Effect of Noise and Amplification on Speech Perception in Individuals with Auditory Neuropathy Spectrum Disorder: Electrophysiological and Behavioural Study

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Kumari Apeksha

Under the guidance of

Dr. Ajith Kumar U

All India Institute of Speech and Hearing

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Abstract

Introduction: Individuals with Auditory neuropathy spectrum disorder (ANSD) complaint of poor speech understanding in quiet and in presence of noise which is disproportionate to their degree of hearing loss. Individuals with ANSD also show presence of cortical potential, in spite of abnormal/ absent auditory brainstem response. The primary aim of this study was to investigate effect of noise and amplification on speech perception in individuals with normal hearing sensitivity and with ANSD.

Methods: Total of 30 individuals with ANSD and 30 age matched normal hearing individuals participated in this study. Their age ranged from 16 years to 55 years with the mean age of 28.26 years. Individuals with ANSD had pure-tone average of less than 55 dB HL in both the ears. Those individuals who fulfilled the selection criteria underwent both behavioral and electrophysiological measurements. The behavioral measures included assessing syllable identification and speech perception in noise (SNR-50). Electrophysiological testing included recording of P300. Four speech stimuli - /ba/, /da/, /ma/, and /pa/ were used for syllable identification and for P300 measure and sentences in presence of speech babble were used to find speech perception in noise. The entire testing was done in two listening conditions - quiet and at +10 dB signal-to-noise ratio (SNR) and in two amplification conditions - with and without hearing aids.

Result: Significantly poor speech identification scores in quiet and at +10 dB SNR was observed in individuals with ANSD compared to normal hearing individuals. **S**equential **INF**ormation **A**nalysis (*SINFA) revealed that individuals with ANSD perceived manner better than place followed by voicing. The SNR-50*

was poor for individuals with ANSD compared to normal hearing individuals. P300 showed prolongation in latency and reduction in amplitude of P300 response in both in quiet and in noise. Spatiotemporal analysis showed statistically significantly different templates maps in individuals with ANSD compared to normal hearing. Use of hearing aids did not significantly improve speech perception or P300 in individuals with ANSD.

Conclusions: Individuals with ANSD showed impaired speech perception on both behavioural and electrophysiological measures. The presence of noise adversely affected the speech processing skills in individuals with ANSD and individuals with ANSD got limited benefit with the amplification devices.

Chapter 1

Introduction

Auditory neuropathy spectrum disorder (ANSD) is a clinical condition with normal cochlear function and disordered neural function along the auditory pathway (Starr, Picton, Sininger, Hood, & Berlin, 1996). The clinical finding shows elevated or absent auditory brainstem response (ABR) along with the presence of otoacoustic emission (OAE) and cochlear microphonics (Berlin et al., 2005; Berlin, Hood, Morlet, Rose, & Brashears, 2003; Rance et al., 1999; Starr et al., 1996; Starr, Sininger, & Pratt, 2000). However, many recent studies have shown that OAEs may disappear with time in individuals with ANSD. The age of onset of the symptoms is found to be between 15 years to 20 years (Jijo & Yathiraj, 2012; Kumar & Jayaram, 2006) in Indian population. The prevalence of ANSD is reported to be 0.54% among individuals with the permanent sensorineural hearing loss (Kumar & Jayaram, 2006). Females are more affected than the males with a ratio of 1: 2 (Kumar & Jayaram, 2006).

The etiologies of ANSD is very diverse and include neonatal hyperbilirubinemia, premature birth, generalized metabolic toxins, ototoxic drugs exposure, anoxia, low birth weight, exchange transfusion (Berlin et al., 2010). Genetic abnormality is also one of the causes for ANSD (Kim et al., 2004; Manchaiah, Zhao, Danesh, & Duprey, 2011; Varga et al., 2003; Wang, Gu, Han, & Yang, 2003). Temporal bone studies have shown normal outer and inner hair cells with loss of auditory nerve fibers and/or demyelination of fibers in adults with ANSD (Buchman et al., 2006; Liu, Bu, Wu, & Xing, 2012; Roche et al., 2010).

The audiometric thresholds in individuals with ANSD can vary widely (Berlin et al., 2010; Kraus et al., 2000; Kumar & Jayaram, 2006; Rance et al., 1999; Sininger & Oba, 2001), consistent with the diverse etiology. Sininger and Oba (2001) for example, reported an even distribution of pure-tone hearing thresholds in their corpus of individuals with ANSD. In addition, fluctuation in hearing threshold is a common occurrence in individuals with ANSD. Audiograms with better hearing in mid to high frequency (2 kHz and 4 kHz) region are most prevalent in individuals with ANSD. The high frequency hearing loss configuration most commonly seen in individuals with sensory-neural hearing loss is rare in individuals with ANSD (Jijo & Yathiraj, 2012; Kumar & Jayaram, 2006). Speech perception abilities in individuals with ANSD is typically disproportionate to pure-tone hearing loss (Berlin et al., 2010; Kumar & Jayaram, 2006). Effect of noise on speech perception skills in individuals with ANSD tend to be extreme (Apeksha & Kumar, 2017b; Berlin et al., 2010; Narne, 2013; Narne et al., 2015; Rance et al., 2007). Individuals with ANSD show severe temporal processing deficits. Disruption in the synchrony/phase locking of the auditory nerve fibres is thought to be responsible for poor temporal perception in individuals with ANSD (Berlin et al., 2010; Narne, 2013; Narne et al., 2015; Rance et al., 2007; Sininger & Oba, 2001; Zeng & Liu, 2006). Poor temporal encoding in individuals with ANSD results in a range of real-life listening difficulties such as problems in localization and speech perception. The perception of short duration dynamic cues such as voice onset time (Kumar & Jayaram, 2013), burst duration (Kumar & Jayaram, 2013) and the formant transition (Hassan, 2011; Kumar & Jayaram, 2005, 2011) are affected in individuals with ANSD.

Despite the absence or severe disruption of ABRs, auditory cortical potentials are typically present, but, with reduced amplitude and prolonged latency in individuals with ANSD (Abdeltawwab, 2014; Kraus et al., 2000; Kumar & Jayaram, 2005; Narne & Vanaja, 2008b). N1-P2 complex is reported to be present in individuals with ANSD in response to tones (Michalewski, Starr, Zeng, & Dimitrijevic, 2009; Narne & Vanaja, 2008b; Starr et al., 1996) and to speech stimuli (Kraus et al., 2000; Kumar & Jayaram, 2005; Narne, Prabhu, Chandan, & Deepthi, 2014; Narne & Vanaja, 2008b). Previous studies have demonstrated good relationship between cortical evoked potentials and speech perception skills in individuals with ANSD (Kumar & Jayaram, 2005; Michalewski et al., 2009; Narne & Vanaja, 2008b). Cortical evoked potentials, especially, P1 and the N1/P2 complex is reported to be a good predictor of behavioural outcomes in children with ANSD using cochlear implant or hearing aids (Alvarenga et al., 2012; Rance, Cone-wesson, Wunderlich, & Dowell, 2002). The latency of the cortical auditory potentials is also reported to be related to temporal processing skills in individuals with ANSD (Michalewski et al., 2009). However, earlier components of cortical evoked potentials reflect the first recurrent activity but not the complex process involved in speech processing.

Speech perception/discrimination is not a passive process, but it involves the active participation of the listener. Speech perception is affected by several environmental and physiological factors such as the ability to direct attention towards the object/sound source. Apart from these factors, speech perception is also controlled by memory and previous sound associations. Therefore, to observe the neural networks underlying speech perception, it may be necessary to employ electroencephalogram (EEG) recording paradigms targeting active identification

processes such as P300. In this context, assessment of P300 potentials in individuals with ANSD may provide important information about cortical correlates of active listening. In light of aforementioned studies, the primary aim of this study was to examine the effect of noise and amplification on speech processing skills in individuals with ANSD using electrophysiological and behavioural measures.

1.1. Need for the study

Individuals with ANSD show speech perception difficulties that are disproportionate to the degree of hearing loss. Growing body of evidence suggests that multiple factors contribute in mediating the perceptual difficulties in individuals with ANSD. Auditory event related potentials offer an excellent temporal resolution to understand the deleterious effects of neural asynchrony on cortical representation of speech. Exploring the relationship between the neural matrices and the behavioural performance provides valuable information regarding the brain-behaviour relations.

Justification to use electrophysiological measures. A large body of evidence suggests that listeners with ANSD show a significant impairment in temporal processing and this leads to extreme difficulty in understanding speech. These difficulties are primarily attributed to the dyssynchronous firing of the auditory nerve (Berlin, Hood, & Rose, 2001; Starr et al., 1996; Zeng, Oba, Garde, Sininger, & Starr, 1999). This abnormal input at the lower level of the auditory system leads to the abnormal encoding of speech at the cortical level (Kumar & Jayaram, 2005; Narne et al., 2014; Narne & Vanaja, 2008b). In spite of having a similar pure-tone hearing loss, speech perception skills vary widely in individuals with ANSD. The underlying neural mechanisms responsible for this variance in speech perception can be explored if appropriate electrophysiological measures are employed. Apart from

providing complimentary evidence to behavioural measures, electrophysiological tools can be used to study the brain-behavioural relationship (Tremblay & Kraus, 2002). Among the electrophysiological measures, P300 potential measured using active oddball paradigm has been widely used to study the conscious perception. It is also suggested that P300 reflects the stimulus encoding, recognition, and classification. Furthermore, P300 is a more robust response with an amplitude of 10-20 µV (Polich & Kok, 1995; Polich & Starr, 1983) as compared to other auditory cortical potentials that range between 0.5-10 µV (Duncan et al., 2009; Kutas & Iragui, 1998).Therefore, using P300 as an electrophysiological measure of cortical processing of speech in individuals with ANSD is relevant. Though the presence of background noise is a ubiquitous property of verbal communication there are no studies investigating the cortical responses to speech in noise in individuals with ANSD. Moreover, use of high-density electrodes to study the cortical processing will reveal the modulations in scalp topographies which can reflect upon the sources generating these potentials and the adaptation due to peripheral abnormality.

Justification to assess speech perception in presence of noise. Speech understanding in noise is a universal phenomenon. Individuals with ANSD reports of poor understanding of speech in quiet and performance deteriorates even more in presence of noise (Apeksha & Kumar, 2017b; Berlin et al., 2010; Narne et al., 2014; Narne & Vanaja, 2009a; Narne, 2013). Since the speech perception in presence of noise is a commonly encountered situation by the individuals with ANSD which they find difficult to cope up, it needs to be explored in detail.

Justification to assess speech perception with and without amplification. One of the rehabilitation approach used with individuals with ANSD is hearing aids

(HAs) (Deltenre et al., 1999; Gokdogan et al., 2016; Norrix & Velenovsky, 2014). Results of benefit from the HA in individuals with ANSD is equivocal (Barman, Sinha, & Prabhu, 2016; Jijo & Appu, 2015; Jijo & Yathiraj, 2013a; Narne et al., 2014). So to check the efficacy of the HA, it is better to do a behavioural measurement along with an electrophysiological measurement. Comparing aided and unaided response will throw light on the efficacy of amplification in individuals with ANSD. There are no studies reported in the literature on cortical representation of aided speech in individuals with ANSD. Therefore, speech perception with and without amplification systems are studied in individuals with ANSD.

1.2. Aim of the Study

The study aimed to investigate effect of noise and amplification on speech perception in individuals with normal hearing sensitivity and with ANSD.

1.3. Objectives of the study

1. To compare the speech identification scores between individuals with normal hearing sensitivity and with ANSD.
2. To compare speech identification scores obtained with and without amplification device in individuals with normal hearing sensitivity and ANSD.
3. To compare P300 responses in terms of amplitudes, latency and scalp topographies between individuals with normal hearing sensitivity and with ANSD.
4. To investigate the relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD.

1.4. Hypotheses

The null hypotheses formed to investigate objectives of the study are as follows:

1. There is no statistically significant difference between speech identification scores of individuals with normal hearing sensitivity and individuals with ANSD.
2. There is no statistically significant difference between the speech identification scores obtained with and without amplification device in individuals with normal hearing and ANSD.
3. There is no statistically significant difference between individuals with normal hearing sensitivity and with ANSD in terms of amplitude, latency and scalp topographies of P300.
4. There is no statistically significant relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD.

Chapter 2

Review of Literature

Auditory Neuropathy Spectrum Disorder (ANSD) previously been referred as Auditory Neuropathy (AN, Starr, Picton, Sininger, Hood, & Berlin, 1996) or Auditory Dys-synchrony (AD, Berlin, Hood, & Rose, 2001) is a hearing disorder affecting inner hair cell, spiral ganglion or eighth nerve. Individuals with ANSD can have abnormality in inner hair cells (Amatuzzi et al., 2001), kernicteric deposits on spiral ganglion fibers (Shapiro & Nakamura, 2001) or abnormal myelination of VIIIth nerve (Starr et al., 2001, 2004). Post mortem report of the temporal bone of the individuals with ANSD has showed normal inner and outer hair cells in terms of number and appearance, whereas showed a reduction in number and demyelination of the auditory ganglion cells and nerve fibers (Starr et al., 2003). Starr (2009) categorized auditory neuropathy (AN) as Type I and Type II. Type I AN is a post synaptic disorder affecting the number and function of auditory nerves whereas Type II AN is a presynaptic disorder affecting inner hair cells function (Starr, 2009). Post synaptic problem might include abnormal synchronous activity in the nerve endings which can accompany OPA1 mutation due to altered mitochondrial function (Carelli, Ross-Cisneros, & Sadun, 2004; Yu-Wai-Man & Chinnery, 2013). There can also have conduction difficulty along the auditory nerve (Butinar et al., 1999; Rance, Fava, Baldock, & Chong, 2008). Presynaptic disorder mainly includes abnormal neurotransmitter releases which might accompany otoferlin gene mutation (Marlin et al., 2010; Santarelli et al., 2009). In both the subtypes of AN, the perceptual consequence are similar but the symptoms were reported to vary in terms of severity across individuals (Michalewski et al., 2009).

The prevalence of ANSD was reported to be 10% in infants who failed hearing screening (Rance et al., 1999), 7% to 10% in children with severe or profound hearing loss (Starr, 2009) and an overall prevalence of 1.2% taking all the age groups together (Penido & Isaac, 2013). It is quite diverse disorder in terms of its etiology and time course. The etiologies may involve drug agents (carboplatin), toxic or metabolic processes (hyperbilirubinemia and anoxia), infection (mumps), and hereditary neuropathies (Charcot-Marie-Tooth syndrome), disorder affecting inner hair cells and so on (Amatuzzi et al., 2001; Butinar et al., 1999; Starr et al., 2004). Starr and colleague reported 42% of their ANSD patients to have an association with hereditary neurological disorders, 10% of them had toxic, metabolic, immunological and infectious causes and 48% of them had no known causes (Starr et al., 2000). In Indian population, 61 individuals of 21,236 individuals (0.28%) with hearing impairment were diagnosed as having ANSD (Kumar & Jayaram, 2006). While considering sensorineural hearing loss, the prevalence of ANSD was reported to be 0.54%, that was approximated to be 1 in every 183 individuals who were diagnosed with the permanent sensorineural hearing loss (Kumar & Jayaram, 2006).

Considering the age wise prevalence of the individuals with ANSD, Penido and Isaac (2013) considered 2,292 individuals with sensorineural hearing loss, out of which 27 (1.2%) were diagnosed as having ANSD. Out of the total population considered,14.8% of the individuals were in the age range of zero to 20 years, 33.4% were in age range of 21 to 40 years, 44.4% in range of 41 to 60 years and 7.4% were above 60 years of age (Penido & Isaac, 2013). Based on the case history, the age of onset of symptoms was in adolescence and adulthood for 82% of the patient and it was in childhood (<10 years) in 18% of the individuals (Narne, Prabhu, Chandan, &

Deepthi, 2014). Gender effect, that is, female to male ratio was reported to be 1.25:1 (Narne, Prabhu, Chandan, & Deepthi, 2014). This ratio was reported to be little higher (2:1) in Kumar and Jayaram (2006) study.

2.1. Audiological Test Findings

Individuals with ANSD shows presence of cochlear microphonics, abnormal or absent auditory brainstem response, with or without abnormalities of otoacoustic emission (Berlin, Hood, Cecola, Jackson, & Szabo, 1993; Rance et al., 1999). Researchers have also reported abnormal temporal processing (Kumar & Jayaram, 2005; Zeng, Oba, Garde, Sininger, & Starr, 1999) and difficulty in speech perception especially in presence of noise in individuals with ANSD (Kraus et al., 2000; Starr et al., 1991; Zeng, Kong, Michalewski, & Starr, 2005; Zeng et al., 1999).

2.1.1. Pure Tone Audiometry. The individual's pure-tone audiogram can range anywhere from normal hearing sensitivity to profound hearing loss (Berlin et al., 2010; Starr et al., 2000). Penido and Isaac (2013) investigated the prevalence of hearing loss in individuals with ANSD. Result showed 29.6% of their participants to have mild hearing loss, 55.5% had moderate hearing loss, 7.4% had severe and 7.5% had profound degree of hearing loss. All the participants had bilateral ANSD but there was no mention about the symmetry of the problem.

The audiometric configuration shows variation across individuals with ANSD. Starr and colleagues (1996) reported the raising configuration (low-frequency hearing loss) in 50% of the individuals, flat configuration in 30% of the individuals and sloping configuration (high frequency hearing loss) in 20% of the individuals with ANSD. Zeng et al. (1999) also reported raising configuration (moderate to

severe hearing loss at low frequencies and mild to moderate hearing loss at high frequencies) to be most prevalent in individuals with ANSD. Kumar and Jayaram (2005) reported peaked configuration of hearing loss to be present in 8 (57%) individuals, raising in 5 (36%) individuals and flat in 1(7%) individual out of total 14 individuals with ANSD. In 2006, Kumar and Jayaram reported peaked audiogram to be present in 26 (42%) out of total 61 individuals with ANSD. Other configurations were flat (18%), raising (18%), saucer shaped (13%) and sloping (4%) pattern of hearing loss.

The symmetry of thresholds or symmetrical hearing loss can be operationally defined as the difference in threshold of less than 15 dB between two ears at a particular frequency. Threshold symmetry was reported to be variable across studies (Berlin et al., 2010; Rance et al., 1999). Starr and colleague (2001) reported symmetrical hearing thresholds for all the 33 participants included in their study. A similar finding was also observed by Kumar and Jayaram (2005). In another study, bilateral ANSD was observed in 241 (93%) individuals out of total 260 and unilateral ANSD was observed in only 19 (7%) of the individuals (Berlin et al., 2010). In a recent study, bilateral ANSD was reported in almost 98% of the total population (198 individuals with ANSD) considered and only 2% had unilateral ANSD (Narne, Prabhu, Chandan, & Deepthi, 2014).

2.1.2. Speech Audiometry. Speech recognition ability reported to vary from no recognition ability to fairly good recognition ability in quiet and is found to be more affected in presence of noise (Berlin et al., 2010; Narne et al., 2014; Narne & Vanaja, 2009a; Narne, 2013; Zeng & Liu, 2006). The speech perception measures was out of proportion to the degree of hearing loss (Kraus, Bradlow, Cheatham, &

Cunningham, 2000; Zeng, Kong, Michalewski, & Starr, 2005; Zeng, Oba, Garde, Sininger, & Starr, 1999). Speech recognition scores in individuals with ANSD were found to be significantly poor than that expected in a patient with sensorineural hearing loss (Yellin, Jerger, & Fifer, 1989). The individuals with ANSD typically complain of difficulty in understanding speech which is independent of audibility (Sininger & Oba, 2001; Zeng, Oba, Garde, Sininger, & Starr, 2001). Zeng and colleague (1999) observed a range of word recognition scores from 0% to 56%, with an average of 18% which was significantly lower than that for individuals with normal hearing. Kumar and Jayaram (2005) reported open set speech identification scores to vary from 0% to 95% with mean scores of 41.7%. They reported a good correlation between speech identification scores and low frequencies (250 Hz, 500 Hz, & 1000 Hz) hearing thresholds but no significant correlation between speech identification scores and threshold at high frequency (2000 Hz, 4000 Hz, & 8000 Hz). Similar finding was also observed by Kumar and Jayaram in 2006.

Rance et al. (2007) evaluated three groups of children, children with ANSD, with cochlear hearing loss and those with normal hearing sensitivity. Open and closed set speech identification ability was assessed using CNC words and adaptive spondee in noise test respectively. The 3 signal-to-noise ratio (SNR) selected were 0 dB, +5 dB, +10 dB and in quiet. The mean SNR required to identify spondee was -11.5 dB for normal hearing group and -2.5 dB for the ANSD group, with cochlear hearing loss group lying in between. The open set identification also showed a reduction in scores with the addition of noise. The reduction in scores in presence of noise was much more compared to the cochlear hearing loss and individuals with normal hearing. Narne and Vanaja (2008b) investigated speech perception ability of

individuals with ANSD. They measured speech identification scores for 10 individuals with ANSD and 10 normal counterparts. The speech identification scores ranged from 0% to 100% with a mean of 42% for the individuals with ANSD and 96% for individuals with normal hearing. The variability in scores was also more (25.4%) for individuals with ANSD as compared to the normal hearing (2.5%). In yet another study, Narne and Vanaja (2009a) investigated the effect of background noise on speech identification abilities of 15 individuals with ANSD. Unprocessed and processed (envelope enhanced) speech in four different listening conditions (+10, +5 and 0 dB SNR and in quiet) were used to assess the effect of background noise on speech identification ability. The speech stimuli used were bisyllabic words and the background noise used was speech spectrum shaped noise. All the 15 participants were categorized as good performer or poor performer based on their speech identification scores in quiet. The results showed poor speech identification scores in presence of noise than in quiet. Reduction in speech identification scores with SNR was more evident for the poor performers than the good performers. The reduction in scores was higher than that observed in normal hearing individuals and cochlear hearing loss. In a recent study, speech audiometry was done for 173 individuals with ANSD (Narne et al., 2014). Out of 173 individuals, speech scores were obtained only from 102 individuals (59%) in quiet and from 33 individuals (19%) in presence of noise. Speech in noise test was done at 0 dB SNR. Among the 102 individuals, considering the cut off of 50% scores, only 44% of the individuals with ANSD got scores above and 56% of the individuals got below the cut off scores.

2.1.3. Impedance Measurement. Impedance measurement showed the absence of stapedial reflexes in all the participants (Narne & Vanaja, 2009b; Penido & Isaac, 2013; Starr et al., 1996; Zeng et al., 1999). The absence of acoustic reflexes can help the audiologists to differentially diagnose the individuals with ANSD with that of the individuals with mild to moderate degree of cochlear loss. In one of the study, acoustic reflexes were absent in 90% of the individuals with ANSD and 10% individuals showed elevated thresholds in spite of normal Type A tympanogram (Berlin et al., 2005). Starr et al. (2000) reported normal middle ear muscle reflex in 7 % of the individuals, elevated reflex in 2% of the client and absent in 91 % of the participants.

2.1.4. Auditory Brainstem Responses (ABR). Auditory brainstem responses are typically absent in individuals with ANSD, even at maximum stimulation level regardless of behavioral thresholds (Rance et al., 1999; Starr et al., 1996). The reason could be either because of the reduction in the number of neural elements that contribute to the response or it could be a disruption in the integrity of the neural signal temporally. For the response to be present, the neural firing should be timed such that it discharges almost identical after each test stimuli. A dys-synchrony of even a fractions of a millisecond can disrupt the response and result in unrecognizable waveform (Kraus et al., 2000; Starr et al., 1991). Thus the difficulty in perceptual processing of sound especially in presence of noise depends on the degree of disruption in neural synchrony. Starr and colleague (1996) recorded ABR for ten individuals with ANSD and reported absent responses for 9 out of 10 individuals. Wave V was present for one of the participants at 90 dB nHL and at stimulus rate of 11/sec and 28/sec. The wave V was delayed to 6.2 ms and 6.8 ms for

both the ears in individuals in whom the ABR response was present. In yet another study, wave V without preceding wave I was reported to be present in 13 (21%) out of 60 test ears of individuals with ANSD (Starr et al., 2001). The mean amplitude of the wave V was reported to be significantly lower (0.10 μV) than that observed in normal hearing individuals (0.51 μV). Wave V latency was delayed in 10 out of the 16 recordings from individuals with ANSD. There was no significant difference in cochlear microphonics amplitude in individuals with or without preserved wave V in the ABR. Narne et al. (2014) recorded ABR for 392 ears with ANSD. ABR was present in only 28 ears (7.14%) and were absent in 364 ears (92.85%) with ANSD. Even though the ABR response was present in 28 ears with ANSD, it showed poor wave morphology.

