MMN in Sensorineural Hearing loss: A Clinical Measure of Speech Perception

THESIS

By

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Under the Guidance of

Prof. Asha Yathiraj

Submitted to the University of Mysore in 2005

CERTIFICATE

This is to certify that the thesis entitled, **MMN in Sensorineural Hearing Loss: A Clinical Measure of Speech Perception,** submitted by M. Reddy Sivaprasad, for the degree of Doctor of Philosophy in Speech and Hearing to the University of Mysore, was carried out at All India Institute of Speech and Hearing, Mysore under guidance.

Place: Mysore

Date: 8-6-05

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CERTIFICATE

This is to certify that the thesis entitled, **MMN in Sensorineural Hearing Loss: A Clinical Measure of Speech Perception,** submitted by M. Reddy Sivaprasad, for the degree of Doctor of Philosophy in Speech and Hearing to the University of Mysore, was carried out at All India Institute of Speech and Hearing, Mysore.

Place: Mysore

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Prof. M. Jayaram
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DECLARATION

I declare that this thesis entitled, **MMN in Sensorineural Hearing Loss: A Clinical Measure of Speech Perception,** which is submitted herewith for the award of the degree of Doctor of Philosophy in the field of Speech and Hearing to the University of Mysore, Mysore, is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysore, under the guidance of Prof. Asha Yathiraj, Head, Department of Audiology, All Institute of Speech and Hearing, Mysore. I further declare that the results of this work have not been previously submitted for any degree.

Place: Mysore

Date:08, June 05 M. Reddy Sivaprasad

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INTRODUCTION

Perception of speech is a prerequisite for the development of communication. For decades, it has been the subject of speech scientists, to find the cues that listeners use to perceive speech (Mendel & Danhauer, 1997; Pickett, 1999). It has also been of interest to several other sciences such as audiology (Rout, 1996; Mendel & Danhauer, 1997; Vandana, 1998), speech-language pathology (Travis, 1957; Eisenson, 1973; Bernthal & Bankson, 1993), psychology and education (Erber, 1974) to understand this phenomenon for the formulation of theoretical frameworks, assessment protocols and management regimes for tasks, which are based on speech perception.

The study of speech perception is basic to every aspect of audiology, including its theoretical and research foundations of how the auditory mechanism works, and the administration of the diagnostic and rehabilitative regimes in delivering services to clients of different ages and several types of hearing problems. The assessment and rehabilitative regimes have undergone and still continue to undergo several changes in their content, and administration. These changes are parallel to developments in speech perception sciences (Mendel & Danhauer, 1997). Changes are also due to growing needs to assess a variety of clients such as cochlear implantees, users of sophisticated hearing aids and those with auditory processing disorders (Diefendorf, 1988). A majority of these clients are young children.

It is necessary to use specialized techniques to assess the speech perception abilities of young children. Techniques based on behavioural responses such as behavioural observation audiometry (Eilers, 1980) and visual reinforcement audiometry (Diefendorf, 1988) are used to measure their speech perception abilities.

These methods are mainly restricted to evaluating speech awareness and speech discrimination. Speech identification testing is possible in older children. Other techniques based on auditory evoked potentials have also been used to measure basic speech perception abilities. While the techniques based on behavioural responses measure a wide range of auditory abilities such as speech awareness, speech discrimination and speech identification, techniques in auditory evoked potentials have been restricted to measure only awareness and discrimination abilities.

Auditory evoked potentials (AEP) represent the neural activity in the auditory system evoked by a sound stimulus. AEPs consist of a series of bioelectric events generated at various levels of the auditory system. Based on the way of elicitation AEPs may be classified into exogenous and endogenous potentials. Exogenous potentials are those, which may be directly elicited by the stimulus, whereas the endogenous potentials are generated by an internal response to the external event and is usually due to cognition (McPherson, 1996). Auditory evoked brainstem response (ABR) is the most widely used exogenous potential. P300 and mismatch negativity (MMN) are examples of well known endogenous potentials.

MMN has been gaining impetus as a measure to assess speech discrimination. Naatanen and Escera (2000) defined MMN as "an electric brain response, a negative component of the event-related potential (ERP), elicited by any discriminable change (deviant) in some repetitive aspect of auditory stimulation (standard), usually peaking around at 100-200 ms from change onset" (p.105). An MMN is elicited, when a sound discriminably changes in frequency, intensity, duration, or phase of tone-burst stimuli. It can also be observed for complex changes in phonemes (Aaltonen, Niemi, Nyrke & Tuhkanen, 1987; Naatanen, Paavilainen & Reinikainen, 1989; Sams, Paavilainen, Alho & Naatanen, 1985; Paavilainen, Karlsson, Reinikainen & Naatanen, 1989).

There are several reasons for the widespread use of MMN across several disciplines ever since it was discovered by Naatanen, Gaillard and Mantysalo (1978). It is the only objective measure of central auditory processing that may accurately correlate with behavioural perceptual measures (Kraus & Cheour, 2000; Ponton et al., 2000). It is an objective measure of the duration of echoic memory (Pekkonen, 2000). An objective index of general brain degeneration (Pekkonen, 2000), and the gross functional state of the brain can be obtained using MMN (Fischer, Morlet & Giard, 2000; Kane et al., 2000; Morlet, Bouchet & Fischer, 2000). Importantly, MMN can be elicited in the absence of attention, i.e., when no task performance is required (Naatanen, Paavilainen, Tiitinen, Jiang & Alho, 1993; Paavilainen, Tiitinen, Alho & Naatanen, 1993) and is easy to administer.

MMN can also be recorded magnetically (MMNm) and this method is used in the source analysis of MMN and study of cognitive parameters (Lounasmaa, Hari, Joutsiniemi & Hamalainen, 1989). Application of MMN in the field of speech and hearing to measure speech discrimination is in its infancy. Research in this area though scanty, has made its mark. Literature reveals that the potential has been used in studying the cognitive and auditory related aspects of the brain functioning of individuals with speech and language disorders.

Aaltonen, Tuomainen, Laine and Neimi (1993) recorded MMN in four aphasics using speech and tone-burst stimuli. It was observed that the MMN for speech stimuli was absent in those with temporal lobe lesions but was present in those with frontal lobe lesions. However, the MMN for tone-bursts could be recorded in both the groups. This study highlighted the usefulness of speech evoked MMN in differentiating temporal lobe lesions from the frontal lobe lesions. In a similar study, Wertz, Auther, Sims, Abou, Kirshner and Duncan (1998) showed that the speech-evoked MMN was absent in 54% of their twenty-four aphasics and that when it was present, the duration of MMN correlated with the severity of aphasia, as demonstrated by standard aphasic batteries. Ilvonen et al. (2003) reported that the MMN parameters changed and the morphology improved with a recovery from aphasia, as shown by the Boston's diagnostic aphasia examination.

MMN is used in studying the subtle auditory deficits shown in children with learning disabilities (LD). Kraus, Koch, McGee, Nicol and Cunningham (1999) studied the just noticeable differences (JNDs) for formant transitions of stops in normal children and those with LD. They found that there was a good correlation between the perceptual JNDs and the minimum deviance at which the MMN could be observed. They recommended the usage of both psychophysical and electrophysiological evaluation of LD children. Similar results were shown by Bradlow et al. (1999) and Kraus et al. (1996).

With the autistic children, limited research has been carried out using MMN. Kemner, Verbaten, Cuperus, Camfferman and VanEngeland (1995) showed that the autistic children showed abnormal MMN or abnormal lateralization of MMN. They attributed the results to under-stimulated auditory systems in the autistic children. In such children, prolonged peak latencies and attenuated peak amplitudes over the left frontal cortex for auditory frequency change MMN were reported by Gomot, Giard, Adrien, Barthelemy and Bruneau (2002). MMN amplitude in autistic children was found to be more when compared to that of normal children (Ferri et al., 2003) elicited for an intensity deviance.

The cognitive and auditory deficits in children with CATCH syndrome have also been studied using MMN. CATCH syndrome is caused by a micro deletion in chromosome 22, and is characterized by a cleft palate and cardiac anomalies. Cheour et al. (1997) showed that these children had shorter auditory memory when compared to the age matched healthy controls. Similar results have been shown in school age children and in neonates with CATCH or non-syndromic cleft palate (Ceponiene et al., 1999; Ceponiene et al., 2000; Cheour et al., 1998 a,b). Based on these results, they suggested a need for early intervention in these children.

The possibility to evaluate the discrimination abilities in children with cochlear implants has also been examined. Groenen, Snik and van den Broek (1996) found a relation between the speech perception and MMN quality. In a study to compare the tone-burst evoked and the speech evoked MMN, Kilney, Boerst and Zwolan (1997) showed that the speech evoked MMN was longer in latency when compared to that of the tone-burst evoked MMN. They also found significant correlations between the speech recognition scores and latencies of the MMN. They recommended that use of MMN is feasible and informative in children with cochlear implants.

MMN was also used to study the effects of training after cochlear implantation. Kraus et al. (1993) recorded MMN in well trained children with cochlear implants for speech contrasts and found that they were identical to those seen in normal-hearing individuals. Ponton et al. (2000) also showed similar results. They found that in children with good spoken language perception, MMN was robust. They also showed that the maturation of MMN was symmetrical in amplitude over both hemispheres, whereas it is initially much larger over the contralateral hemisphere in normal-hearing children. They suggested that compared to Ni, the MMN is a better measure of basic auditory processes necessary for the development of spoken language perception skills in children and adults with profound hearing loss who use cochlear implants.

Sivaprasad (2000) evaluated MMN in individuals with a sensorineural hearing loss using tone-bursts. Tone-bursts of 1 kHz and 6 kHz at 40 and 60 dB SL (with respect to pure tone threshold) were used to record MMN in individuals with mild-to-moderate sensorineural (SN) hearing loss. The MMN was identical to that seen in normal-hearing individuals and no effects of degree and configuration of hearing loss was observed.

Oates, Kurtzberg and Stapells (2002) used the /ba/-/da/ contrast to explore the effects of sensorineural hearing loss on MMN. They reported that MMN latency was prolonged with an increase in hearing loss. A behavioural task to measure reaction time latency was used in a discrimination task and indicated that MMN peak latency could be the predictor of inherent speech perception problems in the individuals with hearing impairment. However, the study included only a small group of subjects, and used only one speech contrast. The study used the reaction time as the behavioural measure. A large-scale study to explore the effects of sensorineural hearing loss in detail is required.

Need for the study

There is a need to study the potential application of MMN in assessing speech perception abilities with several different speech contrasts and many subjects with SN hearing loss for its routine clinical use. There are several reasons for conducting the present study, which are discussed below.

Usage of speech in recording MMN

Speech-evoked MMN needs to be widely studied because of its inherent advantages. It reflects the representation of dynamic properties of the speech signal; it also reflects dynamic neural properties of the brain; and with respect to more long-term dynamic processes, it is modifiable with learning and experience over time (Kraus and Cheour, 2000).

Inspite of the advantages, there is a dearth in research utilizing speech-evoked MMN. It is also to be noted that the phenomenon is not studied for all phonetic contrasts. The literature indicates that studies have used only 2-4 contrasts in recording an MMN (Kraus et al., 1999; Aaltonen et al., 1994). However, there are several other speech contrasts that need to be explored. It is necessary for an audiologist to know whether different phonetic contrasts result in different MMN waveforms. If a difference occurs, it is necessary to know which contrast can predict behavioural speech perception better.

Normative data

There are several practical problems such as effects of stimulus, recording and interpretation variables identified that constrain the clinical application of speech-evoked MMN (Lang et al., 1995). Lack of studies that have included subjects on a large scale (Kraus et al., 1999) also poses an external validity problem for the data to be used in the clinic. No recent studies have also evaluated large groups of subjects.

Further, there is a need to identify the normal variations in MMN and a specific MMN configuration, if any, to a particular phoneme contrast, for clinical applications. In addition, age specific norms for different MMN parameters are not available for clinical use. Hence, it is necessary to study subjects on a large scale on several phonetic contrasts for identifying these variations.

Overall effects of SN hearing loss on MMN

MMN is known to reflect cortical level processing. Hence, in humans it is used to study the underlying deficits in neurophysiological processes in individuals with cognitive and language impairments (Pekkonen, Jousmaki, Partanen & Karhu, 1993; Korpilahti & Lang, 1994). However, such studies have included only those subjects with normal-hearing. Individuals with a peripheral hearing loss have rarely been studied. The few studies that have carried out research using MMN on individuals with hearing impairment have used a limited number of subjects. Kraus and McGee (1994), based on a study on two individuals with hearing impairment, indicated that there can be effects of SN hearing loss on speech evoked MMN. Oates, Kurtzberg and Stapells (2002) used a single speech contrast on eleven subjects and showed that the MMN peak amplitude was readily affected by the presence of hearing loss and it was significantly attenuated. However, the effects of hearing loss on MMN peak latency were rather small. The study indicates the need for a large-scale research to draw reliable generalizations regarding the effects of hearing loss on MMN.

Effects of degree and audiogram configuration of hearing loss on MMN

The degree and audiogram configuration of SN hearing loss may affect speech-evoked MMN, despite Sivaprasad (2000) showing that degree of hearing loss and audiogram configuration did not affect MMN, using tone-bursts. Though Oates, Kurtzberg and Stapells (2002) showed that MMN peak amplitude and peak latency are affected by the degree of hearing loss, using speech, it is necessary to examine the same issue on a large population. There is a need to know if the speech evoked MMN would be able to predict variations in speech perception that occurs as a function of degree and audiogram configuration.

Objective measurement of speech perception in the difficult-to-test population

Usually, audiological diagnostic and rehabilitative regimes do not include a measure of speech discrimination for young children and difficult-to-test population. It is necessary to have an objective measure to understand the speech perception difficulties in them. A correlation between the subjective speech identification scores, speech discrimination scores and the objective MMN needs to be established. This information will help the audiologist to determine the speech discrimination abilities in very young children. Further, such a study may help in understanding speech perception difficulties in adult aphasics and acquired neuro degenerative disorders, on whom it is difficult to carry out behavioural tests.

Objective tool for predicting the need for aural rehabilitation outcomes

Studying the effects of a SN hearing loss on MMN characteristics would add to the current understanding of neurophysiological bases of speech perception, in individuals with a SN hearing loss. This may help in developing regimes and procedures for aural rehabilitation. As shown by Musiek and Baran (1996), there is a great need for central auditory evaluation in hearing aid management programs. Given the context, there is a need for an objective tool such as speech-evoked MMN, to evaluate such deficits and predict the outcome of a hearing aid in children with a SN hearing loss.

Effects of age on speech-evoked MMN

MMN is ontogenetically the earliest ERP and acquires adult like pattern by early school age (Naatanen & Escera, 2000). It needs to be replicated as to whether the children show adult like pattern in the Indian context. It is known that the phoneme dimensions vary across languages (Williams, 1980). Hence, studies about phoneme contrasts in the west cannot be directly applicable in India.

Objective tool for evaluating training effects

Determining the efficacy of rehabilitation based on behavioural measures may be difficult, particularly when evaluating young children or individuals with little or no experience with normal-hearing (Ponton & Don, 1995). MMN has been shown to be useful in evaluating the success of auditory training after cochlear implantation (Ponton et al., 2000). Given that, cochlear implantation is being done for several young children across the world including India, there is a need for such an objective tool. The information obtained from speech-evoked MMN may be useful in mapping/programming a cochlear implant. Based on the speech discrimination abilities, as evaluated through MMN, it may be decided whether the map/program of a cochlear implant needs to be altered or not.

In case of rehabilitation with a hearing aid, there is a need for an objective tool to evaluate the efficacy of auditory learning. Speech-evoked MMN may be used as an objective tool for measuring the efficacy of rehabilitative procedures, by comparing the pre- and post-therapy recordings of MMN.

Objectives of the study

Due to the dearth in literature on MMN, more studies need to be carried out to evaluate speech discrimination in persons with a sensorineural hearing loss. In order to study this, the following objectives were taken up:

- Finding the effects of age on speech-evoked MMN.
- Comparing speech-evoked MMN for individuals with normal-hearing and SN hearing loss.
- Finding the effects of degree and audiogram configuration on speech-evoked MMN, in individuals with SN hearing loss.
- Determine the variations in MMN as a function of phonetic contrast.
- Determine the correlation between speech-evoked MMN with behavioural speech identification scores and the speech discrimination scores.

In order to study the above objectives a review of literature has been carried out on behavioural and electro physiological methods of studying speech perception abilities in individuals with normal-hearing and hearing impairment.

REVIEW OF LITERATURE

The assessment of the ability to discriminate speech sounds of an individual is one way to determine the individual's auditory perceptual abilities. Theories have been proposed to explain the phenomenon that takes place during a speech discrimination task. Research has been conducted to examine the theories as well as to study the speech discrimination abilities in different subject populations based on age, linguistic origin, auditory and/or cognitive abilities. Both behavioural and electrophysiological methods have been employed to evaluate the speech discrimination abilities in children and adults. An electrophysiological tool that is found promising in the evaluation of discrimination abilities is the mismatch negativity (MMN). The following review examines all these issues.

1. Speech Discrimination and its Assessment

Distinguishing between similar stimuli is the fundamental psychophysical ability of a sensory system. Speech and non-speech stimuli have been used to study this resolving power of the auditory system. Speech discrimination has been defined as the process of distinguishing among speech sounds or words by differentiating them as 'same' or 'different' (Nicolosi, Harryman & Kresheck, 1978). It involves detecting the feature(s) that differentiates between the sounds.

1.1 Cues for speech sound discrimination

Generally, speech discrimination tasks in the audiological scenario have used meaningful or nonsense syllables based on distinctive features of speech sounds for clinical purposes. The contrasts are shown to have basis in spectral, temporal and intensity differences. An example list of these contrasts and their spectral or temporal basis is shown in the Table L.I. While a majority of studies have utilized gross distinctive features, a few have used finer segmental cues to study speech discrimination.

Table L.I

Example of cues involved in speech sound discrimination and their acoustical basis

Sounds to be discriminated	**Feature***	**Acoustical basis***
/a/-/i/	Place of the tongue	Formant frequency
/e/-/i/	Tongue height	Formant frequency
/ka/-/ga/	Voicing	VOT
/ka/-/pa/	Place of articulation	Formant transition
/ma/-/pa/	Nasality	Nasal pole and zero
/sa/-/Ja/	Fricative place	Frequency of frication
/la/-/ra/	Manner of articulation	Third formant frequency

Note. * Pickett (1999)

1.2 The phoneme perception theory of speech discrimination

van Hessen and Schouten (1992) have proposed a comprehensive theory called, phoneme perception theory (PPT) for speech sound discrimination based on the trace context theory (TCT) proposed by Macmillan, Goldberg and Braida (1988). The latter was influenced by the theory of intensity resolution (Durlach and Braida, 1969). According to the PPT, the speech sounds first form 'traces' in the auditory system (trace mapping) and will be processed separately in a temporal order. The stimulus will be given a label and stored as a phoneme label (labeling and phoneme label). The trace is also influenced by the context of the given sounds i.e., the position of a stimulus in the continuum of stimuli presented (context labeling) and thus resulting in a 'context label'. Based on the length of the inter stimulus interval, the stimulus imprint will undergo some fading process, resulting in a faded 'trace'. The second stimulus will also undergo the same processing. At the end of the trial, the discrimination decision is based on the two phoneme labels, or on the two context labels, or the two traces or a combination of these. This decision takes place outside the model in an undifferentiated box called 'decision'. The model has not described processes taking place in the box.

