SNR-50, at the time of baseline evaluation and follow-up evaluation non parametric Wilcoxon Signed Ranks test was used. This was done as there was a large variability in the data obtained as can be seen in the Table 4.3 and Figure 4.1 . Though statistically significant difference between baseline and follow-up evaluations was not observed, SNR-50 was better in the follow-up evaluation compared to the baseline evaluation. Silman, et al. (1993) found that speech performance in noise worsened from the test to re-test in the unaided ear and improved from test to re-test in the aided ear, but there was no significant difference between initial and follow-up testing. Initial testing was done 6 to 12 weeks post hearing aid fitting and follow-up was done one year after initial testing. Similar results were reported by Bentler et al. (1993a) in a follow-up study. No significant improvement in HINT and Nonsense Syllable Test (NST) scores in noise was seen 1, 3, 6 and 12 months post hearing aid fitting. However, visual inspection of raw data indicates an improvement in scores between initial testing and follow-up at one month. Taken together, these findings suggest that though there may be differences in the aided ear, a significant difference may not be noted. It could be hypothesized that longer duration of hearing aid usage could result in more apparent differences between the aided and unaided ear.

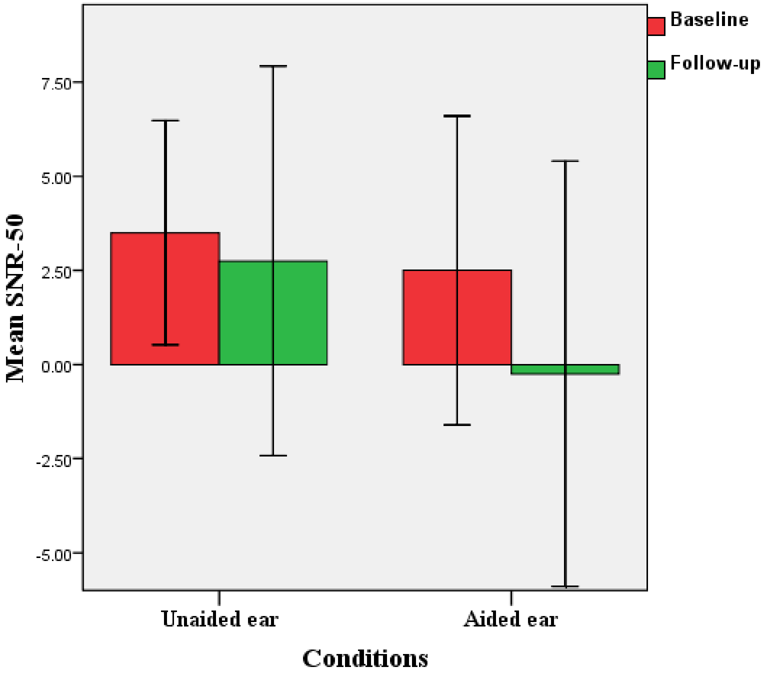


Figure 4.1: Mean and standard deviation (+/- 1 SD) for unaided SNR-50 scores in aided and unaided ear during the baseline and follow-up evaluations

Descriptive statistics for SNR-50 in the aided conditions revealed large variability in the data. Table 4.4 depicts mean and standard deviation (SD) for aided SNR-50 in aided ear during the baseline and follow-up evaluations.

Table 4.4: Mean and Standard Deviation (SD) for aided SNR-50 in aided ear during the baseline and follow-up evaluations

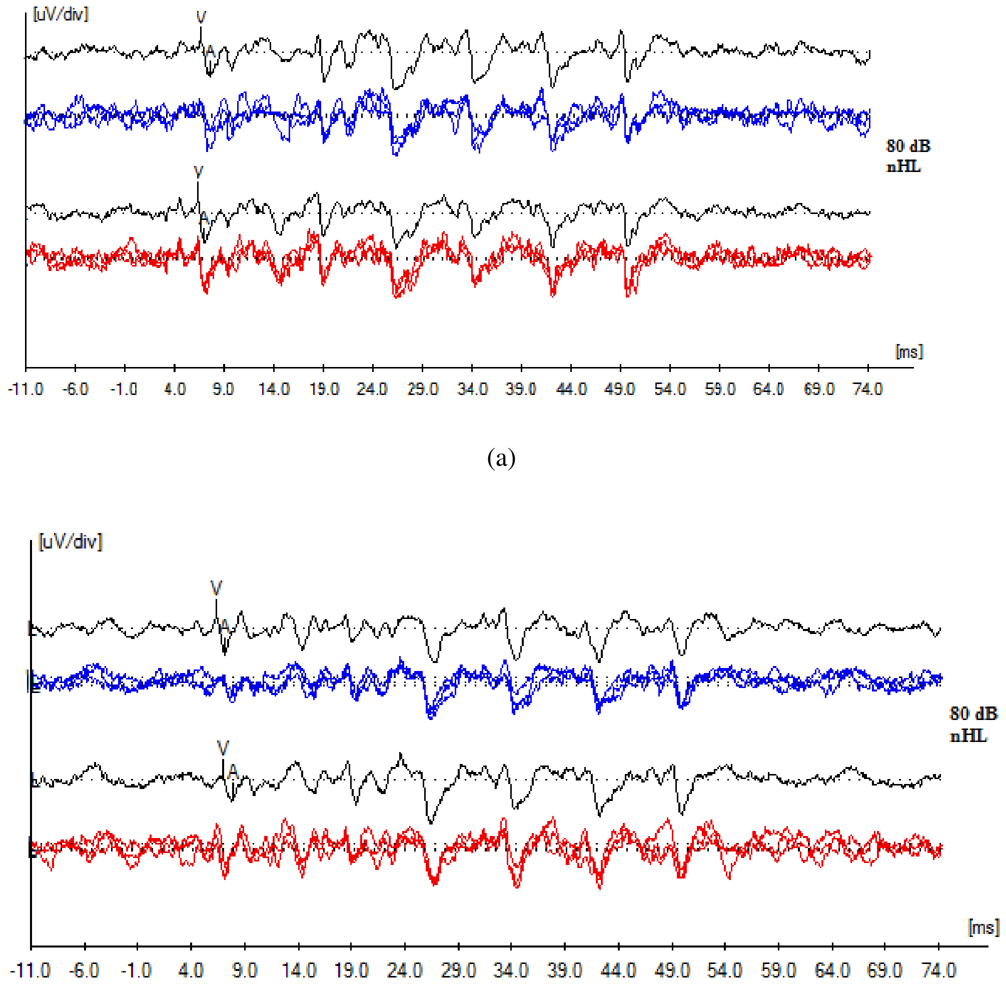
Aided SNR-50		
Aided Ear		
Baseline	*Follow-up*	*p*
4.75 (3.11)	0.50 (3.16)	0.03

To compare the aided performance for SNR-50 during the two evaluations, Wilcoxon Signed Ranks test was used. It was noted that the individuals required a lower SNR in the follow-up evaluation and this difference was statistically significant ($p<0.05$). Gatehouse (1992) also reported a benefit in signal-to-noise ratio in the aided ear of monaural hearing aid users 6-12 weeks post hearing aid fitting. It could be an individual becomes more accustomed to the amplified sound through the hearing aid (Gatehouse, 1992), therefore better performance is seen after a period of hearing aid usage.