2.1.5. Otoacoustic Emission. The otoacoustic emission (OAEs) is a measure to assess the functioning of outer hair cells and helps in differentiating sensory from neural component of the hearing loss. It is unexpected to get normal OAEs in individuals with no brainstem response in individuals with the sensory hearing loss but a common finding in individuals with the neural hearing loss (Rance, 2005). Several researchers have reported normal otoacoustic emission in individuals with ANSD (Kumar & Jayaram, 2006; Narne et al., 2014; Starr et al., 1996). Contralateral suppression of OAEs was not observed in individuals with ANSD (Berlin et al., 1993; Hood, Bordelon, & Rose, 2003). The reason could be the abnormal functioning of the afferent or efferent part of the reflex arc (Hood, Bordelon, & Rose, 2003). Another report by Starr and colleague (1996) showed clear recognizable waveforms for the transient otoacoustic emission for all the participants. Distortion product otoacoustic emission showed reduced response at

high (above 4 kHz) and low frequencies (below 1 kHz) and normal responses at mid frequencies. Contralateral suppression of OAEs was not observed (Starr et al., 1996). Starr and colleagues (2001) reported TEOAEs to be present in 44 ears (70%) of the 63 test ears and were absent in 19 ears (30%) of individuals with ANSD. TEOAEs were absent bilaterally in eight individuals and unilaterally in three individuals. They reported no significant relationship between pure-tone average and the presence or absence of TEOAEs. In yet another study by Narne et al. (2014), TEOAEs were present in 75% of the ears and was either absent or partially present in 25% of the ears tested out of a total of 392 ears.

2.1.6. Other psychophysical measures. Zeng et al. (1999) reported normal or near normal temporal integration function for all the 8 individuals with ANSD except one. They reported detection thresholds to decrease at a rate of about 3 dB per doubling of signal duration up to 100-200 ms which was similar to that of individuals with normal hearing. In contrast to the above findings, Gap detection measure showed impaired scores for all the individuals with ANSD. In normal hearing individuals, the gap detection threshold was found to be 20 to 30 ms at low intensity levels which improved to 2-3 ms at high intensity levels. The individuals with ANSD showed abnormal result for both low and high-level signals. Individuals with ANSD showed 2-25 times greater gap detection thresholds as compared to normal hearing individuals (Zeng et al., 1999). The normal hearing individuals showed more sensitivity to slow temporal fluctuation which tended to decrease with increase in rate of fluctuation. Individuals with ANSD showed impaired sensitivity for both slow and fast temporal fluctuation. The average peak sensitivity was -10.2 dB at low modulation frequencies which was about one-third of the values for

normal hearing individuals. In yet another study, Kumar and Jayaram (2005) assessed temporal modulation transfer function in individuals with normal hearing and in individuals with ANSD. Peak sensitivity showed difference for normal hearing individuals (-17.36 dB) and for ANSD (-6.6 dB). The individuals with ANSD could not detect modulation depth of 0 dB (100%) at higher modulation frequencies. Just noticeable difference (JND) was assessed in individuals with ANSD (Kumar & Jayaram, 2005). Stimulus /da/ varying in transition duration was used to assess the JND. Out of total 14 individuals with ANSD, only four individuals with ANSD were able to differentiate transition duration of less than 100 ms and 10 individuals were able to differentiate transition duration more than 100 ms. The finding shows that the individuals with ANSD have poor duration discrimination skill. Kumar and Jayaram (2011) evaluated the speech perception ability of individuals with ANSD for temporally modified speech syllables. The syllables considered were velar /ka/, alveolar /ta/, retroflex /ta/ and bilabial /pa/ and their voiced cognate. The formant transition of the syllables was lengthened and correct identification responses with unmodified and modified syllables were noted. The result showed better perception for speech sounds with longer transition duration. The information transmitted was improved for voicing cues from 0.129 in the unmodified condition to 0.464 in the modified condition. There was improvement seen in the transmission of place information from 0.186 in unmodified to 0.514 in the modified condition. Total information transmitted also showed improvement from 0.812 in unmodified to 1.535 in the modified condition. It was concluded that the lengthening of the transition duration enhances the perception of speech syllables.

2.2. Cortical representation of speech in individuals with normal hearing and with ANSD

In spite of abnormal representation of the signal at the brainstem level in individuals with ANSD, auditory cortical potentials (P1-N1-P2 & Mismatch Negativity) are typically present in individuals with ANSD (Abdeltawwab, 2014; Alvarenga et al., 2012; Apeksha & Kumar, 2017a; Dimitrijevic et al., 2011; Michalewski et al., 2009; Narne et al., 2014; Narne & Vanaja, 2008b). Abdeltawwab (2014) reported prolonged latency of P1, N1, and P2 peaks and reduced amplitude of N1-P2 complex in individuals with ANSD compared to normal hearing individuals. Vanaja and Manjula (2002) recorded P1-N1-P2 response in 5 individuals with ANSD. The response was present in 3 out of 5 individuals with ANSD. The response obtained in all 3 individuals differed in terms of latency, amplitude, and wave morphology. Latencies of the peaks were delayed with normal morphology in one individual, amplitude was reduced with normal latency in the second individual, and the third individual showed delayed latency, reduced amplitude and poor wave morphology for the P1-N1-P2 response. They also observed a relationship between the presence of P1-N1-P2 and the duration of the disorder, as the duration of disorder increased, the P1-N1-P2 response disappeared.

Another group of researchers, Narne and colleague (2014) recorded P1-N1-P2 using speech stimuli /da/ in 114 ears out of 392 ears with ANSD. Out of total 114 ears, 77 ears showed a response in spite of abnormal ABR. Out of 77 ears with present P1-N1-P2 response, 28 ears showed prolonged latency (187 ms) for N1 and rest 39 showed latency value within normal limits (102 ms). When the P1-N1-P2 response was correlated with that of the speech perception scores perceptually, out of

77 ears with P1-N1-P2 present, 71% of the total had speech scores >50%. In contrast, in 37 individuals with absent P1-N1-P2, only 22% had speech identification scores > 50%. So both the measures can be positively correlated, as an increase in the incidence of one measure increases the incidence in the response to other measures and vice versa. The authors suggested LLR as the possible indicator of the speech perception ability in individuals with ANSD. Kraus et al. (2000) recorded P1-N1-P2 responses as well as mismatch negativity (MMN) in individuals with ANSD. The stimuli used to elicit P1-N1-P2 were synthetic /ba/ and /pa/ syllables. There was the difference in latencies of the peaks for both the syllable. The response elicited using /ba/ syllable showed similar response as that of normal subjects whereas it was delayed than normal for /pa/ syllable. One more observation made was related to the number of peaks obtained with respect to the voiceless stimuli. In normal individuals, two peaks were observed when the stimuli were voiceless, first P1' peak was related to aspiration and second peak was to the onset of voicing (Koch, McGee, Bradlow, & Kraus, 1999; Sharma & Dorman, 1999). In an individual with ANSD, the second peak was evident without the first peak being present. This shows the irregularities in the representation of the signal in individuals with ANSD. Mismatch negativity was also recorded using two syllable combination, /ba-wa/ and /da-ga/. The result showed a clear MMN with normal morphology, duration, area for /ba-wa/ continuum but elicited no response for /da-ga/ continuum. This suggests that the individuals with ANSD can discriminate two stimuli differing in formant duration but fails when the difference is in formant onset frequency.

In one of the study, Kumar and Jayaram (2005) recorded P1-N1-P2 and MMN responses using natural /da/ as well as synthesized /da/ stimuli, from 14 individuals

with ANSD. They reported P2/N2 complex to be present in all 14 individuals whereas P1/N1 complex was present only in 10 individuals. They reported latency and amplitude of P1-N1-P2 to be well within normal range in individuals if the response was present. They reported no relationship between presence or absence of P1-N1-P2 peaks and degree of hearing loss and also speech identification scores. Considering MMN, 5 out of 14 individuals showed no response. Out of 9 subjects who showed MMN response, 5 individuals could not discriminate the stimulus contrast behaviourally. There was a significant correlation between MMN peak latency and speech identification scores. Out of total 14 participants, 10 could not discriminate the stimulus contrast behaviourally. This suggested that presence of MMN does not confirm the presence of behavioural discrimination in individuals with ANSD. In another study by Gabr (2011), MMN was elicited in individuals with ANSD using tonal pairs differing in frequency by 50 Hz. The result showed prolongation in latency of MMN for individuals with ANSD. The amplitude of MMN did not show significant difference across groups. There was no significant correlation observed between MMN latency and speech discrimination scores but showed a positive correlation between the amplitude of MMN at 4000 Hz and the speech discrimination scores. Majority of the above mentioned studies have used either P1-N1-P2 or MMN responses to study the perception of speech in individuals with ANSD. P1-N1-P2 response reflects the recurrent activity in the auditory pathway and gives information only about the reception of the sound at the cortical level. On the other hand, MMN represent the passive discrimination ability of the individuals with ANSD and gives no information about the active involvement of the individual with ANSD. MMN also restrict the information about the involvement of memory and previous sound association. Among electrophysiological measures,

P300 response is one of the reliable cortical potential to study active discrimination skills.

The P300 is a human event related potential which occurs at a latency of 300 ms from the onset of the stimulus. P300 potential occurs when the subject detects a task relevant stimulus and makes a sensory discrimination (Picton, 1992). P300 can be reliably recorded using oddball paradigm, wherein the subject detects the infrequent target stimulus in the train of frequent standard stimuli (Ritter & Vaughan, 1969). It can also be elicited by the omission of stimulus from a train of stimuli. It is an endogenous potential which is more related to the psychological reaction of the subject rather than the physical characteristics of the stimuli (Picton, 1992). The P300 response can be maximally recorded from the midline electrodes with at least a minimum of three scalp electrodes (Fz, Cz, & Pz) and more electrodes would give information about the scalp topography (Duncan et al., 2009). The brain topography shows centroparietal activation for P300 potential (Picton, 1992; Polish, 2003). Medial temporal lobe in specific is generator site of P300 response (Halgren et al., 1980; Paller, McCarthy, Roessler, Alllison, & Wood, 1992). P300 latency represents classification speed, that is the time required to detect and respond to the target stimulus (Kutas, McCarthy, & Donchin, 1977; Magliero, Bashore, Coles, & Donchin, 1984). Latency is a more reliable indicator of cognitive processing than the amplitude, as latency is not much affected by attention (Picton, 1992). The superior the cognitive function of the individuals shorter the P300 latency (Emmerson, Dustman, Shearer, & Turner, 1989; Pelosi et al., 1992; Picton, 1992). P300 amplitude depends on the attention allocated to the task and the memory load. P300 amplitude reduces with increase in memory load as the task processing demands

increases (Donchin & Coles, 1988). A normal P300 response indicates that the subject is processing the incoming stimulus cognitively and helps in demonstrating brain's ability to discriminate stimuli (Picton, 1992). Delay or abnormally small P300 response, indicates a probable abnormality in the cognitive processing (Picton, 1992). Since P300 measurement presents with wide limits of variability, it should not be used in isolation and should be complemented with other assessments (Picton, 1992). In one of the study, Starr et al. (1996) recorded P300 on individuals with ANSD using 1000 Hz tone as the standard and 2000 Hz tone as the target. P300 was elicited from 3 individuals with ANSD and it was found to be normal in all the 3 individuals. Since it was done on a very small sample, the inference should be drawn with the caution. Apeksha and Kumar (2017a) recorded P300 response in individuals with normal hearing and with ANSD using /ba/-/da/ stimulus contrast. Result suggested prolonged latency and reduced amplitude of P300 response in individuals with ANSD. Behavioural measures showed poor sensitivity and longer reaction time for individuals with ANSD compared to normal hearing sensitivity.

2.3. Rehabilitative options for individuals with ANSD

The two main treatment approaches for individuals with ANSD are to improve the listening environment of the individuals and to modify/amplify the signal reaching the individual's ear. The listening environment of the individuals with ANSD can be improved by improving the signal-to-noise ratio (Berlin et al., 2005). Frequency modulated (FM) listening system is found to be effective in improving the speech perception and general communication skills in individuals with ANSD as it improves the overall SNR (Gokdogan et al., 2016; Rance, Corben, Du Bourg, King, & Delatycki, 2010). The second approach aims to amplify the signal reaching

the listener's ear by using amplification devices, such as hearing aids and cochlear implants. Groups of researchers reported limited or no benefit from the amplification devices (Berlin et al., 2010, 2003; Sininger, 1995; Starr et al., 1996) while other groups of researchers reported improvement with amplification devices (Gokdogan et al., 2016; Jijo & Yathiraj, 2013a; Roush, Frymark, Venediktov, & Wang, 2011; Yuvaraj & Jayaram, 2016). The current hearing aid technology doesn't address enhancing the temporal envelope of the speech signal to compensate for temporal processing deficits associated with ANSD. The use of non-linear compression circuit in the hearing aids results in deterioration in performance of individuals with ANSD (Jijo & Appu, 2015; Rance et al., 2002; Starr et al., 1996) as it reduces the amplitude fluctuation in the spectral envelope of the speech signal and thus reduces the contrast between the consonant and the vowels (Narne & Vanaja, 2008a; Rance, McKay, & Grayden, 2004). Many researchers suggest the use of hearing aids with linear amplification for individuals with ANSD (Jijo & Appu, 2015; Tasell, 1993; Zeng & Liu, 2006). Envelope enhancement of the speech signal showed improvement in consonant identification in individuals with ANSD (Narne & Vanaja, 2008a, 2009b). Enhancement of temporal cues, such as lengthening of voice onset time, burst duration, transition duration has shown improvement in speech perception (Kumar & Jayaram, 2011, 2013) whereas modifying the signal by stretching the entire stimuli results in improvement in consonant perception (Jijo & Yathiraj, 2013b). Cochlear implant is effective in improving functional hearing in individuals with ANSD (Fernandes, Morettin, Yamaguti, Costa, & Bevilacqua, 2014; Rance et al., 1999; Roush et al., 2011). It can be used in isolation or coupled with FM device, to improve the SNR reaching the ear.

Rance et al (2002) investigated the speech perception ability of 18 children with ANSD and age matched children with sensorineural hearing loss. They also recorded P1-N1-P2 in them using tone burst and speech tokens along with behavioural speech perception test. Tone stimuli included 400 Hz and 440 Hz tone burst and speech stimuli included CVC tokens /bad/ and /dad/ presented in oddball paradigm. They analyzed peak-to-peak amplitude of P1/N1 and N1/P2 and latencies of individual peaks. Even though all the 15 children showed poor speech perception skills in unaided condition, 8 children with ANSD showed improvement in aided condition compared to unaided condition. In terms of latency and amplitude, when P1-N1-P2 response was present, showed response similar to normal hearing children and had significant open-set speech perception ability. In cases with absent P1-N1-P2 response, speech perception was reported to be significantly poor (<10%). They found a strong association between presence of P1-N1-P2 response and the aided phoneme score in children with ANSD. Vanaja and Manjula (2002) found a good relationship between the presence of P1-N1-P2 response and improvement on aided speech identification in individuals with ANSD. They suggested use of FM device over hearing aids in individuals with ANSD. Gokdogan et al. (2016) showed better speech perception with the use of cochlear implant in one group of children with ANSD. Another group of children using hearing aid also showed improvement in speech perception. Both the groups of children showed significant improvement on different measures, Infant-Toddler Meaningful Auditory Integration Scale (IT-MAIS), Meaningful Use of Speech Scale (MUSS) and on LittleEARS. Language measure, Preschool Language Scale also showed improvement.

Berlin et al. (2010) reported limited/ no benefit of hearing aids in 86% of the individuals with ANSD. Only 14% of the individuals with ANSD showed benefit with the use of hearing aids. Similarly, Jijo and Appu (2015) showed poor performance for the hearing aid processed speech in individuals with ANSD. The unprocessed signal resulted in best perception scores followed by hearing aid processed speech with varying compression settings. While considering compression setting for the individuals with ANSD, linear compression or non-linear compression with long attack/ release time should be considered (Jijo & Appu, 2015). It can be inferred from the above mentioned studies that the individuals with ANSD is a heterogeneous population with the wide variation in clinical symptoms. They also show limited benefit with the amplification devices.

Chapter 3

Methods

The aim of the present investigation was to compare the auditory performances of individuals with normal hearing and auditory neuropathy spectrum disorder (ANSD) on a range of behavioural and electrophysiological measures. Specifically, the study employed syllable identification and speech perception in noise as behavioural measures and P300 as an electrophysiological measure to assess the speech perception skills. Furthermore, the study also investigated the effect of amplification on the speech perception in individuals with normal hearing and ANSD.

3.1. Research Design

In order to investigate the objectives of the study, both between-subject design and within-subject design (Charness, Gneezy, & Kuhn, 2012) were used. Between-subject design was used in order to compare speech perception ability of individuals with normal hearing and with ANSD on behavioral and electrophysiological measures. The effect of noise and amplification on speech perception ability was compared using within-subject design. The participants were selected based on purposive convenient sampling.

3.2. Participants

A total of 60 individuals participated in the study. There were 30 individuals with ANSD and 30 age matched normal hearing individuals. The number of participants were decided based on the sample size of the previous studies (Abdeltawwab, 2014; Dimitrijevic et al., 2011; Gabr, 2011; Kumar & Jayaram,

2005). The diagnosis of all the participants with ANSD was done by a certified audiologist and a qualified neurologist. The diagnosis was based on the recommendation given by Starr, Sininger, and Pratt (2000). According to this recommendation, the individuals with ANSD should have the presence of otoacoustic emission, absence of auditory brainstem response and normal tympanometric findings with the absent acoustic reflexes.

Participant selection criteria. Following inclusion criteria were used to recruit the participants in ANSD group.

- Participants in the age range from 16 to 55 years.
- Pure-tone average (average of air conduction pure-tone hearing thresholds at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz) of less than 55 dB HL in both the ears.
- "A" type tympanogram with no ipsilateral and contralateral acoustic reflexes.
- Absent auditory brainstem response at 90 dB nHL.
- Normal transient evoked otoacoustic emissions (TEOAEs).

Following inclusion criteria were used to recruit normal hearing listeners

- Age matched with the ANSD listeners.
- Pure-tone hearing thresholds less than 15 dB HL at octave frequencies between 250 Hz to 8000 Hz.

- 95% to 100% speech identification scores at 40 dB sensation level (ref: average hearing thresholds at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz) and greater than 60% speech identification scores at 0 dB signal-to-noise ratio (SNR).
- "A" type tympanogram with ipsilateral and contra-lateral reflexes at normal sensation levels for 500Hz, 1000 Hz and 2000 Hz.
- Identifiable auditory brainstem response peaks (wave I, III and V) at 90 dB nHL with normal peak latency and amplitude.
- Presence of normal TEOAEs.

Furthermore, participants in both the group did not report of any history of middle ear infections, speech language disorders, cognitive deficits, exposure to loud noise or intake of ototoxic drugs. These were ensured from a structured interview. A qualified neurologist ruled out the space occupying lesion or peripheral neuropathies in individuals with ANSD through a clinical examination or magnetic resonance imaging, as required. All participants were native speakers of Kannada. All the participants were given information about the purpose of the study and their written consent was taken prior to the study. The study adhered to the 'Ethical guidelines for bio-behavioural research involving human subjects' set by All India Institute of Speech and Hearing, Mysuru. The ethical committee approval was obtained prior to the commencement of the study (Appendix I). Details demographic and audiometric findings in individuals with ANSD are provided as Appendix IIA and IIB. Figure 3.1 shows the mean hearing thresholds along with the range in individuals with ANSD across octave frequencies from 250 Hz to 8000 Hz.

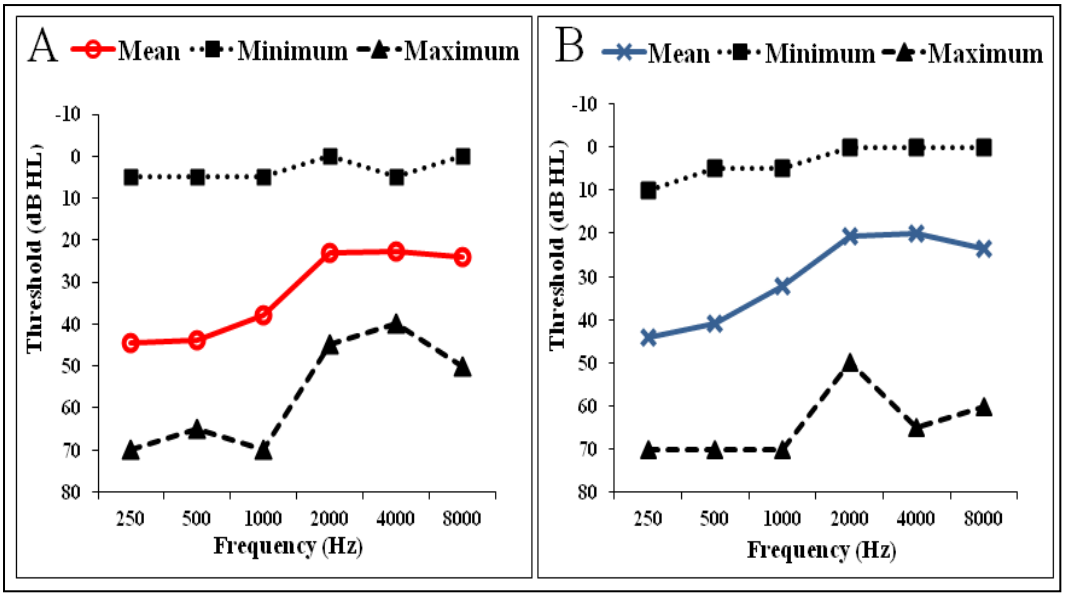


Figure 3.1. Pure-tone hearing thresholds of right ear (A) and left ear (B) in individuals with ANSD.

Out of 60 ears of individuals with ANSD, 31 ears showed rising configuration, 21 ears showed flat configuration and 8 ears showed peaked configuration of audiogram. Classification of audiogram was based on Pittman and Stelmachowicz (2003). Table 3.1 shows the demographic and basic audiological characteristics of all participants with ANSD.

Table 3.1

Demographic and audiological characteristics of individuals with ANSD

Participants	Age (Years)	Gender	Pure-Tone Average* (dB HL)		Speech Identification Scores (%)	
			Right Ear	Left Ear	Right Ear	Left Ear
ANSD 1	20	F	32.5	36.2	45	40
ANSD 2	16	F	38.75	20	65	50
ANSD 3	26	F	15	22.5	92	92
ANSD 4	55	M	46.25	47.5	50	45
ANSD 5	21	M	30	6.25	50	10
ANSD 6	36	M	22.5	18.75	30	20
ANSD 7	24	M	43.75	30	35	35
ANSD 8	18	M	28.75	25	30	30
ANSD 9	20	M	18.75	25	15	60
ANSD 10	21	M	31.25	35	40	45
ANSD 11	37	F	20	16.25	40	15
ANSD 12	35	M	30	22.5	40	25
ANSD 13	19	F	36.25	23.75	30	20
ANSD 14	26	F	28.75	22	45	35
ANSD 15	54	M	41.25	36.25	40	35
ANSD 16	20	M	31.25	32.5	50	45
ANSD 17	27	M	35	30	45	40
ANSD 18	18	F	48.75	52.5	60	55
ANSD 19	48	M	31.25	30	45	35
ANSD 20	36	F	47.25	37.25	68	76
ANSD 21	21	F	10	12.5	45	65
ANSD 22	30	M	22.5	20	30	25
ANSD 23	24	F	35	45	35	45
ANSD 24	37	F	53.75	41.25	60	45
ANSD 25	17	F	37.5	28.75	75	40
ANSD 26	17	F	27.5	33.75	25	25
ANSD 27	41	F	8.75	7.4	30	45
ANSD 28	20	F	17.5	15	20	15
ANSD 29	24	M	28.75	31.25	35	40
ANSD 30	40	F	45	43.75	50	50

Note. *-average of air conduction hearing thresholds at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz.

3.3. Instrumentation and software

The following instruments and the software were used in the study.

1. A calibrated two channel diagnostic audiometer, Madsen OB922, version 2.64 (GN Otometrics, Denmark) with calibrated TDH-39 headphones and

Radio Ear B-71 bone vibrator was used to estimate the air and bone conduction thresholds. Speech recognition threshold and speech recognition scores in quiet were estimated using the same audiometer and headphones.