The TCT claims that speech discrimination is essentially same as that of the intensity discrimination given that the TCT has its roots in the theory of intensity resolution (Durlach and Braida, 1969). The PPT and TCT differ mainly in their claims about the role of long-term memory in speech discrimination. While the PPT attributes the resolving power to the 'labeling' of the ability, in contrast the TCT hypothesizes that sensory non-linearity and context anchors help in distinguishing the stimuli, which do not decrease with increasing inter stimulus intervals (ISI). However, the PPT showed that speech discrimination improves with ISI until an optimum is reached, after which the performance gradually decreases. Though the PPT was good enough to explain the discrimination performance for stop consonants, the TCT was better in explaining the vowel discrimination data. The block diagram of the PPT is shown in Figure L.I.

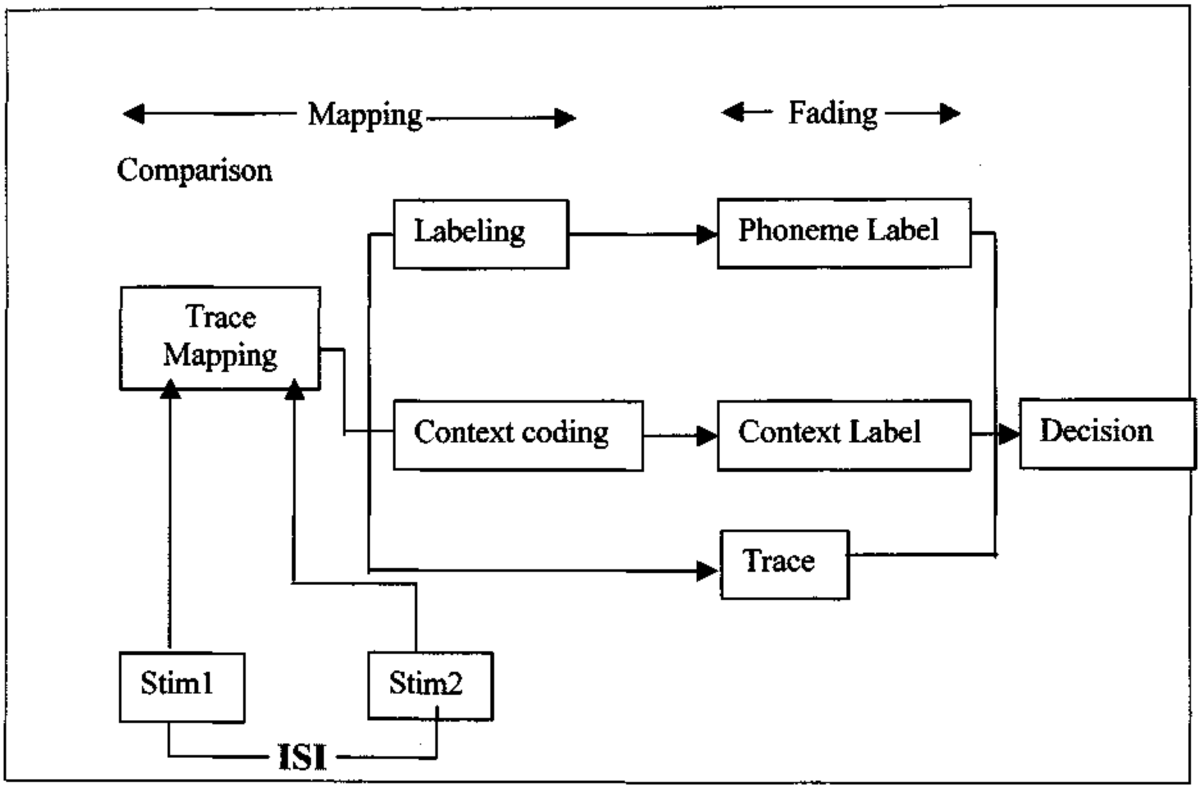


Figure L1. Block diagram of the phoneme perception theory.

1.3 Speech sound discrimination in aduhs and children

Though it was shown that infants can discriminate speech syllables correctly even at birth (Eilers, 1980), it was shown that infants have immature auditory sensitivity to speech sounds. Nozza, Rossman and Bond (1991) tested infants and adults for the discrimination accuracy of/ba/-/da/ and /ba/-/ga/ contrasts with an adaptive discrimination procedure. Using a visual reinforcement procedure they measured the discrimination accuracy of infants, in terms of the minimum intensity of the stimuli required for a discrimination response, while, a multiple choice method was used with adults to measure this. They found that infants required an additional 25-28 dB SPL intensity (of the stimuli) to achieve a discrimination threshold, when compared to adults. It indicates that infants have poor sensitivity to speech contrasts compared to adults.

The speech perception abilities continue to develop in children. Allen and Wightman (1992) studied 47 children in the age range of 4-9 years, for vowel and fricative spectral pattern discrimination. The stimuli varied in amplitude spectra. They reported that the vowel discrimination scores surpassed fricative discrimination, but the vowel discrimination was better in the 9 year-old children compared to the 4 year-old children. The discrimination of fricative patterns was poor in the children and adult-like scores were achieved only at the age of 9 years. They also observed that the performance of the children deteriorated when the discrimination task was in the presence of noise, even at a 25 dB signal-to-noise ratio presentation. This study again shows that the auditory resolution capacity especially in adverse listening conditions shows a developmental trend into late childhood.

Several studies carried out using different speech perception tasks, showed that adult-like scores are obtained by the age of 7-8 years. Sussman (1993) studied 5-6 year old children and adults for a discrimination accuracy in a continuum of /ba/-/da/ syllables. The average sensitivity of the children was poorer when compared to adults. The study supports that younger children have a poorer sensitivity to minimal differences in speech sounds.

Elliott, Longinotti, Meyer, Raz and Zucker (1981) examined 6-10 year old children and adults on a discrimination task for the continuum /ba-da-ga/. The study children secured perfect scores at all points of the continuum. Menon (2005) used the /pa/-/ta/ and /da/-/ta/ continuum with 40 Kannada speaking normal children in a discrimination task. Their age ranged from 8-12 years. The study reported no age related changes in the discrimination accuracy. The study showed that the discrimination of CV syllables is attained by the age of 8 years. Discrimination of consonants, especially the fricatives showed a continuous improvement throughout the early school years and reached an adult like perception by the age of 8-9 years (Abbs & Minifie, 1969; Allen & Wightman, 1992). These studies collectively imply that discrimination of syllables in a continuum attains a plateau by the age of 7-8 years.

There are a few studies, which employed traditional speech audiometry tasks to study developmental changes. Fior (1972) showed that scores in traditional speech identification tests using monosyllables reached near 100% by the age of 7 years. Hnath-Chisolm, Laipply and Boothroyd (1998) used speech pattern contrasts in vowels and consonants to measure developmental trends in 5-10 year old children. They reported that for all the stimuli, 7-year-old children obtained adult-like scores. Thus, the review-indicates that children at 7-8 years achieved adult-like scores in most of the behavioural speech perception tasks. Speech discrimination performance is also shown to be affected by the presence of a sensorineural hearing loss as shown by several behavioural and electrophysiological measures such as the mismatch negativity.

2. Sensorineural Hearing loss

Sensorineural (SN) hearing loss is a general term used to describe a condition characterized by damage to both the cochlear and neural structures within the cochlea resulting in varying degrees of hearing loss, proportional to the extent of damage (Gelfand, 2001). Several pathologies cause lesions in the cochlea and the adjoining neural structures within the cochlea. These are known to induce further changes in the auditory system that may have adverse effects on the auditory perceptual skills.

2.1 Effects of SN hearing loss on the Central Auditory System

The lesions in the cochlear hair cells lead to damage of the neurons within and rostral to the cochlea as shown in cats (Shepherd & Hardie, 2001). In humans, degeneration of the neurons secondary to cochlear lesion is shown in the spiral ganglion cells (Hinjosa, Blough & Mhoon, 1987; Nadol, Young & Glynn, 1989), cochlear nucleus, medial superior olivary complex and the inferior colliculus (Moore, Niparko, Perazzo, Miller & Linthicum, 1997). The number of spiral ganglion cells surviving after the damage to the cochlea, are reported to have correlations with the degenerative changes seen in the nuclei of the central auditory pathway. Clark et al. (1988) described a reduction in the volume of the cochlear nucleus compared to normal controls. Although these studies used cochlear ablation as a method to study changes in the adjoining neural structures, it is reasonable to assume that less severe changes might take place in the neural structures as a result of disease/ disorder leading to less severe hearing loss.

The responses seen in the auditory cortex for such cochlear lesions is termed as the 'injury-related plasticity' of the auditory cortex (Irvine, 2000). In cats, it is shown that the cochlear lesions after one to two months could cause cortical reorganization in terms of the cochleotopical representation of the cortical neurons (Irvine, 2000). The electrophysiological recordings of the neurons have shown that the response areas of the fibres representing the injured cochlear site have broadened their response properties. Rajan and Irvine (1996) showed that the neurons in the primary auditory cortex showed broadened frequency characteristics when the ear contralateral to the lesion was stimulated. The responses were intact when the frequency response characteristics were obtained by stimulating the damaged cochlea.

From the review on the existing literature on this issue, it may be said that the cochlear lesions induce changes in the physiology and the structure of the central auditory nuclei and the auditory cortex, which may reflect in auditory perception skills. In the next section, literature regarding the effects of sensorineural hearing loss on speech perception abilities at the phoneme level is reported.

2.2 Effects of SN hearing loss on speech sound perception

Studies described below show that the vowel and consonant perception in individuals with hearing impairment is far from a simple attenuation of audibility and controlled stimuli are needed to explore it. They also show that the inter-individual differences in perceptual abilities can be explained by the degree and configuration of hearing loss. The literature delineated below includes only those studies that used monosyllabic or even simpler stimuli to evaluate the effects on segmental feature perception

2.2.1. Effects of SN hearing loss on vowel perception

It is generally agreed that listeners with hearing impairment show considerably better perception for vowels than for consonants as indicated by the percent score in recognition tasks (Revoile & Pickett, 1982). The work outlined below shows that vowel recognition for some vowels and vowel features are affected by hearing loss and the perception of closely spaced vowels may be adversely affected by hearing loss.

Pickett et al. (1972) studied four groups of hard-of-hearing students with mean hearing losses of 67, 73, 82, and 88 dB HL. They were presented with 50 monosyllabic words in a closed-set format to the better ear at 6 dB above each listener's most comfortable level. The vowel recognition scores for these groups were 91%, 76%, 62%, and 48% respectively. It was concluded that with increasing hearing loss more vowel confusions were observed for those vowels with low frequency F1.

Vowel formant transitions were studied in synthesized consonant vowel syllables in listeners with moderately-severe flat sensorineural hearing loss subjects by Martin, Pickett and Colten (1972). They found that hearing loss had no effect on detecting even the small transition lengths, but the detection of such cues was affected in some vowels where the low frequency formants masked the transitions at high frequencies.

Risberg (1976) used a rhyme test with moderate to profound hearing loss children, where they were required to identify vowels in monosyllabic words. He found that listeners with severe-to-profound hearing loss tended to confuse vowels even when vowels differed in formant frequencies. He also found in those with moderate-to-severe hearing loss, had vowel confusions with those vowels that could be distinguished by their formants above 1500 Hz.

In a similar study, Fourcin (1976) investigated vowel recognition with two-formant synthesised vowels /i/,*/u/*, and /a/ in listeners with hearing loss. The vowels had the same Fl values but were distinguishable by the amplitude of F2. He showed that those listeners with a severe hearing loss had difficulty in recognising /i/ and /u/, but could correctly identify /a/. In contrast, Boothroyd (1984) used several vowels, which differed in their place and height in monosyllabic words to study vowel perception in moderate-to-profound hearing loss listeners. Results confirmed that vowel height to be least affected by hearing loss. Even listeners with profound hearing loss could secure comparative scores with those of normal-hearing.

In order to explore the psychoacoustic basis of vowel deficits, Turner and Henn (1989) compared vowel recognition with measures of frequency resolution in hearing and listeners with hearing impairment. They found that differences in frequency resolution together with the vowel spectra information correlated with vowel recognition scores and thus accounting for individual differences.

Richie, Kewly-Port and Coughlin (2003) studied young adults with sloping mild-to-moderate SN hearing loss for recognition and discrimination of vowels *H* e A ae *el* at conversation levels and also at louder presentation levels. Subjects performed better in both discrimination and identification tasks at louder levels than at conversation levels. This study clearly shows that there is a significant effect of hearing loss even in mild-to-moderate hearing impairment groups. This study points out an interesting fact that vowel perception improved with presentation level and amplification certainly improves vowel perception.

In summary, the vowel perception in listeners with hearing loss is generally affected by the degree of hearing loss. However, the perception of low vowels is not affected by the degree of hearing loss. Significant inter-individual differences have been noticed in vowel perception scores even if the degree of hearing loss is controlled. The perceptual scores correlate well with the spectral resolution rather than the degree of hearing loss.

2.2.2. Effects of SN hearing loss on consonant perception - Place of articulation

Consonants can be distinguished by means of their place of articulation, which has a basis in the rate of change of frequency in the formants of the preceding and/or the following vowels. The acoustic cue is identified as the formant frequency change usually occurring in the higher frequencies (Sher and Owens, 1974; Reed, 1975).

Godfrey and Millay (1978) asked listeners with mild and moderate SN hearing loss to identify synthesized /be/ and /we/ syllables across a range of transition durations from 10 to 120 ms in 10 ms steps. Two kinds of responses were seen one group attained maximum score with transitions of 40 ms or less and 80 ms or more for /be/ and /we/ respectively. The other group did not perform above chance level for all transition durations.

Synthesized syllables /bi/, /di/, and /gi/ were used by Ochs, Humes, Ohde and Grantham (1989), in a recognition task with listeners with normal-hearing (with and without noise) and those with a high frequency hearing loss. Stimuli had a 'moving F2' and 'straight F2' to assess the perception of the place in stop consonants. All the listeners could recognize the place. However, those with a high frequency hearing loss and normal-hearing, in presence of noise showed confusions. They concluded that the perception of /b/ and /d/ is harder than that of /g/ because of their onset characteristics.

Hedrick, Schulte and Jesteadt (1995) found that burst/vowel relative amplitude seemed important for discriminating synthetic /pa/-/ta/ contrast pair by mild-to-moderate adults with hearing loss. In contrast, the control group of normally hearing adults showed dependence on the vowel transitions rather than the burst/ vowel amplitude. Greater than normal dependence on the release bursts by adults with mild-to-moderate hearing loss for stop consonant identification was also shown by Revoile, Kozma-Spytek, Nelson and Holden-Pitt(1995).

Using the perceptual-weighting strategies and performance audibility functions Pittman and Stelmachowicz (2000) studied the perception of voiceless fricatives /s/, / /, /f/ and// in children and adults with normal-hearing and moderate hearing loss. They changed the intensity of the aperiodic noise in the fricative consonants and studied their effect on fricative recognition. Results indicated that for /s/ and *l\l* perception, all listeners rated fricative portions as heavily important when compared to other consonantal portions. Listeners with hearing loss performed maximally at low audibility levels of the fricative noise for the perception of /s/ and / / consonants in a performance-intensity task.

It may be noted from the above review that the acoustic cues are used among listeners with hearing loss are different from those used by listeners with normal-hearing. Further studies are required in this line to find out additional cues used by listeners with hearing loss in syllable final positions.

2.2.3. Effects of SN hearing loss on consonant perception - Voicing

Perception of voicing in stop consonants is widely studied in listeners with hearing impairment. As shown below, voicing is relatively less vulnerable to the effects of hearing loss atleast till severe degree of hearing loss. However, results may be limited to voicing in stop consonants, more studies are required in this line using other speech sounds.

Bennett and Ling (1973) studied voicing perception for initial stops using CV monosyllabic words in children with normal-hearing and with a severe hearing loss. Stimuli were prepared with systematic variations in voice-onset-time (VOT) were presented at comfortable listening levels. Normal-hearing children distinguished voiced from unvoiced by VOTs between 20 ms to 40 ms. Children with a hearing loss showed inconsistency in responses and tended identify more unvoiced than voiced stops at VOTs of 60 ms or more.

Another cue 'Fl cut-back' was studied in children with hearing loss by Fourcin (1976). Cut-back of Fl was varied so that for some stimuli Fl cue did not coincide with the initial VOT cue as it would in natural speech. It was found that children with hearing loss needed both cues for correct perception.

Dorman, Marton, Hannley and Lindholm (1985) studied the effect of spread of masking from Fl on voicing perception. Fl was eliminated entirely from the stimuli and they were presented to listeners with mild-to-moderate sloping hearing loss. The authors did not find any effect of removal of Fl since there was no improvement in scores.

The use of acoustic cues by listeners with moderate-to-severe hearing loss was studied by Revoile, Pickett, Holden-Pitt, Talkin and Brandt (1987). This study used stops with varying VOT and other cues such as flattening of FO. Results confirmed that VOT was the strongest cue used by this population to identify voiced stops. This study did not support the study by Bennett and Ling (1973), and the differences may be because of the subjects used in the latter study had more severe hearing loss.

It can be concluded from voicing perception studies that subjects with hearing loss do not perceive voicing cues similar to listeners with normal-hearing. The listeners with hearing loss required additional cues for perception of voicing in consonants. Studies have used standardised speech perception tests and materials to study the perceptual deficits present in the individuals with hearing impairment.

2.2.4 Effects ofSN hearing loss on Speech perception test scores

Erber (1974) used spondees to measure the speech identification scores in 144 older children, whose pure tone average (average of thresholds at 500 Hz, 1000 Hz and 2000 Hz) ranged from mild to profound hearing impairment. Their scores significantly declined from near perfect scores to below chance level with an increase in hearing loss from mild to profound hearing loss.

Schwartz and Surr (1979) studied the consonant perception in individuals with normal-hearing and high frequency hearing loss and found that the mean scores were slightly lower than normal in individuals with a high frequency hearing loss in the California consonant test. Similarly, Danhauer, Hiller and Edgerton (1984) using the Nonsense syllable test found that the adults with moderate hearing loss performed with scores 10-15% lower the normal scores. Likewise, Butts, Ruth and Schoney (1987) used nonsense syllables in an identification task, in 109 subjects with varying degrees of hearing thresholds. They found that the scores declined with an increasing degree of SN hearing loss irrespective of age of the clients.

Studies have collectively shown that presence of hearing loss affects the performance in a standardised speech perception test. The decline in performance is however related to the degree of hearing loss. A high frequency hearing loss however, showed only a slight decline in scores when compared to that with normal-hearing individuals.

3. Mismatch Negativity (MMN)

In recent years, MMN has been receiving much attention as an objective method of assessing discrimination abilities (Naatanen, 2000). It is one of the event-related potentials (ERP) that can be used to assess the auditory system.

Event-related brain potentials (ERP) are induced by either environmental (such as sensory stimulus) or endogenously occurring (such as decision making) events. ERPs appear as transient changes in the ongoing electrical brain activity within a short time preceding or following the eliciting event (Stapells, 2002). An ERP is a composite of several components that are generated by parallel streams of neural activity, overlapping in time. A component, thus, is such a voltage contribution to the ERP, which reflects a functionally discrete stage of neural processing, occurring in a restricted cerebral area.

ERPs can be classified according to their timing relative to the stimulus onset, polarity, anatomical site of generation or function reflected by them. Based on the latency of the responses, auditory ERPs may be classified into short-latency, middle-latency and long-latency responses (Stapells, 2002). Auditory brainstem responses

(ABR) and Slow Negativity-10 (SN 10) can be called as the short-latency responses, which occur within 20-25 ms after the stimulus presentation. The auditory middle latency responses comprise of a series of peaks Pa, Na, Pb and Nb, which occur within 40-50 ms latencies. Late latency responses occur after 50 ms stimulus presentation and they comprise of a variety of potentials. In simpler form, they comprise of four peaks PI, Nl, P2 and N2. The ERPs P300, mismatch negativity (MMN), contingent negative variation (CNV), N400 can also be classified as late latency responses based on then-latencies, though they require special stimulus paradigms to record (Stapells, 2002).