4.2 Electrophysiological measures

4.2.1 Speech-Evoked ABR

Figure 4.2(a) shows unaided ABR at baseline evaluation while Figure 4.2(b) shows unaided ABR during follow-up of one of the participants.



(a)

(b)

Figure 4.2: Speech-evoked ABR for a participant (a) Unaided ABR during baseline evaluation (b) Unaided ABR during follow-up evaluation. Blue and Red colours depict recordings for left (aided) and right (unaided) ear respectively. Black waveform is the weighted average of the recordings.

A clear, replicable peak V could be visually identified in only four out of eight of the participants. Therefore, Wilcoxon Signed Ranks test was used to compare the two evaluations. Table 4.5 depicts the mean and standard deviation for latency and amplitude of V peak.

Table 4.5: Mean and Standard Deviation (SD) for latency and amplitude of wave V, in aided and unaided ear, during the baseline and follow-up evaluation

Parameter	*Unaided Ear*			*Aided Ear*		
	Baseline	*Follow-up*	*p*	*Baseline*	*Follow-up*	*p*
Latency (ms)	8.56 (3.80)	9.16 (4.97)	0.59	8.79 (2.92)	8.30 (2.82)	0.08
Amplitude (μV)	0.29 (0.12)	0.27 (0.10)	0.58	0.22 (0.06)	0.24 (0.03)	0.69

Delay in latency of V peak was seen for the unaided ear during the follow-up evaluation as compared to the baseline evaluation. Whereas, a slightly earlier peak V was seen on follow-up for the aided ear. However, the difference between baseline and follow-up evaluations was not statistically significant in both the ears. There are mixed results in literature too regarding hearing aid usage and ABR measures. Munro, et al. (2007) also reported similar latency values in click evoked ABR for fitted and non-fitted ear in listeners with at least two years of monaural hearing aid experience.

In the present study, a slight decrease in the amplitude of wave V for the unaided ear was noted at the the follow-up evaluation. Also, a slight increase in the amplitude of wave V for the aided ear was seen at follow-up. These differences were not statistically significant ($p>0.05$). Munro, et al., (2007) reported an increase in the mean amplitude of wave V to SN-10 for the fitted ear with at least two years of hearing aid usage. Changes with presentation level were also reported suggesting intensity dependence of plasticity effects. Sakhuja et al. (2010) reported shortening of wave V as well as increase in amplitude following monaural hearing aid usage. Philibert, et al. (2005) found shortening of wave V latency only for the right ear in bilateral hearing aid users.

ABR is dominated by neurons with strong time-locked excitatory responses to sound onset. The wave amplitudes are enhanced by neural synchrony, particularly responses that originate from the brainstem (Phillips, Hall, & Boehnke, 2002). The wave V also depends on the onset characteristics of the stimulus. Longer rise times result in decreased synchronous firing of nerve units (Spoendlin, 1972). Reduced amplitudes and delayed latencies in the speech-evoked ABR have also been found in elderly individuals. Increasing age could be consistent with a reduction in synchronous neural firing to transient changes in speech and impaired neural encoding of the duration and offset of a stimulus in the aging auditory system (Vander Werff & Burns, 2011). Absence of visually identifiable wave V in some of the participants in the present study may be related to the stimulus characteristics, degree of hearing loss and the age of the individuals. For those individuals in whom wave V could be identified, an increase in amplitude and a slight decrease in latency was noted for the aided ear. Probably with longer duration of hearing aid usage these changes may become more apparent.

Information regarding the coding of fundamental frequency, first formant frequency and higher harmonics was extracted using FFT in order to assess the amount of activity occurring over all these three frequencies. Table 4.6 depicts the mean and standard deviation for the amplitude of fundamental frequency (F0), first formant (F1) and higher harmonics.