2. A calibrated GSI-Tympstar middle ear analyzer (Grason-Stadler, MN, USA) was used to perform tympanometry and reflexometry.
3. ILO V6 otoacoustic emission system (Otodynamics Ltd, Hatfield, UK) was used to record otoacoustic emission.
4. Biologic Navigator Pro version 7.0.0 (Natus Medical Incorporated, CA, USA) evoked potential system was used to record auditory brainstem response.
5. A laptop with Intel Core i5 processor connected to MicroBook II (Motu, Massachusetts, USA) sound card, loaded with Pratt (Boersma & Weenink, 2013), AuxViewer (Kwon, 2012), Statistical package for the social sciences (SPSS Inc, Illinois, USA), Cartool (https://sites.google.com/site/cartoolcommunity/home), Paradigm stimulus presentation software (www.paradigmexperiments.com) and FIX software (University college of London) was used to record and analyse speech stimuli and evoked potentials.
6. A calibrated loudspeaker (DB technologies, Bologna, Italy) was used to present the stimuli for behavioural and electrophysiological experiments.
7. A 64 channel Compumedics Neuroscan (Compumedics, NC, USA) electroencephalogram (EEG) recording equipment with a Synamps^2 amplifier for recording P300. A Stim^2 system by Compumedics Neuroscan was used for the stimulus presentation and to capture the participant's

response during the oddball identification task. Acquire module of Scan 4.5 version software was used to record raw EEG output from the electrode cap. Edit module of Scan 4.5 version software was used for offline analysis of EEG**.**

8. Fastrack 3D digitizer (Polhemus, Colchester, USA) was used to digitize the location of the electrodes.
9. Sound level meter model 2270 (Bruel & Kjaer, Naerum, Denmark) was used to calibrate the output levels of the speakers.

3.4. Test Environment

All the testing were carried out in a well-illuminated, distraction-free, sound-treated, air-conditioned room with the noise levels within permissible limits as per the American National Standards Institute (2008) guidelines. All the electrophysiological testing was done in electrophysiology lab of Department of Audiology.

3.5. Stimuli

3.5.1. Stimuli for Syllable Identification. Four naturally produced speech syllables, /ba/, /da/, /ma/, and /pa/ were used for identification task. These four speech syllables were chosen as they represent different phonetic features, that is, place, manner and voicing. Previous reports have shown that individuals with ANSD have difficulty in perceiving these syllables (Narne & Vanaja, 2008a). These Consonant-Vowel (CV) syllables were recorded from a male native speaker of Kannada. The stimuli were recorded using Praat software using a condenser microphone kept at a distance of 15 cm from the speaker's mouth and stored on to a computer. MicroBook II sound card interface was used to connect the microphone to

the computer. The sampling rate of 44,100 Hz was used. Five utterances of each syllable were recorded. All the recorded syllables were played to six native speakers of Kannada who were also qualified Speech-Language Pathologists. The stimuli were presented binaurally through Sennheiser 449 headphones at a comfortable listening level. One syllable was presented at a time. The judges were asked to rate each syllable in terms of intelligibility, naturalness, and quality of the recording on a three point rating scale. The stimuli that obtained the highest rating were selected. The syllable duration was kept constant (240 ms) for all the speech tokens by truncating the final portion of the vowel. The waveform and the spectrogram of all the four syllables are shown in Figure 3.2 and the phonetic features of all the consonants are given in Table 3.2.

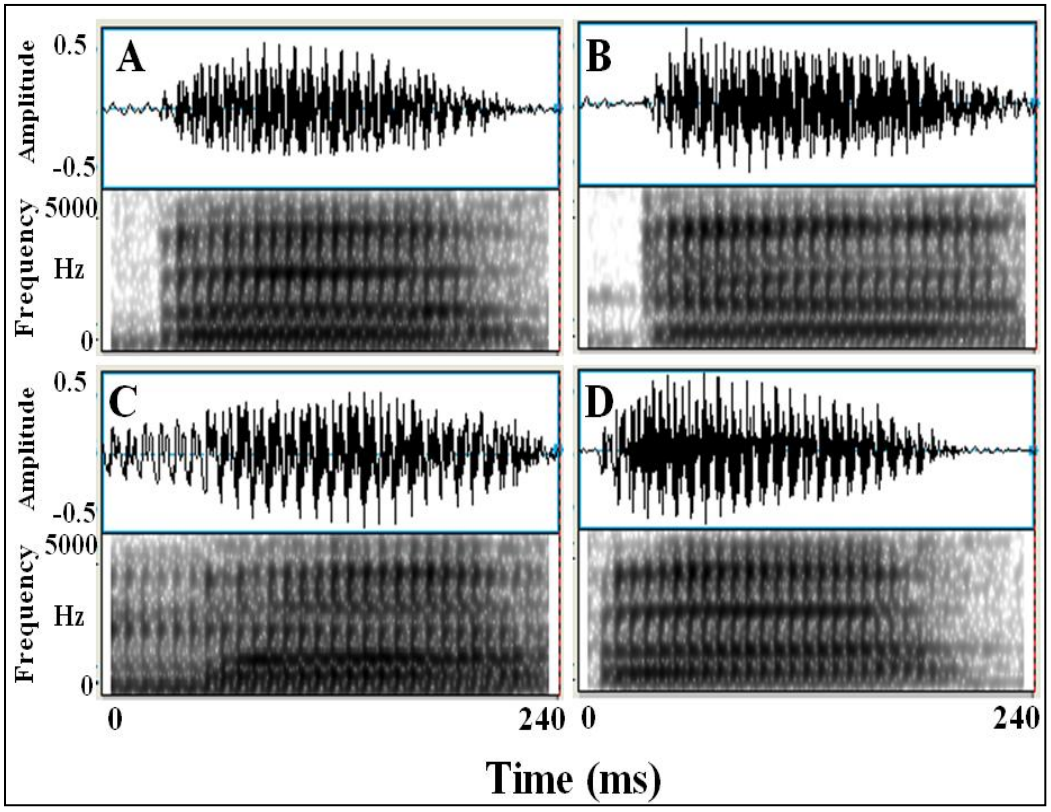


Figure 3.2. Waveform and spectrogram of all the four syllables - /ba/ (A), /da/ (B), /ma/ (C) and /pa/ (D).

Table 3.2

Phonetic features of the four consonants

	/b/	**/d/**	**/m/**	**/p/**
Voicing	Voiced	Voiced	Voiced	Unvoiced
Place	Labial	Dental	Labial	Labial
Manner	Plosive	Plosive	Nasal	Plosive

The syllables were mixed with speech noise at +10 dB signal-to-noise ratio (SNR) using the AuxViewer software. The spectrum of the speech noise used is depicted in Figure 3.3. A script was written for mixing syllable with speech noise in the AuxViewer platform and the output was saved as .wav file. SNR was selected based on a pilot study. This pilot study indicated that performance of individuals with ANSD dropped below chance level at SNRs poorer than +10 dB.

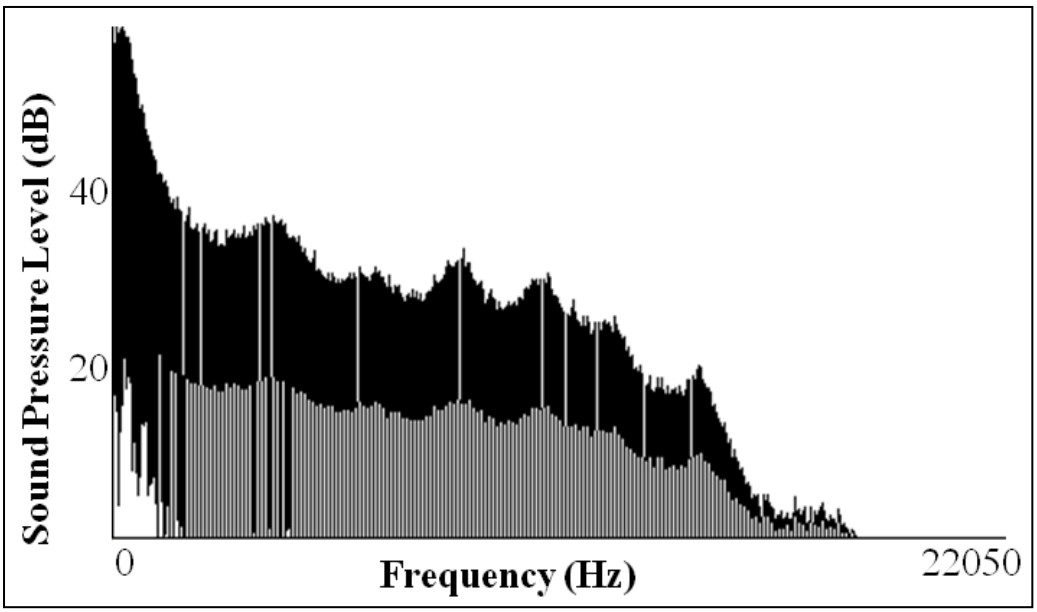


Figure 3.3. The spectrum of speech noise.

3.5.2. Stimuli for Speech in Noise (SIN) test. Sentence list developed by Methi, Avinash, and Kumar (2009) was used to estimate speech perception in noise. This test consists of seven lists of sentences, each list having seven sentences with five keywords in each. In each list, the SNR decreased from +20 dB to -10 dB, from first to seventh sentence in 5 dB steps.

3.5.3. Stimuli for Event-Related Potentials (ERPs). CV syllables /ba/, /da/, /ma/ and /pa/ used in the syllable identification task was also used to record ERPs. ERPs in oddball paradigm was recorded from all the participants using stimulus contrast which differed in the place (/ba-da/), the manner (/ba-ma/), and the voicing contrasts (/ba-pa/). In addition, ERPs were also recorded using /ba-da/ contrast at +10 dB SNR. Figure 3.4 shows /ba/ and /da/ stimuli in the presence of speech noise. Speech noise used was same as that used for the behavioural experiment and was gated on and off during the presentation of each CV syllable. The noise was gated on 1000 ms prior and remained until 1000 ms after the CV syllable. The noise had 200 ms of ramp at the onset and the offset to minimise the onset and offset responses elicited by noise. This stimulus design helped us to separate the ERPs elicited by noise from that of speech efficiently. The continuous background noise was not preferred while eliciting P300 response at +10 dB SNR, because it may cause neural adaptation in individuals with ANSD (Wynne et al., 2013).

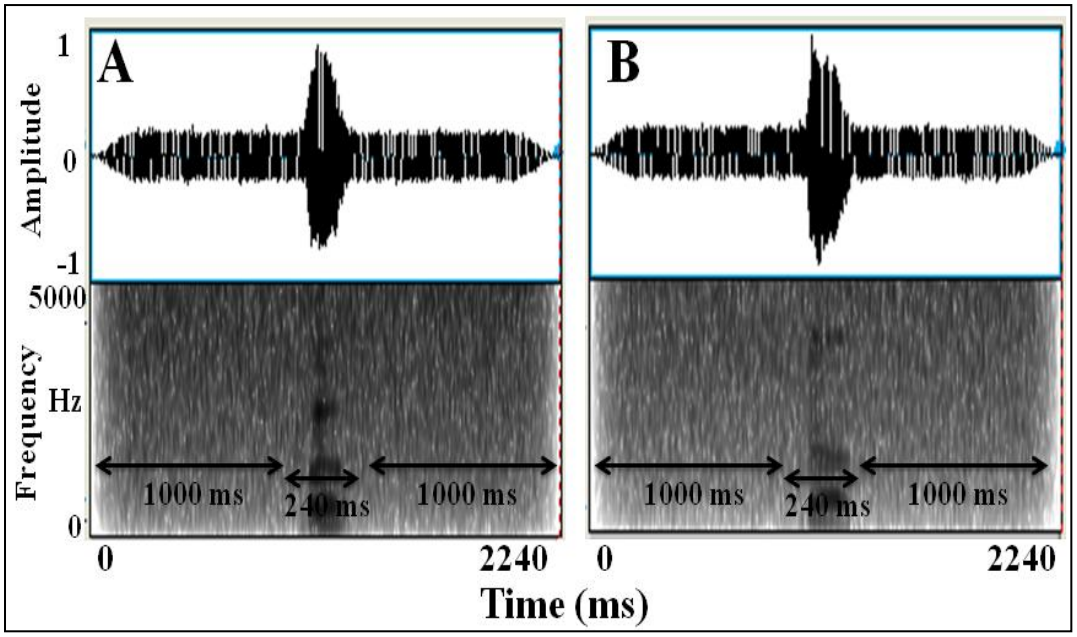


Figure 3.4. The waveform and spectrogram of stimulus /ba/ (A) and /da/ (B) at +10 dB SNR.

3.6. Procedure

First, all the prospective participants were assessed for their candidacy. As part of this, the participants answered a structured interview which had questions regarding demographic data (name, age, gender etc.), otological problems, occupational noise exposure and ototoxicity. Following this, the participants went through an otoscopic examination, pure-tone hearing assessment, speech identification test, and immittance evaluation. Only those individuals who fulfilled the inclusion criteria mentioned above were selected for the study. All the participants underwent both behavioural and electrophysiological assessments. The behavioral measures included assessing syllable identification and speech perception in noise. Electrophysiological testing included the recording of P300.

3.6.1.Behavioral measure. The speech perception of individuals with normal hearing as well as with ANSD was assessed using two behavioural measures - syllable identification test and SIN test.

Syllable Identification Test. The stimuli were presented at the 75 dB SPL using a loudspeaker kept at a one-meter distance and 0° azimuth from the participant. The loudspeaker was connected to the laptop through Microbook II sound card interface. All the eight CV syllables (four stimuli in quiet and four stimuli in presence of noise) were presented in random order to the participants in order to avoid familiarization effect. Participants were asked to repeat verbally or point on the computer screen (depending on their comfort) to the syllables heard. Each syllable was presented 10 times thus making a total of 80 stimulus presentations. Presentation of the stimuli was controlled using Paradigm software. The number of syllables identified correctly was calculated separately in both quiet and noise conditions. Responses were analysed by constructing a confusion matrix. Feature information transferred was analysed using FIX (Feature Info Xfer) software.

SIN test. In this, the SNR required to understand 50% of the words in a sentence was assessed (SNR-50) using speech perception in noise test in Kannada (Methi et al., 2009). The stimuli were presented at the 75 dB SPL using a loudspeaker kept at a one-meter distance and 0° azimuth from the participant. The loudspeaker was connected to the laptop through MicroBook II sound card interface. The participants were instructed to verbally repeat the sentences. The responses of the participants were audio recorded for further offline analysis. The SNR-50 was obtained under two different conditions – with and without hearing aids. Two test lists were administered in each condition. In the aided condition, the participants wore digitally programmable behind the ear (BTE) hearing aids binaurally. The same model of hearing aids was used for all the participants. The hearing aids were

programmed using manufacturer specific programming software and the gain provided was in accordance with NAL-NL1 fitting formula. The hearing aids selected had 12 channels. The hearings aids gain was programmed to first fit and compression setting was set to a linear mode with other special features such as noise reduction algorithm, sound recovery, bass boost deactivated. The linear amplification mode was used as non-linear compression might distort the incoming signal for individuals with ANSD (Jijo & Appu, 2015; Tasell, 1993; Zeng & Liu, 2006). The program change button and the volume controls were deactivated in order to avoid change in settings during the course of the testing. Aided performance of individuals with normal hearing sensitivity was assessed using same hearing aids but programmed to 10 dB HL flat thresholds across all frequencies. This was done to avoid loudness discomfort in normal hearing listeners. For individuals with ANSD, the hearing aid gain was programmed based on the audiometric thresholds. After applying the first fit, no further modifications were done during the entire testing.

Analyses. A score of one was given to each correctly identified keyword. The number of correct keywords recognized at each SNR was counted. The SNR-50 was calculated using the Spearman-Karber equation (Finney, 1952) as:

$$\text{SNR-50} = I + \tfrac{1}{2}(d) - (d)(\#\ \text{correct}) / (w)$$

where:

I = the initial presentation level (dB)

d = the attenuation step size (decrement)

correct = total number of correct keywords

w = the number of keywords per decrement. The SNR-50 was calculated for each list separately and an average of two lists in unaided and two in aided conditions were calculated.

3.6.2. Electrophysiological measure. P300 was recorded as per the guidelines provided by Duncan et al. (2009). Few of the important guidelines that were considered in the present study are

1. Use of oddball paradigm, as it elicits robust P300 and reveals about how the brain discriminates stimuli and process probability.

2. Minimum three recording sites (Fz, Cz, and Pz), or denser electrode arrays to obtain scalp distribution of P300.

3. Recording EEG from both the mastoids with one mastoid serving as a reference for all EEG channels as well as for other ear mastoid and later re-referencing all EEG channels to the mathematical average of two mastoids.

4. A minimum of 36 or more artifact-free trials after correction for ocular contributions.

Considering these key points, the following stimuli and procedure were used to record P300 in the current study. The P300 was recorded for all the three phonetic contrast, place (/ba/-/da/), manner (/ba/-/ma/) and voicing (/ba/-/pa/) in the quiet condition. However, at +10 dB SNR, only place contrast /ba/-/da/ was used to elicit P300 response. The place contrast was used because discrimination of place of articulation is more affected by noise than voicing and manner (Boothroyd, 1984; Hornsby, Trine, & Ohde, 2005; Miller & Nicely, 1955). P300 was also recorded for the /ba/-/da/ contrast with the hearing aids. The hearing aid model and electroacoustic characteristic were same as used in the behavioural assessment. The Stim2 module of Neuroscan EEG system was used for the presentation of the stimuli. The stimuli were presented using Gentask module. In both quiet and at +10

dB SNR condition, the trigger was placed at the onset of the CV stimuli. A total of 250 stimuli were presented wherein the frequent stimulus was presented in 80% of the trials and the infrequent stimulus was presented in 20% of the trials. The stimuli were presented at 75 dB SPL through loudspeaker kept at a one-meter distance and at 0° azimuth. The output of the loudspeaker was calibrated at a regular interval using the sound level meter in order to avoid any change in the output intensity of the signal during the experiment. A 64 channel Compumedics Neuroscan EEG equipment with Synamps^2 amplifier was used to record continuous EEG. The participants were made to sit comfortably on a reclining chair in a sound-treated room. A 64 channel QuickCap^{TM} with silver chloride sintered electrodes were placed on the scalp to record EEG responses. The QuickCell uses liquid electrolyte and cellulose based transmission and control system was used with the QuickCap^{TM}. Before the EEG recording, the electrode locations were digitized using Fastrack 3D digitizer (Polhemus, Colchester, USA). These electrode locations were used to create topographic maps. After digitization of the electrodes locations, EEG was picked up from 64 channels on the scalp placed according to the 10-10 electrode placement system (Chatrian, Lettich, & Nelson, 1985) with a left mastoid (M1) as reference. An additional electrode was placed on the right mastoid (M2). A ground electrode was placed mid-way between Fpz and Fz electrode locations. Additionally, to record horizontal and vertical eye movements, two bipolar ocular channels were also used. The electrodes were placed above and below left eye as well as on outer canthi of both eyes for this purpose. All the electrode impedances were kept below 20 kΩ. 20 kΩ is the standard impedance typically maintained in high density EEG acquisition procedures. The electrode locations are shown in Figure 3.5. Participants were sitting comfortably in a reclining chair during the ERP recording sessions and were

instructed to press a button with their preferred finger each time they heard the deviant stimulus in the train of standard stimuli. The participants were asked to stay as still as possible during the recording and also to reduce the eye movements.

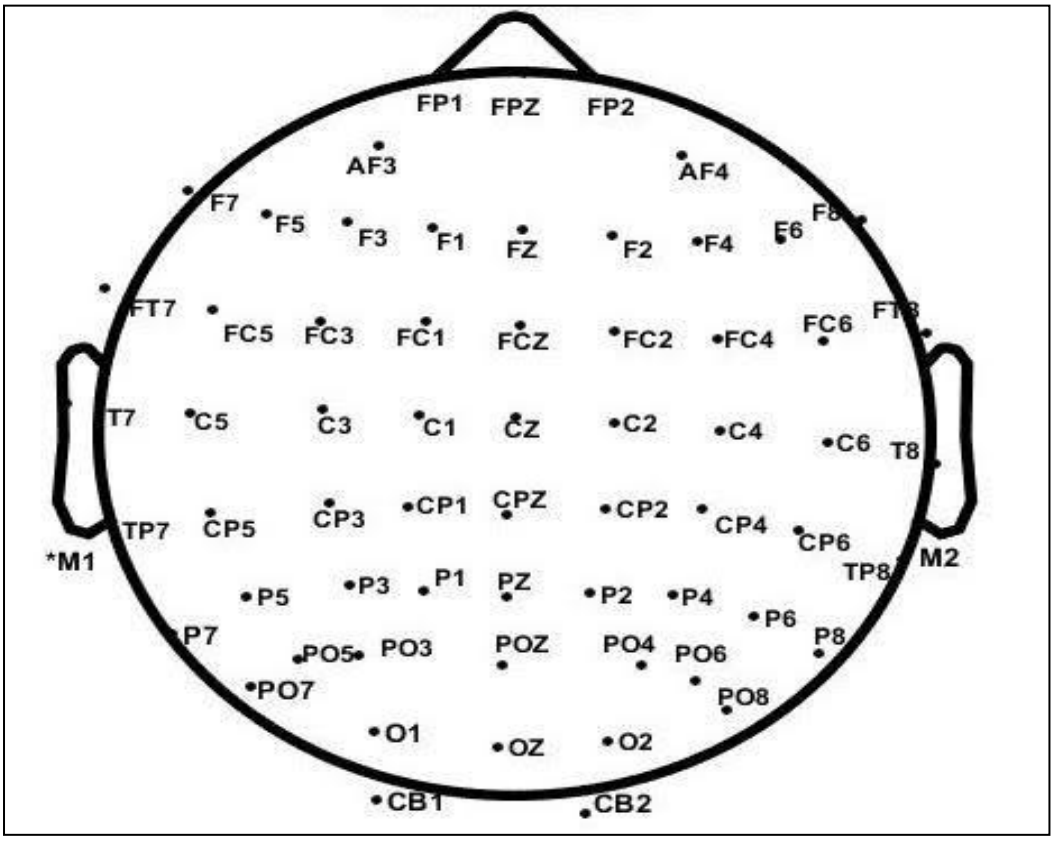


Figure 3.5. Electrode locations used in the present study for the ERP recording.

Following this, long latency response (LLR) was collected for 50 stimuli (only for the deviant stimuli) presented in repetitive paradigm. Rest was provided between recordings if the participant requested for it. The order of recordings was counterbalanced across participants. Table 3.3 shows the summary of the protocol that was used to record P300.

Table 3.3

Stimulus and Acquisition parameter for recording P300 in an oddball paradigm

Stimulus Parameter		
Conditions	With hearing aids	Without hearing aids
	Quiet	Quiet
	+10 dB SNR	+10 dB SNR
Transducer	Loudspeaker	
Standard to deviant ratio	4 to 1 (80:20)	
Intensity	75 dB SPL	
Inter-stimulus Interval	2240 ms in quiet condition and 3240 ms in noise condition	
Number of trials	200 frequent and 50 infrequent	
Acquisition Parameter		
No of channels	Inverting electrode – mastoid	
	Non-inverting electrode – all cap electrodes	
	Ground – ground electrode of cap	
	2 bipolar electrode pairs for VEOG & HEOG	
A/D conversion rate	1000	
Filter Setting	0.10 Hz to 100 Hz	
Sorting Criteria	Stimulus (frequent & infrequent)	

The reaction time (RT) and the sensitivity were calculated based on the button press response for the identification of the oddballs. The RT is measured as the time gap between the presentation of the stimulus and the response (Shelton & Kumar, 2010; Woods, Wyma, Yund, Herron, & Reed, 2015). It was measured in millisecond. Sensitivity measure the strength of the signal. It is a static incorporating both hit rate and false alarm rate (Oates, Kurtzberg, & Stapells, 2002). Hit rate is the percentage of correct identification of the target stimuli whereas false alarm rate is a percentage of incorrect identification of the target in the control condition. The continuous EEG waveform was subjected to the following offline processing. The DC offset was corrected with a polynomial order of three, in order to decrease the

drift in the waveforms. Ocular artifact reduction was done using weighted subtraction based on linear regression as recommended by Semlitsch, Anderer, Schuster, and Presslich (1986). The responses were band-pass filtered at 0.10-30 Hz (FIR 30dB/octave zero phase shift) to separate the cortical low-frequency components from the sub-cortical high-frequency components. The responses were re-referenced to the mathematical average of left and the right mastoids. The re-referenced response was epoched for a total duration of 1000 ms with pre-stimulus duration of 200 ms and averaged. The data from the bad channels were interpolated using spline interpolation. Bad channels were defined as those with large electrical drifts or amplitude spikes larger than 75 μV.

***Latency and amplitude analyses*.** After above mentioned pre-processing multi-step ERP analysis was carried out. In the traditional waveform analyses, the averaged ERP for deviant stimuli was used for marking P300 peak. Peaks were marked in the waveforms obtained from three electrodes: Fz, Cz, and Pz. These three electrodes were chosen because of the higher amplitude of P300 at midline electrodes and a minimum of three electrodes are necessary to characterize P300 (Duncan et al., 2009). The region that had a maximum amplitude between 300 to 700 ms (Duncan et al., 2009) was considered as P300 and its peak amplitude and latency were noted for further statistical analyses.