According to their relation to the sensory input, ERP components are classified into *exogenous* (or obligatory) and *endogenous.* The *exogenous* ERP components are those that not only need a sensory stimulus but also are obligatorily elicited by the occurrence of the appropriate stimulus (Naatanen, 1992). The exogenous components are determined by physical stimulus characteristics and change their properties only in relation to stimulus features. The *endogenous* components, in contrast, reflect internally generated mental events. The endogenous components are not obligatory to the stimulus occurrence and vice versa. They may be elicited without sensory stimulation. Their parameters are only partially related to the physical stimulus features (Donchin, Ritter & McCallum, 1978). Endogenous components are greatly variable, the sources of this variability being, in addition to the nature of the internal event, a person's age, state of consciousness, experience or other cognitive capabilities. Both early and middle-latency ERPs are thought to be exogenous. Among the long-latency ERPs, exogenous components in adults are represented by the P1-N1-P2-N2 complex, whereas the endogenous components are the MMN, N2b, P300 family of responses, PN (processing negativity) and CNV (contingent negative variation). Steinschneider and Dunn (2004) recommended the terms 'sensory evoked potentials' and 'processing-contingent potentials' as alternative to 'exogenous' and 'endogenous' potentials.

3.1 Definition of MMN

The MMN is an electrical brain response, a negative component of the ERP, elicited by any discriminable change (deviant) in some repetitive aspect of auditory stimulation (standard), usually peaking at 100-200 ms from change onset (Naatanen & Escera, 2000). The classic paradigm for recording the MMN involves presenting a regular train of auditory 'standard' stimuli in which occasional 'deviant' stimuli differ from the others in terms of some physical attribute such as frequency.

The standard stimuli typically evoke an N1-P2 complex, but if the stimuli are presented at a rapid rate, this response to the standards stimuli is quite small. The response to the deviant stimulus contains two negative waves, which are most clearly seen if the standard response is subtracted from the deviant response. The difference waveform shows a negative wave at the latency of Nl and a later negative wave called the MMN. The first wave is probably the result of enhanced Nl in the deviant response. This negativity indicates detection of the change in stimuli.

3.2 The generators of MMN

The MMN generating system is shown to be rather complex as it involves several neural systems that are mainly feature-specific in nature. Several cortical and sub-cortical regions are shown to be involved in the generation of MMN. This can be construed based on studies on the polarity reversal at the mastoids (Paavilainen, Alho, Reinkainen, Sams & Naatanen, 1991), scalp electrical potential mapping (Giard, Perrin, Pernier & Bouchet, 1990; Deouell, Bentin & Giard, 1998), source modeling (Scherg & Picton, 1990), MEG data (Hari et al., 1984; Sams, Kaukoranta, Hamalainen & Naatanen, 1991) and intracerebral recordings in humans (Kropotov et al., 2000). The source modelling and intracerebral recordings indicated that the primary, secondary and associative auditory cortices on the supra temporal plane, have been shown to be the generators of MMN. The positron emission tomography (Tervaniemi et al., 1999) and the functional magnetic resonance imaging (Celsis et al., 1999) have also indicated the role of primary auditory cortex and the prefrontal cortex in MMN generation. The scalp current density analysis (SCD) also indicated the role of not only the auditory cortex but also that of the pre-frontal cortex (Deouell et al., 1998). Giard et al. (1990) proposed that the MMN generator at the supra-temporal plane may be related to the memory representation of the auditory stimuli, whereas that at the frontal cortex might generate the neuro-electric signal leading to attention switching response. An additional contribution to MMN generation by the parietal lobe was also found by hemodynamic analysis using the positron emission tomography (PET) in response to change in the auditory stimulus (Celsis et al., 1999).

A strong contribution from the non-primary thalamocortical pathways, especially for certain stimulus contrasts has also been reported. Dipole source analysis consistently indicated a non-primary auditory cortex contribution to MMN (Scherg & Picton, 1990). Direct intracerebral recordings also showed that the non-primary pathway was active in the generation of MMN (Kropotov et al., 2000).

Feature-specific generators of MMN have also been reported. The precise location of the cortical MMN sources has been shown to differ depending on the nature of the sound (i.e., simple, complex, or phonemic, the deviating feature (Frodl-Bauch, Kathmann, Moller & Hegerl, 1997), and even the feature parameters (Sivaprasad, Iyengar &Vanaja, 2001). Kraus, McGee, Carrell, King, Littman & Nicol (1994) have shown that when speech sound contrasts were used, the MMN could be recorded always from the cortex whereas the thalamic regions were selective to certain speech contrasts to generate MMN.

Hemispheric specialization is also shown through MMN generation. A larger MMN is elicited for tones, over the right hemisphere, irrespective of the ear stimulated (Korpilahti & Lang, 1994; Csepe, 1995). However, for speech stimulus there appears to be a controversy on the issue of asymmetry. Aaltonen et al. (1994) reported no asymmetry for speech contrasts. Kraus et al. (1999) also showed no hemispheric asymmetry for the /da/-/ga/ and /ba/-/wa/ contrasts in school children. However, Sharma and Kraus (1995) showed that the MMN amplitude was more over the left hemisphere for a /ba/-/da/ contrast in adults. Naatanen and Alho (1997) also found the left-hemisphere dominance for MMN amplitude when native language prototypes of vowels were used in adults and children.

Discrepancies in the findings of studies on MMN may be on account of the method used in the studies. Several variables in relation to the stimulus, recording or subject parameters can affect the response.

3.3 Variables affecting MMN

MMN, though considered as an endogenous potential, is adversely affected by several physical and physiological variables. The variables that affect MMN may be classified as stimulus variables, recording variables and subject variables. The knowledge about these factors is important in deciding the presence of MMN in an individual.

3.3.1 Stimulus Variables

Several stimulus parameters and paradigms have been noted to influence MMN recordings. These variables are discussed below.

3.3.1.1 Inter stimulus Interval (ISI).

The ISI facilitates the representation of the stimulus and detect a change from the one stored in the sensory memory (Naatanen, 1992). Usually, an ISI of 300-500 ms is used in MMN recording (Lang et al. 1995). However, studies indicate that an ISI as short as 150 ms may be used for shorter stimuli such as tones (Javitt, Grochowski, Shelley & Ritter, 1998). For long duration stimuli such as speech tokens, an ISI of 300-500 ms is used to obtain an MMN. Naatanen (1992) suggests that a longer ISI of 450 ms will result in better MMN waveforms for tone bursts. No optimal values have been reported for speech stimuli, in literature.

3.3.1.2 Probability of the deviant.

In a classic oddball paradigm, a deviant occurs randomly and the gap between two deviants is determined by a predetermined mathematical expression. Though low probability of the deviant increases the amplitude of the MMN, the total recording time would be prolonged with such short probabilities. The optimum probability is shown to be 0.1 to 0.2 in a pseudo-random sequence (Naatanen, Paavilainen, Alho, Reinikainen & Sams, 1987).

It is noted that the amplitude of MMN strongly depends upon the fact that two deviants should not occur in a row (Lang et al., 1995). It has also been noted that the MMN amplitude is more sensitive to the interdeviant interval rather than the interstimulus interval (Javitt et al., 1998).

3.3.1.3 Stimulus differences.

Smaller physical differences between the standard and the deviant evoke smaller amplitude MMN. On the other hand, very large differences cause the subject to switch attention (Naatanen, 1995). This may cause MMN to get contaminated with responses such as the P3 and N2. A frequency deviance of 50-100 Hz is shown to be optimal for frequency deviance MMN (Lang et al., 1995). No definite upper limits for intensity deviance, duration deviance and deviance for complex stimuli, has been reported.

3.3.1.4 Interaction between different stimulus parameters.

MMN is generated by any perceivable physical difference between the standard and the deviant stimuli. However, each of the acoustic parameters (frequency, intensity and duration of tone-bursts) of a stimulus also interacts in a complex fashion with the other parameters, to affect the results (Sivaprasad, Iyengar & Vanaja, 2001). The frequency and the intensity are related via equal loudness contours and the duration of the tone affects the loudness of the tone. In case of speech stimuli, if the tokens are not normalized after synthesizing, the intensity difference will also play a role in eliciting the

MMN (Szymanski, Yund & Woods, 1999). The interaction effects are to be avoided by selecting the optimum stimulus parameters.

3.3.1.5 Number of averages.

Currently the application of MMN is limited to analysing the group data because of the poor signal-to-noise ratios. The number of deviant averages determines the overall noise in the subtracted waveform. However, it takes longer test times for the overall recording if more deviants are to be averaged. For all practical purposes one-quarter to one-half deviants of the total number of stimuli are to be averaged for better signal-to-noise ratios (Picton, Linden, Hamel & Maru, 1983). It is observed that even with 250-400 deviant averages, MMN is not observed in normals (Lang et al., 1995). Picton (1995) has called for studies to detect whether multi-channel recordings could help detect MMN better in such cases.

3.3.2 Recording variables

MMN is also shown to be susceptible to several recording variables such as stimulus paradigms, electrode placement, subject's attention as discussed below.

3.3.2.1 Recording paradigms.

Stimuli are presented in a predefined paradigm, which has a particular fashion of standard-deviant stimulus combination. Several stimuli paradigms have been used to record MMN, which resulted in a broader understanding of the MMN mechanisms.

Simple invariance.

The simple invariance is a stimulus presentation paradigm to record MMN. It involves a situation wherein all the standard stimuli are identical in every possible way. Infrequent stimuli differ in any one discriminable manner as shown in Figure L.2. The first panel in the figure illustrates a train of identical stimuli (S) containing a stimulus (D) whose frequency is different from the rest of the stimuli. The representations of invariance are established for all the parameters. The classic example is the simple oddball paradigm, such as that used in the discovery of MMN (Naatanen, Gaillard, & Mantysalo, 1978). It is crucial that all the standards are identical.

Complex invariance.

In this paradigm, none of the stimuli at any moment are identical, but some features of these stimuli are identical. An example is a paradigm of tones of different frequencies and intensities such that no two tones have the same combination of frequency and intensity. There are therefore no standard stimuli as such. However, if the tone deviates with respect to a feature that is otherwise constant, such as duration, it elicits an MMN (Gomes, Ritter & Vaughan, 1995). This is illustrated in the second panel of the Figure L.2. All 'S' stimuli are different from each other except that all of them have the same duration. The 'D' stimulus has a different duration. The MMN system finds what feature is constant and establishes this invariance.

Hyper complex invariance.

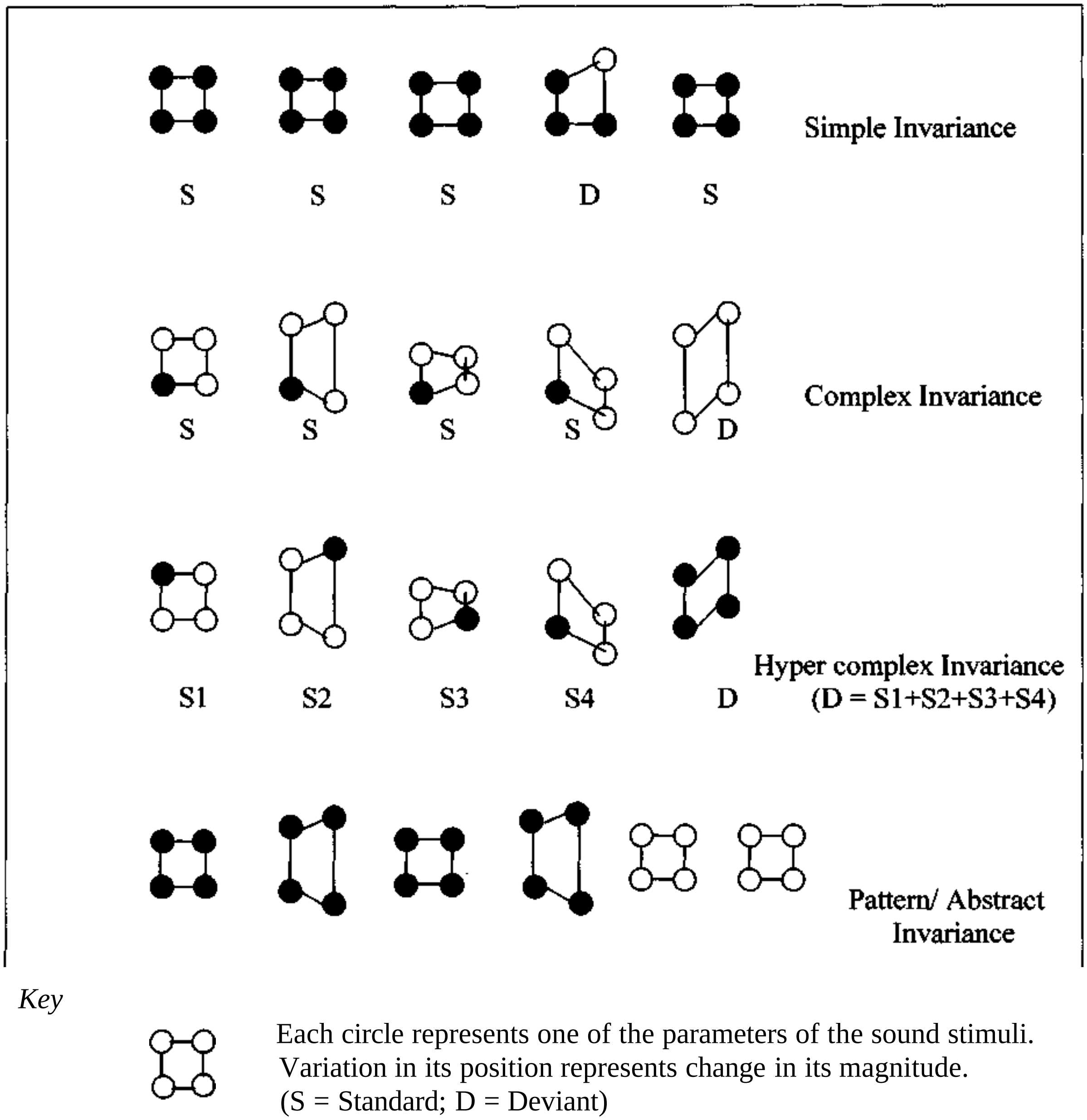
The hyper complex invariance represents the paradigm in which the standard stimuli may be in several forms, each defined by a particular set of stimulus features, and the deviant stimulus is the rare occurrence of a stimulus combining different features from all the standard stimuli. An example of this is the use of three standard stimuli characterized by one of three different intensity-frequency combinations (Gomes, Ritter, Vaughan & Miller, 1997). The deviant 'D' as shown in the third panel of Figure L.2, has the frequency of one of the standard stimuli and the intensity of another standard stimulus.

Pattern invariance.

In this paradigm, MMN is elicited by the relation between different stimuli. An example is a tone that regularly alternates between two frequencies as it repeats. A deviant stimulus is the occasional repetition of the previous frequency rather than the standard alternation to the other frequency (Alain & Woods, 1994). In this situation the pattern of alternation is the invariant and the disruption of this pattern, as depicted in the fourth panel of the Figure L.2., elicits an MMN.

Abstract invariance.

In this phenomenon the invariance across stimuli cannot be determined on the basis of the absolute physical attributes of stimuli. Saarinen, Paavilainen, Schroger, Tervaniemi and Naatanen (1992) used pairs of stimuli that had a particular relationship (e.g., the second tone was higher in frequency than the first tone) and the deviant pair was unlike this relationship, as shown in the bottom panel of Figure L.2 elicits an MMN. Pattern and abstract invariances are clearly related. Pattern invariance clearly depends on the specific features of the stimuli that make up that particular pattern, and abstract invariance depends on the relationship between stimulus features independently of their specific values.



Each circle represents one of the parameters of the sound stimuli.
Variation in its position represents change in its magnitude.
(S = Standard; D = Deviant)

Figure L.2. **Variances in stimulus paradigms that elicit MMN.**

All types of invariance except for the pattern invariance could be used in the classical oddball paradigm. All these versions of invariance have been used in eliciting MMN. However, the simple invariance method offers more flexibility and is more desirable to be used for speech perception experiments because of the exclusive auditory demands involved in the task. The data from Gomes, Ritter, Vaughan and Miller (1997), Alian and Woods (1994) and Saarinen et al. (1992) suggests that though different stimulus paradigms could be used to elicit an MMN, the MMN parameters such as the peak latency and peak amplitude does not get affected by the type of paradigm.

3.3.2.2 Attention to stimuli.

MMN can be recorded independent of attention, it can be recorded in comatose subjects (Simpson et al., 2002). A passive condition is preferable to avoid mixed waveforms caused by the N2-P3 waves typically obtained in active attention conditions (Naatamen. 1995). Watching a TV, reading or dichotic presentation of stimuli (Lang & Mikola 1994) are the methods used to divert the attention of the subject while recording MMN.

3.3. 2.3 Electrode placement.

IN most of the studies midline electrodes (Cz, Fz, Pz) have been used as the scalp sites for non-inverting electrodes (Lang et al., 1995; Stapells, 2002; Picton, Alain, Otten, & Ritter 2000). Lang et al. (1995) recommended using atleast seven scalp sites (Cz, C3, C4,Fz,F3,F 4 and Fpz) for finding the scalp distribution of the MMN amplitude. Studies which have used all the 21 electrodes of 10-20 system for finding scalp current density *analysis and* MMN generators (Scherg & Picton, 1990; Lang et al., 1995). They also recommended using the electrode site yielding the maximum amplitude for analysis purposes.MMN is shown to invert at the mastoids and the nose (Scherg & Picton, 1990). This property of MMN has often been used to confirm the presence of MMN. Hence, the mastoid or the nose can be used as the reference electrode site (Lang et al., 1995). One-or two-channel electro-oculo-gram has also been used to eliminate the artefacts contaminating MMN (Lang et al., 1995).

3.3.2.4 Identification criteria and measures of MMN.

MMN identification has been a subject of discussion. Different criteria have been used across laboratories. Visual detection has been the most widely used method to identify MMN, but this method is shown to be prone to clinician bias and is difficult to be used when small and individual recordings are to be identified. However, to analyse group data visual detection seems to be very useful (McGee, Kraus & Nicol, 1997). Currently research recommends the use of alternate way to the traditional visual detection method. Several statistical procedures such as point-by-point Mest, integrated MMN (MMNi) and principal component analysis of subaverages of the difference wave (PCI) have been proposed (Mc Gee et al., 1997; Ponton, Don, Eggermont & Kwong, 1997) for identification of MMN in the individual recordings, but are still to be validated.

Detecting and analysing MMN is less problematic in a group data (Stapells, 2002). It is now accepted that group data can easily be compared between different groups and reliable decisions can be made. Peak latency, peak amplitude and mean amplitude within a predetermined window are the most common MMN measures used in the literature. Less common are the parameters such as onset and offset latencies, MMN area and MMN duration, because of the difficulties found in defining them (Stapells, 2002). However, the literature does not suggest optimal parameters specific to a contrast or a subject population. A review of identification methods and MMN measures is described in Table L.2. From the table L.2., it can be observed that the criteria used most commonly by the researchers are:

Method to obtain MMN: Subtract standard wave from the deviant wave and obtaining a grand mean average of the subtracted waveforms.

Method to locate negativity in the subtracted wave: Through visual inspection, locate the first negative peak after N_1 whose amplitude is less than -0.5 micro V and use this to identify MMN in individual recordings.

Baseline activity to be adjusted: Average of the absolute amplitude obtained for the 50 ms pre-stimulus in the subtracted waveform.