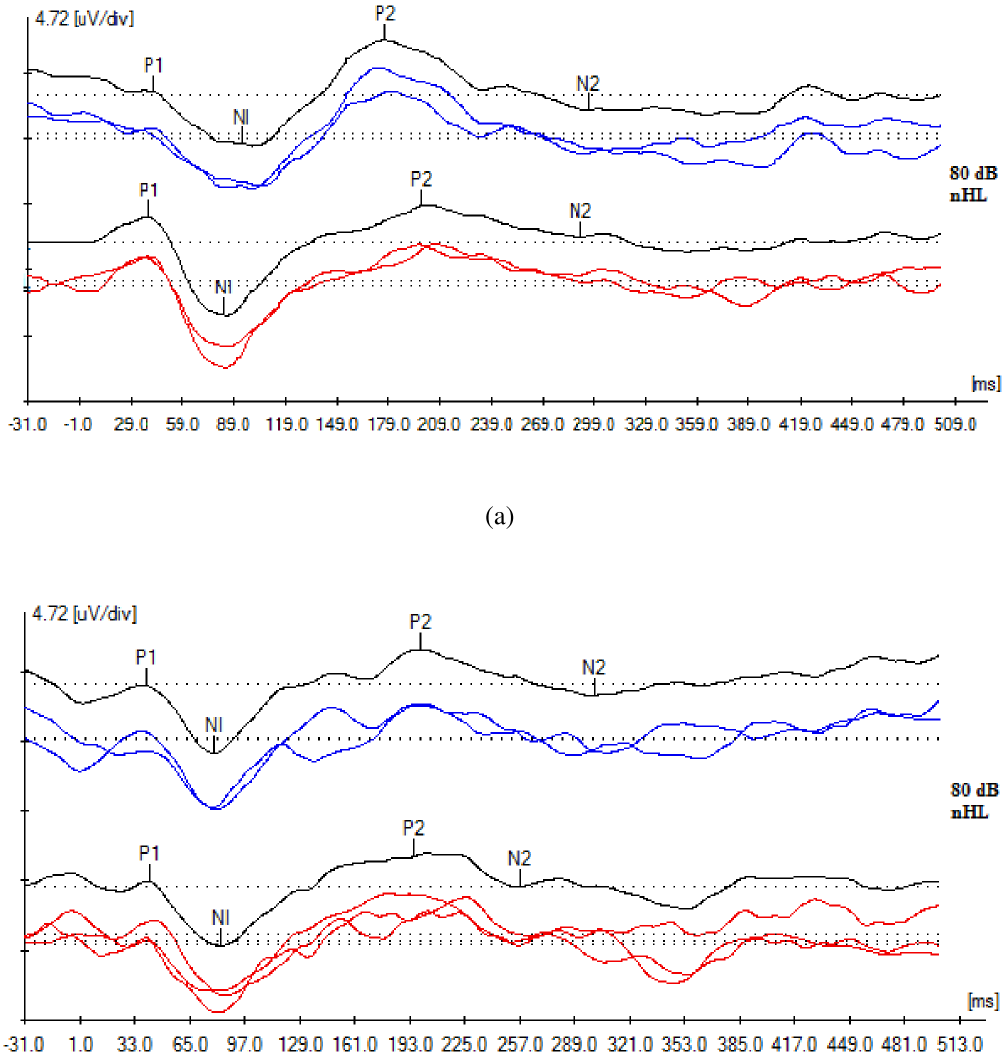
Table 4.6: Mean and Standard Deviation (SD) for amplitude of F0 , F1 and higher harmonics in aided and unaided ear during the baseline and follow-up evaluations.

Parameter	*Unaided Ear*			*Aided Ear*		
	Baseline	*Follow-up*	*p*	*Baseline*	*Follow-up*	*p*
F0 Amplitude	5.27 (1.81)	4.97 (2.57)	0.88	5.50 (4.61)	6.09 (2.33)	0.88
F1 Amplitude	0.79 (0.32)	1.03 (0.54)	0.07	0.71 (0.29)	0.72 (0.26)	0.90
Higher harmonics amplitude	0.34 (0.10)	0.33 (0.08)	0.78	0.30 (0.09)	0.34 (0.07)	0.16

Statistically significant difference was not seen for any of the parameters in any of the conditions or evaluations. A thorough survey of the literature did not reveal any study using speech- evoked ABR for evaluating plasticity and/or acclimatization effects in hearing aid users. FFR coding is impaired in sensorineural hearing loss and second formant information is not encoded (Plyler & Ananthanarayan, 2001). In the present study, F0 coding was preserved in the participants and poor encoding of F1 and higher harmonics was seen. The stimulus has higher energy at F0 region compared to its harmonics (Ladefoged, 1996) and higher energy components are better coded at the neuronal level. Also, F0 has a lower frequency compared to its harmonics which results in better phase locked response (Chandrashekharan & Kraus, 2010). Preserved sustained brainstem responses in mild to moderate sensorineural hearing loss has also been reported by Sumesh and Barman (2007).

4.2.2 Speech-Evoked LLR

ALLR was also done at the two evaluations and P1, N1, P2, N2 peaks were visually identified. Figure 4.3(a) shows unaided LLR at baseline evaluation while Figure 4.3(b) shows unaided LLR during follow-up for one of the participants. Table 4.7 depicts mean and standard deviation for latency and amplitude of each of the peaks. Figure 4.4 depicts mean latency and standard deviation of P1, N1, P2, and N2 in aided and unaided ear during the two evaluations.



(a)

(b)

Figure 4.3: Speech-evoked LLR for a participant (a) Unaided LLR during baseline evaluation (b) Unaided LLR during follow-up evaluation. Blue and Red colours depict recordings for left (aided) and right (unaided) ear respectively. Black waveform is the weighted average of the recordings.

Table 4.7: Mean and Standard Deviation (SD) for latency and amplitude of P1, N1, P2, and N2 in aided and unaided ear during the baseline and follow-up evaluations.

Parameter		*Unaided Ear*			*Aided Ear*		
Measure	*Peak*	*Baseline*	*Follow-up*	*p*	*Baseline*	*Follow-up*	*p*
Latency (ms)	P1	47.66 (8.68)	67.09 (41.84)	0.28	44.43 (4.36)	52.15 (17.29)	0.32
	N1	95.29 (14.02)	116.99 (42.66)	0.26	99.27 (19.30)	99.95 (19.12)	0.82
	P2	187.92 (33.62)	208.80 (29.60)	0.33	181.43 (31.42)	187.79 (24.21)	0.59
	N2	303.36 (41.69)	311.92 (31.71)	0.62	293.34 (47.09)	289.74 (38.66)	0.74
Amplitude (μV)	P1	1.37 (1.19)	1.19 (0.98)	0.58	1.46 (1.11)	1.00 (1.10)	0.04
	N1	3.77 (1.62)	3.35 (1.62)	0.97	3.67 (1.83)	4.12 (1.66)	0.97
	P2	2.92 (2.30)	2.74 (1.87)	0.49	3.29 (2.31)	2.90 (2.04)	0.49
	N1-P2	6.69 (3.33)	6.08 (3.11)	0.34	6.93 (3.52)	7.90 (3.66)	0.002
	N2	0.83 (1.12)	0.86 (0.72)	0.06	1.21 (1.11)	0.49 (0.56)	0.09