Modulations in the ERP waveform amplitudes were analyzed by performing a series of unpaired/paired t-tests between the waveforms. These analyses and spatiotemporal analyses described below were conducted using the Cartool software. To minimize family-wise errors, the correction was made by applying a temporal criterion of 70 continuous time-frames for the persistence of differential effects (Guthrie & Buchwald, 1991). The result of this test provides an overview regarding

the time points and the electrodes at which the response differed between the two waveforms. This analysis was carried out between the

- Waveform of infrequent stimuli in oddball paradigm and waveform of same stimuli presented in repetitive paradigm, to ascertain the presence of P300.
- Responses to deviant stimuli between the groups were used to highlight the difference in the response obtained between the two groups.
- Responses to deviant stimuli between unaided and aided, quiet and +10 dB SNR, in individuals with normal hearing and with ANSD, to see the differences in the response obtained in different conditions (amplification and noise) for both the groups.

Spatiotemporal analyses. The pattern analysis of the scalp topography was done using the Cartool software. The steps involved in this analysis was similar to that reported by other researchers (De Santis, Clarke, & Murray, 2007; Murray et al., 2004; Spierer, Tardif, Sperdin, Murray, & Clarke, 2007). The segmentation was based on the cluster analysis. The segmentation was carried out on the grand averaged waveforms. It was depicted as the color coded global field power (GFPs) with each color representing different cluster map. The clustering method used for this study was topographic atomize and agglomerate hierarchical clustering implemented in Cartool. This was based on the assumption that electrical configuration of the scalp does not vary randomly with time but shows stability over long periods of time (ten to hundreds of ms) (Lehmann & Skrandies, 1980). Only those stable topographies that lasted more than 70 ms were considered. This analysis resulted in a limited number of topographies for each group averaged ERP data which are referred as template maps. The optimal number of template maps was identified using a modified Krzanowski-Lai criterion (Krzanowski & Lai, 1988). As

the topographical differences in the scalp-recorded potentials are indicative of changes in the underlying generator, this analysis helps in determining whether same or different neural networks were activated.

Test-Retest reliability of SNR-50 and P300 parameters

To assess the reliability of the measures used in the study, behavioral measure (SNR-50) and the electrophysiological measures (latency & amplitude of P300) were repeated in 10% of the participants with a minimum gap of one month between the measurements.

Statistical analyses

The data obtained from the behavioural and electrophysiological measures were analyzed using appropriate statistical tests. Descriptive statistics including mean, median, standard deviation and quartile deviation, were estimated for all the parameters in this study. Shapiro-Wilks test of normality was done to assess the distribution of the data. Mann-Whitney U test was done to compare the response obtained from individuals with normal hearing and with ANSD on behavioural and ERP measures. Wilcoxon signed-rank test was carried out for within the group analyses. Spearman's rank correlation analysis was done to find the relationship between the behavioral measures (SNR-50, RT, and sensitivity) and the electrophysiological measures (latency and amplitude of P300). Cronbach's Alpha was used to check the test-retest reliability of behavioral measures (SNR-50, RT, and sensitivity) and the electrophysiological measures (latency and amplitude of P300).

Chapter 4

Results

The present study aimed to investigate the cortical representation of speech in individuals with auditory neuropathy spectrum disorder (ANSD) in quiet and at +10 dB signal-to-noise ratio (SNR). This study also investigated the effect of amplification on speech evoked cortical potentials in individuals with ANSD. Furthermore, the study also investigated the relationship between behavioural and electrophysiological measures using correlational approach. The data obtained from all the measures were analyzed using appropriate statistical tools and the results have been categorized under following headings

4.1. Comparison of syllable identification scores between individuals with normal hearing sensitivity and with ANSD.

4.1.1. Comparing speech identification scores of individuals with normal hearing and with ANSD on syllable identification test.

4.1.2. Comparing speech identification scores obtained in quiet and +10 dB SNR in individuals with normal hearing and with ANSD.

4.2. Comparison of speech identification scores obtained with and without amplification device in individuals with normal hearing sensitivity and ANSD.

4.2.1. Comparing SNR-50 response of individuals with normal hearing and with ANSD on Speech in noise (SIN) test, without amplification device.

4.2.2. Comparing SNR-50 response of individuals with normal hearing and with ANSD on Speech in noise (SIN) test, with amplification device.

4.2.3. Comparing SNR-50 responses, with and without amplification device in both the groups.

4.3. Comparison of P300 responses in terms of amplitudes, latency and scalp topographies between individuals with normal hearing sensitivity and with ANSD.

4.3.1. P300 in quiet in individuals with normal hearing and with ANSD.

4.3.2. P300 at + 10 dB SNR in individuals with normal hearing and with ANSD.

4.3.3. Effect of amplification on P300 in individuals with normal hearing and with ANSD.

4.4. Relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD.

4.1. Comparison of syllable identification scores between individuals with normal hearing sensitivity and with ANSD

This section of the results addresses the objective 1 - to compare the speech identification scores between individuals with normal hearing sensitivity and with ANSD. For this purpose, confusion matrix was created by pooling the data from all the participants. Separate confusion matrices were created for each group (normal hearing and ANSD) and listening conditions (quiet and +10 dB SNR). Tables 4.1A show the group confusion matrices for individuals with normal hearing sensitivity in quiet and at +10 dB SNR respectively. Tables 4.1B show the confusion matrices for individuals with ANSD in quiet and +10 dB SNR, respectively. In these confusion matrices, the number in each cell is the number of times a given stimulus (speech

sound shown at the beginning of each row) was identified as the sound shown at the top of the column. The number of correct responses (for all sounds) can be obtained by totaling the numbers along the main diagonal (by adding the bold numbers). A preliminary look at the matrix reveals that individuals with normal hearing sensitivity showed near perfect identification scores for syllables presented in quiet. Identification scores were slightly reduced at +10 dB SNR in normal hearing listeners. Addition of the noise resulted in confusion between /ba/ and /pa/ in normal hearing listeners.

Table 4.1A

The group confusion matrix obtained from individuals with normal hearing in quiet and at +10 dB SNR

	Individuals with normal hearing									
	Response									
Stimuli	**In Quiet**	/ba/	/da/	/ma/	/pa/	**+10 dB SNR**	/ba/	/da/	/ma/	/pa/
	/ba/	**300**	0	0	2	/ba/	**260**	2	0	3
	/da/	0	**299**	0	0	/da/	1	**298**	1	0
	/ma/	0	1	**299**	0	/ma/	0	0	**298**	0
	/pa/	0	0	1	**298**	/pa/	39	0	1	**297**

Note. Maximum score possible is 300.

Table 4.1B

The group confusion matrix obtained from individuals with ANSD in quiet and at +10 dB SNR

	Individuals with ANSD									
	Response									
Stimuli	**In Quiet**	/ba/	/da/	/ma/	/pa/	**+10 dB SNR**	/ba/	/da/	/ma/	/pa/
	/ba/	**265**	32	0	57	/ba/	**129**	53	23	49
	/da/	11	**246**	1	10	/da/	43	**151**	23	28
	/ma/	7	12	**299**	14	/ma/	41	24	**207**	5
	/pa/	17	10	0	**219**	/pa/	87	72	47	**218**

Note. Maximum score possible is 300.

Mann-Whitney U test was used to assess the statistical significance of the difference in syllable identification scores between the two groups (normal hearing & ANSD) and the results are shown in Table 4.2. The results showed that identification scores were significantly better in normal hearing individuals compared to individuals with ANSD for /ba/, /da/, and /pa/ syllables in quiet and for all the syllables at + 10 dB SNR. The identification of syllable /ma/ was found to be similar in two groups in the quiet condition as shown in Table 4.2.

Table 4.2

Significance of the difference for the syllable identification score between individuals with normal hearing sensitivity and with ANSD in quiet and at +10 dB SNR

Conditions	Syllables	Z value	r value
Quiet	/ba/	3.21*	0.41
	/da/	2.80*	0.36
	/ma/	0.00	0.00
	/pa/	5.47**	0.70
+ 10 dB SNR	/ba/	4.89**	0.63
	/da/	5.50**	0.71
	/ma/	4.69**	0.60
	/pa/	5.26**	0.68

Note. * = $p < 0.01$, ** = $p < 0.001$, r = effect size.

Wilcoxon signed-rank test revealed that addition of noise significantly reduced the identification of /ba/ in normal hearing individuals ($z = 2.95$, $p < 0.01$) with large effect size ($r = 0.53$). Effect of noise did not significantly alter the identification scores of other syllables in normal hearing listeners [/da/ ($z = 0.00$, $p > 0.05$), /ma/ ($z = 0.00$, $p > 0.05$), /pa/ ($z = 1.00$, $p > 0.05$)]. Individuals with ANSD showed confusions in the perception of all the syllables in quiet as well as at +10 dB SNR. Wilcoxon signed-rank test revealed the reduction in identification of /ba/ ($z = 4.54$, $p < 0.001$), /da/ ($z = 3.70$, $p < 0.001$) and /ma/ ($z = 3.73$, $p < 0.001$) with large effect size for /ba/ ($r = 0.82$), /da/ ($r = 0.67$) and /ma/ ($r = 0.68$) with the addition of noise in

individuals with ANSD. Noise did not significantly alter the identification scores of /pa/ syllable ($z = 0.52$, $p > 0.05$) in individuals with ANSD.

Sequential **INF**ormation **A**nalysis (SINFA) was carried out on the confusion matrix obtained from individuals with normal hearing and with ANSD in quiet and in noise separately. This analysis provides the amount of information transfer from stimulus to response for a set of phonetic features. The maximum information in bits that could be transmitted for the four stimuli of the present study is 2. The results of this analysis are shown in Figure 4.1. In Figure 4.1, y-axis represents the information transmitted for that feature. Zero indicates no transmission of that particular feature and a value of 1 indicates maximum transmission. It is clear from the Figure 4.1 that the information transmitted reduced in the presence of noise for both normal hearing individuals and individuals with ANSD. However, this reduction was more drastic in individuals with ANSD compared to individuals with normal hearing. In individuals with normal hearing in quiet, information transmission was similar for all the three features - place, manner and voicing. With the addition of noise, there was a reduction in transmission of voicing information. In individuals with ANSD, manner information was transmitted better than the place and the voicing feature. The pattern of information transmission remained same with the addition of noise with the overall reduction in information transmission for all the features in individuals with ANSD.

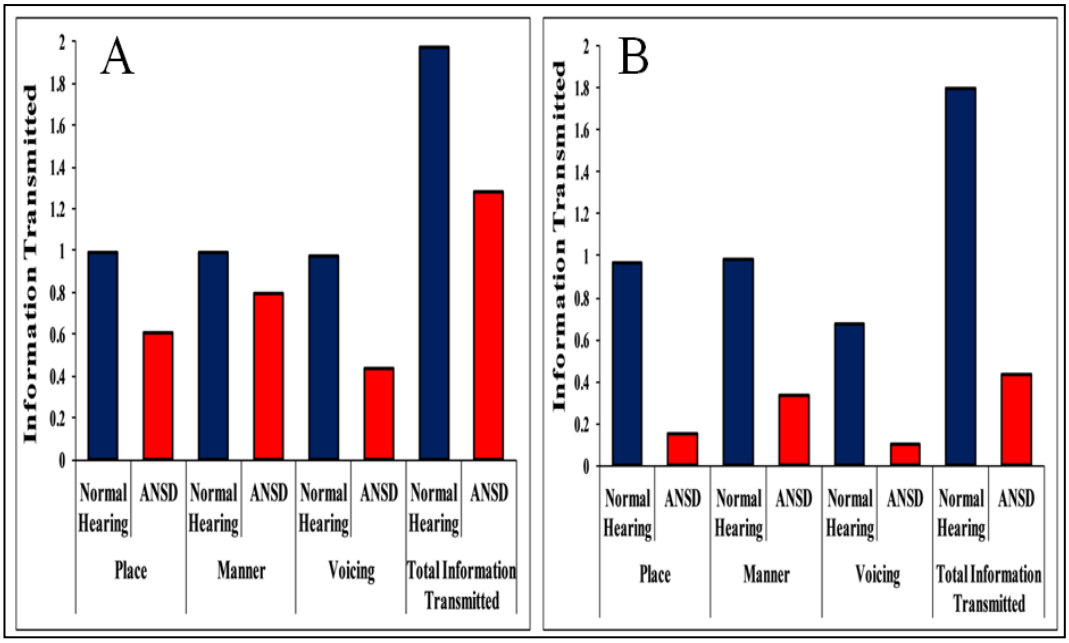


Figure 4.1. Information transmitted in individuals with normal hearing and with ANSD in quiet (Panel A) and at +10 dB SNR (Panel B). In case of place, manner and voicing feature y axis represents the information transmitted for that feature. Zero indicates no transmission of that particular feature and a value of 1 indicates maximum transmission of that feature. In case of total information transmitted y axis represents the total information transmitted in bits.

4.2. Comparison of speech identification scores obtained with and without amplification device in individuals with normal hearing sensitivity and ANSD

This section of the results addresses the objective 2 - to compare speech identification scores in individuals with normal hearing and in ANSD, with and without amplification device. Signal-to-noise ratio required to identify the 50% of the words correctly (SNR-50) was calculated for both the group of individuals using Spearman-Karber equation.

Table 4.3 shows SNR-50 in individuals with normal hearing and with ANSD. It is evident from Table 4.3 that the SNR-50 was better in individuals with normal hearing compared to individuals with ANSD. Individuals with normal hearing were able to understand the 50% of the presented sentences even at negative SNRs. The

variation in responses was also more in individuals with ANSD as compared to normal hearing individuals.

Table 4.3

SNR-50 in individuals with normal hearing and with ANSD in unaided and in aided condition

Condition	Individuals with normal hearing				Individuals with ANSD			
	Mean	SD	Median	QD	Mean	SD	Median	QD
Unaided	-6.81	2.36	-7	2.06	7.51	6.22	7.25	5.37
Aided	-5.83	1.39	-5.5	0.5	7.11	5.75	5.5	4.25

Note. SD = Standard Deviation, QD = Quartile deviation.

Mann-Whitney U test showed lower SNR-50 in individuals with normal hearing in the unaided ($z = 6.65$, $p < 0.001$) and in the aided ($z = 6.69$, $p < 0.001$) conditions with large effect size in both the unaided ($r = 0.85$) and in aided ($r = 0.86$) compared to individuals with ANSD. Wilcoxon signed-rank test showed that normal hearing individuals had better scores in the unaided condition compared to aided condition ($z = 2.22$, $p < 0.05$) with medium effect size ($r = 0.40$). However, in individuals with ANSD, there was no significant difference between the SNR-50 values in the two conditions ($z = 0.650$, $p > 0.05$).

4.3. Comparison of P300 responses in terms of amplitudes, latency and scalp topographies between individuals with normal hearing sensitivity and with ANSD

This section addresses the objective 3 - to compare P300 responses in terms of amplitudes, latency and scalp topographies between normal hearing individuals and individuals with ANSD. Latency, amplitude and the scalp topography of P300 were compared between individuals with normal hearing and ANSD. The data from 30 individuals with normal hearing and 28 individuals with ANSD were considered for the analyses because data from two individuals with ANSD showed a large electrical

interference and hence were discarded. The latency and the amplitude of the P300 response were noted down and statistical analyses were done using SPSS software. Spatiotemporal pattern analysis was done using the Cartool software. The latency and the amplitude values obtained from both the groups followed non-normal distribution on Shapiro-Wilks test ($p < 0.05$). Therefore, non-parametric statistical tests were done.

4.3.1. P300 in quiet in individuals with normal hearing and with ANSD:

General characteristics. Table 4.4 shows the reaction time (RT) and sensitivity measures obtained for the button press responses during the acquisition of P300. From the Table 4.4, it can be observed that participants in both the groups identified the occurrence of the deviant syllable with greater than 90% accuracy.

Table 4.4

Reaction time (RT) and the sensitivity measures in quiet in normal hearing individuals and in individuals with ANSD

Measures	Stimulus pairs	Individuals with normal hearing				Individuals with ANSD			
		Mean	SD	Median	QD	Mean	SD	Median	QD
RT (ms)	/ba/-/da/	441.69	106.2	472.50	99.87	592.37	109.03	588.10	102.6
	/ba/-/ma/	451.63	100.58	423.90	72.42	582.31	122.38	564.85	61.02
	/ba/-/pa/	441.06	102.83	432.60	80.23	589.67	103.23	587.95	80.61
Sensitivity	/ba/-/da/	0.986	0.022	0.995	0.002	0.902	0.147	0.960	0.065
	/ba/-/ma/	0.995	0.0008	0.996	0.0005	0.971	00.065	0.989	0.008
	/ba/-/pa/	0.992	0.0120	0.996	0.001	0.927	0.095	0.976	0.054

Note. SD = Standard Deviation, QD = Quartile deviation, ms = millisecond, RT = Reaction time.

Furthermore, Mann-Whitney U test showed that individuals with ANSD had significantly poor sensitivity compared to normal hearing individuals in identifying the oddball for all three stimuli contrasts - /ba/-/da/ ($z = 4.82$, $p < 0.001$), /ba/-/ma/ ($z = 4.16$, $p < 0.001$) and /ba/-/pa/ ($z = 4.75$, $p < 0.001$) with large effect size for all the three contrast ($r > 0.50$). Mann-Whitney U test also revealed that individuals with

ANSD had significantly longer RT compared to normal hearing individuals in identifying the oddball for all three stimuli contrasts - /ba/-/da/ ($z = 4.48$, $p < 0.001$), /ba/-/ma/ ($z = 4.01$, $p < 0.001$) and /ba/-/pa/ ($z = 4.31$, $p < 0.001$) with large effect size ($r > 0.50$) for all the three contrasts. The grand averaged ERPs obtained in response to stimulus /ba/-/da/, /ba/-/ma/, and /ba/-/pa/ contrasts from individuals with normal hearing and ANSD are shown in Figure 4.2 and 4.3 respectively. Last waveforms in the Figures 4.2 and 4.3 show the global field power (GFP). GFP is the single reference independent measure of response strength. Mathematically, GFP is the root mean square amplitudes across average referenced electrodes at a given instance in time (Lehmann & Skrandies, 1980; Murray, Brunet, & Michel, 2008). From the Figure 4.2 and 4.3, it can be seen that a positive peak (P300) was prominent in the waveform of deviant stimuli after 300 ms. This was the case for both the groups. It can also be seen that GFP had a higher amplitude in 300 to 500 ms time range in deviant waveform compared to the waveform obtained in the repetitive paradigm, confirming the presence of P300 in both the groups. Presence of P300 was further statistically confirmed by performing randomization test with 10,000 permutations at each time point between waveforms obtained in oddball and repetitive paradigms. The waveforms had to differ significantly ($p < 0.05$) from each other for 70 continuous time-frames to demonstrate the persistence of differential effects as mentioned in the method. This analysis was carried out using the Cartool software and results are depicted in the lower panel of Figure 4.2 and 4.3 for normal hearing and ANSD group respectively. In Figure 4.2 and 4.3, time is plotted on x-axis and scalp electrode locations are plotted on the y-axis. The dark bars indicate the time-frame and the electrodes at which there were significant differences between the waveforms of frequent and infrequent stimuli. From Figure 4.2 and 4.3,

it can be noticed that there were significant differences between the waveforms in oddball and repetitive paradigms in the time-frame of conventional P300 (300 ms – 700 ms), especially at the central and parietal electrodes indicating the presence of P300 in both the groups for all the contrasts.

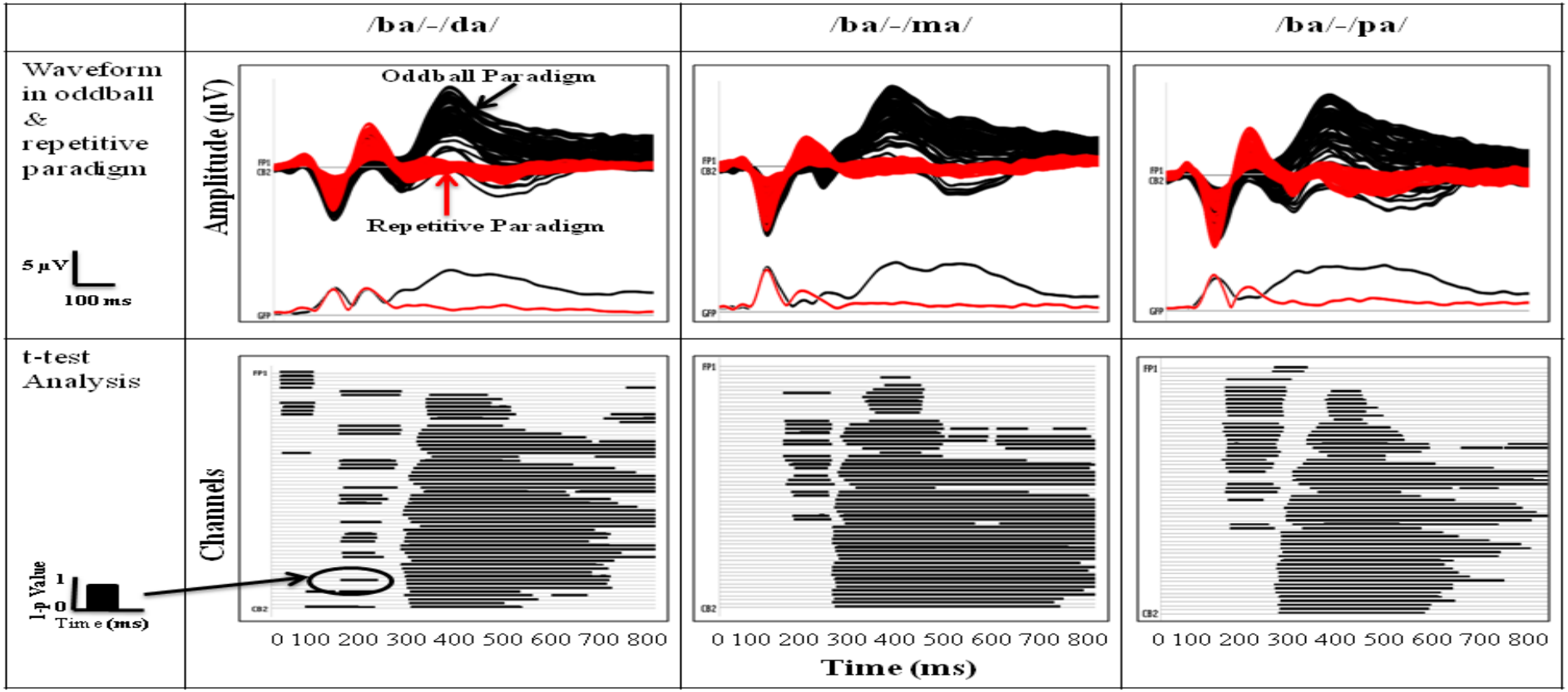


Figure 4.2. The grand average waveform obtained from individuals with normal hearing in response to deviant stimuli in oddball paradigm (black tracing) and same stimuli in repetitive paradigm (red tracing) in 64 channels. The dark shaded areas in the lower panel show the region of significant difference ($p < 0.05$) on the point-wise paired randomization test. Time in ms is plotted on the x-axis and scalp electrode locations are shown on the y-axis in the bottom panel.