Parameters to be obtained from MMN: Peak latency, Onset latency, Offset latency, Peak amplitude and MMN area

It can be construed that the criteria used most frequently by researchers would be the most preferred one. These criteria are recommended to be used by researchers conducting studies on MMN.

Table L.2

Review of MMn criteria and parameters used in literature

Sl. No.	**Author**	**Population**	**Stimulus**	**Group/ Individual analysis**	**MMN analysis**			
					Method to obtain MMN	**Method to locate MMN**	**Baseline electrical activity**	**Parameters studied**
1	Sams etal. (1985)	Normal-hearing	Tones	Group & Individual	Deviant minus Standard	Visual inspection: Based on grand mean wave	Mean voltage over 60 ms pre-stimulus	Peak amplitude, and peak latency
2	Oades(1991)	Normal-hearing	Tones	Group & Individual		Visual inspection: The maximum negativity within 150-300 ms		Peak latency
3	Pekkonen et al. (1993)	Normal-hearing	Tones	Individual	Deviant minus Standard	Visual inspection: The negativity around 100-200 ms		Peak latency, and area
4	Aaltonenetal. (1994)	Normal-hearing	Natural phonemes	Individual	Deviant minus Standard	Visual inspection		Peak latency, peak amplitude and onset latency
5	Maiste etal. (1995)	Normal-hearing	Natural phonemes	Individual	Deviant minus Standard	Visual inspection	Mean voltage over 50 ms pre-stimulus	Peak latency

Continued. . . .

Sl. No.	**Author**	**Population**	**Stimulus**	**Group/ Individual analysis**	**MMN analysis**			
					Method to obtain MMN	**Method to locate MMN**	**Baseline electrical activity**	**Parameters studied**
6	Groenenetal. (1996)	Normal-hearing children and cochlear implantees	Clicks	Group & Individual	Deviant minus Standard	1. Visual inspection: The maximum negativity within 250 ms 2. Statistical method: Point-by-point t-test		Peak latency, peak amplitude, duration and area
7	Aaltonen etal. (1997)	Normal-hearing	Speech glides	Group & Individual	Deviant minus Standard	Visual inspection: Based on grand mean wave	Mean voltage over 50 ms pre-stimulus	Peak latency and peak amplitude
8	McGee etal. (1997)	Normal-hearing	Synthetic speech phonemes	Group & Individual	Deviant minus Standard	1. Visual inspection: The maximum negativity within 350 ms 2. Statistical method: a. point-by-point t-test b. Integral measures	Mean voltage over 100 ms pre-stimulus	Duration, onset-peak amplitude, offset-peak amplitude and area
9	Ponton (1997)	Normal-hearing	Clicks	Group & Individual		Statistical method: Using integral measures		Peak amplitude

Continued....

Sl. No.	Author	Population	Stimulus	Group/ Individual analysis	MMN analysis			
					Method to obtain MMN	Method to locate MMN	Baseline electrical activity	Parameters studied
10	Ceponiene et al. (1998)	Normal-hearing	Tones	Group & Individual	Deviant minus Standard	Visual inspection: The maximum negativity around 200 ms	Mean voltage over 50 ms pre-stimulus	Absolute peak amplitude, peak amplitude
11	Pang etal. (1998)	Normal-hearing	Phonemes	Individual	Deviant minus Standard	Visual inspection: The maximum negativity within 150-250 ms		Peak amplitude
12	Bradlow et al. (1999)	Normal-hearing children and children with learning problems	Synthetic phonemes	Group & Individual	Deviant minus Deviant alone	Visual inspection: The maximum negativity around 200 ms	Mean voltage over 50 ms pre-stimulus	Area
13	Kraus etal. (1999)	Normal-hearing and children with learning problems	Synthetic phonemes	Individual	Deviant minus Deviant alone	Visual inspection: The maximum negativity 100-500 ms after Nl	Mean voltage over 50 ms pre-stimulus	Peak latency, Peak amplitude, Duration and area

Continued . . . .

SI. No.	Author	Population	Stimulus	Group/ Individual analysis	MMN analysis			
					Method to obtain MMN	Method to locate MMN	Baseline electrical activity	Parameters studied
14	Sharma and Doiman (1999)	Normal-hearing	Synthetic phonemes	Group & Individual	Deviant minus Standard	Visual inspection: The maximum negativity following Nl	Mean voltage over 50 ms pre-stimulus	Area
15	Ponton et al. (2000)	Normal-hearing	Clicks	Group & Individual		Statistical method: Using integral measures		Peak amplitude
16	Shafer et al. (2000)	Normal-hearing	Tones	Group & Individual	Deviant minus Standard	Visual inspection: The maximum negativity around 100-320 ms	Mean voltage of each epoch (subtracted from each epoch)	Peak amplitude and peak-to-peak latency
17	Sivaprasad (2000)	Subjects with hearing loss	Tones	Individual	Deviant minus Standard	Visual inspection: The maximum negativity around N2-P3 region		Peak latency, peak amplitude, onset and offset latencies and area
18	Jaramillo et al. (2001)	Normal-hearing	Speech phonemes and Tones	Group & Individual	Deviant minus Standard	Visual inspection	Mean voltage over 100 ms pre-stimulus	Peak amplitude
19	Kujalaetal.(2001)	Normal-hearing	Tones	Group & Individual	Deviant minus Standard	Visual inspection	Mean voltage over 50 ms pre-stimulus to 50 ms post-stimulus	Peak latency and peak amplitude

Continued.

SI. No.	Author	Population	Stimulus	Group/ Individual analysis	MMN analysis			
					Method to obtain MMN	**Method to locate MMN**	**Baseline electrical activity**	**Parameters studied**
20	McGeeetal. (2001)	Normal-hearing adults and children; and guinea pigs	Synthetic speech phoneme	Group	Deviant minus Standard	Visual inspection: The maximum negativity around 200 ms	Mean voltage over 90 ms pre-stimulus	Area and onset latency
21	Titova and Naatanen (2001)	Normal-hearing	Natural phonemes	Individual	Deviant minus Standard	Visual inspection: The maximum negativity around 140-180 ms	Mean voltage over 100 ms pre-stimulus	Peak amplitude
22	McCaslin (2002)	Normal-hearing	FM tones	Group	Deviant minus Standard	Visual inspection: The negativity after Nl	Mean voltage over 50 ms pre-stimulus	Peak latency, peak-to-peak amplitude, area and onset latency
23	Oates et al (2002)	Normal-hearing and subjects with hearing loss	Natural phonemes	Group & Individual	Deviant minus Standard	Visual inspection: The maximum negativity around 80-400 ms	Mean voltage over 100 ms pre-stimulus	Peak latency and peak amplitude

3.3.3 Subject variables

MMN is an endogenous response and is susceptible to several physiological issues also. Lang et al. (1995) have attributed absent MMN in one-third of a group of 139 healthy adults atleast partly to physiological issues. The subject variables can be on account of factors within a subject or factors across subjects.

Intra-subject factors

Prolonged recording of MMN (Lang et al., 1995), sleep (Lang et al., 1995), pitch discrimination skills (Aaltonen et al., 1994) and stage of vigilance have been shown to adversely affect the MMN amplitude. Lang et al. (1995) showed that periodical pauses between successive recordings in case of continuous recordings improved MMN amplitude, and hence is necessary for optimal MMN recording. Pekkonen, Rinne and Naatanen (1995) used both frequency and intensity deviance to elicit an MMN. They reported a considerable intra-subject variability that had cross-session correlation coefficients of 0.6 or less. In contrast, they reported that repeatability at the group level was good.

MMN and its magnetic counterpart (MMNm) have been used to study a wide range of clinical disorders. They basically aimed at studying two parameters i.e., speech discrimination and sensory memory. Speech discrimination has been studied in individuals with hearing impairment, cochlear implantees, dyslexics, autistics, cleft palate clients, and aphasics. However, sensory memory deficits have been evaluated in clients with cleft palate, schizophrenia, and autism. Studies have used either MMN alone or in combination with other event related potentials and behavioural measures.

3.3.3.1 Autism.

It is well known that autistic children show hyper or hypo sensitivity to sensory stimuli such as auditory stimuli. Some therapy techniques for autistics even incorporated auditory integration activities in their regimes. MMN studies showed somewhat controversial results in this population. No abnormalities in MMN of autistic children compared to attention deficit hyperactive disorder, dyslexia and normal children were noted by Kemner et al. (1995). More recently, prolonged peak latencies and attenuated peak amplitudes over the left frontal cortex for auditory frequency change were reported by Gomot et al. (2002). MMN amplitude in autistic children was more when compared to that of normal children (Ferri et al., 2003) elicited for an intensity deviance in tones.

3.3.3.2 Specific Language Impairment and Learning disability.

It is demonstrated that children and adults with specific language impairment (SLI) have temporal perception problems. It is hypothesized that the temporal deficits lead to SLI (Tallal, Sainburg, & Jernigan, 1991). Korpilahti and Lang (1994) studied SLI children using MMN for frequency and duration deviance. They found that MMN was attenuated in children with SLI for both types of deviance. In a similar line, Kaur (2003) used three duration deviances to study MMN in Kannada-speaking normal and SLI children. For all deviances, MMN was significantly attenuated in SLI children when compared to that of the normal children. However, all children with SLI do not demonstrate auditory perceptual deficits for behavioural measures of speech perception (McArthur & Hogben, 2001). This indicates that MMN is sensitive to subtle perceptual deficits in these children which is not detected by behavioural measures.

MMN has also been used to study the underlying subtle auditory deficits in children with learning disability (LD) using speech and non-speech sounds. Laapanen and Lyytinen (1997) found that infants at-risk for learning deficits at a later age showed significantly attenuated MMN in response to duration deviant MMN. Kraus et al. (1999) showed that children with learning disability had poor behaviourally just discriminable scores for /da/-/ga/ but not for /ba/-/wa/ contrast pairs. Also, the /da/-/ga/ contrast failed to evoke any MMN whereas /ba/-/wa/ had a significant MMN. They attributed such selective spectro-temporal impairment to dysfunction at the cortical level. In a similar line, Bradlow et al. (1999) found that discrimination thresholds for syllables with short transition duration were higher and that the effect reduced when the transition duration increased. These studies consistently demonstrated the presence of underlying auditory perceptual deficits in these children.

3.3.3.3 Cleft lip and palate.

Children with cleft lip and palate are shown to have cognitive deficits when compared to age-matched normals (Richman, 1980). It was reported that they have congenital central nervous system anomalies leading to these deficits (Nopoulos et al., 2002). Ceponine (2001) studied short-term memory using MMN in infants and children with different types of clefts. In newborns with a cleft palate only and no cleft lip, MMN was absent for tones. With increasing age, the short-term memory deficit persisted even in childhood. Children with cleft lip and palate had no abnormality in MMN at birth. However, by school age, subtle anomalies in MMN were noted. This study supports the hypothesis that children with cleft lip and palate have underlying auditory memory deficits leading to language problems.

3.3.3.4 Aphasia.

Several subjective tests are available to assess the speech and language deficits in aphasics. MMN has also been used to assess auditory discrimination deficits in this population, which is a result of brain damage. MMN for tonal frequency differences was found to reflect the spontaneous neural recovery, which correlated with the Boston's diagnostic aphasia evaluation test (Ilvonen et al., 2003).

Csepe, Osman-Sagi, Molnar and Gosy (2001) showed that speech evoked MMN, rather than that for tones has been a more precise indicator of the speech processing deficits at the cortical level in aphasics. Abnormal MMN patterns were demonstrated in children with dysphasia also (Korpilahti & Lang, 1994). Overall, MMN abnormalities have been compared with the striking language deficits in this population.

3.3.3.5 Sensorineural hearing loss.

The presence of a SN hearing loss has been shown to affect discrimination abilities. Polen (1984) reasoned that the late components of the auditory ERP evoked by phonemes, might be altered in the presence of a sensorineural hearing impairment because of: (a) the lack of high frequency information caused by hearing loss, that may be detrimental to discriminate phonemes, (b) loss of frequency resolution that may compound this problem and (c) increased difficulty in discrimination for any task is known to increase the latency of the ERP. To check these effects Sivaprasad (2000) tested thirty subjects with mild and moderate degree of hearing loss for MMN evoked by intensity deviance. The study did not show any difference in the MMN peak latency, peak amplitude, onset latency, offset latency, duration and area obtained between the subjects with normal-hearing and hearing loss at equal sensation levels (SL). The study concluded that this lack of difference reflects their intact intensity discrimination abilities.

Oates et al. (2002) used a /ba/-/da/ speech contrast and showed that the MMN peak amplitude was readily affected by the presence of hearing loss and it was significantly attenuated in the severe and profound loss subjects. However, the effects of hearing loss on MMN peak latency were rather small. The study indicates the need for a large-scale research to draw reliable generalizations regarding the effects of hearing loss on MMN.

From the above studies it can be observed that MMN is generally affected depending on the clinical condition of the client. There is no consensus among the studies regarding the kind of variation seen in the response, for a particular condition. The method used and the subject variables could have resulted in the differences in findings.

Inter-subject factors

Aaltonen, Eelora, Lang, Uuspaikka and Tuomainen (1994) have noticed that at a group level, the most significant factor influencing the MMN amplitude variation was the individual influence. Variation between the individuals in MMN parameters cannot entirely be explained by different stages of vigilance, varying EEG interference, or other factors. Other factors such as differences in dipole orientation (Lang et al., 1995), age (Lang et al., 1995) and gender (Aaltonen et al., 1994) are also to be considered in dealing with the group data.

3.3.3.6 Cochlear implantation.

Earlier studies using MMN on subjects with cochlear implants utilised it as an objective index of auditory discrimination (Ponton & Don, 1995). The focus now has shifted to using MMN to differentiate those cochlear implantees with good performance from those with poor performance (Wable, Abbeele, Gallego, & Frachet, 2000). By varying inter-stimulus-interval (ISI) of the stimuli on children with cochlear implants, MMN were recorded. It was found that they exhibited auditory short-term memory deficits. Wable et al. (2000) found correlations between MMN responses and subjective speech perception scores in implanted children. The review suggests that MMN could be used both as an objective index of speech perception and also as a tool to study the auditory memory deficits in this population.

3.3.3.7 Age.

MMN could be recorded in the early stages of life. It is shown to be ontogenetically the earliest evoked discriminative response of the human brain to be recorded. This is based on the research done on preterm infants of 30-34 weeks gestational age (Cheour-Luhtanen et al., 1995) for tonal stimuli with frequency contrasts. Cheour-Luhtanen et al. (1995, 1997) also recorded MMN in the neonates and three month old infants for tonal stimuli with frequency and duration contrasts. Alho (1995) showed that MMN peak latency decreases with increase in age from infancy to school age.

Iyengar (2000) studied thirty normally hearing children aged between 7-10 years for MMN elicited by intensity deviance. The study reported a gradual decrease in MMN peak latency with age, whereas the MMN peak amplitude and MMN area remained the same with age. Martin, Shafer, Morr, Kreuzer and Kurtzberg (2003) studied fifty-three school children aged between 4-11 years and twelve adults with age ranging from 22-38 years for frequency contrasts. The peak latency and peak amplitude showed a significant difference between the groups and the peak latency decreased with increase in age and the peak amplitude remained the same. Kraus et al. (1999) have shown that MMN peak latency, onset latency and peak amplitude did not change with increase in age from 6 to 16 years for speech sound contrasts.

The differences in findings across studies can be attributed to the stimulus contrast used to record MMN. It can be observed from the above studies that MMN varied as a function of maturation depending on the stimulus contrast. While, the literature on MMN evoked for tonebursts consistently showed effects of maturation, the studies using speech contrasts have differed in their results regarding maturational effects.

3.4 Psychophysical correlates of MMN

In order to verify whether MMN reflects behavioural auditory perception, it has been correlated with several psychophysical phenomena. These include difference limens, categorical perception, speech discrimination, comodulation masking release (CMR), McGurk effect and effects of auditory training. An insight into these studies is essential to identify the processes intersecting between behavioural and electrophysiological bases of discrimination.

3.4.2 MMN as an electrophysiological correlate of Comodualtion release of masking (CMR) & McGurk Effect

Comodulation masking release (CMR) is a perceptual phenomenon, related to the ability to perceive signals in noisy background (King, 1996). Using a behavioural paradigm in guinea pigs, tones were presented either in amplitude-modulated noise (comodulated) or in noise bands differing in amplitude modulation (conflicting). It was found that perceptually a tone was easier to hear when presented in comodulated noise than when presented in the conflicting noise because the amplitude modulation is used to group the auditory signals. King, McGee, Rubel, Nicol, and Kraus (1995), using needle electrodes, were able to obtain an MMN in guinea pigs for tonal deviants at the level of the mid brain, thalamus and cortex, for the comodulation conditions but not for the conflicting noise conditions. Their findings indicate that MMN correlates with some stimulus paradigms used in behavioural CMR experiments and does not with others.

McGurk effect demonstrates a perceptual fusion between audio and visual information in speech perception under the condition of audiovisual discrepancy created by dubbed videotapes (McGurk & MacDonald, 1976). Under this condition an acoustic syllable is perceived differently depending on the accompanying visual-speech cues. Sams et al. (1991) recorded magnetic MMN elicited by identical acoustical speech sounds when the deviant stimulus had discrepant visual cues. They proposed that McGurk effect has its neural correlate originating at the level of auditory cortex based on the highest amplitude recorded at that level. MMN has also been used in studying perceptual phenomena like the categorical perception.

3.4.3 MMN as an electrophysiological correlate of categorical perception and perceptual magnet effect

It is well demonstrated in speech discrimination experiments that the perceptual spaces for vowels and consonants are warped. It is the perceptual distance between two stimuli, as evidenced by a subject's ability to discriminate them. It is not always a straight forward function of their distance measured along physical dimensions such as frequency or time (Jusczyk, 1986; Liberman, 1996; Liberman & Blumstein, 1988; Repp, 1984).

Categorical perception is a condition wherein a listener is better able to discriminate between sounds which have been identified as belonging to different phonetic categories than between sounds which have been identified a belonging to the same phonetic category (Sharma & Dorman, 1999). Kuhl (1987) referred to a categorical perception like phenomenon for some synthetic vowels and semi vowels as the "perceptual magnetic effect," thus distinguishing it from the categorical perception in consonants. According to Kuhl, Williams, Lacerda, Stevens and Lindblom (1992) the magnet effect is characterized by highest discriminability within a category whereas the same is observed across the phonemic categories in categorical perception.

The neural correlate of the categorical perception has been investigated using MMN. Maiste, Wiens, Hunt, Scherg, and Picton (1995) have recorded MMN for /ba/-/da/ contrasts on an F2 continuum even at the perceptual difference limen threshold level. They concluded that MMN could be the neurophysiological correlate of the psychophysical ability, categorical perception. Sharma and Dorman (1999) have also recorded MMN for VOT continuum of/da/-/ta/ contrasts and found that the amplitude of

MMN varied across the contrasts and was largest for the across pair category than for the within category pairs. They also proposed that the MMN could be the neurophysiological correlate of categorical perception.

Aaltonen et al. (1997) have recorded MMN for vowels in Finnish listeners, which correlated with the psychophysical data of magnet effect. Sharma and Dorman (1999) have replicated the study of Aaltonen et al. (1997) study and concluded that MMN appears to sensitive to within category differences for the English vowel *I'll.*

Researchers have also observed that brain activity can be reflected by changes in the evoked potentials, as a result of auditory training. The ability of MMN to predict psychophysical fine grain discrimination and other perceptual phenomena has been useful in assessing the effectiveness of auditory training.