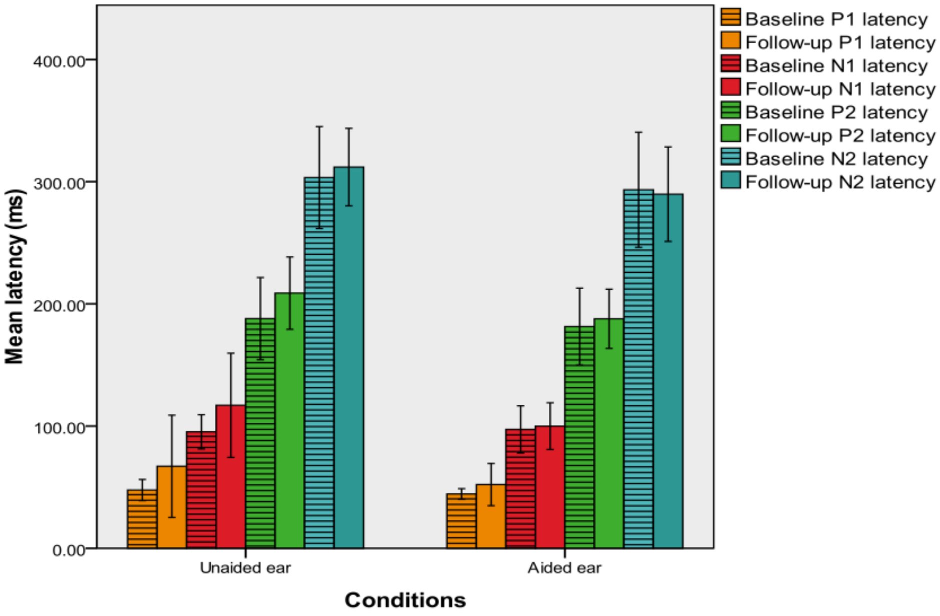


Figure 4.4: Mean and standard deviation (+/- 1 SD) for latency of P1, N1, P2, and N2 in aided and unaided ear during the baseline and follow-up evaluations. The hatched bars depict baseline evaluation, while the non-hatched bars depict follow-up evaluation.

Two-way repeated measures ANOVA was done to compare the P1 latency during the two evaluations for both the ears. There was statistically no significant difference in the two ears between the two evaluations. Though on close observation, it can be noted that the latency of P1 for the unaided ear is more prolonged than in the aided ear at the follow-up evaluation.

Due to high variability in the data obtained for P1 amplitude, Wilcoxon Signed Ranks test was used. There was statistically no significant difference in the amplitude for the unaided ear. As compared to the baseline evaluation, a statistically significant decrease in amplitude of P1 was noted for the aided ear.

Two-way repeated measures ANOVA for latency of N1 revealed presence of interaction effect ($p<0.05$). However, paired t-test did not reveal significant differences between any of the conditions or evaluations. Also, two-way repeated measures ANOVA for amplitude of N1 did not reveal any statistically significant differences.

There was no significant difference on two-way repeated measures ANOVA for latency and amplitude of P2 between the two evaluations. However, paired t-test for N1-P2 amplitude revealed a significant increase in the N1-P2 amplitude in the aided ear as compared to the unaided ear ($p<0.005$). Seven out of eight participants wore hearing aids on the left side. Paired t-test, comparing the performance of left and right ears for the seven individuals, revealed a significant increase in the N1-P2 amplitude for only the left ear at follow-up evaluation only. There was no difference between the two ears at the baseline evaluation. This suggests that the changes seen in N1-P2 amplitude was not due to auditory pathway asymmetry as reported by Philibert et al. (2005).

Two-way repeated measures ANOVA for N2 latency revealed no significant difference between the two evaluations for both ears. Due to high variability in the data, Wilcoxon Signed Ranks test was used to compare the amplitude of N2. There was no statistically significant difference between the two evaluations for the same.

Inconsistencies in the behavioural and electrophysiological findings following hearing aid usage has been reported in literature (McCullagh, 2009). Even though participants showed an improvement in measures of speech intelligibility following hearing aid usage, similar changes in electrophysiological measures was not seen. There is paucity of research assessing plasticity changes using electrophysiological measures following hearing aid usage. The N1-P2 complex is thought to reflect synchronous neural activation of structures in the thalamic-cortical segment of the central nervous system in response to auditory stimulation (Naatanen & Picton, 1987; Woods, 1995; Wolpaw & Penry, 1975). Significant increase in the N1-P2 complex amplitude for the aided ear reflects greater synchronization in the structures due to introduction of new amplified signal. Also, experience-induced changes can be reflected in the N1-P2 complex (Ponton et al. 2001; Tremblay, Kraus, McGee, Ponton, & Otis, 2001). Auditory pathway asymmetry cannot be used to explain the changes seen in the aided ear of the individuals as no difference was found between the two ears at baseline evaluation. Therefore, the changes in N1-P2 amplitude may be taken to be evidence of changes due to experienced induced plasticity.

In the present study, more changes were noticed in the cortical potentials than in the brainstem potentials. This suggests that plasticity occurs earlier in cortical than in brainstem structures. Madhok and Maruthy (2010) also noted earlier and larger changes in cortical than brainstem potentials following training in individuals with normal hearing. They attributed these changes to difference in the number of cortical and brainstem neurons. Higher number of neurons in the cortex could result in greater scope for neural arborization and in turn plasticity. Statistically no significant changes were seen in any other latency or amplitude measure (except P1). This finding is in consonance with McCullagh (2009) who reported changes only in N1 latency. However, it should be kept in mind that amplitude measures are more susceptible to fluctuations in signal to noise ratios during different test sessions (Munro et al., 2007). A slight prolongation of all peaks in the unaided ear as against stability of latencies in the aided ear could be an indicator towards early onset of auditory deprivation. It could be that the amplification period was not long enough to elicit more pronounced changes in the aided ear.

To summarize, in users with monaural hearing aid, after two to three months of hearing aid usage, more changes were seen in the behavioural measures than in the electrophysiological measures. Within the behavioral measures, the speech identification scores (SIS) for the aided ear was significantly larger at the follow-up evaluation in both the aided and the unaided conditions. Also, there was a significant improvement in the SNR-50 for the aided ear in the aided condition. Amongst the electrophysiological measures, only amplitude of N1-P2 was significantly larger in the aided ear at the follow-up evaluation as compared to the baseline evaluation.

Though the participants had a self reported hearing aid usage of at least 5-6 hours per day, data-logging facility was not present in any of the hearing aids used by the participants. Hence, hearing aid usage could not be objectively monitored. Amongst electrophysiological measures, cortical potentials are more sensitive in evaluating changes associated with plasticity. It could be that larger time gap between the first and follow-up evaluations or a series of follow-up evaluations could reveal larger changes in performance of both the aided and the unaided ears.