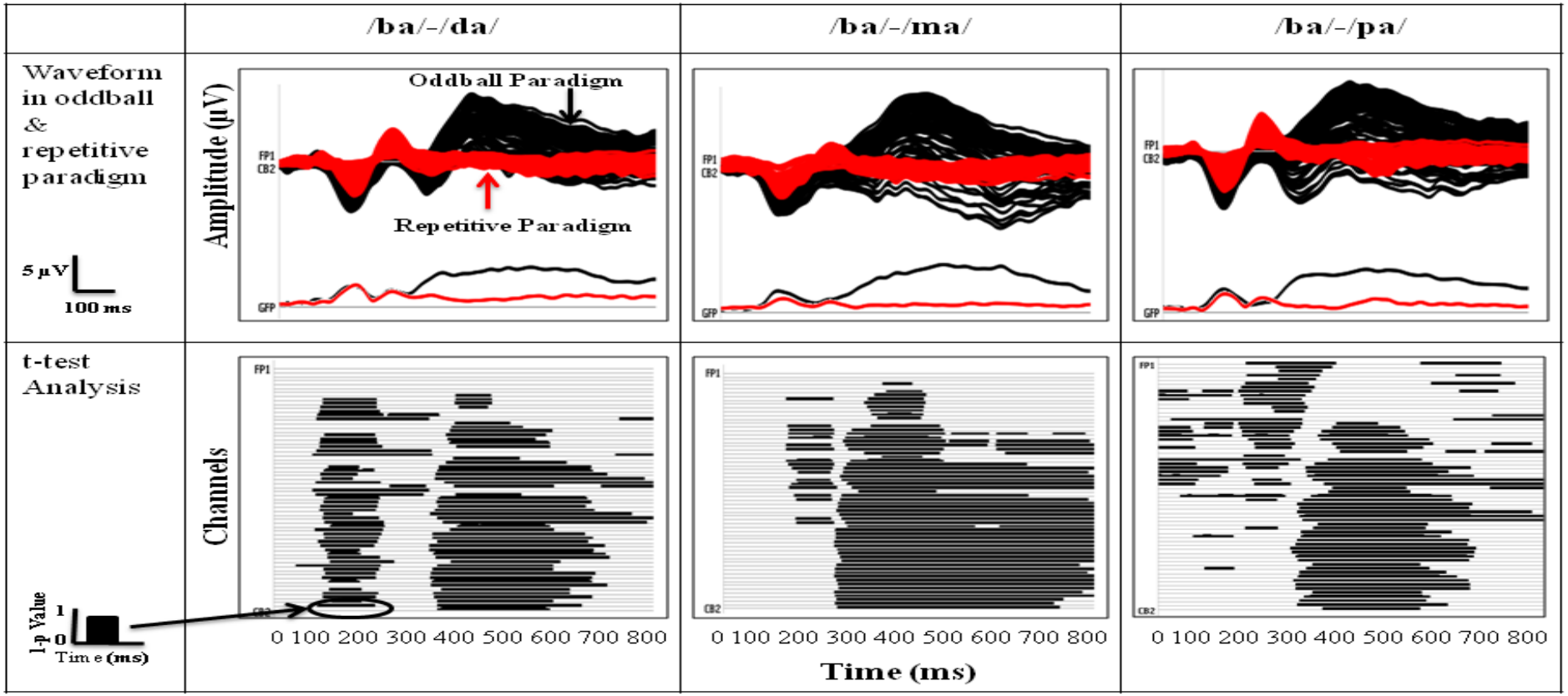


Figure 4.3. The grand average waveform obtained from individuals with ANSD in response to deviant stimuli in oddball paradigm (black tracing) and same stimuli in repetitive paradigm (red tracing) in 64 channels. The dark shaded areas in the lower panel show the region of significant difference ($p < 0.05$) on the point-wise paired randomization test. Time in ms is plotted on the x-axis and scalp electrode locations are shown on the y-axis in the bottom panel.

4.3.2. P300 in quiet in individuals with normal hearing and with ANSD:

Waveform analyses. P300 latency and the amplitudes measured at three midline electrodes, Fz, Cz, Pz are shown in Table 4.5. Figure 4.4 shows the grand average waveform obtained from individuals with normal hearing and with ANSD for the three speech contrasts /ba/-/da/, /ba/-/ma/, and /ba/-/pa/ at three midline electrodes. From the Figure 4.4 and Table 4.5, it can be seen that P300 latency was prolonged and amplitude was reduced for all the stimulus contrast and at all three electrode locations in individuals with ANSD.

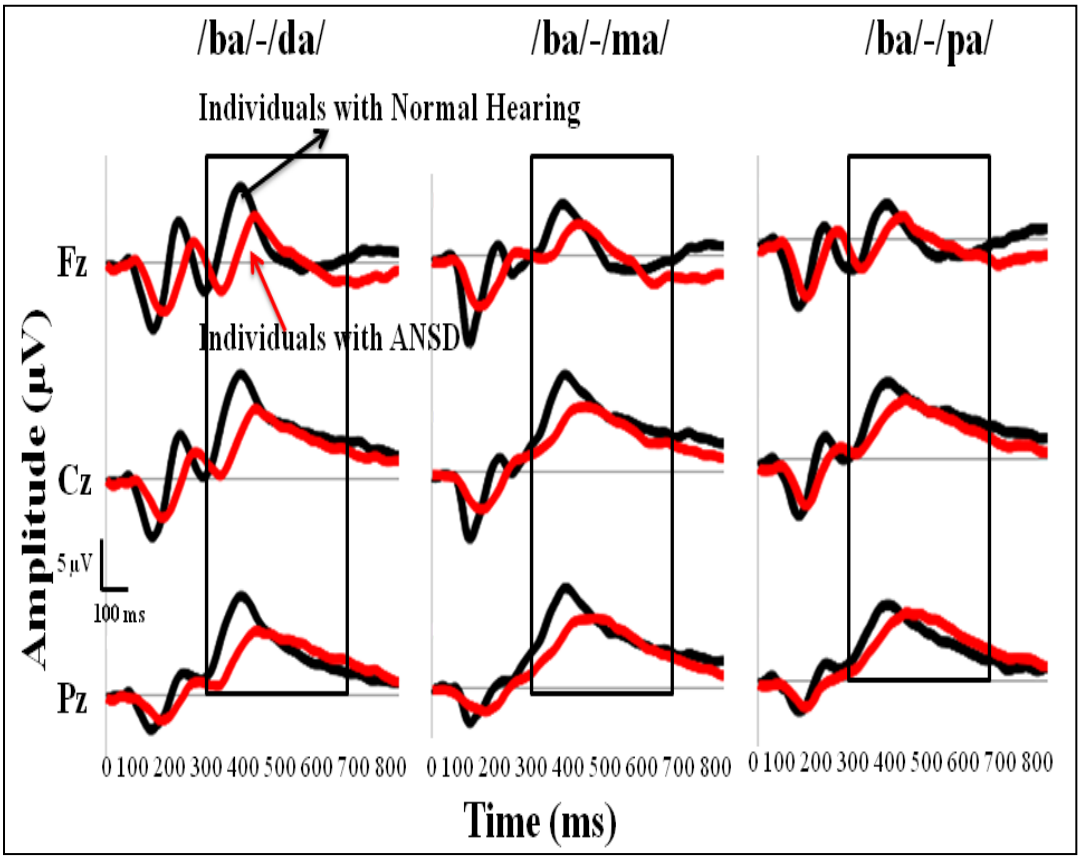


Figure 4.4. The grand average waveform obtained in response to stimulus pairs /ba/-/da/, /ba/-/ma/ and /ba/-/pa/ in individuals with normal hearing and with ANSD. The black boxes in the latency range of 300 ms to 700 ms show the presence of P300 peak.

Table 4.5

Latency and the amplitude of the of P300 response across channels (Fz, Cz, and Pz) and stimuli (/ba/-/da/, /ba/-/ma/, and /ba/-/pa/) for normal hearing individuals and with ANSD

	Channel	Stimulus pairs	Individuals with normal hearing				Individuals with ANSD			
			Mean	SD	Median	QD	Mean	SD	Median	QD
Latency (ms)	Fz	/ba/-/da/	368.64	20.49	365	11.25	407.36	23.96	406	14
		/ba/-/ma/	357.07	30.30	354	13.5	401.40	34.11	398.50	21.25
		/ba/-/pa/	362.03	38.51	352	23.25	390.82	49.22	398.0	32.5
	Cz	/ba/-/da/	367.58	22.25	364	12.5	412.85	27.61	407	21
		/ba/-/ma/	371	35.29	365	14	424.11	48.88	424.50	37.12
		/ba/-/pa/	359.93	32.65	352	14.5	413.18	56.32	405	35
	Pz	/ba/-/da/	371.43	25.88	369.5	12.12	423.51	41.14	409	25.5
		/ba/-/ma/	370.63	29.21	367	15.62	433.80	51.89	428	38.5
		/ba/-/pa/	371.93	41	364	27.5	417.51	57.38	410	43
Amplitude (µV)	Fz	/ba/-/da/	8.80	5.05	7.87	3.19	7.19	5.05	6.31	4.42
		/ba/-/ma/	7.71	3.87	7.27	3.30	6.85	4.02	6.60	2.72
		/ba/-/pa/	4.78	4.05	3.75	2.58	5.29	4.58	4.72	3.13
	Cz	/ba/-/da/	10.41	5.08	9.60	3.19	7.19	5.06	6.38	4.01
		/ba/-/ma/	10.05	4.47	10.05	2.62	7.47	4.62	6.25	3.94
		/ba/-/pa/	7.41	4.06	6.83	3.56	6.63	4.38	6.28	3.15
	Pz	/ba/-/da/	9.35	4.06	9.11	2.58	6.66	4.19	5.45	2.32
		/ba/-/ma/	9.66	4.01	10.47	2.70	7.72	4.61	6.01	3.37
		/ba/-/pa/	7.84	3.48	7.15	2.85	6.83	4.07	5.95	2.90

Note. SD = Standard Deviation, QD = Quartile Deviation, ms = millisecond, µV = microvolt.

Statistical significance of the differences in the latency and amplitude between two groups was assessed using Mann-Whitney U test and the result is shown in Table 4.6. From the Table 4.6, it can be seen that individuals with ANSD had a significantly prolonged latency of P300 for all three stimulus contrasts at all the three midline electrodes. However, the amplitude of P300 was significantly reduced in individuals with ANSD at Cz and Pz electrode locations for /ba/-/da/ contrast.

Table 4.6

Significance of difference for the latency and the amplitude across three midline channels (Fz, Cz, and Pz) and three stimuli pairs (/ba/-/da/, /ba/-/ma/, and /ba/-/pa/) between individuals with normal hearing and with ANSD

Channels	Stimuli	Latency (ms)		Amplitude (μV)	
		Z value	r value	Z value	r value
Fz	/ba/-/da/	4.73***	0.66	1.19	0.16
	/ba/-/ma/	4.04***	0.59	0.66	0.09
	/ba/-/pa/	2.32*	0.33	0.371	0.05
Cz	/ba/-/da/	5.30***	0.70	2.25*	0.30
	/ba/-/ma/	4.24***	0.57	1.85	0.25
	/ba/-/pa/	3.92***	0.52	0.73	0.09
Pz	/ba/-/da/	5.11***	0.67	2.58*	0.34
	/ba/-/ma/	4.66***	0.62	1.75	0.23
	/ba/-/pa/	3.29**	0.44	1.36	0.18

Note. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ms = millisecond, μV = microvolt, r = effect size.

4.3.3. P300 in quiet in individuals with normal hearing and with ANSD:

Topographic pattern analyses. The spatiotemporal analysis was done using the Cartool software. Spatial cluster analysis was performed on group averaged waveforms obtained from both the groups of individuals for the three stimulus contrasts - /ba/-/da/, /ba/-/ma/ and /ba/-/pa/. The result of this analysis is the limited number of scalp topographies for each group averaged ERP data which are referred as segments or template maps. Results of the topographic pattern analyses for both the groups are shown in Figure 4.5.

A total of 10 statistically significant template maps accounted for 94% of the variance in the data across both the groups. The scalp topography was same for both the groups for all three stimulus contrast till 152 ms and showed differences thereafter. In P300 region individuals with normal hearing and ANSD exhibited centro-parietal positive topographies with minor but statistically significant variations as shown in the lower panel of Figure 4.5.

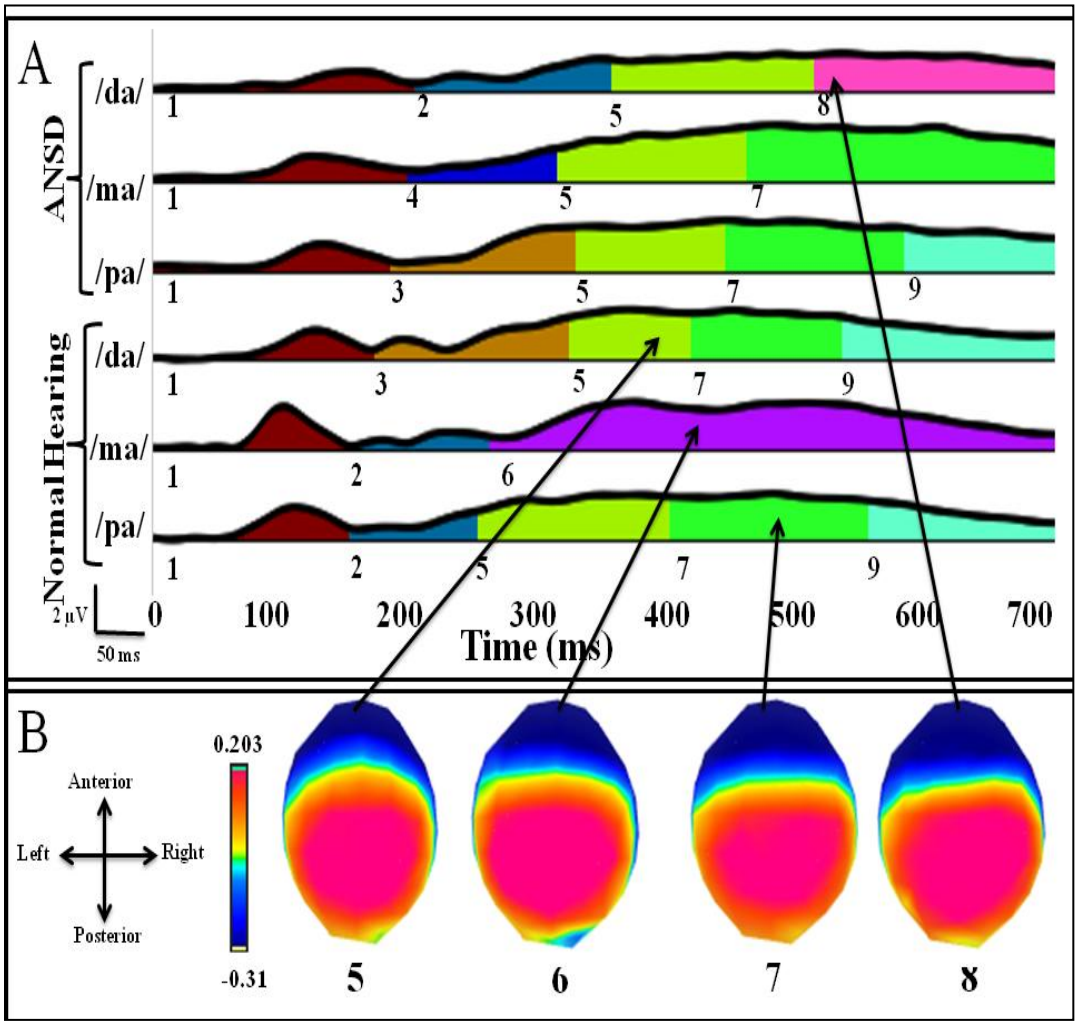


Figure 4.5. The result of topographic pattern analysis showing the time region at which statistically significant different template maps occurred as shown in Panel A. Panel B shows the different scalp topographies obtained in the time region of P300.

4.3.4. P300 at + 10 dB SNR in individuals with normal hearing and with ANSD: General characteristics.

This section describes the P300 obtained at +10 dB SNR for /ba/-/da/ stimulus contrast in individuals with normal hearing and ANSD. Table 4.7 shows the RT and sensitivity in identifying the deviant syllable in the oddball paradigm for both the groups. Responses obtained in quiet condition are also provided for the reference purpose.

Table 4.7

Reaction time (RT) and the sensitivity measures for the response elicited in quiet and at +10 dB SNR in individuals with normal hearing and with ANSD

Parameter	Condition	Individuals with normal hearing				Individuals with ANSD			
		Mean	SD	Median	QD	Mean	SD	Median	QD
RT (ms)	Quiet	441.69	106.51	420.8	80.46	592.35	109.03	587.95	89.27
	+10 dB SNR	486.16	119.08	460	93.52	702	133.15	701.05	69.45
Sensitivity	Quiet	0.99	0.006	0.99	0.001	0.92	0.08	0.97	0.05
	+10 dB SNR	0.98	0.01	0.99	0.003	0.78	0.20	0.85	0.12

Note. SD = Standard Deviation, QD = Quartile Deviation, ms = millisecond.

Mann-Whitney U test revealed a significantly longer RT in individuals with ANSD compared to normal hearing individuals in both quiet ($z = 4.48$, $p < 0.001$) and at +10 dB SNR ($z = 4.94$, $p < 0.001$) with large effect size both in quiet ($r = 0.58$) and at +10 dB SNR ($r = 0.66$). Individuals with ANSD had significantly poorer sensitivity in identifying the oddball stimuli compared to individuals with normal hearing in both quiet ($z = 4.82$, $p < 0.001$) and at +10 dB SNR ($z = 5.47$, $p < 0.001$) with large effect size in quiet ($r = 0.63$) and at +10 dB SNR ($r = 0.71$). Wilcoxon signed-rank test revealed significantly better sensitivity and shorter reaction time in quite compared to +10 dB SNR in both the groups as shown in Table 4.8.

Table 4.8

Pair-wise comparison between quiet and at +10 dB SNR condition for individuals with normal hearing and with ANSD

	Listening conditions	RT (ms)		Sensitivity	
		Z value	r value	Z value	r value
Individuals with normal hearing	Quiet - +10 dB SNR	3.65**	0.66	3.06*	0.55
Individuals with ANSD	Quiet - +10 dB SNR	4.40**	0.86	3.64**	0.68

Note. * = $p < 0.01$, ** = $p < 0.001$, ms = millisecond, r = effect size.

Grand averaged ERP for /ba/-/da/ stimulus contrast in quiet and at +10 dB SNR are shown in Figure 4.6 and 4.7 for individuals with normal hearing and ANSD respectively. Last waveforms in Figure 4.6 and 4.7 show the GFP across time for two groups. From the Figure 4.6 and 4.7, it can be inferred that a positive peak (P300) was prominent in the waveform of deviant stimuli after 324 ms in normal hearing individuals and after 394 ms in individuals with ANSD. It can also be seen that GFP had a higher amplitude in 321ms to 420 ms time range in the deviant waveform for normal hearing individuals and in 360 ms to 541 ms time range in ANSD individuals compared to the waveform obtained in repetitive paradigm, confirming the presence of P300 in both the groups. Presence of P300 was further statistically confirmed by performing randomization test with 10,000 permutations at each time point between the waveforms obtained in oddball and repetitive paradigms. The waveforms had to differ significantly ($p < 0.05$) from each other for 70 continuous time-frames to demonstrate the persistence of differential effects as mentioned in the method. Results are depicted in the lower panel of Figure 4.6 and 4.7 for normal hearing and ANSD group respectively. In Figure 4.6 and 4.7, time is plotted on the x-axis and scalp electrode locations are plotted on the y-axis. The dark bars indicate the time frame and the electrodes at which there were significant

differences between the waveforms of frequent and infrequent stimuli. From Figure 4.6 and 4.7, it can be noticed that there were significant differences between the waveforms in oddball and repetitive paradigms in the time frame for conventional P300 (300 ms – 700 ms), specifically at the central and parietal electrodes.

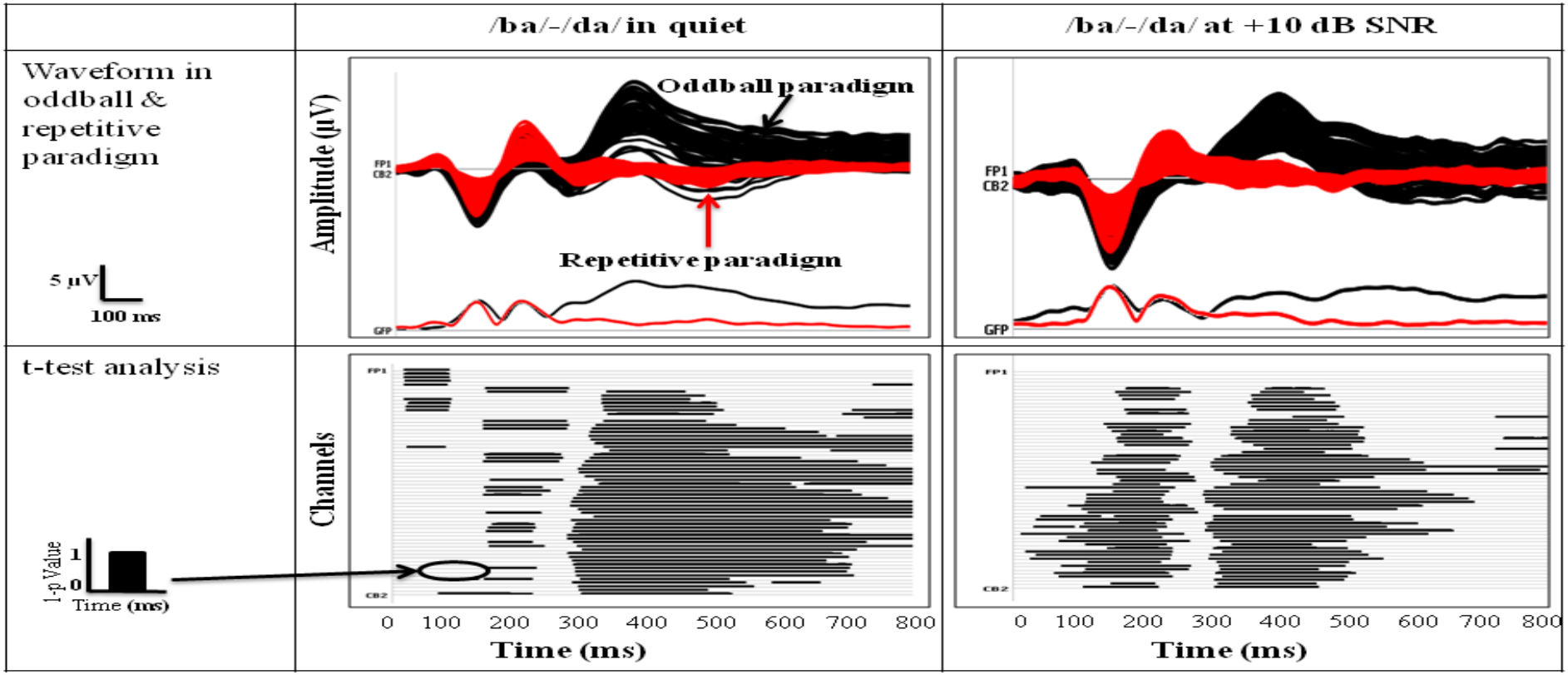


Figure 4.6. The grand average waveform obtained from individuals with normal hearing in response to deviant stimuli in oddball paradigm and same stimuli in repetitive paradigm in quiet and at +10 dB SNR. The dark shaded area in the lower panel shows the region of significant difference ($p < 0.05$) on point-wise paired randomization test. Time in ms is plotted on the x-axis and scalp electrode locations are shown on the y-axis in the bottom panel.

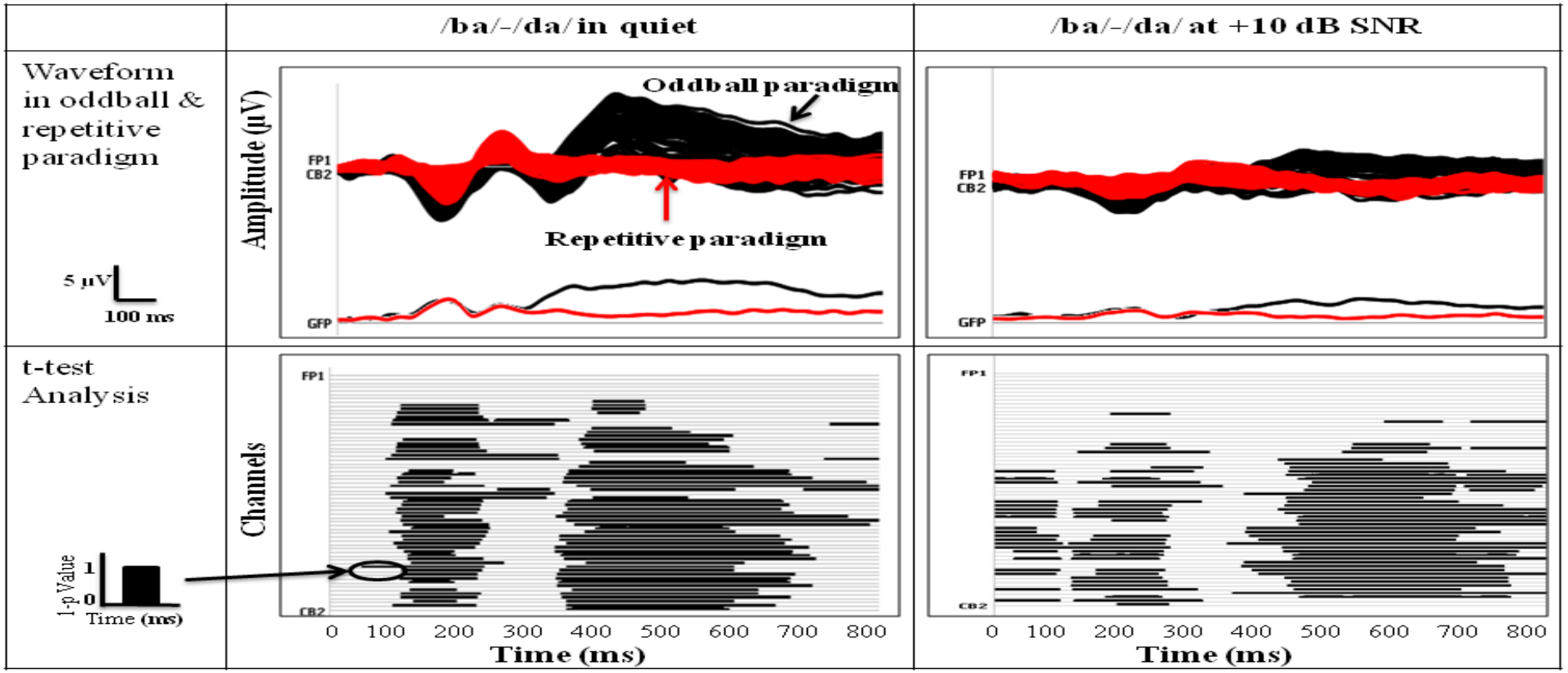


Figure 4.7. The grand average waveform obtained from individuals with ANSD in response to deviant stimuli in oddball paradigm and same stimuli in repetitive paradigm in quiet and at +10 dB SNR. The dark shaded area in the lower panel shows the region of significant difference ($p < 0.05$) on point-wise paired randomization test. Time in ms is plotted on the x-axis and scalp electrode locations are shown on the y-axis in the bottom panel.