3.4.4 MMN as an objective index of effectiveness of auditory training

Generally, the effect of auditory training is measured using psychophysical tasks. The after effects of auditory training are explained on the basis of reorganization of physiological characteristics of the auditory cortical neurons based on animal experiments. In humans, there was an extensive search for a tool that helps in measuring such effects non-invasively. MMN as an index of auditory discrimination has been used to evaluate such effects after discrimination training in humans. Naatanen, Schroger, Karakas, Tervaniemi and Paavilainen (1993) have reported that MMN reflected the changes after discrimination training for tonal contrasts.

The magnitude and the duration of MMN have been reported to increase after training listeners for discrimination of synthetic vowel contrasts (Kraus et al., 1995). Increased duration and magnitude of MMN over the left hemisphere has also been reported for the non-native consonantal contrasts. MMN has also been used to show that the changes in the brain activity after auditory discrimination training for non-native VOT contrasts occur even before it is functionally demonstrated in psychophysical tasks (Tremblay, Kraus & McGee, 1998). It has been implicated in many such studies that MMN could thus be used in selection of appropriate amplification regime for children and infants.

From the review of literature it can be summarised that speech discrimination assessment is one way of determining the individual's perceptual abilities. Behavioural methods have been used for this purpose. As shown by these methods, speech discrimination abilities continue to develop till the age of 7-8 years. Sensorineural hearing loss is also shown to affect speech perception abilities. It not only reduces an individual's audibility but also affects their speech perception abilities. Variations in discrimination as a result of age and clinical conditions have been evaluated effectively using mismatch negativity (MMN). Studies have shown that MMN responses correlate with behavioural discrimination abilities. It can be used to document the changes in discrimination abilities as the result of perceptual training. Hence, it is considered a useful tool to determine speech perception abilities in normal as well as the clinical population.

METHODS

The main aim of the study was to find the correlation between the behavioural and electrophysiological measures of speech perception in subjects with normal-hearing and hearing loss. In addition the effects of degree and slope of hearing loss on each of these measures was also aimed to study. The following method was used in studying the aims.

Subjects

In total, 121 subjects participated in the study. They were classified into two subgroups: experimental and control groups. The experimental group comprised of adults and children with a hearing loss, whereas the control group had normal-hearing age-matched subjects.

Experimental group

Clients registered at All India Institute of Speech and Hearing, Mysore, were recruited for the study. The following criteria were used in the process of recruiting the subjects:

- They should be diagnosed as having sensori-neural hearing loss,
- The duration of hearing loss should be atleast six months,
- Pure tone average (PTA) should be between 26-65 dB HL at least in one ear,
- TEOAEs should be either reduced in amplitude or absent corresponding to the degree of SN hearing loss,
- They should have no history of other otological and neurological problems, and
- No history of congenital or pre-lingual hearing loss (to rule out the effects of deviant/delayed language),

This group was further subdivided into two groups based on the chronological age of the subjects:

- Group I (8-18 yrs)
- Group II (18-55 yrs)

Group II was further sub grouped into four groups based on the degree of hearing loss and the audiogram slope. The subgroups were as follows:

- Degree of hearing loss
  - Mild hearing loss (26-40 dB HL)
  - Moderate-severe hearing loss (41-65 dB HL)
- Audiogram slope
  - Flat hearing loss
  - Sloping high frequency hearing loss

The group I was not classified into subgroups because subjects with mild or sloping hearing loss is that age group were difficult to obtain.

Control group

Normal children and adults matched in age with those of the experimental group were included in the study. They were chosen if they passed the hearing screening tests, which included:

: Pure tone average (PTA) less than or equal to 15 dB HL

: 'A' type tympanogram and reflex thresholds present at normal levels

: No history of neurological or otological problems

The group was classified into group I (8-18 yrs), and group II (18-55 yrs) based on their age.

The demographic characteristics of the subjects, which include their age, years of morbidity and pure tone average, are given in Table M.I.

Table M.I

Demographic and audiological details of the subjects

		Mean age (in years)	**Mean PTA** (in dB HL)	**Mean years of morbidity**
Control Group	*Adults (N=22)*	35.0 (18-55)	10.0 (0-15)	-
	Children (N=15)	9.0 (8-18)	8.7 (5-15)	
Experimental Group	*Adults-Mild (N=25)*	38.0 (18-55)	33.8 (20-40)	7.0 (3-8)
	Adults-Moderate (N=32)	39.0 (18-55)	54.4 (41-55)	9.0 (7-12)
	Children (N=27)	12.0 (8-18)	52.0 (41-55)	4.0 (2-6)

Note: The values in parentheses are the range values of the raw scores

Instrumentation

The following instruments were used to record and collect the data:

- Orbiter OB922 (Madsen Electronics, Denmark), a calibrated clinical two-channel audiometer, to diagnose the hearing loss and to administer tests for speech identification and speech discrimination scores.
- GSI-33 (Grason-Stadler Inc., USA), a calibrated middle ear analyzer to administer tympanometry and reflexometry,
- ILO 292 (Otodynamics Inc., UK), an oto acoustic emission analyzer to run a screening TEOAE.
- A computer with Cool Edit Pro version 2 (Syntrillium Inc., USA) and Audiolab (Voice and Speech systems, India) software to record and scale the

speech stimuli to be used in MMN recording, speech identification and the speech discrimination tasks,

- Praat software for the acoustic analysis of the recorded stimuli,
- Smart EP version 2.12 C (Intelligent Hearing Systems, USA) to generate stimuli and record the MMN responses,
- Philips audio CD player to present the recorded stimuli for speech recognition threshold, speech discrimination and speech identification testing

Stimuli

Eleven vowels (V) and consonant-vowel (CV) syllabi were used as test stimuli. They include: /a/, /i/, *Id*, /ka/, /ga/, /pa/, /ma/, /sa/, /la /, /la/ and /ra/. The 4-formant frequencies and their onset frequencies are described in Table M.2. Praat speech analysis software used to obtain this information. The spectrograms are shown in Figure M.I.

These stimuli were used for eliciting the speech identification scores (for nonsense syllables). Bisyllabic meaningful words of speech identification test in Kannada (Vandana, 1998) were used as stimuli for eliciting the speech identification scores of meaningful words. For the discrimination tasks (behavioural and objective) and the eleven CV tokens were grouped into seven phoneme pairs. Each pair would evaluate a specific phoneme contrast, as shown in Table M.3.

Table M.2

The formant frequencies (in Hz) and their onset frequencies (in Hz, in brackets) for different speech sounds

	F_1	F_2	F_3	F_4
/a/	639	977	2840	3640
/i/	302	2352	2365	3771
/e/	414	2198	2910	3842
/ka/	687 (355)	1168 (1215)	2758 (2839)	3725 (3747)
/ga/	554 (403)	1008 (1263)	2721 (2887)	3734 (3412)
/pa/	648 (689)	977 (976)	2449 (2552)	3481 (3508)
/ma/	564 (355)	1093 (1119)	2192 (2600)	3342 (3556)
/sa/	682 (1501)	1233 (2266)	2772 (4224)	3730 (4989)
/Ja/	655 (355)	1468 (1931)	2522 (2743)	3611 (3508)
/la/	752 (403)	1179 (1215)	2650 (3317)	3613 (4272)
/ra/	713 (785)	1231 (1358)	2529 (2218)	2627 (3460)

Table M.3

Phoneme pairs used for eliciting MMN and speech discrimination scores and the respective contrasts

Stimuli	**Phoneme Contrast**
/a/-/i/	Front-mid constriction
/i/-/e/	Height of the tongue
/ka/-/ga/	Voicing
/ka/-/pa/	Plosive-place
/pa/-/ma/	Nasal
/sa/-/ja/	Sibilant-place
/la/-/ra/	Liquid-place

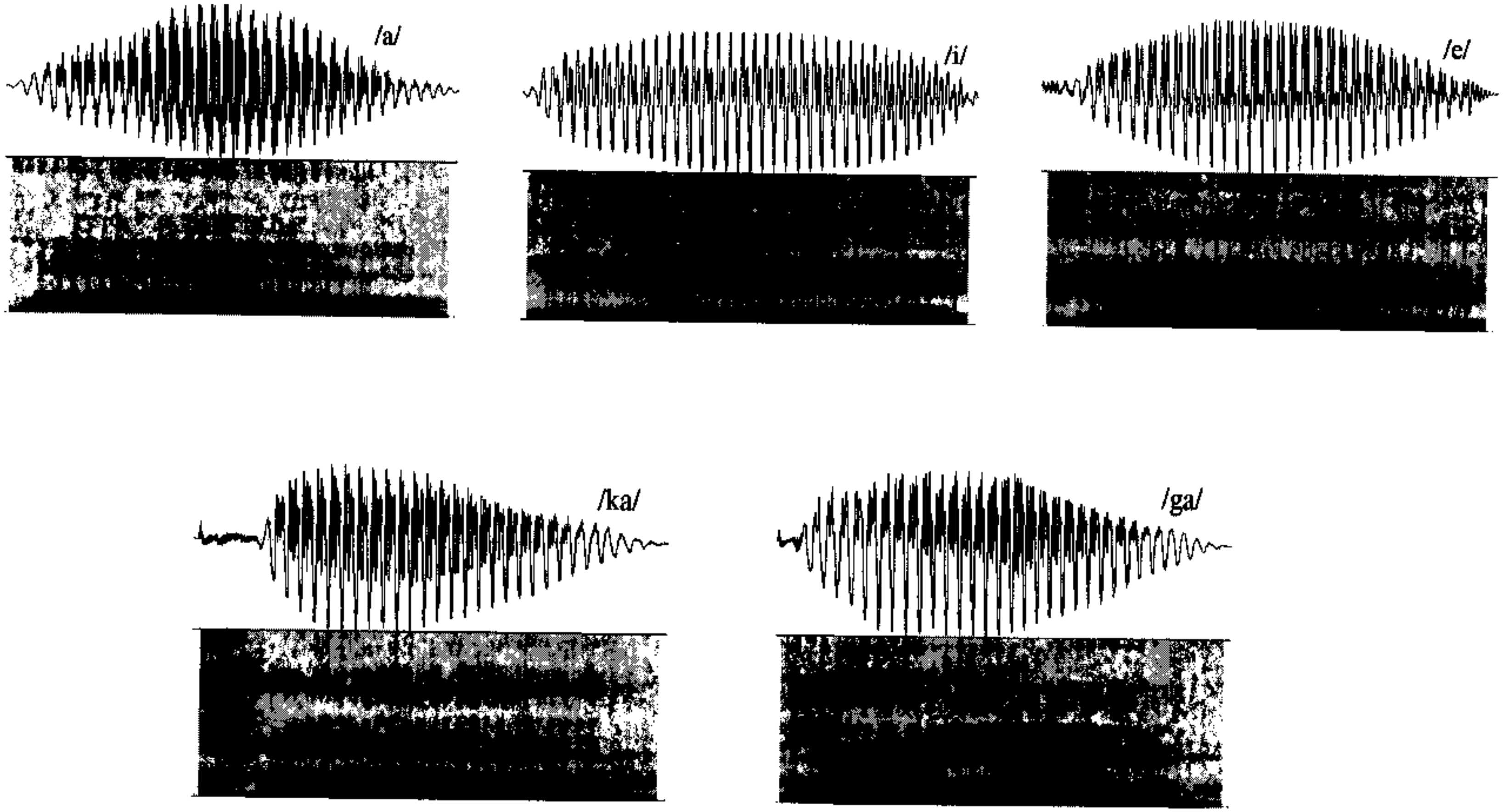


Figure Mi. Spectrographic and waveform views of the CV syllables (continued...)

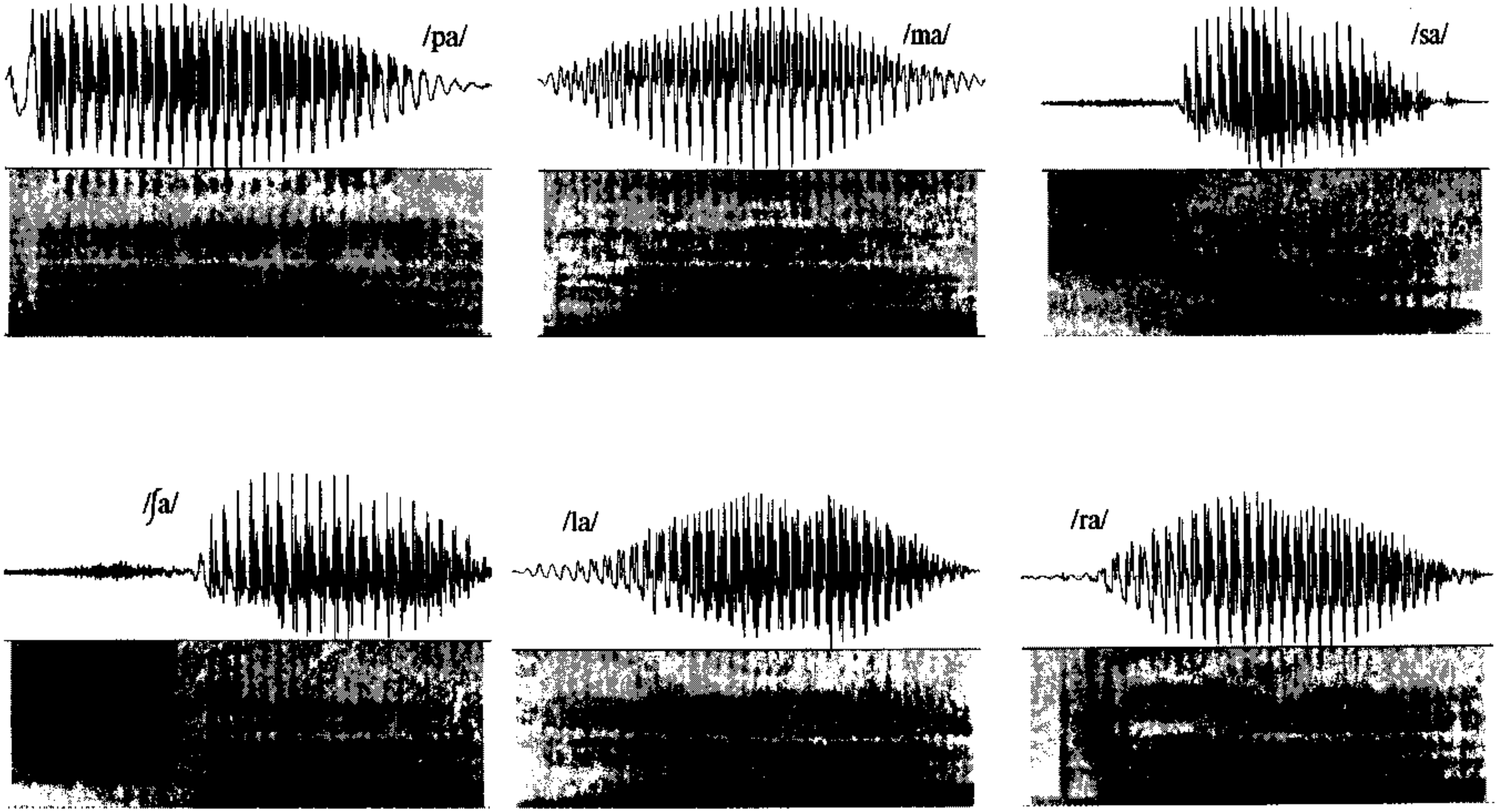


Figure M.I. Spectrographic and waveform views of the CV syllables

Recording

A male speaker whose mother tongue was Kannada (a language widely spoken in Karnataka, South India) was chosen as the speaker. The V, CV tokens and bisyllabic words were recorded into a Pentium IV computer via a microphone (Sony F500) placed at a distance of 15 cm form the lips of the speaker. The recorded stimuli were digitized using a 16-bit processor at 22,050 Hz sampling frequency. They were then scaled to maintain equal intensity. Further the V and CV tokens were truncated to a maximum duration of 250 ms, using the Audiolab software, as the instrument for recording of MMN does not permit the use of longer stimuli. The stimuli were then transferred into a compact disc for further administration with the subjects. An interstimulus interval of 3 seconds was introduced between the stimuli for behavioural assessment of speech perception.

Procedure

The control group subjects underwent a pure tone hearing screening at 250 Hz, 500 Hz, and 1 kHz; and immittance evaluation. A detailed diagnostic hearing evaluation was administered on the experimental group. The tests included:

- AC and BC thresholds from 250 Hz to 8 kHz,
- Immittance evaluation, and
- TEOAE screening.

The pure tone average (PTA), the average hearing threshold at 500 Hz, 100 Hz and 2000 Hz frequencies was established for each of the subjects. Their speech recognition thresholds (SRT) were obtained once a subject is recruited into the study. The spondee-pair material developed at All Institute of Speech and Hearing, Mysore was used for establishing SRTs for each of the subjects. The pairs were presented at

20 dB HL above ones PTA. If the subject repeated two out of three pairs correctly, the presentation level was decreased in 5 dB steps, till the lowest level at which the subject repeated two out of three spondee-pairs correctly. This was considered the SRT.

In addition all the subjects underwent a battery of speech identification, speech discrimination tests. The following were the tests administered on both the groups:

- Speech Discrimination Scores (SDS)
- Speech Identification Scores (for non-sense syllables)
- Speech Identification Scores (for meaningful words) and,
- Mismatch Negativity (MMN)

Speech Discrimination Scores (SDS)

The seven pairs of tokens were presented at a level of 40 dB SL (with reference to SRT) using the CD player and each pair was repeated three times in the list in a random manner. The subjects were instructed to say whether the pair of speech sounds he hears are the same or different. The number of pairs correctly discriminated was recorded to elicit the SDS. The SDS was defined as the number of correctly discriminated pairs of syllables. The list of stimuli used for eliciting SDS is given in Appendix 1.

Speech Identification Scores for non-sense syllables (SIS-N)

The recorded material of eleven syllables was presented at a level of 40 dB SL (with reference to SRT) via the CD player. The subjects were instructed to repeat the test item and the total number of correctly identified syllables was recorded. The speech identification score (SIS) was based on the number of tokens correctly identified. The stimuli used in this test are given in Appendix 2.

Speech Identification Scores for meaningful bisyllabic words (SIS-M)

The Speech identification test for children in Kannada (Vandana, 1998) was administered at a level of 40 dB SL (with reference to SRT) via the CD player. The subjects were instructed to repeat the test items and the total number of correctly identified words was noted. The speech identification score (SIS) was calculated based on the number of correctly identified bisyllabic words. Appendix 3 shows the list of stimuli used for eliciting SIS-M.

Mismatch Negativity (MMN)

Subjects were seated comfortably in an armed chair. A video film was played to distract their attention from the auditory task. They were instructed not to pay attention to the sounds presented to their ear. There were rest periods for a few minutes after every recording of MMN. Stimuli were presented through ER-3A insert phones. Four silver electrodes were placed on four sites on the scalp and nose to pickup the MMN response. The sites included:

- Fpz - common
- Cz - non-inverting (channel 1)
- Pz - non-inverting (channel 2)
- F3 - non-inverting (channel 3)
- F4 - non-inverting (Channel 4)
- Nose tip - inverting

After cleansing the electrode sites on the scalp with surgical spirit and a skin-preparation solution, the silver electrodes filled with standard EEG paste were placed and fixed with a surgical tape. It was ensured that the impedance at each electrode site was less than 5 k Ohm, and the inter electrode impedance difference was less than

3 k Ohm. The phoneme contrast pairs were the same as those used in the behavioural speech discrimination task. The first phoneme of pair each was the deviant stimulus and the second was the standard one. The stimulus and recording parameters for MMN is given in Table M.4.