Chapter 5

Summary and Conclusion

The present study aimed to document the changes in behavioural and electrophysiological measures in monaural hearing aid users before and after a period of hearing aid usage. Specific objectives of the study were:

1. To compare the unaided performance for the following measures in the unaided and aided ear:
   (a) The speech identification scores (SIS) at the time of baseline evaluation and after a period of two to three months.
   (b) Signal-to-Noise Ratio-50 (SNR-50) at the time of baseline evaluation and after a period of two to three months.
   (c) The Auditory Brainstem Response (ABR) at the time of baseline evaluation and after a period of two to three months.
   (d) The Auditory Long Latency Responses (ALLR) at the time of baseline evaluation and after a period of two to three months.
2. To compare, the aided performance on the following measures in the aided ear:
   (a) The speech identification scores (SIS) at the time of baseline evaluation and after a period of two to three months.
   (b) Signal-to-Noise Ratio-50 (SNR-50) at the time of baseline evaluation and after a period of two to three months.

The study was conducted in two phases:

1. Phase I: At the time of hearing aid fitting (baseline evaluation)
2. Phase II: Two to three months after the hearing aid fitting (follow-up evaluation)

Ten participants with bilateral symmetrical moderate hearing loss were considered in Phase I. The participants were in the age range of 18 to 65 years (Mean= 53.40 years, SD=14.62 years). There were eight participants in Phase II due to attrition and lack of consistent hearing aid usage. All the participants were naïve monaural hearing aid users. The following data were collected from each of the participants during baseline and follow-up evaluation.

1. In the unaided condition:
    (a) Speech identification scores
    (b) Signal-to-Noise Ratio-50 (SNR-50)
    (c) Speech-evoked ABR and LLR
2. Whereas, in the aided condition:
    (a) Speech identification scores
    (b) Signal-to-Noise Ratio-50 (SNR-50)

Descriptive statistics were done for each of the measures. The results were then analyzed using appropriate statistical tools such as two-way repeated measures ANOVA, paired t-test, and Wilcoxon Signed Ranks test. The results of the present study can be summarized as follows-

1. Comparison of the unaided performance in the unaided and aided ear for the speech identification scores (SIS) at the time of baseline and follow-up evaluations revealed statistically significant interactions between the evaluations (baseline & follow-up) and conditions (aided & unaided ear). Paired t-test revealed a significant improvement in SIS at the time of follow-up in the aided ear. However, in the unaided ear, statistically significant difference was not present between the two evaluations. Thus, improvement in SIS for the aided ear could be due to plasticity contributing towards acclimatization.

2. Comparison of the aided performance in the aided ear for the speech identification scores (SIS) at the time of baseline and follow-up evaluation revealed statistically significant difference between the two evaluations. This finding is in consonance with the findings of Gatehouse (1989) that changes due to plasticity are evident at the same level which the aided ear is accustomed to receiving.

3. Wilcoxon Signed Ranks test was used to compare the unaided performance in the aided and the unaided ear for SNR-50. There was statistically no significant difference between the two evaluations in both the aided and the unaided ear. However, it was observed that the participants required a lower SNR in the follow-up evaluation as compared to the baseline evaluation.

4. On comparing the aided performance for SNR-50 during the two evaluations, a statistically significant difference was noted. The participants required a lower SNR during the follow-up evaluation. This suggests that the aided ear becomes accustomed to listening to sounds at a higher presentation level. Therefore, the individuals require a lower SNR perform to perform better in the presence of noise.

5. A clear replicable peak V in the speech-evoked ABR waveform could be visualized in only four out of eight participants. Wilcoxon Signed Ranks test revealed no significant difference between the two evaluations in peak V latency and amplitude for the aided and the unaided ear. FFT analysis of the sustained portion of the ABR revealed preserved coding of F0 in all of these participants. Poor encoding of F1 and higher harmonics was seen. Also, there was no significant difference in the amplitude of F0, F1 and higher harmonics between the two evaluations.

6. No significant difference was seen between the two evaluations for P1, N1, P2, and N2 latency. Also, no significant difference was seen N1, P2, and N2 amplitude. Statistically significant reduction in P1 amplitude was noted in the follow-up evaluation. There was also a significant improvement in N1-P2 amplitude between the two evaluations. On close observation, P1 latency for the unaided ear

was more prolonged than in the aided ear at the follow-up evaluation. Also, more changes were seen in the cortical potentials than in the brainstem potentials. This finding is in consonance with that of Madhok and Maruthy (2010). Thus, cortical potentials may be more sensitive in measuring changes due to plasticity.

7. Only one of the eight participants used hearing aid on the right side. Excluding this participant, a paired t-test was used to compare baseline and follow-up evaluations for the left and right ear. Of all the measures, significant difference was noted for only N1-P2 amplitude in the left ear exclusively. No significant difference was found between right and left ears for both the evaluations. Therefore, ear asymmetry was not seen in baseline evaluation. This finding could imply that the changes in N1-P2 amplitude seen in the aided ear only were not due to ear asymmetry. This suggests that plasticity due to re-introduction of sound (Willott, 1996) in the previously unaided ear could lead to better synchronization of nerve fibres thereby manifesting as an improvement in N1-P2 amplitude (Tremblay, 2007). Longer and more consistent usage of hearing aid could result in larger changes in all the measures.

5.1 Clinical implications

1. There is a paucity of research in evaluating changes due to plasticity in behavioural and electrophysiological measures in naïve hearing aid users. The present study attempts to shed more light in this area of research. The most significant finding of the study was the change seen in N1-P2 amplitude between the two evaluations. This implies that longer duration of hearing aid usage can result in further improvement in the performance of the aided ear. This finding can be useful in counselling individuals with hearing impairment towards using their hearing aids for longer periods of time during the day.

2. Although not statistically significant, close observation of the data revealed that the unaided ear performed poorer in all the measures. The performance of the unaided ear might worsen if no amplification is provided, suggesting a possible

deprivation effect. Therefore, this finding may be used to counsel individuals with aidable hearing impairment, to use binaural hearing aids or to at least alternate the hearing aid between the two ears on a regular basis.

3. The findings of this study can also be used to counsel naïve hearing aid users who have difficulty in adjusting to amplification. The brain requires time to adjust to amplification i.e., Hearing Aid Brain Rewiring Accommodation Time (HABRAT) (Gatehouse & Killion, 1993). Therefore hearing aid users may be motivated to start using their hearing aid for increasingly longer periods of time in order to obtain more benefit.