4.3.5. P300 at + 10 dB SNR in individuals with normal hearing and with ANSD: Waveform analyses. P300 latency and the amplitudes measured at three midline electrodes, Fz, Cz, Pz are shown in Table 4.9. Latency and amplitude of P300 in quiet condition are provided in Table 4.5. Figure 4.8 shows the grand average waveform obtained in quiet and at +10 dB SNR in both the groups. From the Figure 4.8 and Table 4.9, it can be seen that P300 latency was prolonged and amplitude was reduced at +10 dB SNR compared to the quiet condition in both the groups.

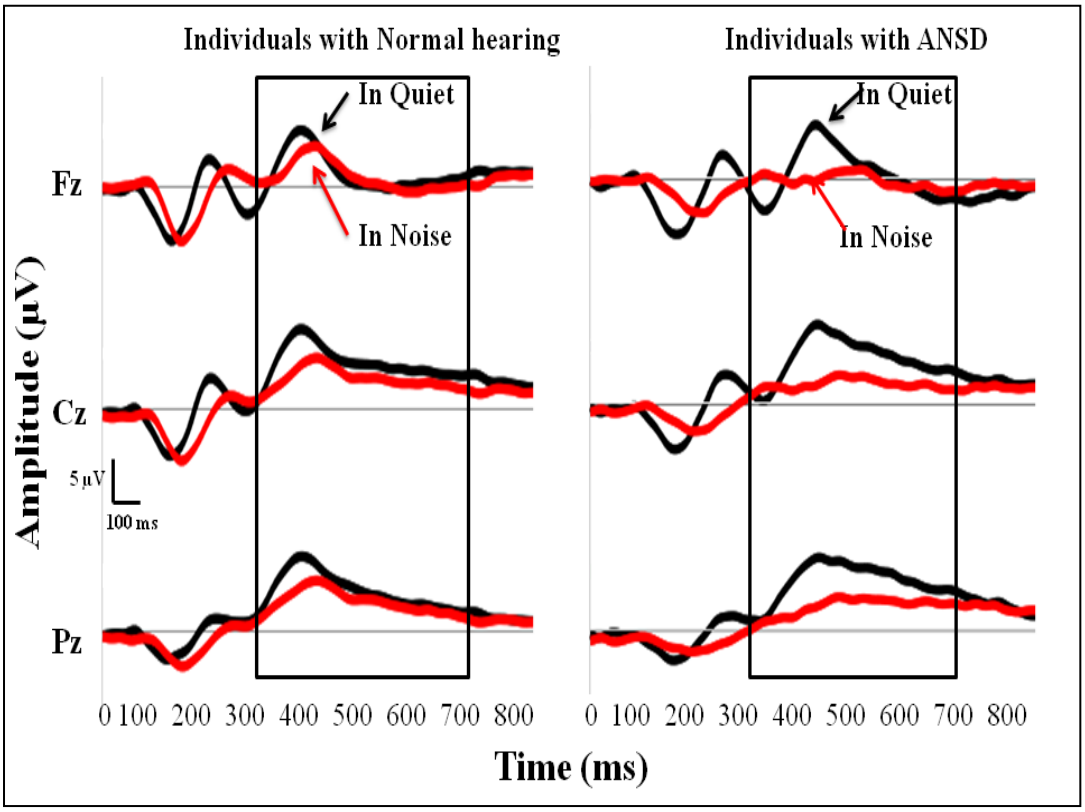


Figure 4.8. The P300 response obtained for stimulus contrast /ba/-/da/ in oddball paradigm in quiet (black trace) and at +10 dB SNR (red trace) for individuals with normal hearing and with ANSD. The positive peak in the time range of 300 ms to 700 ms (black boxes) show the presence of P300 peak.

Table 4.9

The latency and the amplitude of P300 response for stimulus pair /ba/-/da/ at +10 dB SNR in normal hearing individuals and with ANSD across three midline channels

Parameter	Channels	Individuals with normal hearing				Individuals with ANSD			
		Mean	SD	Median	QD	Mean	SD	Median	QD
Latency (ms)	Fz	395.17	25.33	396.5	11.25	459.47	45.35	446	27.5
	Cz	395.78	26.29	397	16.12	468.31	42.77	465	31.5
	Pz	402.17	31.87	405	20.75	467.89	36.66	465	21
Amplitude (μV)	Fz	7.15	4.60	7.89	3.76	4.52	4.98	2.50	3.15
	Cz	7.89	3.83	7.77	3.03	5.33	4.48	4.12	3.08
	Pz	7.46	3.81	8.01	3.62	5.41	3.66	4.15	1.93

Note. SD = Standard Deviation, QD = Quartile Deviation, ms = millisecond, μV = microvolt.

Table 4.10 shows the results of Mann-Whitney U test between two groups for latency and amplitude measures. Normal hearing individuals had significantly shorter latency and higher amplitude of P300 responses compared to individuals with ANSD at +10 dB SNR.

Table 4.10

Significance of difference for the latency and the amplitude of P300 response at +10 dB SNR across channels

Channels	Latency (ms)		Amplitude (μV)	
	Z value	r value	Z value	r value
Fz	4.54**	0.677	2.00*	0.298
Cz	5.03**	0.734	2.47*	0.360
Pz	5.02**	0.726	1.88	0.272

Note. * = $p < 0.05$, ** = $p < 0.001$, ms = millisecond, μV = microvolt, r = effect size.

Wilcoxon signed-rank test was done to analyze the statistical significance of differences in the latency and amplitude of P300 responses between quiet and at +10 dB SNR within each group. The results are shown in Table 4.11. From Table 4.11 it can be seen that P300 latency was significantly prolonged and amplitude was

significantly reduced in the presence of noise at the majority of electrode locations in both the groups.

Table 4.11

Pair-wise comparison between quiet and at +10 dB SNR condition for individuals with normal hearing and with ANSD

	Channels	Latency (ms)		Amplitude (µV)	
		Z value	r value	Z value	r value
Individuals with normal hearing	Fz	3.70***	0.71	1.89	0.36
	Cz	3.61***	0.68	2.71**	0.51
	Pz	3.99***	0.74	2.23*	0.41
Individuals with ANSD	Fz	3.23**	0.83	2.15*	0.55
	Cz	3.62***	0.83	2.33*	0.53
	Pz	3.28**	0.75	2.17*	0.50

Note. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ms = millisecond, µV = microvolt, r = effect size.

4.3.6. Effect of noise on P300 in individuals with normal hearing and with ANSD: Topographic pattern analyses. Figure 4.9 shows the results of spatiotemporal analyses of ERPs obtained in quiet and +10 dB SNR in both the groups. The figure shows the template maps along with the GFPs obtained from individuals with normal hearing and with ANSD in quiet and at +10 dB SNR. A total of 10 statistically significant clusters accounting for 87% of the variance in the collective group averaged data were observed. In both the group of individuals, there were centro-parietal positive topographies with minor but statistically significant variations during P300 time window. Scalp distribution was more diffused in individuals with ANSD compared to normal hearing individuals.

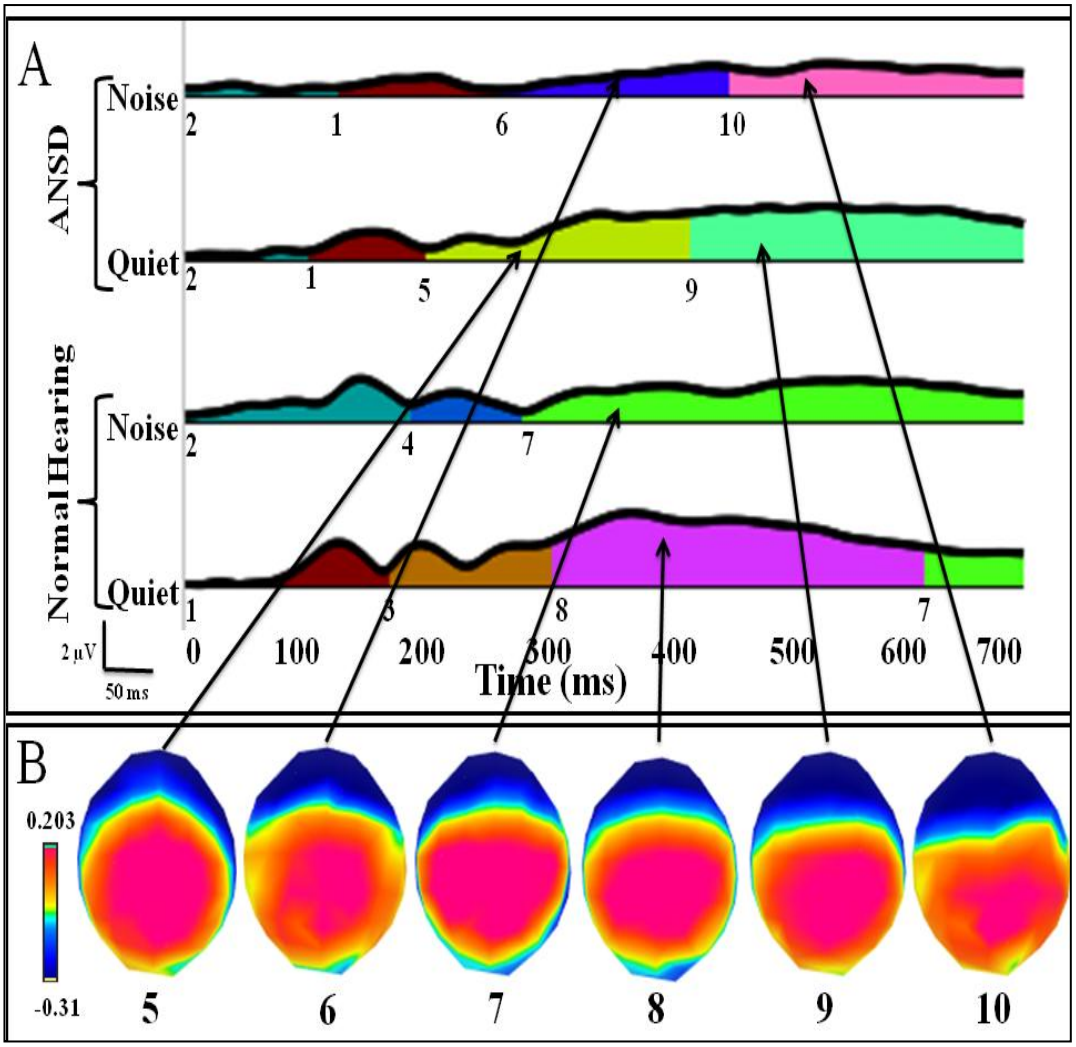


Figure 4.9. The result of topographic pattern analysis showing the time region at which statistically different template maps occurred as shown in Panel A. Panel B shows the six different templates which lie in the time region of P300.

4.3.7. Effect of amplification on P300 in individuals with normal hearing and with ANSD: General characteristics. The effect of amplification was assessed by recording P300 response to stimulus contrast /ba/-/da/ in quiet and at +10 dB SNR, with and without hearing aids in both the groups of individuals. Table 4.12 shows the RT and the sensitivity measures for both the groups in quiet aided and the noise aided conditions. The RT and the sensitivity measures in unaided conditions are given in Table 4.7.

Table 4.12

Reaction time (RT) and the sensitivity measures for the response elicited in quiet aided and in noise aided condition in normal hearing individuals and with ANSD

		Individuals with normal hearing				Individuals with ANSD			
		Mean	SD	Median	QD	Mean	SD	Median	QD
RT (ms)	Quiet Aided	486.90	128.71	472.5	99.87	636	128.46	588.10	102.6
	Noise Aided	514.66	151.53	459.95	122.13	720.71	720.71	111.98	75.30
Sensitivity	Quiet Aided	0.98	0.02	0.99	0.002	0.90	0.14	0.96	0.065
	Noise Aided	0.98	0.02	0.99	0.006	0.73	0.21	0.76	0.12

Note. SD = Standard Deviation, QD = Quartile Deviation, ms = millisecond.

Mann-Whitney U test showed that individuals with ANSD had significantly longer RT in quiet aided ($z = 3.78$, $p < 0.001$) and in noise aided ($z = 4.39$, $p < 0.001$) condition, with large effect size for quiet aided ($r = 0.50$) and noise aided ($r = 0.59$) compared to individuals with normal hearing. The individuals with ANSD showed significantly poorer sensitivity in quiet aided ($z = 4.91$, $p < 0.001$) and in noise aided ($z = 5.95$, $p < 0.001$) condition with large effect size for quiet aided ($r = 0.64$) and noise aided ($r = 0.78$) as compared to individuals with normal hearing. Wilcoxon signed-rank test revealed significantly shorter reaction time in quiet aided compared to noise aided condition in individuals with normal hearing. The individuals with ANSD showed better sensitivity and shorter reaction time in quite aided compared to noise aided condition as shown in Table 4.13.

Table 4.13

Pair-wise comparison between quiet aided and noise aided condition for individuals with normal hearing and with ANSD

	Listening conditions	RT (ms)		Sensitivity	
		Z value	r value	Z value	r value
Individuals with normal hearing	Quiet Aided-Noise Aided	2.09*	0.38	0.31	0.05
Individuals with ANSD	Quiet Aided-Noise Aided	3.64**	0.72	4.42**	0.83

Note. * = $p < 0.05$, ** = $p < 0.001$, ms = millisecond, RT = reaction time, r = effect size.

ERPs recorded for /ba/-/da/ stimulus contrast in quiet, in quiet aided, in noise and in noise aided condition are shown in Figure 4.8 and 4.9 for individuals with normal hearing and ANSD respectively. Last waveforms in the Figure show the GFP across time for two groups. From the Figure, it can be inferred that a positive peak (P300) was prominent in the waveform of deviant stimuli after 330 ms in normal hearing individuals and after 380 ms in individuals with ANSD in quiet aided condition. In noise aided condition, a positive peak was prominent in the waveform of deviant stimuli after 350 ms in normal hearing and after 423 ms in individuals with ANSD. Presence of P300 was further statistically confirmed by performing randomization test with 10,000 permutations at each time point between waveforms obtained in oddball and repetitive paradigms. The waveforms had to differ significantly ($p < 0.05$) from each other for 70 continuous time-frames to demonstrate the persistence of differential effects as mentioned in the method. This analysis was carried out using Cartool software and results are depicted in the lower panel of Figure 4.10 and 4.11 for normal hearing and ANSD individuals respectively. The dark bars indicate the time frame and the electrodes at which there were significant differences between the waveforms of frequent and infrequent stimuli.

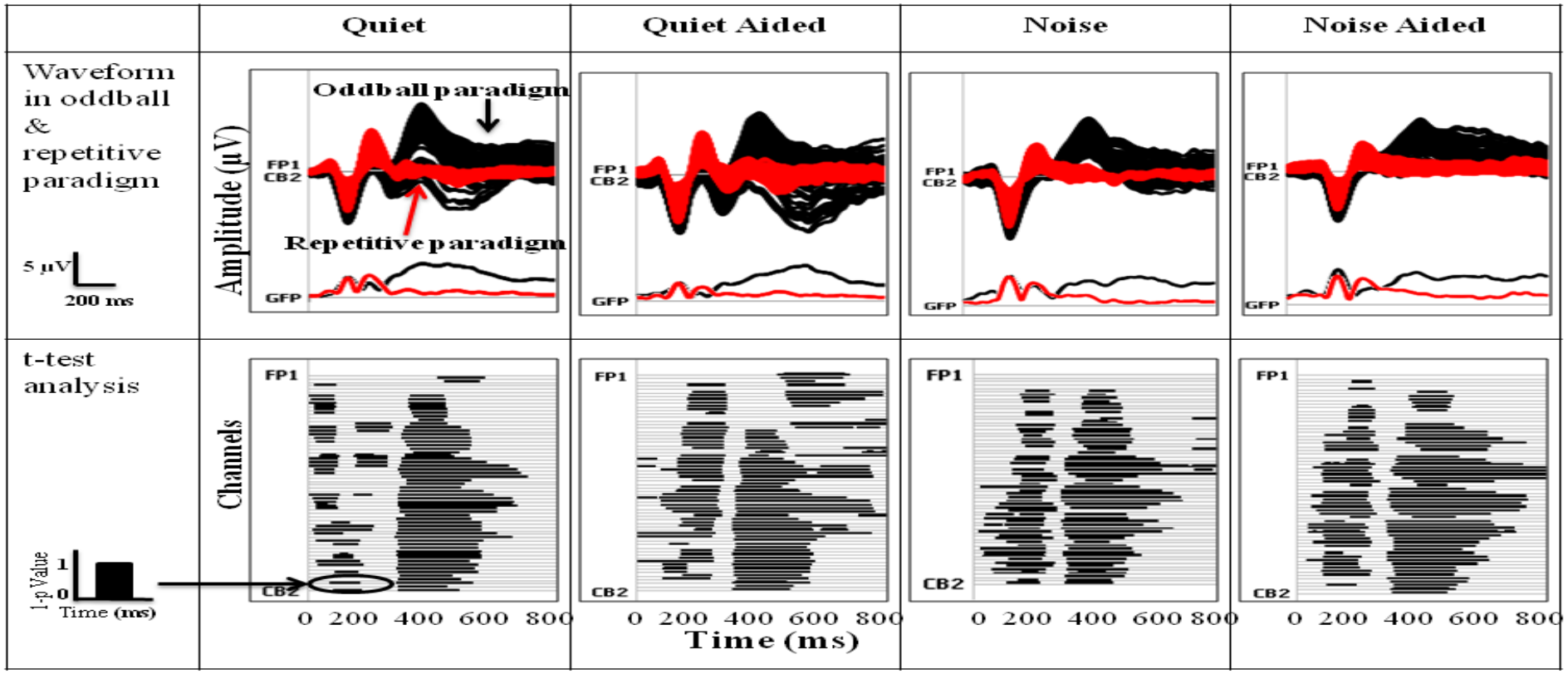


Figure 4.10. The grand average waveform obtained from individuals with normal hearing in response to stimulus pairs /ba/-/da/ in oddball paradigm (black tracing) and to /da/ in repetitive paradigm (red tracing) in quiet, in quiet aided, in noise and in noise aided condition. The dark shaded area in the lower panel shows the region of significant difference ($p < 0.05$) on point-wise paired randomization test. Time in ms is plotted on the x-axis and channel locations are shown on the y-axis in the bottom panel.

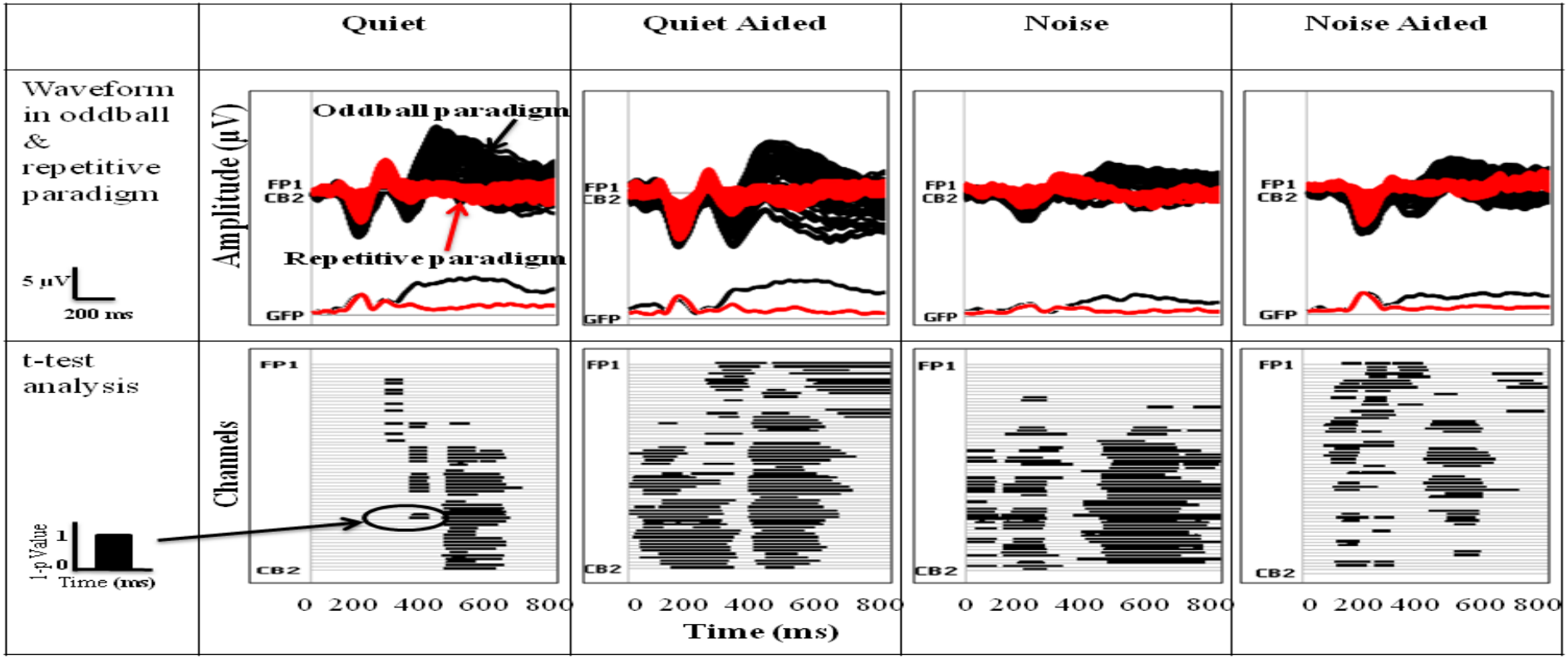


Figure 4.11. The grand average waveform obtained from individuals with ANSD in response to stimulus pair /ba/-/da/ in oddball paradigm (black tracing) and to /da/ in repetitive paradigm (red tracing) in quiet, in quiet aided, in noise and in noise aided condition. The dark shaded area in the lower panel shows the region of significant difference ($p < 0.05$) on point-wise paired randomization test. Time in ms is plotted on the x-axis and channel locations are shown on the y-axis in the bottom panel.

4.3.8. Effect of Amplification on P300 in individuals with normal hearing and with ANSD: Waveform analyses. Figure 4.12 shows the grand averaged ERP waveforms with and without hearing aids in normal hearing and individuals with ANSD at three midline electrodes.