Table M.4

The stimulus and recording parameters in MMN recording

Stimulus	V, CV syllables
Repetition rate	1.6/second
Intensity of the stimuli	40 dB SL
Probability of the deviant	4:1
Transducer	ER-3A insert phones
Channel #1	C_z-Nose
Channel #2	P_z-Nose
Channel #3	F3-Nose
Channel #4	F4-Nose
Time window	-50 to 408 ms
Filter setting	1-30 Hz
Amplifier gain	X50k
Number of averages (deviants)	150-200

Interpretation of MMN responses

Studies published in the peer-reviewed journals were reviewed and a set of steps to extract and identify an MMN was formulated. From each recording, MMN was obtained by subtracting the average response for the frequent stimuli from that of the infrequent. For the identification of the MMN through visual detection, a grand average of MMN waveforms was obtained for each of the sub groups. Steps to record and identify an MMN were as follows:

- Step l. Obtain a grand mean average of the subtracted waveforms within a group.
- Step2. By visual identification, locate the first negative peak after Nl whose amplitude is less than - 0.5 microvolts and note the latency range in the grand mean waveform.
- Step3. Use this latency range to identify MMN in individual recordings.
- An average of the absolute amplitude obtained over the 50 ms prestimulus in the subtracted waveform is considered the baseline and is subtracted from the rest of the MMN wave.

Once the MMN was identified, then the following parameters were extracted from the MMN of every subject:

- Peak Latency - The time in ms at which the negativity reached its peak in the subtracted waveform.
- Onset latency - The time in ms at which the negativity started in the subtracted waveform.
- Offset latency - The time in ms at which the negativity reached to the baseline activity in the subtracted waveform.
- Peak Amplitude - The maximum amplitude of the peak of the negativity with respect to the baseline. This was measured in microvolts.
- MMN area - The area under the negative trough, derived from multiplying the peak amplitude with MMN duration.

- Area - The product of duration (difference between the onset and offset latencies) of the negativity in ms and the peak amplitude in microvolts. This was measured in ms X microvolts.

The data thus obtained was subjected to statistical analysis, which included non-parametric t-tests, regression analysis and ANOVA.

RESULTS AND DISCUSSION

A total of 121 subjects, of whom 37 were normal-hearing individuals and 84 were individuals with a hearing loss, participated in the present study. They underwent both psychophysical and electrophysiological evaluation. The data obtained was subjected to statistical analysis. A commercially available statistical software package SPSS version 10.0 was used for all the statistical computations. The results are discussed for the following parameters:

I. Speech perception - Behavioural tests
    a. Mean and Standard Deviation of the scores
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I. Speech perception - Behavioural tests

In the behavioural experiments, speech discrimination scores (SDS), speech identification scores for nonsense syllable pairs (SIS-N) and speech identification scores for meaningful speech material (SIS-M), were obtained. The maximum scores were 21,11 and 50 respectively for these tasks. These scores were based on the number of items present in each of the tasks. All the 121 subjects participated in these tasks.

La. Mean and Standard deviation of the speech perception scores

To obtain the mean and standard deviation, the subjects were subgrouped as the control (normal-hearing) and experimental (hearing loss) groups. Each of these groups was further divided into adult and child groups. The experimental group was further divided into subjects with mild and moderate hearing loss, based on the degree of hearing loss. However, this division of groups, based on degree of hearing loss could not be done in children as all the subjects had moderate hearing loss. The mean and standard deviation (SD) for the pure tone average (for the frequencies 500 Hz, 1000 Hz and 2000 Hz) as well as the three behavioural speech perception tests is depicted in Table R.I.

As is evident from the mean percent scores, almost perfect scores were achieved by both groups, in all the speech perception tests. Results showed that the highest scores were obtained by normal-hearing adults and children in all the speech perception tasks followed by adults with mild and moderate degrees of hearing loss. Children with a hearing loss performed relatively poorly. Their scores fell between that of the adults with a mild and moderate hearing loss. They obtained scores higher than the adults with a moderate hearing loss and less than those with a mild hearing loss. Using ANOVA it was found that in all the tasks the children performed significantly poorly when compared to age-matched controls (*p* < 0.01). The differences in scores for all the speech perception tests among adults were not significant between the mild and moderate hearing loss groups and also between the normal-hearing and the mild hearing loss group (*p* > 0.05). However, the differences in all the scores were significant between the normal-hearing group and those with a moderate hearing loss (*p* < 0.05).

Table R.I

Mean, Standard Deviation (SD) of raw scores obtained in speech perception tasks

		SIS-M (max: 50)		**SIS-N (max: 11)**		**SDS (max: 21)**	
		Mean	**SD**	Mean	**SD**	Mean	**SD**
Control Group	*Adults*[a]	49.6 **(99.8%)**	**0.3**	**10.9** **(99.5%)**	**0.8**	**20.9** **(99.8%)**	**0.5**
	Children[b]	49.9 **(99.7%)**	**0.6**	**11.0** **(99.2%)**	0.9	**20.8** **(99.8%)**	**0.7**
Experimental Group	*Adults-Mild*	49.6 **(97.1%)**	**1.0**	**10.8** **(99%)**	**0.5**	**20.8** **(98.8%)**	**0.6**
	Adults-Moderate[d]	47.1 **(94.6%)**	**4.6**	**10.1** **(96.7%)**	**1.4**	**19.7** **(96.8%)**	**2.1**
	Children[e]	48.3 **(95.3%)**	**3.4**	**10.5** **(97.2%)**	**1.2**	20.4 **(97.7%)**	**1.7**

Note. [a]N = 22. [b]N=15. [c]N = 25. [d]N = 32. [e]N = 27.

Percentage of the scores is shown in parentheses.

The variability in scores was more in subjects with a higher degree of hearing loss. While the normal-hearing subjects and the adults with a mild degree of hearing loss showed less dispersion in scores, those adults with a moderate degree of hearing loss showed greater variability. It was more for the meaningful speech identification task. Probably the complexity of the material in this test made it more difficult, resulting in more variability.

I.b. Effects of age on behavioural speech perception tests

In this analysis, only subjects from the control group were included to avoid the effects of a hearing loss. It was found that almost perfect scores were obtained in all the behavioural tasks. Also little variance could be seen in the data. It may be inferred that age had no effects on these speech perception tasks. The nonparametric /-test indicated that there was no significant difference ($t > 0.05$) between the scores obtained by adults and children in the control group.

The perfect scores seen in children is an expected finding. Several studies showed on different speech perception tasks, adult-like scores are obtained by school-age children. Fior (1972) and Hnath-Chisolm et al. (1998) showed that scores in traditional speech identification tests using monosyllables reached near 100% by the age of seven. The ability to discriminate among the vowel sounds was shown to mature relatively early, i.e., by the first year of life (Eilers, 1980). Discrimination of consonants especially the fricatives showed a continuous improvement throughout the early school years and reaches an adult like perception by the age of 6-7 years (Abbs & Minifie, 1969; Allen & Wightman, 1992). However, perception of speech-in-noise and low-predictability sentences tends to continue to develop throughout school age and matures by 12-14 years of age (Elliott, 1979). Thus, the findings of the present study are in agreement with the above studies, which showed that basic speech discrimination and identification abilities mature by 7-8 years of age.

I.c. Effects of degree of hearing loss on behavioural speech perception tests

Regression analysis was carried out to obtain the effects of hearing loss on speech perception scores. All the subjects were included for this analysis. It was noted that there was a significant effect of degree of hearing loss on all three measures of speech perception shown in Figure R.1. With an increase in hearing threshold level, the SDS, SIS-N and SIS-M scores decreased, which was significant at the 0.01 level. Further analysis using a t-test indicated that though there was no significant difference ($p > 0.05$) between the control and the mild hearing loss group, the difference was significant ($p < 0.01$) when compared to those with a moderate hearing loss.

It is well known that speech perception difficulties increase with increasing the degree of hearing impairment in children and adults. Erber (1974) also noted that speech identification scores significantly declined with an increase in hearing loss from near perfect scores to below chance level, in individuals with hearing loss varying from a mild degree to a profound degree. Studies have also shown that the phoneme recognition scores decreased with increasing hearing loss. Low frequency cues such as the nasal murmurs are perceived accurately by all degrees of hearing impairment except in those with profound hearing loss (Pickett et al., 1972). Voicing is quite well perceived by persons with any degree of hearing impairment (Pickett, 1999). Cues to place of articulation become unavailable with an increase in degree of hearing loss, which leads to more errors in perception of place (Pickett, 1999). Vowel recognition is also shown to decline with an increase in degree of hearing loss (Erber, 1974). The results of the present study also support that all the three speech perception scores decline with an increase in degree of hearing loss. This indicates that as the hearing loss increases, the auditory cues perceived by the individual decrease.

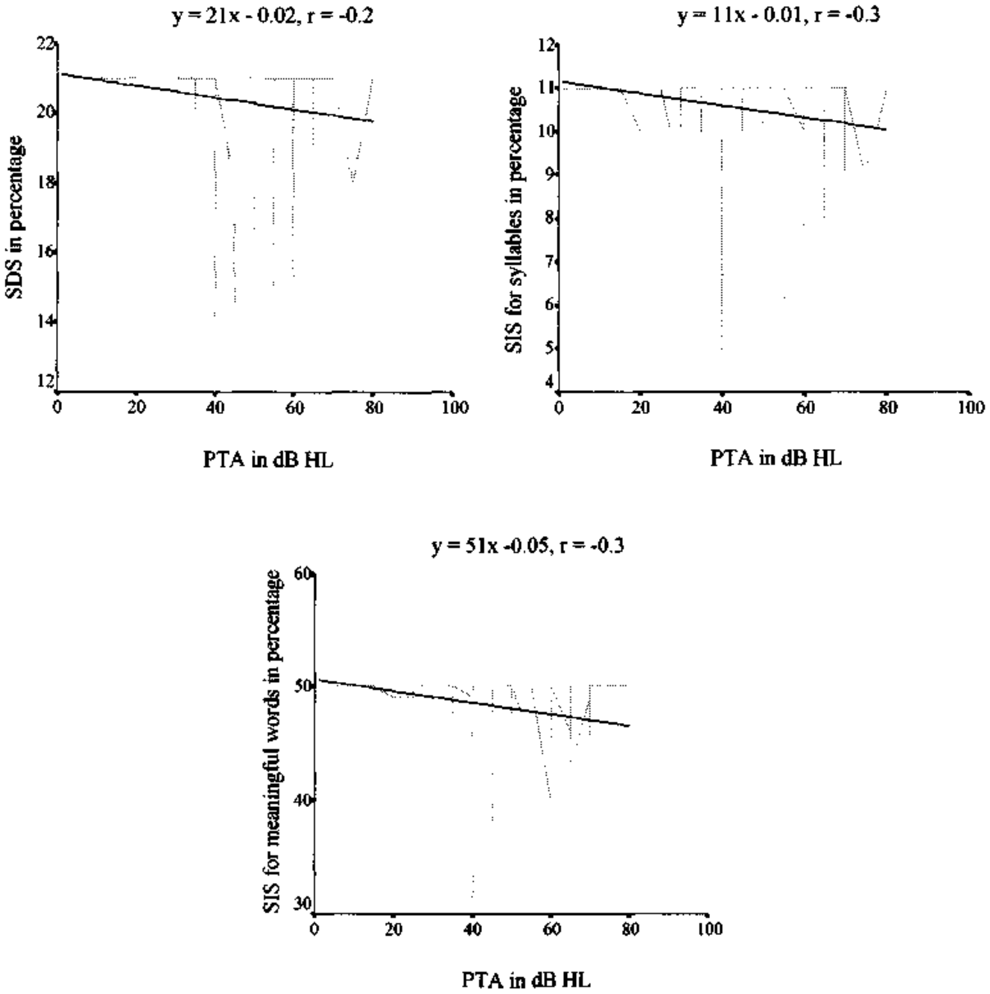
I.d. Effects of audiogram slope on behavioural speech perception tests

The regression analysis revealed statistically no significant effects of audiogram slope on speech perception scores. With an increase in audiogram slope, the behavioural speech perception tasks, i.e., speech discrimination scores ($r = -0.1; p > 0.05$), speech identification scores for nonsense syllable ($r = -0.2; p > 0.05$) and speech identification scores for words ($r = -0.1; p > 0.05$) showed no change.

It is reported in literature that audiogram slope in addition to hearing threshold level is known to influence speech perception scores. Schwartz and Surr (1979) used the California Consonant Test (CCT) and North Western University (NU-6) speech material to study individuals with high frequency hearing loss. They found that the phoneme recognition scores improved with an increase in presentation level but the maximum scores were observed at 40 dB SL and 50 dB SL for the normal and the high frequency hearing loss subjects. They also reported that the maximum scores of the high frequency hearing loss were lower than those of normal-hearing at any presentation level. Maroonroge and Diefendorf (1984) also reported that individuals who have sloping hearing loss after 2 kHz have performed poorly in CCT and the Pascoe's high frequency test. They did not find any effect on NU-6 scores. They concluded that the NU-6 material might not be sensitive in detecting the effects of sloping hearing loss.

In contrast, the present study did not find any such effects of audiogram slope on speech perception scores. It may be because of the material used in the study, which is not sensitive in detecting speech perception difficulties in individuals with sloping hearing loss. Further, the present study did not include individuals with a steep slope. Mascarenhas (2002) noted that speech identification scores are not affected much in gradually sloping hearing loss, but get affected in those with a steeply sloping loss. These factors could also have lead to the audiogram slope not having an effect in the present study.

Thus it may construed from the present study that the behavioural tests i.e., speech identification and speech discrimination tests showed no effects of maturation in the control group, and decreasing scores with increasing degree of hearing loss and no effects of audiogram slope in the experimental group.



$y = 21x - 0.02, r = -0.2$

$y = 11x - 0.01, r = -0.3$

$y = 51x - 0.05, r = -0.3$

Figure R1. The linear regression lines and their equations showing the effects of degree of hearing loss (PTA) on speech perception tasks (SDS, SIS-N, and SIS-M).

II. Speech perception - Mismatch Negativity

In the electrophysiological experiments, MMN was recorded for seven speech contrasts from four electrode sites (C_z, P_z, F_3 and F4) on the scalp. In a majority of the subjects MMN was present. Such a trend was seen in individuals with normal-hearing as well as those with a hearing loss.

The analysis also found that there were significant effects of degree of hearing loss and the audiogram slope on MMN parameters. However, these effects were specific to some phonetic contrasts and scalp sites. The effects of type of phonetic contrast were also found on different MMN parameters.

To check the reliability of the MMN data across four electrode placements for each of the MMN parameters the Cronbach's *alpha* test was administered. The alpha values exceeded 0.8, which indicated a high reliability in the data. The alpha values were very similar across different phonetic contrasts and the scalp sites. Similar alpha values were seen in adults and children in both the control and the experimental groups. Thus, it can be construed that the reliability of the MMN recorded in the study was high.

Il.a. Effects of stimulus contrast on recordability of MMN

The percentage of subjects in whom MMN was recorded was calculated in all the groups for different stimulus pairs across each of the scalp sites. The results are discussed in the individuals with normal-hearing and hearing loss.

(i) Control group

The percentage of adults and children who showed an MMN are shown in Tables R.2 and R.3, respectively. The percentage of adult subjects in whom MMN was present varied across stimuli and the electrode site (Table R.2). Among the vowels, the /a/-/i/ contrast elicited MMN responses more often than the /e/-*/i/* contrast, irrespective of the electrode site in adults. All the consonantal contrasts elicited a similar percentage of MMNs in adults. The percentage of individuals in whom an MMN was present for the consonantal contrasts ranged from 73 % to 95 %. The least number of MMNs were present in the F4 site for the /ma/-/pa/ contrast. The *'equality of correlated proportions'* (McNemar cited in Garrett, 1979) was administered to check if there was a difference between the percentages elicited by different speech contrasts. The critical range value did not show any significant difference ($p > 0.05$) between the percentages of MMNs recorded for any two pairs of stimuli. The critical range values were also insignificant ($p > 0.05$) for all the four electrode sites.

The percentage of children with an MMN for the different speech contrasts and scalp locations is showed in Table R.3. In the control group, it may be noted that the percentage of MMNs present in children was not different from that of the adults for most of the stimuli. The *equality of correlated proportions* indicated that there was no significant difference ($p > 0.05$) between the percentages of children who had an MMN elicited for different speech contrasts. The values were also insignificant (p > 0.05) across any of the four electrode sites. Hence, in normal adults and children any of the speech contrasts and any scalp site may be used to record MMN.

In a study on frequency contrasts using tones, Lang et al. (1995) found that only one-third of a group of 139 normal subjects showed MMN. The subjects had an age range of 20-82 years. However, Joutsiniemi et al., (1998) reported that the percentage of adult subjects who showed an evidence of an MMN was higher when compared that shown by Lang et al. (1995). MMN waveforms could be recorded in 39 of their 40 subjects. They used pure tones with duration as the contrasting feature, where as Lang et al. (1995) used frequency as the contrasting feature. Kraus et al. (1999) also showed that not all their 134 normal-hearing subjects showed evidence of MMN. For the /da/-/ga/ contrast continuum used in their study, the percentage of MMN seen varied from 50.6% to 100% depending on the complexity of the phonetic contrast. They also reported that the percentage varied depending on the MMN identification criteria.

The earlier studies showed that depending on the contrast feature i.e., frequency o intensity, used for the tone-burst stimulus, the number of subjects who showed an MMN varied. The present study showed no such effect of the contrast feature on the percentage of individuals with an MMN. The difference in results may be because of the speech contrasts used in the present study. Further, in the present study a higher number of normal subjects had an MMN when compared to that reported by Kraus et al. (1999). This may be an account of the differences in speech contrast features and naturalness of stimuli used in the two studies. It may be said from the present study that the type of speech contrast being used to record MMN has no effect on the percentage of individuals who show an MMN.

(ii) Experimental group

The hearing impairment reduced the probability of obtaining an MMN in both adults and children, as shown in Tables R.2 and R.3. Irrespective of the stimulus and the electrode position on the scalp, the percentage of MMNs seen reduced with increase in hearing loss in adults (Table R.2). Though the probability of MMNs reduced with the presence of hearing loss in other electrode sites, the C_z site did not show reduction effects in percentage of MMNs for some of the speech contrasts. The P_z site also showed good recordability for some of the speech contrasts.

Table **R.2**

Percentage of adults with an MMN for different speech sound contrasts at four electrode sites

	/a/-/i/	/e/-/i/	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	/sa/-/ja/	/la/-/ra/
Normal-hearing adults							
C,	91	82	95	95	82	77	86
Pz	91	*11*	91	91	73	82	91
F_3	91	*11*	86	86	82	86	86
F_4	95	82	86	77	73	95	91
Mild hearing loss adults							
C_z	88	68	80	95	70	75	74
Pz	76	72	60	88	70	70	68
F_3	80	80	80	84	80	70	74
F_4	76	77	60	84	70	70	68
Moderate hearing loss adults							
C_z	81	61	77	89	80	76	76
Pz	78	65	61	86	77	68	80
F_3	75	67	71	72	78	68	72
F_4	72	61	68	77	70	68	76

Note. All entries are in percentage

Hearing loss reduced the percentage of MMNs for almost all the contrasts in children also. Just like the adult groups, children also showed reduction in the percentage of MMNs seen across all the other scalp sites, irrespective of the stimulus. The fall in percentage with hearing loss was more for the /la/-/ra/ contrast when compared to that of the other contrasts.

Using the /ba/-/da/ speech contrast, Martin, Kurtzberg and Stapells (1999) reported that MMN was present in all the eleven subjects with hearing loss they tested. The percent of individuals who showed MMN fell to 70-80% when masking was used to simulate the effects of degree and slope of hearing loss. Oates et al. (2002) reported that the percentage of adult subjects who showed MMN decreased with an increase in hearing loss. The percentage fell from 80% in the mild hearing loss subjects to 11.1% in subjects with severe hearing loss.