4. A common problem in individuals with hearing impairment is understanding speech in the presence of background noise. Kochkin (2002a) reported that only 30% of the hearing aid users were satisfied with their hearing aids in noisy situations. Kochkin (2002b) also reported that better speech understanding in the presence of background noise is the highest improvement desired by hearing aid users. The findings of the present study reveal that there was a significant improvement in aided SNR-50 following a period of hearing aid usage. Consistent hearing aid usage could lead to larger improvements in SNR and therefore could result in more satisfaction with the hearing aid. This finding too could be incorporated while counselling a naïve hearing aid user.

5.2 Future directions for research

1. Future studies might focus on studying changes due to plasticity in two groups of individuals with hearing impairment. A control group comprising of individuals who do not wear any amplification devices and an experimental group who are naïve hearing aid users. The follow-up evaluations might be spaced over a longer period of time so as to demonstrate pronounced effects of acclimatization and deprivation. Comparison of the data from group with hearing impairment with normal hearing could help to pinpoint whether the changes are due to plasticity or test-retest variations.

2. Since cortical potentials are more sensitive towards measuring changes due to plasticity, future studies might employ a variety of speech signals to measure changes due to plasticity. The findings from such research could then be used to evaluate the relationship between electrophysiological measures and behavioural measures.

3. Research may be conducted for evaluating changes due to plasticity in individuals with symmetrical hearing impairment wearing monaural hearing aids versus binaural hearing aids versus users who alternate the hearing aid between the two ears.

4. Subjective measures such as questionnaires may also be employed to evaluate the benefit due to amplification. Also, hearing aids with data-logging feature can be used to monitor hearing aid usage.

5. Many studies have focused on training and/ or experience related changes in brainstem potentials in individuals with normal hearing. More research can be done in the area of speech-evoked ABR and plasticity in hearing aid users.

References

Amorim, R. M. & Almeida, K. (2007). Study of benefit and of acclimatization in recent users of hearing aids. *Pró-fono : revista de atualização cientfica*, *19*(1), 39–48.

Arkis, P. & Burkey, J. (1994). What WRS's say about client performance, adjustment to hearing aids. Word recognition scores: Do they support adaptation? *Hearing Instruments*, *45*(1), 24–25.

Arlinger, S. & Billermark, E. (1999). One year follow-up of users of a digital hearing aid. *British Journal of Audiology*, *33*(4), 223–232.

Arlinger, S., Gatehouse, S., Bentler, R. A., Byrne, D., Cox, R. M., Dirks, D. D., Humes, L., Neuman, A., Ponton, C., Robinson, K., Silman, S., Summerfield, A. Q., Turner, C. W., Tyler, R. S., & Willott, J. F. (1996). Report of the Eriksholm Workshop on auditory deprivation and acclimatization. *Ear and Hearing*, *17*(3-Suppl), 87S–98S.

Bentler, R. A., Niebuhr, D. P., Getta, J. P., & Anderson, C. V. (1993a). Longitudinal study of hearing aid effectiveness. I: Objective measures. *Journal of Speech, Language, and Hearing Research*, *36*(4), 808–819.

Bentler, R. A., Niebuhr, D. P., Getta, J. P., & Anderson, C. V. (1993b). Longitudinal study of hearing aid effectiveness. II: Subjective measures. *Journal of Speech, Language, and Hearing Research*, *36*(4), 820–831.

Brooks, D. N. (1968). An objective method of determining fluid in the middle ear. *International Audiology*, *7*, 280–286.

Burkey, J. M. & Arkis, P. N. (1993). Word recognition changes after monaural, binaural amplification. *Hearing Instruments*, *44*(1), 8–9.

Chandrasekaran, B. & Kraus, N. (2010). The scalp-recorded brainstem response to speech: neural origins and plasticity. *Psychophysiology*, *47*(2), 236–246.

Cox, R. M. & Alexander, G. C. (1992). Maturation of hearing aid benefit: objective and subjective measurements. *Ear and Hearing*, *13*(3), 131–141.

Cox, R. M., Alexander, G. C., Taylor, I. M., & Gray, G. A. (1996)Benefit acclimatization in elderly hearing aid users.*Journal of the American Academy of Audiology*, *7*(6), 428–441.

Cunningham, J., Nicol, T., Zecker, S. G., Bradlow, A., & Kraus, N. (2001)Neurobiologic responses to speech in noise in children with learning problems: deficits and strategies for improvement. *Clinical Neurophysiology*, *112*(5), 758–767.

Feldman, R. M., Fria, T. J., Palfrey, C. C., & Dellecker, C. M. (1984). Effects of rate of air pressure change on tympanometry. *Ear and Hearing*, *5*(2), 91–95.

Gabriel, D., Veuillet, E., Vesson, J. F., & Collet, L. (2006). Rehabilitation plasticity: influence of hearing aid fitting on frequency discrimination performance near the hearing-loss cut-off. *Hearing Research*, *213*(1-2), 49–57.

Gatehouse, S. (1989). Apparent auditory deprivation effects of late onset: the role of presentation level. *Journal of the Acoustical Society of America*, *86*(6), 2103–2106.

Gatehouse, S. (1992). The time course and magnitude of perceptual acclimatization to frequency responses: evidence from monaural fitting of hearing aids. *Journal of the Acoustical Society of America*, *92*(3), 1258–1268.

Gatehouse, S. (1993). Role of perceptual acclimatization in the selection of frequency responses for hearing aids.*Journal of the American Academy of Audiology*, *4*(5), 296–306.

Gatehouse, S. & Killion, M. (1993). HABRAT: Hearing Aid Brain Rewiring Accommodation Time. *Hearing Instruments*, *44*(10), 29–32.

Gelfand, S. A. & Silman, S. (1993). Apparent auditory deprivation in children: implications of monaural versus binaural amplification. *Journal of the American Academy of Audiology*, *4*(5), 313–318.

Gelfand, S. A., Silman, S., & Ross, L. (1987). Long-term effects of monaural, binaural and no amplification in subjects with bilateral hearing loss. *Scandinavian Audiology*, *16*(4), 201–207.

Guiraud, J., Besle, J., Arnold, L., Boyle, P., Giard, M. H., Bertrand, O., Norena, A., Truy, E., & Collet, L. (2007).Evidence of a tonotopic organization of the auditory cortex in cochlear implant users. *Journal of Neuroscience*, *27*(29), 7838–7846.

Hattori, H. (1993). Ear dominance for nonsense-syllable recognition ability in sensorineural hearing-impaired children: monaural versus binaural amplification. *Journal of the American Academy of Audiology*, *4*(5), 319–330.