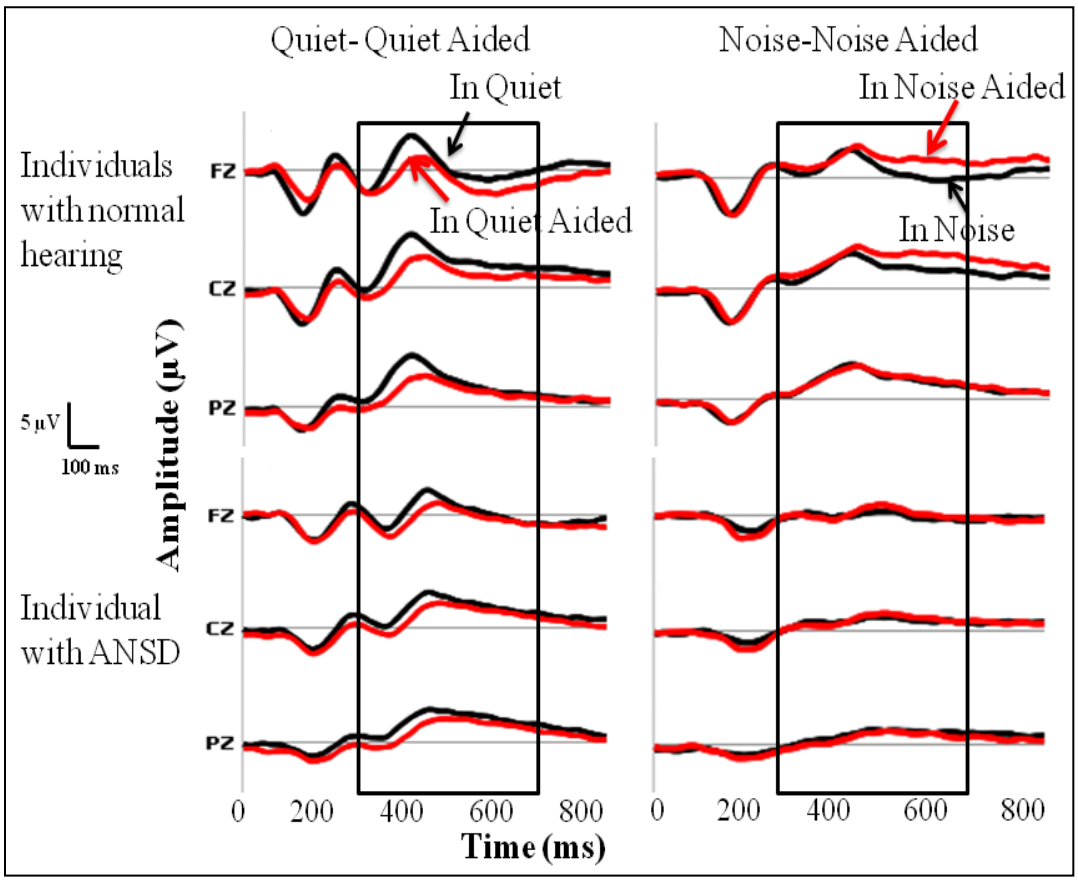


Figure 4.12. The P300 response obtained for stimulus pair /ba/-/da/ in quiet (black tracing) and in quiet aided (red tracing) condition and in noise (black tracing) and in noise aided (red tracing) condition in individuals with normal hearing and with ANSD. The positive peak in the time range of 300 ms to 700 ms (black boxes) show the presence of P300 peak.

Table 4.14 shows the latency and amplitudes of P300 in quiet and at +10 dB SNR with hearing aids. Latency and amplitude values without hearing aid in quiet and noise are given in Table 4.5 and 4.9. As evident from the Table 4.14, with the hearing aids latency was shorter and amplitude was less in quiet condition compared to + 10 dB SNR in both normal hearing and ANSD.

Table 4.14

The latency and the amplitude of P300 response elicited in quiet aided and in noise aided condition across three midline channels (Fz, Cz, and Pz) for both the groups

	Condition	Channel	Individuals with normal hearing				Individuals with ANSD			
			Mean	SD	Median	QD	Mean	SD	Median	QD
Latency (ms)	Quiet Aided	Fz	384.10	25.54	381.50	16	433	39.66	424.5	26.37
		Cz	388.96	25.60	391	18.5	437.92	39.74	428	35.87
		Pz	392.25	32.60	392	18.25	441.69	39.56	437	37.12
	Noise Aided	Fz	409.14	31.11	405	15	475.46	41.58	462	26
		Cz	416.20	34.44	411	13.75	474.41	43.09	459	35.5
		Pz	413.58	30.62	411	19.5	480.07	50.82	478.5	45.12
Amplitude (µV)	Quiet Aided	Fz	6.22	3.99	4.85	2.77	4.90	3.43	3.95	2.06
		Cz	7.31	4.89	6.10	7.19	6.16	4.66	4.80	3.06
		Pz	7.05	3.42	6.23	2.34	5.89	5.27	4.62	3.28
	Noise Aided	Fz	7.88	5.51	6.85	4.37	4.85	3.38	4.6	3.72
		Cz	8.99	4.90	9.47	3.63	5.42	4.08	3.78	3.60
		Pz	7.57	3.95	8.43	3.51	5.35	4.07	3.64	4

Note. SD = Standard Deviation, QD = Quartile Deviation, ms = millisecond, µV = microvolt.

Table 4.15 shows the results of Mann-Whitney U test done to compare latency and amplitude between two groups. From the Tables 4.14 and 4.15, it can be seen that individuals with ANSD had prolonged P300 latency (in all three midline electrodes) and reduced P300 amplitude (at Cz) in both quiet and at +10 dB SNR with the hearing aids.

Table 4.15

Significance of difference for the latency and amplitude parameters of individuals with normal hearing and with ANSD at three channels (Fz, Cz, and Pz) in quiet aided and in noise aided conditions

Channels	Conditions	Latency (ms)		Amplitude (μV)	
		Z value	r value	Z value	r value
Fz	Quiet Aided	4.01**	0.62	1.03	0.15
	Noise Aided	4.32**	0.66	1.66	0.25
Cz	Quiet Aided	4.59**	0.62	0.90	0.12
	Noise Aided	4.49**	0.66	2.46*	0.36
Pz	Quiet Aided	4.28**	0.58	1.78	0.24
	Noise Aided	4.16**	0.63	1.68	0.25

Note. * = $p < 0.05$, ** = $p < 0.001$, ms = millisecond, μV = microvolt, r = effect size.

Further, Wilcoxon signed-rank test was carried out to assess the statistical significance of differences in amplitude and latency of P300 with and without hearing aids within the group and the result is shown in Table 4.16. P300 latency was significantly prolonged in both the groups with the hearing aids in the quiet condition. In normal hearing listeners, with the hearing aids P300 amplitude was also significantly reduced compared to unaided condition. However, there was no significant difference in the latency and amplitude of P300 with and without hearing aids at +10 dB SNR in individuals with ANSD.

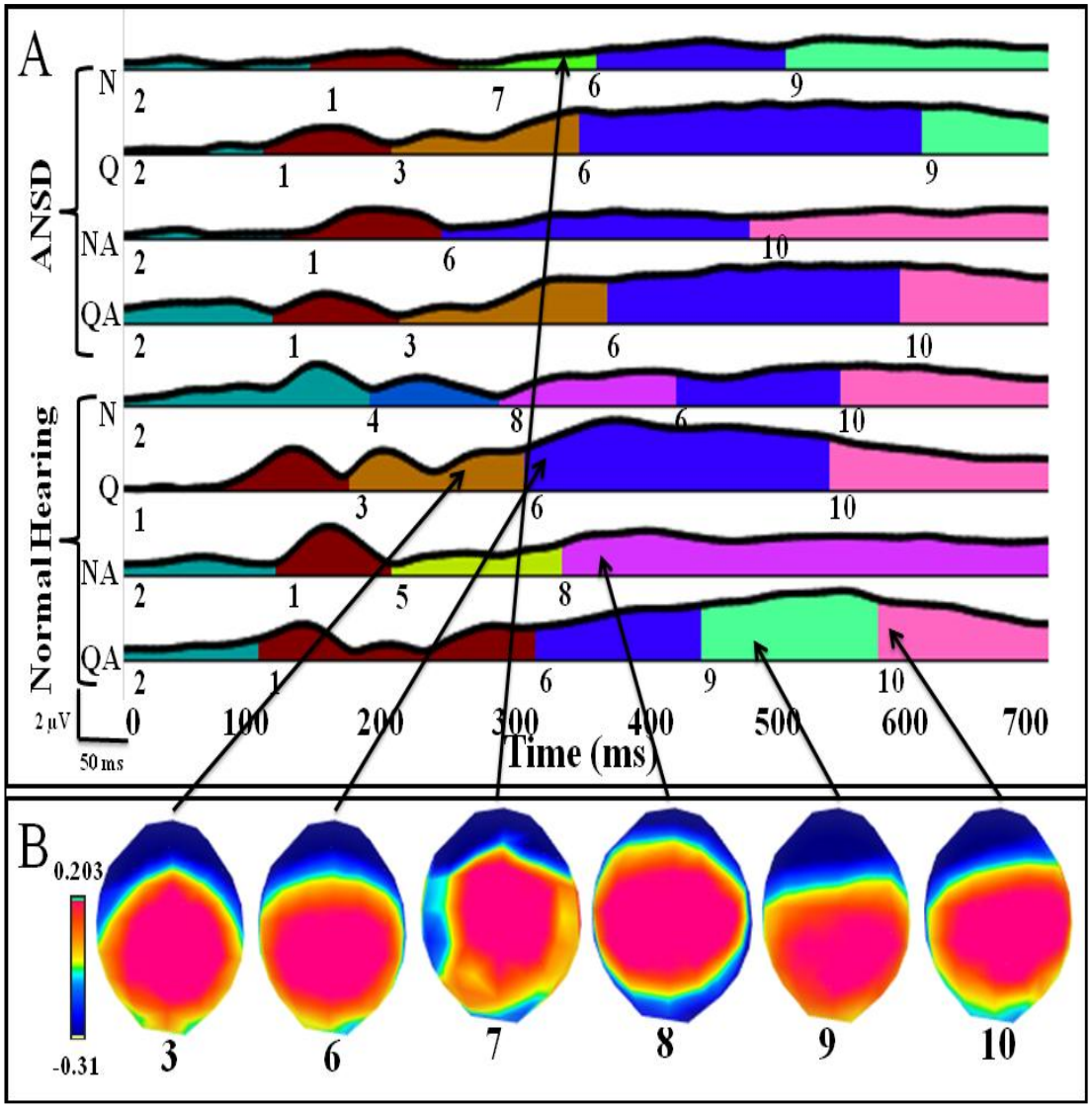
Table 4.16

Pair-wise comparison between unaided and aided condition for individuals with normal hearing and with ANSD

	Conditions	Channels	Latency (ms)		Amplitude (µV)	
			Z value	r value	Z value	r value
Individuals with normal hearing	Quiet-Quiet	Fz	2.73**	0.62	3.13**	0.72
		Cz	3.96***	0.74	3.14**	0.59
	Aided	Pz	3.88***	0.73	3.38**	0.63
	Noise-Noise	Fz	2.37*	0.46	0.34	0.06
		Cz	2.33*	0.44	2.79**	0.53
	Aided	Pz	2.09*	0.39	0.182	0.03
Individuals with ANSD	Quiet-Quiet	Fz	2.90**	0.63	1.82	0.39
		Cz	3.31**	0.64	1.10	0.21
	Aided	Pz	1.88	0.36	1.18	0.32
	Noise-Noise	Fz	0.49	0.12	0.24	0.06
		Cz	0.99	0.27	0.73	0.19
	Aided	Pz	0.45	0.12	1.43	0.39

Note. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ms = millisecond, µV = microvolt, r = effect size.

4.3.9. Effect of amplification on P300 in individuals with normal hearing and with ANSD: Topographic pattern analyses. The spatiotemporal analysis was done using the Cartool software. Spatial cluster analysis was performed on group averaged waveforms obtained from both the groups of individuals for the stimulus pairs /ba/-/da/. Figure 4.13 shows the segmentation file highlighting the GFPs for individuals with normal hearing and with ANSD in both listening and amplification conditions. A total of 10 clusters accounting for 87% of the variance with the collective group averaged data were observed. Six significantly different templates in the time region of P300 (300ms to 700 ms) were identified and the topographies for all the six templates are shown in lower panel of Figure. There was centro-parietal activation of the scalp with little variation across templates in the P300 region for both the groups of individuals.



Note: Q= Quiet, QA= Quiet Aided, N= Noise, NA= Noise Aided

Figure 4.13. The result of topographic pattern analysis showing the time region at which statistically different template maps occurred as shown in Panel A. Panel B shows six different maps obtained in the P300 time region for the different GFPs.

4.4. Relationship between behavioral measures and electrophysiological measures in individuals with normal hearing and with ANSD

This section addresses the objective 4 - to investigate the relationship between behavioural measures (SNR-50, RT and Sensitivity) and electrophysiological measures (latency and amplitude of P300 response) in individuals with normal hearing and with ANSD. Spearman's rank correlation analysis was performed

between behavioural and electrophysiological measures to find the relationship between behavioral measures (SNR-50, RT and Sensitivity) electrophysiological measures (latency and amplitude). Correlational analyses were done separately for both the groups. Table 4.17 shows the correlational coefficient and significance levels between behavioral and electrophysiological measures in individuals with normal hearing and with ANSD in quiet and at +10 dB SNR. In normal hearing listeners, there was significant positive correlation between the reaction time and latency of the P300, and significant negative correlation between SNR-50 and the amplitude of P300 response at Pz in quiet condition. RT also showed negative correlation with amplitude of P300 at Fz and Cz electrode location in quiet. In noise, there was significant positive correlation between sensitivity and the amplitude of P300 response and significant negative correlation between RT and the amplitude of P300 at all the three electrodes. Furthermore, in individuals with ANSD there was significant positive correlation between reaction time in quiet and latency of P300 at all three electrodes. Sensitivity and amplitude of P300 showed positive correlation in presence of noise. RT showed significant positive correlation with the latency at Pz electrode. There were no other systematic significant correlations observed.

Table 4.17

Correlation analysis result for the behavioral measures (SNR-50, RT and Sensitivity) and the electrophysiological measures (latency and amplitude) in quiet and at +10 dB SNR for individuals with normal hearing and with ANSD

		Parameter	Latency (ms)			Amplitude (μV)		
			Fz	Cz	Pz	Fz	Cz	Pz
In quiet	Individuals with normal hearing	SNR-50	0.138	0.151	0.265	-0.218	-0.196	-0.460*
		RT	0.367	0.435*	0.457*	-0.636**	-0.527**	-0.353
		Sensitivity	-0.267	-0.237	-0.182	-0.040	-0.133	-0.014
	Individuals with ANSD	SNR-50	0.163	0.255	0.222	0.104	0.206	0.268
		RT	0.435*	0.418*	0.534**	-0.243	-0.154	-0.209
		Sensitivity	-0.156	-0.290	-0.230	0.364	0.379	0.342
At +10 dB SNR	Individuals with normal hearing	SNR-50	-0.157	-0.156	0.048	-0.237	-0.068	-0.216
		RT	0.177	0.188	0.452*	-0.436*	-0.652**	-0.658**
		Sensitivity	-0.292	-0.301	-0.207	0.378*	0.471*	0.347
	Individuals with ANSD	SNR-50	0.070	0.073	0.077	0.107	0.116	-0.021
		RT	0.214	0.356	0.457*	-0.417	-0.309	-0.319
		Sensitivity	0.081	-0.128	-0.109	0.519*	0.650**	0.602**

Note. * = $p < 0.05$, ** = $p < 0.01$, RT = Reaction time

Scatter plots depicting the significant correlation between the behavioral measures (SNR-50, RT, and sensitivity) and the electrophysiological measures (latency and amplitude of P300) in individuals with normal hearing and with ANSD are shown in Figure 4.14 and 4.15 respectively.

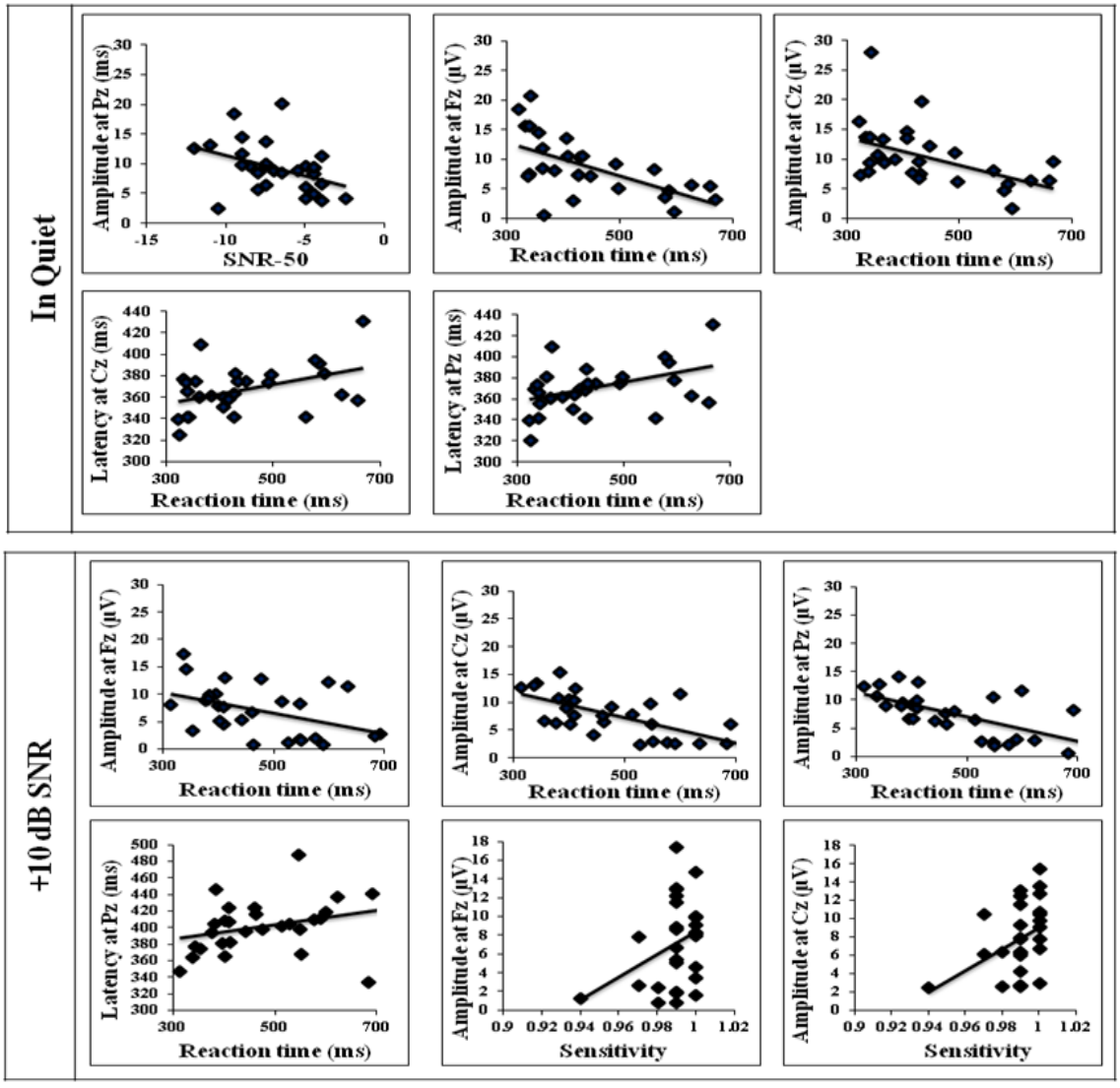


Figure 4.14. Scatter plots showing the significant correlation between behavioral measures (reaction time and SNR-50) and electrophysiological measures (latency and amplitude of P300) in individuals with normal hearing in quiet and at +10 dB SNR.

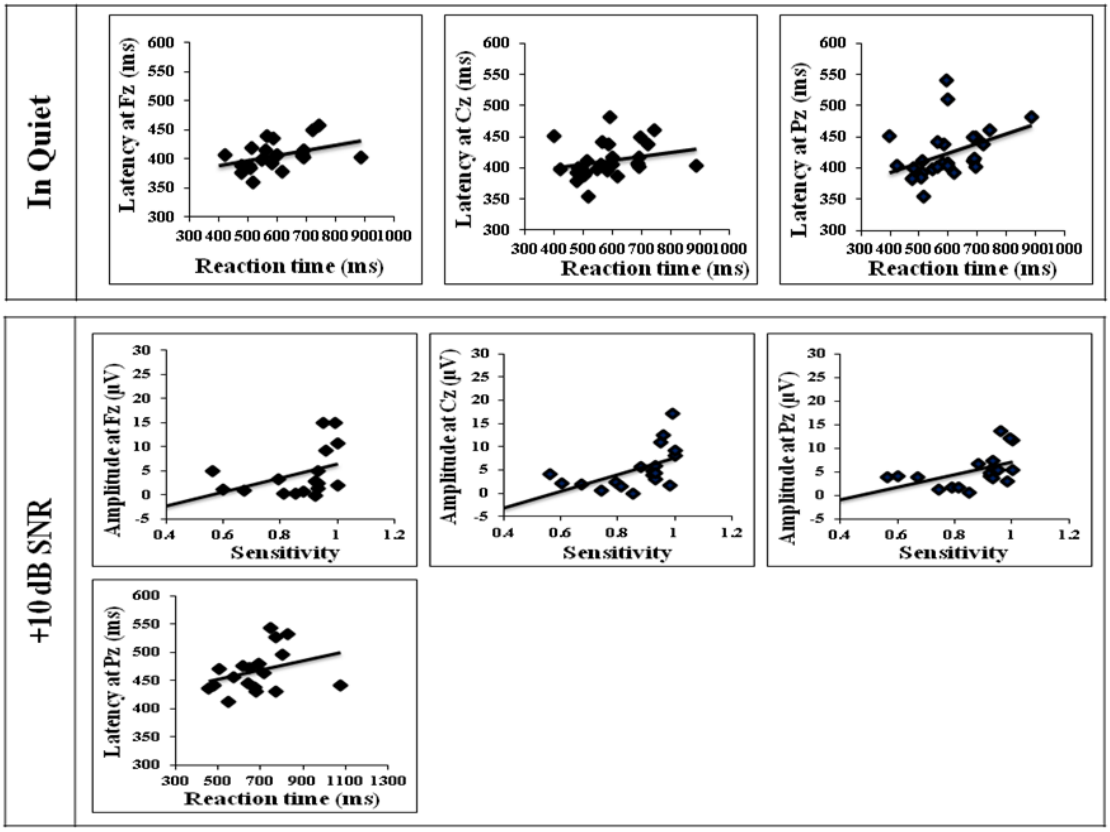


Figure 4.15. Scatter plots showing the significant correlation between behavioral measures (reaction time and sensitivity) and electrophysiological measures (latency and amplitude of P300) in individuals with ANSD in quiet and at +10 dB SNR.

Test-Retest reliability of SNR-50 and P300 parameters

Seven of the participants were retested on SIN (SNR-50) and P300. Cronbach's Alpha was used to check test-retest reliability of latency, amplitude measures of P300 response and SNR-50 obtained from SIN test. The result showed alpha values in the range of 0.677 to 0.694 for the latency and 0.516 to 0.662 for the amplitude parameters of P300 response for 3 midline channels. The SNR-50 showed Cronbach's Alpha value of 0.990 in the unaided condition and value of 0.994 in the aided condition.

Chapter 5

Discussion

Results indicated that individuals with auditory neuropathy spectrum disorder (ANSD) had poor speech perception skills than normal hearing listeners. Speech perception skills deteriorated drastically in the presence of noise in individuals with ANSD compared to normal hearing listeners. Use of amplification device did not improve the speech perception skills significantly in individuals with ANSD. Reliable cortical evoked P300 could be recorded from individuals with ANSD. However, latency, amplitude and scalp topography of P300 differed significantly in individuals with ANSD from that of normal hearing listeners. The results of all the measures are discussed under following headings.

5.1. Comparison of syllable identification scores between individuals with normal hearing sensitivity and with ANSD.

5.2. Comparison of speech identification scores obtained with and without amplification device in individuals with normal hearing sensitivity and with ANSD.

5.3. Comparison of P300 responses in terms of amplitudes, latency and scalp topographies between individuals with normal hearing sensitivity and with ANSD.

5.3.1. P300 in quiet in individuals with normal hearing and with ANSD.

5.3.2. P300 at + 10 dB SNR in individuals with normal hearing and with ANSD.

5.3.3. Effect of amplification on P300 in individuals with normal hearing and with ANSD.

5.4. Relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD.

5.1. Comparison of syllable identification scores between individuals with normal hearing sensitivity and with ANSD

Syllable identification skills were assessed using four syllables differing in phonetic features, the place (/ba/-/da/), the manner (/ba/-/ma/), and the voicing (/ba/-/pa/). Individuals with normal hearing showed near perfect identification scores in both quiet and at +10 dB signal-to-noise ratio (SNR). Identification abilities of individuals with ANSD were significantly poorer compared to normal hearing listeners. The poor performance of individuals with ANSD is not due to the reduced audibility of the stimulus. This is because the stimulus was presented at the suprathreshold intensity and all the participants reported hearing the stimuli at a comfortable level. Individuals with ANSD showed confusions in the perception of all the stimuli in quiet and confusion was more evident in the presence of noise. **S**equential **INF**ormation **A**nalysis (SINFA) revealed that individuals with ANSD had greater difficulty in perceiving voicing cues compared to place and manner cues. Hence null hypothesis 1, "*There is no statistically significant difference between speech identification scores of individuals with normal hearing sensitivity and individuals with ANSD*", is rejected.