Table R.3

Percentage of children with an MMN for different speech sound contrasts at four electrode sites

	/a/-/i/	*/e/-/i/*	**/ka/-/ga/**	**/ka/-/pa/**	**/ma/-/pa/**	**/sa/-/ a/**	**/la/-/ra/**
Normal-hearing children							
C_z	**93**	**80**	**80**	**73**	**93**	**88**	**88**
Pz	90	**87**	**87**	**73**	**93**	**87**	**80**
F_3	90	**80**	**80**	**80**	**93**	**87**	**87**
F_4	92	**80**	**80**	**80**	**93**	**87**	**87**
Hearing loss children							
C_z	85	**81**	**62**	**83**	**87**	**71**	**67**
Pz	89	**73**	**62**	**83**	**83**	**71**	**67**
F_3	85	**69**	**62**	**71**	**87**	**67**	**52**
F_4	89	**69**	**46**	**75**	**83**	**71**	**52**

Note. All entries are in percentage

From the present study and the literature it appears that the audibility of the acoustic cues also has an effect on the percentage of individuals who has an MMN. Overall, it can be said that the type of speech contrast being used to record MMN has no effect on the percentage of individuals who show an MMN. It can be thus be concluded that the audibility of the stimulus contrasts, but not the age and the type of speech contrast have an effect on the percentage of individuals who has an MMN.

III b. Effects of age on speech-evoked MMN

In this analysis, only the control group was included in order to avoid the effects of hearing loss on MMN parameters. The control group, which included children and adults, comprised of 31 subjects. A simple linear regression analysis was used to find the effects of age on peak latency, peak amplitude, onset latency, offset latency and area of MMN. The y-intercept, slope, significance of the slope and the Pearson's correlation coefficient were obtained for each of the stimuli and across different channels on the scalp. The grand mean average of the MMN waveforms recorded for different speech contrasts as shown in Figure R.2 reflect the developmental changes. Only the grand mean at the C_z site has been shown in figures since the recordability of MMN was maximum at this site.

1. Latency parameters

The latency parameters evaluated were peak latency, onset and offset latencies. The effects of maturation on these parameters are discussed.

(i) Peak latency.

The effects of age on peak latency of MMN varied depending on the stimulus contrast. Among the vowels, the peak latency of MMN for the /e/-/i/ contrast decreased with increasing age, which was statistically significant ($r = -0.4; p < 0.01$) across all the scalp sites. However, the peak latency for the /a/-/i/ contrast remained constant ($r = -0.00$ to $0.2; p > 0.05$) in all the scalp locations with advancing age. Figure R.3 depicts the age effects on MMN peak latency for different speech contrasts.

The peak latency of MMN for the consonant contrasts /ka/-/pa/ ($r = 0.1$ to $0.3; p > 0.05$), /sa/-/Ja/ ($r = 0.00$ to $-0.3; p > 0.05$) and /ma/-/pa/ ($r = 0.00$ to $-0.2; p > 0.05$) showed no change with an increase in age. However, the peak latency of MMN for the /la/-/ra/ contrast ($r = 0.5$ to $0.7; p < 0.01$) increased at all the scalp sites with an

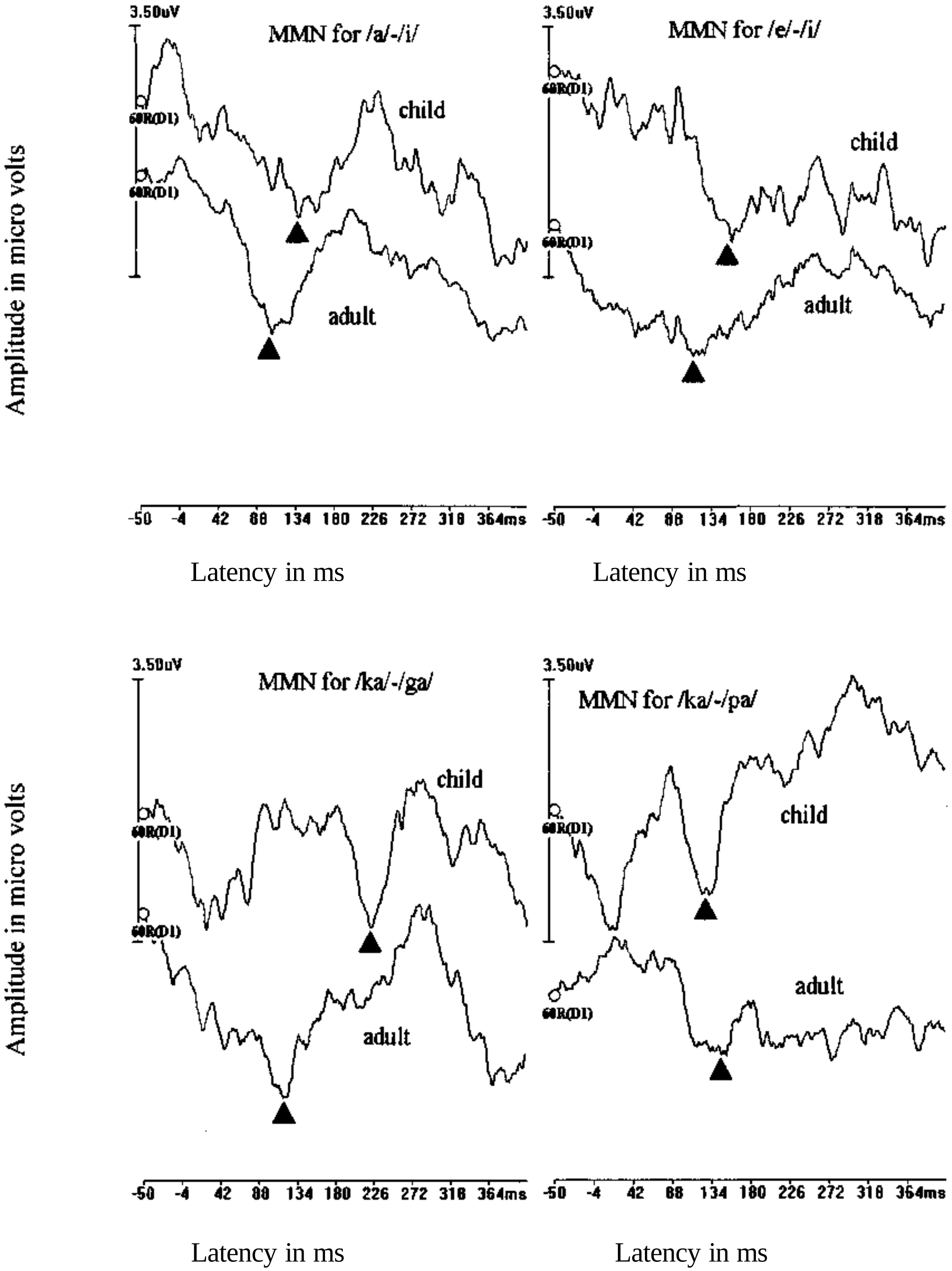


Figure R.2. Grand mean MMN waveforms recorded for different stimuli at C_2 reflecting developmental changes (arrow heads indicate the MMN peaks). (Continued...)

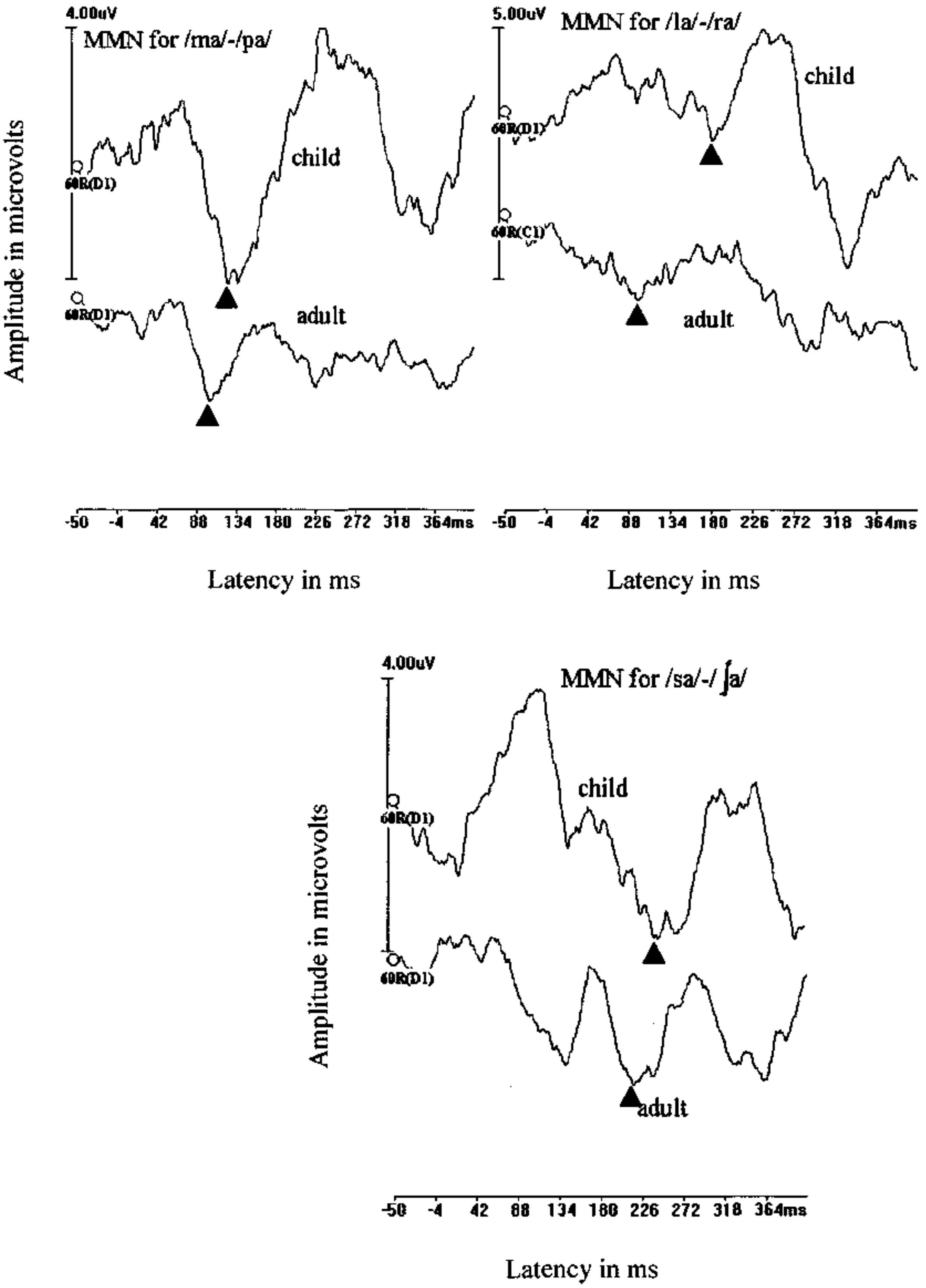


Figure R.2. Grand mean MMN waveforms recorded for different stimuli at C_z reflecting developmental changes (arrow heads indicate the MMN peaks).

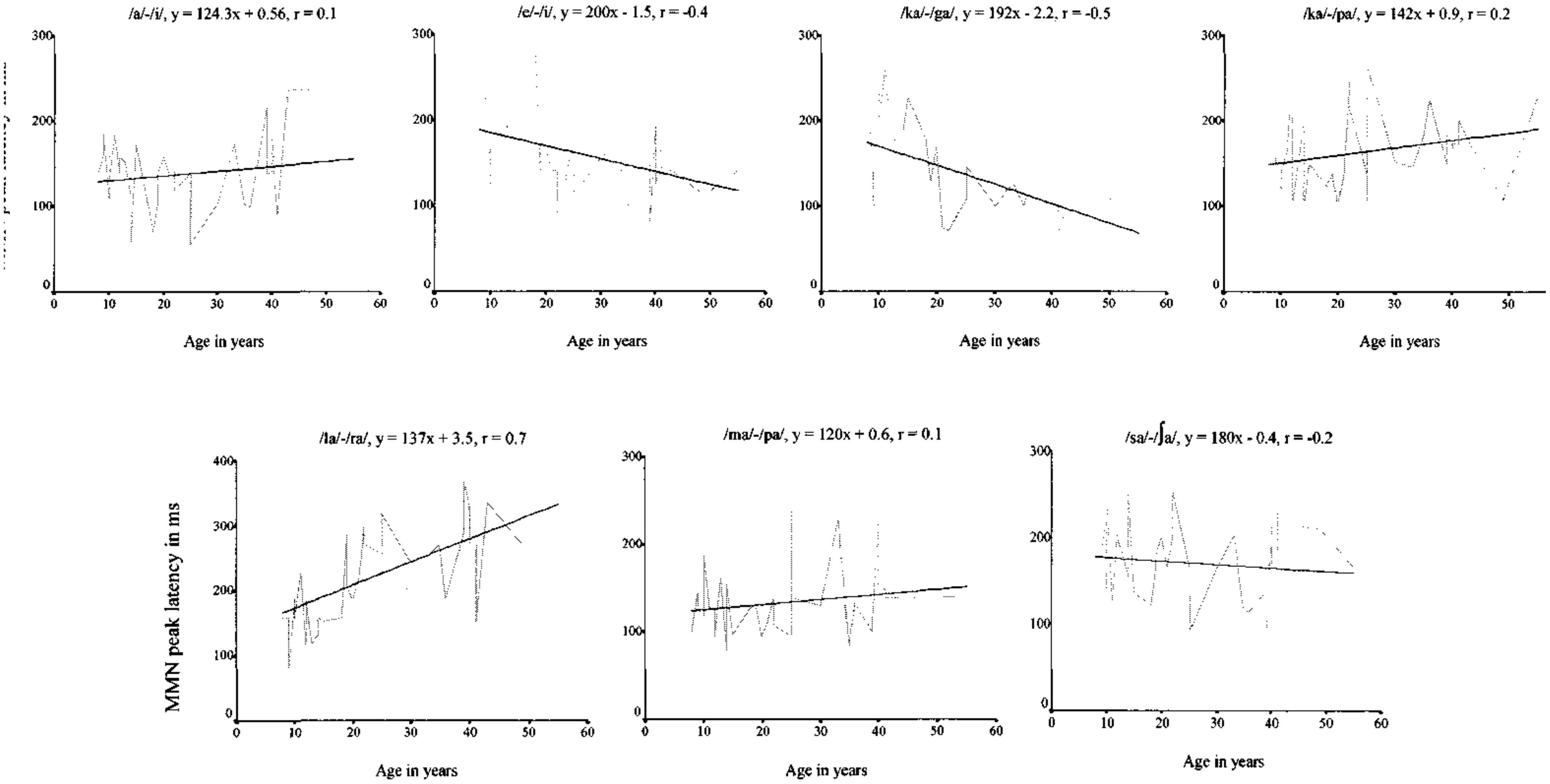


Figure R.3. Effects of maturation on MMN peak latency (in ms) recorded at the Cz site for different speech contrasts.

increase in age, and the /ka/-/ga/ contrast (r = -0.4 to -0.6; $p < 0.01$) resulted in a decrease in peak latencies with maturation. These changes for the /la/-/ra/ and the /ka/-/ga/ contrasts were seen only at the C_z and F_3 sites, whereas the peak latency of MMN did not show any significant change with increasing age at the other scalp sites.

Table R.4

Estimated mean and range of peak latencies of MMN recorded at Czfor different stimuli in msfor adults and children

Stimulus	**Group**	Mean	**Lower Bound**	**Upper Bound**	**Difference (in** ms)
/a/-/i/	**Adults**	129.7	114.0	145.4	1.3
	Children	132.9	113.9	151.9	
/e/-/i/	**Adults**	139.9	119.7	160.2	-52.6**
	Children	197.4	172.9	221.9	
/ka/-/ga/	**Adults**	130.7	110.1	151.3	-71.2**
	Children	180.7	155.7	205.6	
/ka/-/pa/	**Adults**	171.1	150.4	191.8	20.6
	Children	153.8	128.8	178.9	
/ma/-/pa/	**Adults**	125.1	112.0	138.2	12.6
	Children	134.8	118.9	150.7	
/sa/-/Ja/	**Adults**	178.6	157.1	200.1	-15.3
	Children	194.7	168.7	220.7	
/la/-/ra/	**Adults**	265.3	246.9	283.6	110.9**
	Children	161.5	139.2	183.7	

Note. Entries of the 'Difference' column are the result of Children group values subtracted from Adult group values.

*p<0.05. **p<0.01

There was no significant difference [F(21, 37) = 0.303; $p > 0.05$] in the peak latency for all stimuli, between the adults and children of the control group. The interaction effects of stimulus and age were significant ($p < 0.01$). Table R.4 shows the mean and the range (99% confidence interval) of peak latency values for different speech contrasts obtained from the adults and children of the control group. There was a statistically significant difference between adults and the children for the contrasts /e/-*/i/*, */ka/-/gal* and /la/-/ra/ contrasts based on the range of peak latency. MMN peak latencies for the other contrasts resulted in no significant difference between the two age groups.

(ii) Onset latency.

The trend seen in the onset latency of MMN was similar to that seen with the peak latency. This was especially true with the MMN for the vowel contrasts. Among the vowels, the onset latency of MMN for the /e/-*/i/* contrast decreased with increase in age at the F_3 and P_z sites on the scalp which was statistically significant ($r = -0.4$; $p < 0.05$). In contrast, the onset latency for the /a/-/i/ contrast remained constant ($r = 0.00$ to -0.2; $p > 0.05$) with advancing age. Figure R.4 depicts the age effects on MMN onset latency for different speech contrasts.

For all the consonant contrasts, the onset latency showed no significant change with increasing age ($r = -0.2$ to 0.1; $p > 0.05$), except for the /la/-/ra/ contrast. The onset latency of MMN for the /la/-/ra/ contrast increased at all the four scalp sites, with an advance in age ($r = 0.5$; $p < 0.01$). Adults and children of the control group showed no significant difference [$F(21, 37) = 3.1$; $p > 0.05$] in the onset latency for all stimuli. The interaction effects of stimulus and age were significant ($p < 0.01$). Table R.5 shows the significance of difference in onset latency values between the speech contrasts in children and adults.