Holte, L., Margolis, R. H., & Cavanaugh, R. M. (1991). Developmental changes in multifrequency tympanograms. *Audiology*, *30*(1), 1–24.

Hornickel, J., Skoe, E., & Kraus, N. (2009). Subcortical laterality of speech encoding. *Audiology and Neurotology*, *14*(3), 198–207.

Horwitz, A. R. & Turner, C. W. (1997). The time course of hearing aid benefit. *Ear and Hearing*, *18*(1), 1–11.

Hugdahl, K. (2000).Lateralization of cognitive processes in the brain.*Acta Psychologica*, *105*(2-3), 211–235.

Hurley, R. M. (1999). Onset of auditory deprivation. *Journal of the American Academy of Audiology*, *10*(10), 529–534.

Javel, E. & Shepherd, R. K. (2000). Electrical stimulation of the auditory nerve. III. Response initiation sites and temporal fine structure. *Hearing Research*, *140*(1-2), 45–76.

Jerger, J. (1970). Clinical experience with impedance audiometry. *Archives of Otolaryngology*, *92*(4), 311–324.

Johnson, K. L., Nicol, T., Zecker, S. G., Bradlow, A. R., Skoe, E., & Kraus, N. (2008). Brainstem encoding of voiced consonant–vowel stop syllables. *Clinical Neurophysiology*, *119*(11), 2623–2635.

Kamke, M. R., Brown, M., & Irvine, D. R. (2003). Plasticity in the tonotopic organization of the medial geniculate body in adult cats following restricted unilateral cochlear lesions. *Journal of Comparative Neurology*, *459*(4), 355–367.

Khosla, D., Ponton, C. W., Eggermont, J. J., Kwong, B., Don, M., & Vasama, J. P. (2003). Differential ear effects of profound unilateral deafness on the adult human central auditory system.*Journal of the Association of Research in Otolaryngology*, *4*(2), 235–249.

Killion, M. & Niquette, P. A. (2000). What can the pure-tone audiogram tell us about a patient's SNR loss. *The Hearing Journal*, *53*(46-48), 52–53.

Killion, M. C. (1997a). Hearing aids: past, present, future: moving toward normal conversations in noise. *British Journal of Audiology*, *31*(3), 141–148.

Killion, M. C. (1997b). SNR loss: I can hear what people say, but I cant understand them. *The Hearing Journal*, *4*(12), 8–14.

Killion, M. C. (1997c). The SIN report: Circuits haven't solved the hearing-in-noise problem. *The Hearing Journal*, *50*(10), 28–34.

Kochkin, S. (2002a). MarkeTrak VI :10-Year Customer Satisfaction Trends in the US Hearing Instrument Market. *The Hearing Review*, *9*(10), 14–25, 46.

Kochkin, S. (2002b). MarkeTrak VI :Consumers rate improvements sought in hearing instruments: What do hearing instrument users want from us and our products. *The Hearing Review*, *9*(11), 18–22.

Kochkin, S. (2003).MarkeTrak V :Why my hearing aids are in the drawer: The consumer perspective. *The Hearing Jounal*, *3*(2), 34–42.

Kral, A., Hartmann, R., Tillein, J., Heid, S., & Klinke, R. (2002).Hearing after congenital deafness: central auditory plasticity and sensory deprivation. *Cerebral Cortex*, *12*(8), 797–807.

Kraus, N., McGee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., & Koch, D. B. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science*, *273*(5277), 971–973.

Ladefoged, P. (1996). *Elements of acoustic phonetics* (Second ed.). Chicago: University of Chicago Press.

Madhok, P. & Sandeep, M. (2010).Neurophysiological consequence of auditory training: subcortical and cortical structures.*Student Research at AIISH Mysore*, *8*(Part A), 175–183.

McCullagh, J. P. (2009). An investigation of central auditory nervous system plasticity following amplification.(Doctoral dissertation). University of Connecticut, Connecticut, USA. Dissertations Collection for University of Connecticut. (Paper AAI3360701).

McDermott, H. J., Lech, M., Kornblum, M. S., & Irvine, D. R. (1998). Loudness perception and frequency discrimination in subjects with steeply sloping hearing loss: possible correlates of neural plasticity. *Journal of the Acoustical Society of America*, *104*(4), 2314–2325.

Munro, K. J. (2008). Reorganization of the adult auditory system: perceptual and physiological evidence from monaural fitting of hearing aids.*Trends in Amplification*, *12*(3), 254–271.

Munro, K. J., Pisareva, N. Y., Parker, D. J., & Purdy, S. C. (2007). Asymmetry in the auditory brainstem response following experience of monaural amplification. *Neuroreport*, *18*(17), 1871–1874.

Munro, K. J. & Trotter, J. H. (2006). Preliminary evidence of asymmetry in uncomfortable loudness levels after unilateral hearing aid experience: evidence of functional plasticity in the adult auditory system. *International Journal of Audiology*, *45*(12), 684–688.

Naatanen, R. & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: a review and an analysis of the component structure. *Psychophysiology*, *24*(4), 375–425.

Neuman, A. C. (2005). Central auditory system plasticity and aural rehabilitation of adults. *Journal of Rehabilitation Research and Development*, *42*(4-Suppl 2), 169–186.

Palmer, C. V., Nelson, C. T., & Lindley, G. A. (1998). The functionally and physiologically plastic adult auditory system. *Journal of the Acoustical Society of America*, *103*(4), 1705–1721.

Philibert, B., Collet, L., Vesson, J. F., & Veuillet, E. (2002). Intensity-related performances are modified by long-term hearing aid use: a functional plasticity? *Hearing Research*, *165*(1-2), 142–151.

Philibert, B., Collet, L., Vesson, J. F., & Veuillet, E. (2005). The auditory acclimatization effect in sensorineural hearing-impaired listeners: evidence for functional plasticity. *Hearing Research*, *205*(1-2), 131–142.

Phillips, D. P., Hall, S. E., & Boehnke, S. E. (2002). Central auditory onset responses, and temporal asymmetries in auditory perception. *Hearing Research*, *167*(1-2), 192–205.

Plomp, R. (1994). Noise, amplification, and compression: considerations of three main issues in hearing aid design. *Ear and Hearing*, *15*(1), 2–12.

Plyler, P. N. & Ananthanarayan, K. (2001). Human frequency-following responses: representation of second formant transitions in normal-hearing and hearing-impaired listeners. *Journal of the American Academy of Audiology*, *12*(10), 523–533.