One of the major cues for voicing in word/syllable initial position is voice onset time (VOT). The VOT is a short segment low-frequency cue (Summerfield & Haggard, 1977). Previous studies have shown that individuals with ANSD have difficulty in processing short duration speech cues such as VOT (Kumar & Jayaram, 2011, 2013;

Narne & Vanaja, 2008a; Narne et al., 2015). Furthermore, in Kannada, voicing is cued by low frequency voicing pulses and/or pre-voicing. Coding of low frequency is thought to be augmented by the use of temporal information, especially phase locking of neural impulses to the input signal (Greenberg, 1996). It's been reported that individuals with ANSD have difficulty in using the neural phase locking cues to the same extent as normal hearing listeners (Rance et al., 2004). This physiological limitation would have resulted in the poor perception of voicing in individuals with ANSD. Perception of place feature was also affected in individuals with ANSD. Similar results are reported by other investigators as well (Narne & Vanaja, 2008a; Narne et al., 2015). The poor perception of place information in individuals with ANSD may be due to difficulty in coding short duration segmental cues such as burst amplitude and formant transition (Kumar & Jayaram, 2011; Lahiri, Gewirth, & Blumstein, 1984; Ohde & Stevens, 1983).

5.2. Comparison of speech identification scores obtained with and without amplification device in individuals with normal hearing sensitivity and with ANSD

Signal-to-noise ratio necessary to understand 50% of the speech was significantly poorer in individuals with ANSD compared to normal hearing listeners. Similar results are reported by other investigator too (Narne et al., 2015). It's been reported that addition of noise reduces the speech identification scores dramatically in individuals with ANSD. It's been hypothesised that addition of noise reduces the amplitude fluctuations in speech. This affects the perception of segmental cues resulting in a smearing of the consonant-vowel distinction. Thus, the addition of noise to the speech signal reduces the modulations and adds spurious modulations, aggravating the speech

perception deficits seen in individuals with ANSD. However, the exact physiological reasons responsible for poor speech perception in noise in individuals with ANSD are unclear at present. Use of hearing aids did not improve the speech identification scores significantly in both the groups. Hence, null hypothesis 2, "*There is no statistically significant difference between the speech identification scores of individuals with ANSD with and without amplification device*", is accepted.

The poor speech perception in individuals with ANSD has been primarily attributed to poor temporal processing skills (Rance et al., 2004; Zeng et al., 2005, 1999) and not to audibility, use of hearing aids may not have improved the speech perception in individuals with ANSD. It is known that current day hearing aids only amplify the speech and does not enhance the temporal information. No or limited benefit with the hearing aid in individuals with ANSD is reported by other investigators as well. Jijo and Yathiraj (2013) reported improvement in speech perception with the use of hearing aids in only 30% of the individuals with late-onset ANSD. Similarly, Narne et al. (2014) reported hearing aids to be useful in only 39 (30%) out of 128 individuals with ANSD. Out of the 39 individuals, only 26 individuals showed functional benefit from the hearing aids and for rest 13 individuals, it was useful only for the sound detection and awareness. Jijo and Appu (2015) also reported that hearing aids are not effective in improving speech perception in individuals with ANSD.

5.3. Comparison of P300 responses in terms of amplitudes, latency and scalp topographies between individuals with normal hearing sensitivity and with ANSD

The P300 latency, amplitude, and the scalp topography were analyzed for both the groups. The response to target (/da/, /ma/, and /pa/) in oddball paradigm and the

response in repetitive paradigm were compared. In general, P300 peak with its typical characteristics was present in both the groups. However, latency was prolonged and amplitude was reduced in individuals with ANSD. Behavioural results indicated that in all the conditions (quiet, at +10 dB SNR and with hearing aids) listeners of both the groups were able to discriminate the infrequent stimuli with a high level of accuracy. However, the reaction time (RT) was significantly longer in individuals with ANSD compared to normal hearing listeners. Good accuracy while discriminating the contrasts emphasizes the fact that the observed neural differences between two groups are due to differential processing and not because of successful and unsuccessful comparisons and memory updating process. Hence null hypothesis 3, "*There is no statistically significant difference between individuals with normal hearing sensitivity and with ANSD in terms of amplitude, latency and scalp topographies of P300"*, is rejected.

5.3.1. P300 in individuals with normal hearing and with ANSD. In comparision with normal hearing listeners, latency was prolonged and amplitude of P300 peak was reduced in individuals with ANSD for all the three contrasts. P300 latency reflects the time taken from the onset of the signal to the perceptual decision that an event has occurred (Duncan et al., 2009; Picton, 1992). Kutas and Dale (1997) suggested the relationship between the reaction time and the latency of the evoked response. The prolongation in the RT without any change in the P300 latency could be because of the inability in response selection or execution. On the other side, if the P300 latency along with RT shows prolongation, there might be difficulty in stimulus evaluation process (Kutas & Dale, 1997). In the present study, both the RT and the latency were prolonged in individuals with ANSD showing difficulty in speech sound

discrimination. Auditory cortical single unit data have revealed the sensitivity of cortical neurons more to the temporal cues than the intensity cues (Phillips, 1990). Since in individuals with ANSD, temporal cues are poorly represented, may lead to the prolonged latency of the P300 response.

P300 amplitude reflects the information transmission during the stimulus presentation process (Johnson, 1988; Sutton, Braren, Zubin, & John, 1965). The amount of information transferred is inversely proportional to the degree of uncertainty in perceiving an event. Reduced amplitude of P300 indicates increased uncertainty in the evaluation of the stimulus in individuals with ANSD. This could be because of the distorted peripheral input to the auditory system. Prolongation of latency and reduction in the amplitude of obligatory cortical potentials are reported by other investigators as well (Abdeltawwab, 2014; Narne et al., 2014; Yuvaraj & Jayaram, 2016). Narne and colleague (2014) reported Long Latency Response (LLR) to be present in 65% of the ears evaluated. Out of the 65% ears with LLR present, the latencies showed prolongation in 36% of the ears. They concluded the presence of LLR to be a good predictor of speech perception ability in quiet in spite of abnormal brainstem response. The spatiotemporal analysis of the P300 response showed centro-parietal scalp topography in both the groups. The pattern of activation seen in listeners with normal hearing is similar to that observed by several other researchers (Picton, 1992; Polish, 2003; Swick, Kutas, & Neville, 1994). The topography of individuals with ANSD was similar to that seen in normal hearing listeners.

5.3.2. P300 at + 10 dB SNR in individuals with normal hearing and with ANSD

ANSD. P300 with its typical characteristics could be elicited at +10 dB SNR in both the groups. In both the groups, amplitude of P300 was reduced and latency was prolonged in the presence of noise compared to the quiet condition. Moreover, in individuals with ANSD morphology of P300 response was severely affected by the noise. Prolongation of latency in presence of noise indicates that listeners required more time to detect and respond to the target stimulus (Kutas et al., 1977; Magliero et al., 1984). The prolonged latency of P300 implies the sluggish in the decision making process, could also be the result of slowness in the neural conduction velocity. P300 amplitude depends on the attention allocated to the task and the memory load. P300 amplitude reduces with increase in memory load as the task processing demands increases (Donchin & Coles, 1988). Current results show that in presence of noise task processing demands were more in individuals with ANSD and amplitude of P300 decreased drastically affecting the morphology of P300.

Spatiotemporal analysis showed differential scalp topography between quiet and noise conditions in both the groups. In normal hearing listeners scalp topography that was seen in the presence of noise was significantly different from that of quiet from the onset of stimuli. However, in individuals with ANSD differential topography could be observed only from 200 ms post stimulus. In P300 region, centro-parietal positive topography (though with minor variations) was seen in both quiet and noise conditions. However, in individuals with ANSD more diffused scalp topography was seen from 264 ms onwards which was significantly different from that of normal hearing listeners. From these results it can be inferred that there was a differential distribution of electrical

field between two conditions in both the groups. The difference between the two conditions (quiet and noise) in scalp topographies was more in individuals with ANSD. It is a known fact that changes in the electrical topography on the scalp can only be caused by changes in the configuration of underlying brain sources (Song et al., 2015). And hence the time regions where topographical differences were observed between two conditions and groups represent the differential activation of brain network. Furthermore, it should also be kept in mind that same scalp topographies cannot be interpreted as same neural generators due to non-uniqueness of inverse solution problem.

5.3.3. Effect of amplification on P300 in individuals with normal hearing and with ANSD. The P300 responses were recorded using stimulus pair /ba/-/da/ in quiet and in noise, with and without hearing aids in both the groups. Use of hearing aids resulted in reduced amplitude and prolongation of P300 peak in normal hearing listeners. However, use of hearing aids did not result in significant changes in latency (except at Fz and Cz) and amplitude of P300 peak in individuals with ANSD. There are reports of the limited usefulness or even detrimental effects of hearing aids on individuals with ANSD (Jijo & Yathiraj, 2013a; Starr et al., 1996). In Narne et al. (2014) study, hearing aids were used by 39 individuals out of total 128 individuals with ANSD. Out of 39 individuals, 26 individuals showed functional improvement whereas 13 individuals showed limited benefit which was confined only to sound detection and awareness. Of those 26 individuals with presence of LLR, speech understanding was also found to be better in them than the rest 13 individuals who did not show LLR.

Vanaja and Manjula (2002) reported LLR to be present in three individuals, who showed improvement on aided speech identification scores. Individuals who performed poor on speech identification task in aided condition also showed the absence of LLR. The feature of the hearing aids (linear versus non-linear compression circuit) also has an effect on the speech perception. Linear amplification circuit is recommended for individuals with ANSD as the use of non-linear compression circuit in the hearing aids results in deterioration in performance of individuals with ANSD (Jijo & Appu, 2015; Rance et al., 2002; Starr et al., 1996) as it reduces the amplitude fluctuation in the spectral envelope of the speech signal and thus reduces the contrast between the consonant and the vowels and also decreases the overall signal-to-noise ratio (Narne & Vanaja, 2008a; Rance et al., 2004). Several researchers have suggested the use of low gain and wide dynamic range hearing aids (Rance et al., 1999, 2002). The extent of temporal processing impairment in the individuals with ANSD decides the benefit from the hearing aids.

5.4. Relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD

In normal hearing listeners, RT correlated significantly with the latency and amplitude of P300 peak. The nature of the correlation was such that individuals with higher amplitude and shorter P300 latency, were faster in identifying the infrequent stimuli. This relationship between amplitude and RT was maintained even in the presence of + 10 dB SNR in normal hearing listeners. Scatter plots of the data revealed that correlations are not spurious. Longer reaction time along with prolonged latency of

the P300 reflects the speed with which individuals carried out the stimulus evaluation process. In normal hearing listeners, significant positive relationship between sensitivity and amplitude of P300 shows that the individuals with higher amplitude of P300 are more sensitive in identifying the stimuli. It may be recalled that, normal hearing listeners had near perfect scores in identifying the infrequent stimulus both in noise and in quiet.

Individuals with ANSD demonstrated the significant positive correlation between sensitivity and amplitude of P300. Individuals with larger P300 amplitude were better in identifying the infrequent stimulus. Amplitude of P300 reflects the amount of information processed and larger amplitude indicates the better evaluation and categorization of the stimulus. Our results indicate that individuals with ANSD who had higher P300 amplitude were better able to evaluate and categories the infrequent stimulus. P300 amplitudes in individuals with ANSD may reflect their ability in discrimination of speech sounds, especially in noise. Hence null hypothesis 4, "*There is no statistically significant relationship between behavioural measures and electrophysiological measures in individuals with normal hearing sensitivity and with ANSD"*, is rejected.

Chapter 6

Summary and Conclusions

The present study investigated the cortical representation of speech in individuals with normal hearing and with auditory neuropathy spectrum disorder (ANSD) in both quiet and in the presence of noise. This study also investigated the usefulness of amplification on the speech perception skills in individuals with normal hearing and with ANSD. The speech perception skill was assessed using behavioural measure (syllable identification and speech in noise) and electrophysiological measures (P300). Correlational approach was used to investigate the relationship between behavioural and electrophysiological measures.

Total of 60 individuals, including 30 individuals with ANSD and 30 age matched normal hearing individuals participated in the study. The participant's age ranged from 16 years to 55 years with the mean age of 28.26 years and included 14 males and 16 females. The individuals with ANSD had pure-tone average of less than 55 dB HL in both the ears. All the configuration of hearing loss was considered. Individuals who fulfilled the inclusion criteria were considered for the study and underwent evaluation using behavioural and electrophysiological measures. Four speech syllables /ba/, /da/, /ma/ and /pa/ were used for syllable identification and for recording P300 response. The tests were carried out in two listening condition -quiet and at +10 dB signal-to-noise ratio (SNR) and in two amplification conditions - with and without hearing aids (HAs). Effect of amplification on speech perception was assessed using SNR-50.

Syllable identification results showed near perfect identification scores for normal hearing individuals in quiet and at +10 dB SNR. However, individuals with ANSD demonstrated confusion in perception of syllables in quiet and this increased drastically in the presence of noise. In individuals with ANSD, **S**equential **INF**ormation **A**nalysis (SINFA) revealed that individuals with ANSD had greater difficulty in perceiving voicing cues compared to place and manner cues. Speech in noise (SIN) test showed better SNR-50 for individuals with normal hearing as compared to individuals with ANSD. SNR-50 did not show any significant improvements with the use of HAs in individuals with ANSD.

P300 peak with its typical characteristics was present in both the groups. However, latency was prolonged and amplitude was reduced in individuals with ANSD. Behavioural results indicated that in all the conditions (quiet, at +10 dB SNR and with hearing aids) listeners of both the groups were able to discriminate the infrequent stimuli with a high level of accuracy. However, the reaction time (RT) was significantly longer in individuals with ANSD compared to normal hearing listeners. Spatiotemporal analysis showed differential scalp topography between two groups. From these results, it can be inferred that there was a differential distribution of electrical field between two conditions in both the groups. The difference between the two conditions (quiet and noise) in scalp topographies was more in individuals with ANSD. It is a known fact that changes in the electrical topography on the scalp can only be caused by changes in the configuration of underlying brain sources. And hence the time regions where topographical differences were observed between two conditions and groups represent the differential activation of brain network. Furthermore, correlational analyses

indicated that individuals with ANSD who had higher P300 amplitude were better able to evaluate and categories the infrequent stimulus. P300 amplitudes in individuals with ANSD may reflect their ability in discrimination of speech sounds, especially in noise.

Implication of the Study

The study helps in understanding the cortical representation of speech in individuals with ANSD. Results of the study throws light on in spite of same degree of hearing thresholds why there is a large variation in speech processing abilities in individuals with ANSD. This study also complement the findings of other studies which talks about the perceptual as well as electrophysiological tests. Since, this study included both behavioural as well as electrophysiological tests, gives a holistic idea about the speech processing in individuals with ANSD. This study also helps us to know about the coding of speech signal with and without amplification, so that it will aid the audiologist in deciding about the usefulness of amplification in individuals with ANSD. Furthermore, correlational analyses indicated that individuals with ANSD who had higher P300 amplitude were better able to evaluate and categories the infrequent stimulus. P300 amplitudes in individuals with ANSD may reflect their ability in discrimination of speech sounds, especially in noise.

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Appendix I

All India Institute of Speech and Hearing
(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Manasagangothri, Mysore - 570 006.

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು - 570 006.
अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूर - 570 006

ETHICS COMMITTEE APPROVAL FOR BIO-BEHAVIORAL RESEARCH PROJECTS INVOLVING HUMAN SUBJECTS AT AIISH

AIISH ETHICS COMMITTEE (AEC)

Title of the Project	: Effect of Noise and Amplification on Speech Perception in Individuals with Auditory Neuropathy Spectrum Disorder: Electrophysiological and Behavioural Study
Candidate	: Kumari Apeksha
Guide	: Dr. Ajith Kumar U.
Proposed Duration of the Ph.D Program	: 3 years
Estimated Budget Requirements	: Not applicable
Source of Funding	: Not applicable
Reference number of the proposal	: WOF-0240/2014-15 with effect from 4.6.2015
Date on which AEC meeting was held	: 12.11.2015
Clear statement of decision reached at AEC meeting (in the event of a proposal being not approved, a statement of reasons for the same must be indicated)	: **Approved**
Advice & Suggestions (If any)	: Nil

Shyamala K.C

Date: 12.11.2015

Signature & Name of Member Secretary
Dr. Shyamala K.C
Prof. of Language Pathology
Dept. of Speech-Language Pathology
All India Institute of Speech and Hearing, Mysore

Appendix II A

Demographic details and present complaint

Sl. No	Age (Years)/ Gender	Age of Onset (years)	Etiology	Occupation	Tinnitus RE / LE	Characteristics of Tinnitus	Neurological evaluation	ENT evaluation	Nature/ Onset of Problem	Other symptoms
1	20/F	14	Typhoid fever	Shop-keeper	+/+	NA	ANSD	SNHL	Static	NA
2	16/F	15	Jaundice	Student	+/+	Intermittent	ANSD	SNHL	Gradual/ Progressive	Difficulty understanding speech
3	26/F	18	NA	Housewife	+/-	Continuous/ ringing	ANSD	SNHL	Gradual/ Progressive	NA
4	55/M	50	NA	Private	-/-	NA	ANSD	SNHL	Gradual/ Progressive	Difficulty understanding speech
5	21/M	19	Typhoid fever	Student	-/-	NA	ANSD	SNHL	Sudden/ Progressive	Intolerance to loud sound
6	36/M	35	NA	Farmer	+/+	Hitch pitch, Intermittent	ANSD	SNHL	Gradual/ Progressive	Difficulty understanding speech
7	24/M	14	Accident	Farmer	-/-	NA	ANSD	SNHL	Sudden/ Progressive	NA
8	18/M	15	NA	Student	+/+	NA	ANSD	SNHL	Gradual/ Progressive	Poor memory
9	20/M	19	NA	Businessman	NA	NA	ANSD	SNHL	NA	Vertigo since 4-5 months
10	21/M	16	NA	Factory worker	-/-	NA	ANSD	SNHL	Gradual/Static	NA
11	37/F	32	NA	Office worker	+/+	Continuous/ ringing	ANSD	SNHL	Gradual/ Progressive	NA
12	35/M	34	Water diving	Businessman	+/+	Buzzing/ continuous	ANSD	SNHL	Sudden/ Progressive	NA
13	19/F	14	NA	Student	+/-	Continuous/	ANSD	SNHL	Gradual/	NA

						ringing			Progressive	
14	26/F	22	NA	Nurse	+/-	Continuous/ Buzzing	ANSD	SNHL	Progressive	Continuous headache since 4 years
15	54/M	52	NA	Military officer	-/-	NA	ANSD	SNHL	Gradual/ Progressive	NA
16	20/M	18	NA	Private		NA	ANSD	SNHL	Gradual/ Static	NA
17	27/M	22	NA	Computer operator	-/-	NA	ANSD	ANSD	Gradual/ Progressive	NA
18	18/F	17	NA	Student	-/-	NA		ANSD	Gradual/ static	Poor speech understanding
19	48/M	25	NA	Businessman	-/-	NA	ANSD	SNHL	Static	NA
20	36/F	16	NA	Social worker	+/+	NA	ANSD	SNHL	Sudden/ Progressive	NA
21	21/F	19	NA	Private	+/+	Ringing/ intermittent	ANSD	ANSD	Gradual/ Progressive	Blocking sensation
22	30/M	25	NA	Private	+/+	Ringing	ANSD	SNHL	Gradual/ Static	Difficulty understanding speech
23	24/F	15	NA	Student	-/-	NA	ANSD	SNHL	Gradual/ Progressive	NA
24	37/F	27	NA	Officer	+/+	High pitch/ intermittent	ANSD	SNHL	Gradual/ Progressive	Headache
25	17/F	16	NA	student	-/-	NA	ANSD	SNHL	Sudden/Static	NA
26	17/F	15	Fever	student	+/+	NA	ANSD	SNHL	Gradual/ Progressive	NA
27	41/F	30	NA	Teacher	+/+	Buzzing/ intermittent	ANSD	SNHL	Gradual/ Progressive	NA
28	20/F	19.5	NA	Student	+/+	High pitch/ intermittent	ANSD	SNHL	Gradual/ Progressive	NA
29	24/M	22	NA	Student	+/+	NA	ANSD	SNHL	Gradual/ Progressive	Family history of hearing loss
30	40/F	20	Head injury	Housewife	+/+	Ringing/ intermittent	ANSD	SNHL	Gradual/ Progressive	Head injury 20 yrs back

Appendix II B

Audiological findings

Sl. No	Age (Years)/ Gender	Pure-Tone Average (dB HL)		Speech Identification Scores (%)		Speech Perception In Noise scores		Tympanometry		Auditory Brainstem Response (ABR)		Otoacoustic Emission (OAE)		Hearing Aid Trial
		RE	LE	RE	LE	RE	LE	RE	LE	RE	LE	RE	LE	
1	20/F	32.5	36.2	45	40	NA	NA	A	A	NR	NR	+	+	Limited Usefulness
2	16/F	38.75	20	65	50	NA	NA	As	As	NR	NR	+	+	Manage without HA
3	26/F	15	22.5	92	92	NA	NA	A	A	NR	NR	+	+	Manage without HA
4	55/M	46.25	47.5	50	45	NA	NA	A	As	NR	NR	+	+	Manage without HA
5	21/M	30	6.25	50	10	NA	NA	As	As	NR	NR	+	+	Manage without HA
6	36/M	22.5	18.75	30	20	NA	NA	A	A	NR	NR	+	+	Manage without HA
7	24/M	43.75	30	35	35	36%	48%	Ad	A	NR	NR	+	+	Manage without HA
8	18/M	28.75	25	30	30	12%	40%	A	A	NR	NR	+	+	Manage without HA
9	20/M	18.75	25	15	60	NA	NA	As	A	NR	NR	+	+	Manage without HA
10	21/M	31.25	35	40	45	NA	NA	A	A	NR	NR	+	+	Manage without HA
11	37/F	20	16.25	40	15	NA	NA	As	As	NR	NR	+	+	Manage without HA
12	35/M	30	22.5	40	25	NA	NA	A	A	NR	NR	+	+	Manage without HA
13	19/F	36.25	23.75	30	20	40%	44%	Ad	A	NR	NR	+	+	Fitted with Mild gain HA
14	26/F	28.75	22	45	35	32%	48%	As	As	NR	NR	+	+	Limited Usefulness
15	54/M	41.25	36.25	40	35	36%	44%	Ad	Ad	NR	NR	+	+	Manage without HA
16	20/M	31.25	32.5	50	45	NA	NA	A	A	NR	NR	+	+	Manage without HA
17	27/M	35	30	45	40	NA	NA	A	Ad	NR	NR	+	+	Manage without HA
18	18/F	48.75	52.5	60	55	NA	NA	A	A	NR	NR	+	+	Manage without HA
19	48/M	31.25	30	45	35	NA	NA	A	A	NR	NR	+	+	Manage without HA
20	36/F	47.25	37.25	68	76	16%	40%	A	A	NR	NR	+	+	Fitted with Moderate gain HA

21	21/F	10	12.5	45	65	40%	40%	A	A	NR	NR	+	+	Manage without HA
22	30/M	22.5	20	30	25	NA	NA	A	A	NR	NR	+	+	Manage without HA
23	24/F	35	45	35	45	NA	NA	As	A	NR	NR	+	+	Manage without HA
24	37/F	53.75	41.25	60	45	60%	76%	A	A	NR	NR	+	+	Manage without HA
25	17/F	37.5	28.75	75	40	60%	40%	As	As	NR	NR	+	+	Manage without HA
26	17/F	27.5	33.75	25	25	12%	24%	As	As	NR	NR	+	+	Manage without HA
27	41/F	8.75	7.4	30	45	NA	NA	A	A	NR	NR	+	+	HAT not done
28	20/F	17.5	15	20	15	45%	55%	As	As	NR	NR	+	+	HAT not done
29	24/M	28.75	31.25	35	40	24%	28%	A	A	NR	NR	+	+	Manage without HA
30	40/F	45	43.75	50	50	NA	NA	As	As	NR	NR	+	+	Limited usefulness

Note. NR = No response, + = presence of OAE, - = absence of OAE, M = Male, F = Female, NA = information not available, RE= Right Ear, LE = Left Ear, HA = Hearing aid,

List of Publications

1. Apeksha, K., & Kumar, A. U. (2017a). P300 in individuals with auditory neuropathy spectrum disorder. *Journal of Indian Speech Language & Hearing Association*, *31*(1), 23–8. http://doi.org/10.4103/jisha.JISHA

2. Apeksha, K., & Kumar, A. U. (2017b). Speech perception in quiet and in noise condition in individuals with auditory neuropathy spectrum disorder. *Journal of International Advanced Otology*, *13*(1), 83–7. http://doi.org/10.5152/iao.2017.3172

3. Apeksha, K., & Kumar, A. U. (2018). Cortical processing of speech in individuals with auditory neuropathy spectrum disorder. *European Archives of Otorhinolaryngology*, https://doi.org/10.1007/s00405-018-4966-8