Ponton, C. W., Vasama, J. P., Tremblay, K., Khosla, D., Kwong, B., & Don, M. (2001). Plasticity in the adult human central auditory system: evidence from late-onset profound unilateral deafness. *Hearing Research*, *154*(1-2), 32–44.

Purdy, S. C., Kelly, A. S., & Thorne, P. R. (2001)Auditory evoked potentials as measures of plasticity in humans. *Audiology and Neurotology*, *6*(4), 211–215.

Reale, R. A., Brugge, J. F., & Chan, J. C. (1987). Maps of auditory cortex in cats reared after unilateral cochlear ablation in the neonatal period. *Brain Research*, *431*(2), 281–290.

Robinson, K. & Gatehouse, S. (1995). Changes in intensity discrimination following monaural long-term use of a hearing aid. *Journal of the Acoustical Society of America*, *97*(2), 1183–1190.

Robinson, K. & Gatehouse, S. (1996).The time course of effects on intensity discrimination following monaural fitting of hearing aids. *Journal of the Acoustical Society of America*, *99*(2), 1255–1258.

Russo, N., Nicol, T., Musacchia, G., & Kraus, N. (2004). Brainstem responses to speech syllables. *Clinical Neurophysiology*, *115*(9), 2021–2030.

Sakhuja, S., Munjal, S., & Panda, N. K. (2010). Auditory Plasticity. Does It Really Exist? A Preliminary Study. *Global Journal of Medical Research*, *10*(1), 12–15.

Shepherd, R. K., Baxi, J. H., & Hardie, N. A. (1999). Response of inferior colliculus neurons to electrical stimulation of the auditory nerve in neonatally deafened cats. *Journal of Neurophysiology*, *82*(3), 1363–1380.

Silman, S., Gelfand, S. A., & Silverman, C. A. (1984). Late-onset auditory deprivation: effects of monaural versus binaural hearing aids. *Journal of the Acoustic Society of America*, *76*(5), 1357–1362.

Silman, S., Silverman, C. A., Emmer, M. B., & Gelfand, S. A. (1992). Adult-onset auditory deprivation. *Journal of the American Academy of Audiology*, *3*(6), 390–396.

Silman, S., Silverman, C. A., Emmer, M. B., & Gelfand, S. A. (1993). Effects of prolonged lack of amplification on speech-recognition performance: preliminary findings. *Journal of Rehabilitation Research and Development*, *30*(3), 326–332.

Skoe, E. & Kraus, N. (2010).Auditory brain stem response to complex sounds: a tutorial. *Ear and Hearing*, *31*(3), 302–324.

Spoendlin, H. (1972).Innervation densities of the cochlea.*Acta Otolaryngologica*, *73*(2), 235–248.

Staab, W. (2002). Characteristics and Use of Hearing Aids. In Katz, J. (Ed.), *Handbook of Clinical Audiology*, (pp. 631–686)., Baltimore. Lippincott, Williams and Wilkens.

Stelmachowicz, P. G., Kopun, J., Mace, A., Lewis, D. E., & Nittrouer, S. (1995). The perception of amplified speech by listeners with hearing loss: acoustic correlates. *Journal of the Acoustical Society of America*, *98*(3), 1388–1399.

Sumesh, K. & Barman, A. (2007). Brain Stem Responses to Speech in Normal Hearing and Cochlear Hearing Loss Individuals. *Student Research at AIISH Mysore*, *6*(Part A), 187–199.

Tallal, P. & Stark, R. E. (1981). Speech acoustic-cue discrimination abilities of normally developing and language-impaired children. *Journal of the Acoustical Society of America*, *69*(2), 568–574.

Thornton, A. R. & Raffin, M. J. (1978). Speech-discrimination scores modeled as a binomial variable. *Journal of Speech and Hearing Research*, *21*(3), 507–518.

Tremblay, K., Kraus, N., McGee, T., Ponton, C., & Otis, B. (2001). Central auditory plasticity: changes in the N1-P2 complex after speech-sound training. *Ear and Hearing*, *22*(2), 79–90.

Tremblay, K. L. (2003). Central auditory plasticity: Implications for auditory rehabilitation. *Hearing Journal*, *56*(1), 10–17.

Tremblay, K. L. (2007). Training-Related Changes in the Brain: Evidence from Human Auditory-Evoked Potentials. *Seminars in Hearing*, *28*(2), 120–132.

Turner, C. W., Fabry, D. A., Barrett, S., & Horwitz, A. R. (1992). Detection and recognition of stop consonants by normal-hearing and hearing-impaired listeners. *Journal of speech, language, and hearing research*, *35*(4), 942–949.

Turner, C. W., Humes, L. E., Bentler, R. A., & Cox, R. M. (1996). A review of past research on changes in hearing aid benefit over time. *Ear and Hearing*, *17*(3-Suppl), 14S–25S.

Tyler, R. S. & Summerfield, A. Q. (1996). Cochlear implantation: relationships with research on auditory deprivation and acclimatization. *Ear and Hearing*, *17*(3-Suppl), 38S–50S.

Vander Werff, K. R. & Burns, K. S. (2011). Brain stem responses to speech in younger and older adults. *Ear and Hearing*, *32*(2), 168–180.

Vasama, J. P. & Makela, J. P. (1995). Auditory pathway plasticity in adult humans after unilateral idiopathic sudden sensorineural hearing loss. *Hearing Research*, *87*(1-2), 132–140.

Willott, J. F. (1996). Physiological plasticity in the auditory system and its possible relevance to hearing aid use, deprivation effects, and acclimatization. *Ear and Hearing*, *17*(3-Suppl), 66S–77S.

Winholtz, W. S. & Titze, I. R. (1997). Conversion of a head-mounted microphone signal into calibrated SPL units. *Journal of Voice*, *11*(4), 417–421.

Wolpaw, J. R. & Penry, J. K. (1975). A temporal component of the auditory evoked response. *Electroencephalography and Clinical Neurophysiology*, *39*(6), 609–620.

Woods, D. L. (1995). The component structure of the N1 wave of the human auditory evoked potential. *Electroencephalography Clinical Neurophysiology Suppl*, *44*, 102–109.

Yathiraj, A. & Vijayalakshmi, C. S. (2005).Phonemically balanced word list in Kannada. *Developed in Department of Audiology, AIISH, Mysore*.