The mean and range values (99% confidence interval) of onset latencies for different stimuli in adults and children are shown in Table R.5. There were

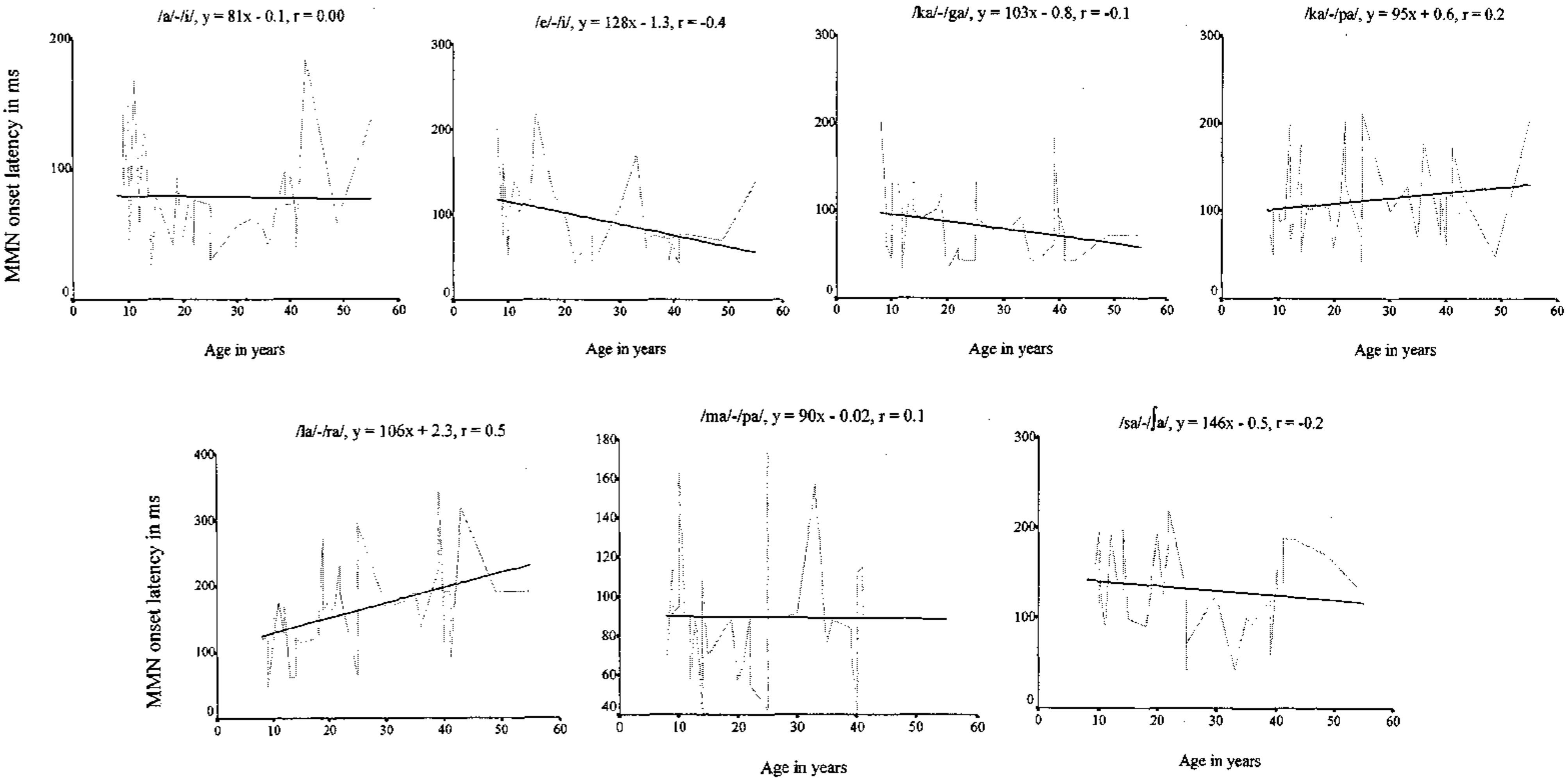


Figure R.4. Effects of maturation on the MMN onset latency (in ms) recorded at the Cz site for different speech contrasts.

significant stimulus and age interactions for onset latency *(p* < 0.01). It may be said that children had longer onset latencies for all the stimuli except for that of the /la/-/ra/. While, the children and adults groups did not overlap in onset latency range for /e/*-/i/, /ka/-/gal* and /la/-/ra/ contrasts, onset latency range for other speech contrasts were overlapping.

Table R.5

Estimated means and range for onset latencies ofMMN recorded at Cz for adults and children

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms)
/a/-/i/	**Adults**	71.2	57.3	85.1	-14.4
	Children	80.6	63.8	97.4	
/e/-/i/	**Adults**	86.3	66.7	105.9	**-45.0****
	Children	132.9	109.3	156.7	
/ka/ -/ga/	**Adults**	78.8	59.3	98.4	**-62.7****
	Children	113.1	89.4	136.7	
/ka/-/pa/	**Adults**	109.9	88.2	131.5	16.2
	Children	101.8	75.6	128.0	
/ma/-/pa/	**Adults**	75.7	65.2	86.3	**-1.9**
	Children	83.0	70.5	96.1	
/sa/-//a/	**Adults**	125.9	102.6	149.2	**-18.1**
	Children	144.0	115.8	172.3	
/la/-/ra/	**Adults**	163.2	139.6	186.7	69.9**
	Children	108.6	80.0	137.1	

Note. Entries of the 'Difference' column are the result of Children group values subtracted from Adult group values.

$*p<0.05$. $**p<0.0l$

***(iii) Offset latency*.**

Among the vowels, the offset latency of MMN for the /e/-/i/ contrast decreased with increasing age at all the scalp sites, which was statistically significant ($r = -0.4$; $p < 0.05$). However, the offset latency for /a/-/i/ contrast remained constant ($r = -0.1$; $p > 0.05$) with advancing age. Figure R.5 depicts the age effect on MMN offset latency for different speech contrasts.

Table R.6

Estimated means and range for MMN offset latencies recorded at Czfor adults and children

Stimulus	Group	Mean	Lower Bound	**Upper Bound**	Difference (in ms)
/a/-/i/	**Adults**	184.0	159.7	208.3	-8.1
	Children	210.4	181.1	239.8	
/e/-/i/	**Adults**	200.4	182.6	218.1	-26.9
	Children	240.7	219.3	262.2	
/ka/-/ga/	**Adults**	194.1	170.8	217.3	-69.7**
	Children	237.1	208.9	265.3	
/ka/-/pa/	**Adults**	230.6	209.5	251.6	19.8
	Children	220.5	195.1	246.0	
/ma/-/pa/	**Adults**	189.9	167.5	212.5	7.9
	Children	194.9	167.7	222.2	
/sa/-/ a/	**Adults**	228.3	206.6	249.9	-32.2*
	Children	238.3	211.9	264.5	
/la/-/ra/	**Adults**	302.2	290.6	313.9	107.7**
	Children	220.9	206.8	234.9	

Note. Entries of the 'Difference' column are the result of 'children group' values subtracted from 'adult group' values.

* P <0.05. **p<0.01

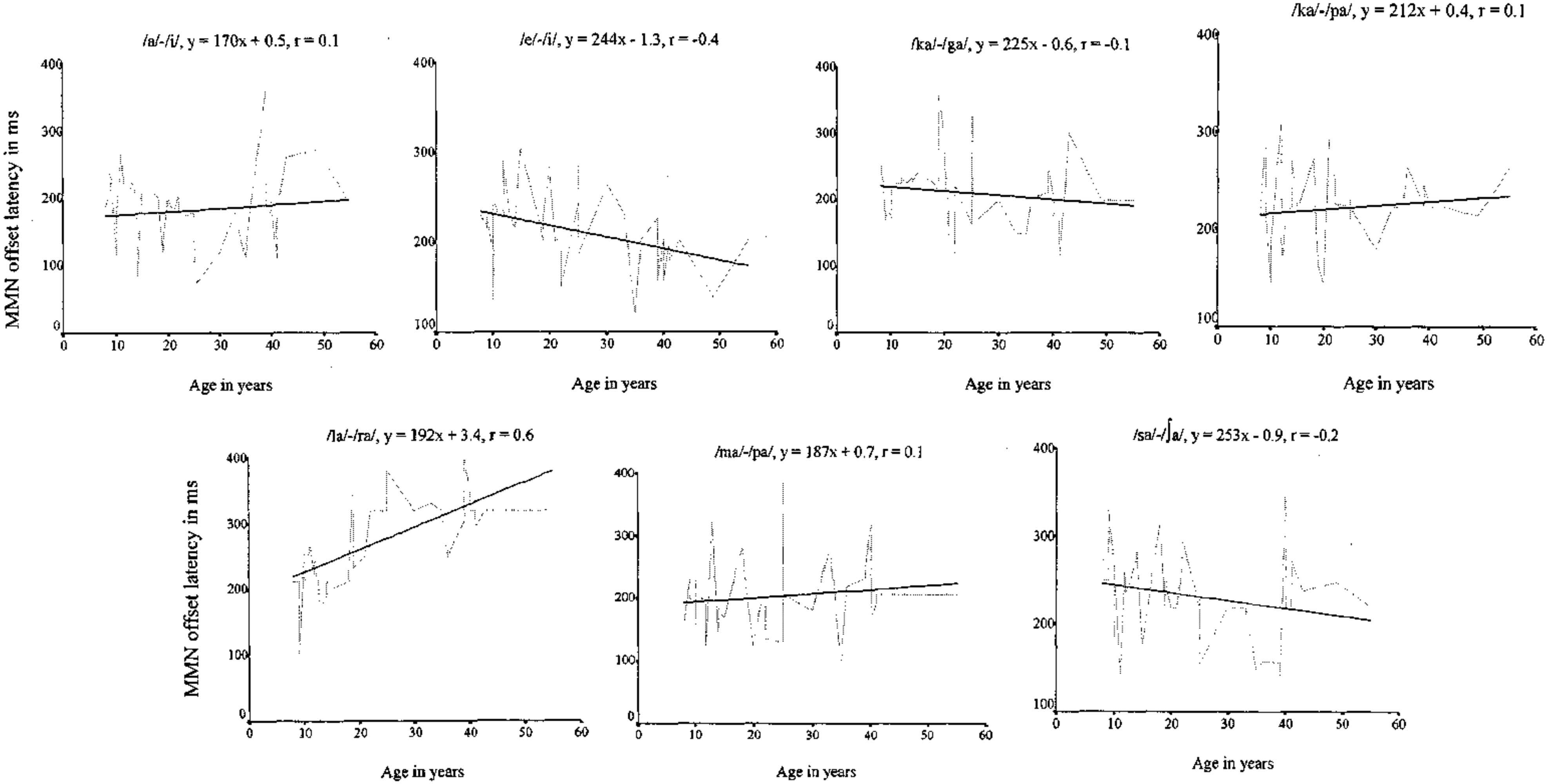


Figure R.5. Effects of maturation on the MMN offset latency (in ms) recorded at the Cz site for different speech contrasts.

No significant difference [$F(21, 37) = 0.74; p > 0.05$] in offset latency for any of the stimulus contrasts, were seen between adults and children of this group. Table R.6 shows the mean and range of the offset latency values between the speech contrasts in children and adults. The interaction effects of age and the stimulus were significant ($p < 0.01$). From Table R.6 it is apparent that the children had higher mean latencies for several speech contrasts. Further, both the groups had exclusive offset latency range for the /ka/-/ga/, /sa/-/Ja/ and the /la/-/ra/ contrasts.

It can be observed from the results of the three latency parameters (peak, onset and offset latencies) that they were similarly affected by age. Among the vowel contrasts, MMN for the *Id-Ill* contrast consistently showed a decrease in peak, onset and offset latencies with increase in age. Among the consonantal contrasts, MMN peak latency of the /ka/-/ga/ contrast showed significant decreases at all scalp sites. In contrast, the peak, onset and offset latencies of the /la/-/ra/ contrast showed increasing trends with increase in age at all scalp locations. The MMN latencies remained unchanged with increasing age for the other speech contrasts. Thus, the results indicate that the differences between the two age groups are specific to a speech contrast. While the/e/-*/i/* and /ka/-/ga/ contrasts are not well perceived in children, the remaining contrasts are well perceived. The prolonged latencies for the /la/-/ra/ contrast seen in adults may be explained by the aging process in adults. The subtle acoustic contrasts in the third formant region in this pair probably made it difficult for the adults to process them.

Consistent with the present study, Martin et al. (2003) showed that the peak latency of MMN evoked for tone-bursts with frequency or duration contrasts, decreased as the result of maturation. They studied normal school children. However, MMN peak latency evoked for the speech contrast /ba/-/da/ (Kraus et al.,

1999) did not change in a group of children with age ranging from 6 to 15 years. The differences in their findings may be due to type of stimuli used for recording MMN. However, the behavioural speech perception scores did not show any maturation effects for the same subject groups. It is possible that electrophysiological changes with age, as shown by MMN, may reflect subtle developmental changes (Steinschnieder & Dunn, 2004) in the auditory neurophysiology and the behavioural responses may not be sensitive to such subtle changes. Thus, the present study reveals the subtle developmental changes in terms of perception for certain speech contrasts.

2. Peak amplitude

The peak amplitude of MMN was relatively unaffected by the age of the subject, for all the speech contrasts, except for the /e/-/i/ contrast. All other vowel and consonant contrasts did not yield any significant change in peak amplitude ($r = -0.4$ to 0.3; $p > 0.05$) with advance in age at any scalp site. The peak amplitude of MMN for the /e/-*/i/* contrast decreased with increasing age *(*$r = 0.4$; $p < 0.05$). This trend was seen only in the frontal sites (F3 and F4) whereas the midline sites (C_z and P_2) did not show such a trend. Figure R.6 depicts the age effects on MMN peak amplitude for different speech contrasts.

There was no significant difference *[*$F(21, 37) = 1.23$; $p > 0.05$] in terms of the MMN peak amplitude, seen between adults and children of this group. However, the interaction effects of stimulus and age were significant *(*$p < 0.01$). Table R.7 shows the mean and range of peak amplitude between the speech contrasts in children and adults. From Table R.7, it may be said that though children had more peak

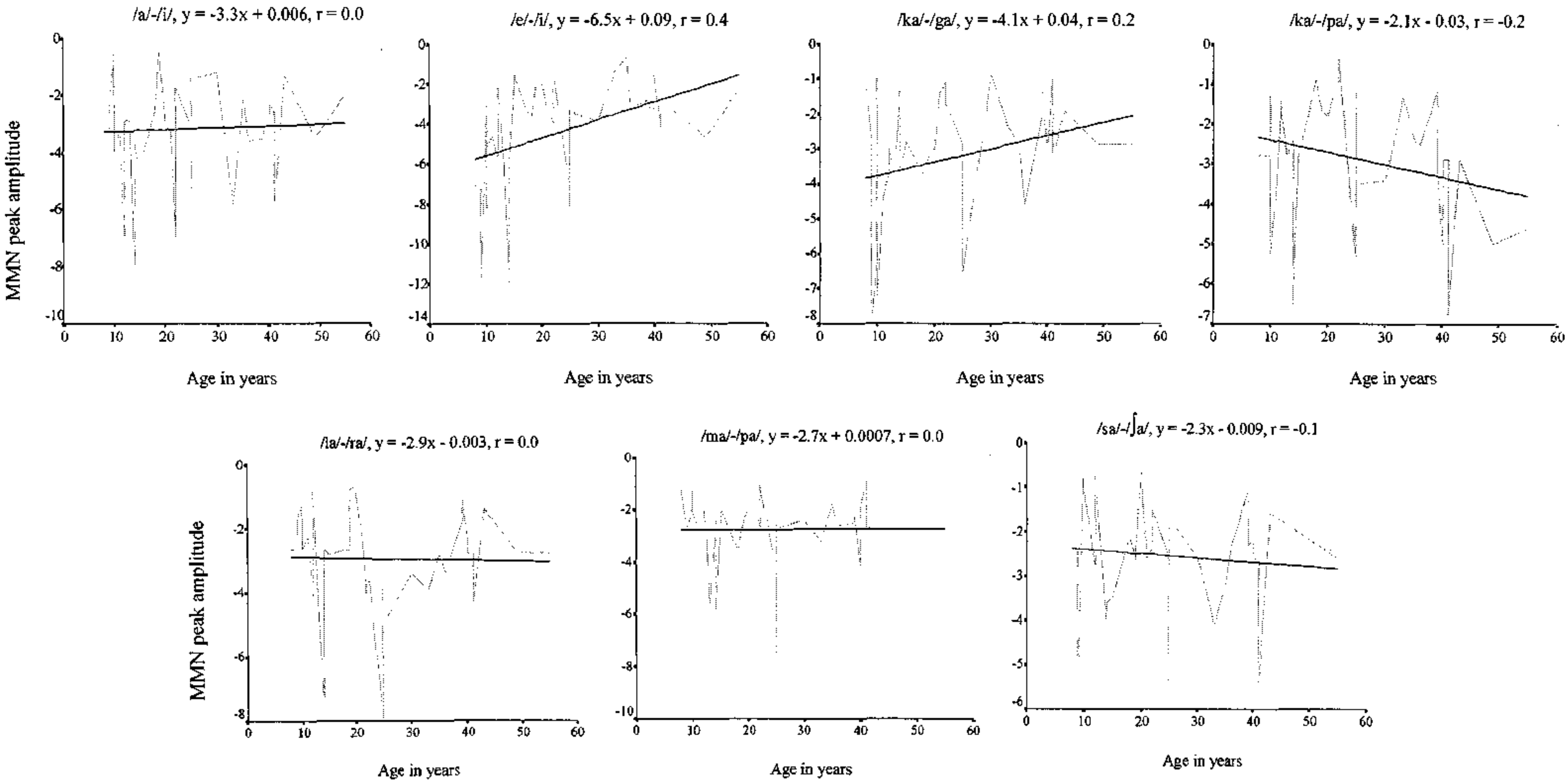


Figure R.6. Effects of maturation on the MMN peak amplitude (in microvolts) recorded at the Cz site for different speech contrasts.

amplitude, the differences were statistically insignificant. The range of peak amplitude overlapped within stimuli.

The results of the present study indicate that the peak amplitude of MMN for all the speech contrasts, except for the /e/- /i/ contrast do not change with age. These findings are in agreement with the findings of Shafer, Morr, Kreuzer and Kurtzberg (2000) who also reported no effect age on the peak amplitude of MMN. They used tones contrasting in frequency to study children aged 4 to 10 years. However, Kraus et al. (1999) found that the MMN peak amplitude for the /ba/-/wa/ and /da/-/ga/ contrasts decreased with increasing age in 6 to 15 years children.

Table R.7

Estimated means and range for peak amplitude of MMN recorded at Cz in adults and children

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in microvolts)
/a/-/i/	**Adults**	-3.9	-5.1	-2.6	0.2
	Children	-4.4	-5.9	-2.8	
/e/-/i/	**Adults**	-3.3	-4.3	-2.2	0.9
	Children	-4.7	-5.9	-3.5	
/ka/-/ga/	**Adults**	-3.3	-4.2	-2.3	0.9
	Children	-4.7	-5.9	-3.5	
/ka/-/pa/	**Adults**	-3.5	-4.4	-2.6	0.0
	Children	-3.1	-4.2	-1.9	
/ma/-/pa/	**Adults**	-3.3	-3.9	-2.6	0.0
	Children	-3.6	-4.5	-2.8	
/sa/-/ a/	**Adults**	-3.4	-4.3	-2.6	-0.2
	Children	-3.7	-4.7	-2.6	
/la/-/ra/	**Adults**	-4.5	-5.4	-3.7	-0.5
	Children	-3.6	-4.7	-2.5	

Note. Entries of the 'Difference' column are the result of 'children group' values subtracted from 'adult group' values.

* $p < 0.05$. ** $p < 0.01$

The present study does not support the findings of Kraus et al. (1999) regarding the changes in MMN peak amplitude for consonantal contrasts. The differences in results may be because of the differences in stimuli and their naturalness. The study by Kraus et al. (1999) used synthetic syllables. The difference in results may also be because of the wide range of the age of the subjects used in the present study. In summary, the results indicate that the peak amplitude of MMN may not be a sensitive parameter of MMN to demonstrate maturational changes.

3. Area

MMN area remained unchanged ($r = -0.2$ to $-0.3; p > 0.05$) at any given scalp site, with increasing age for all the vowel and consonant contrasts. It appears that the adult-like MMN area is attained by the age of 8 years, which was the youngest subject's age included in the present study. The effects of age on MMN area are shown in Figure R.7. The present findings indicate that age has no effect on MMN area for all the speech contrasts. This finding is in consonance with the findings of Kraus et al. (1999), who showed that MMN area did not change in children aged 6 to 15 years.

There was no significant ($p > 0.05$) effect of type stimulus contrast on MMN area. The interaction effects of stimulus and age were also not significant ($p > 0.05$). MMN area seen in the adults and children for the different speech contrasts is shown in Table R.8. The estimated mean MMN area recorded in children was more than that seen in adults (Table R.8) for all the vocalic and the consonantal contrasts except for the /la/-/ra/ contrast. For the /la/-/ra/ contrast adults had a larger mean area than that seen in children. However, these differences were statistically insignificant. The maturational effects on MMN parameters are summarised in Table R.9.

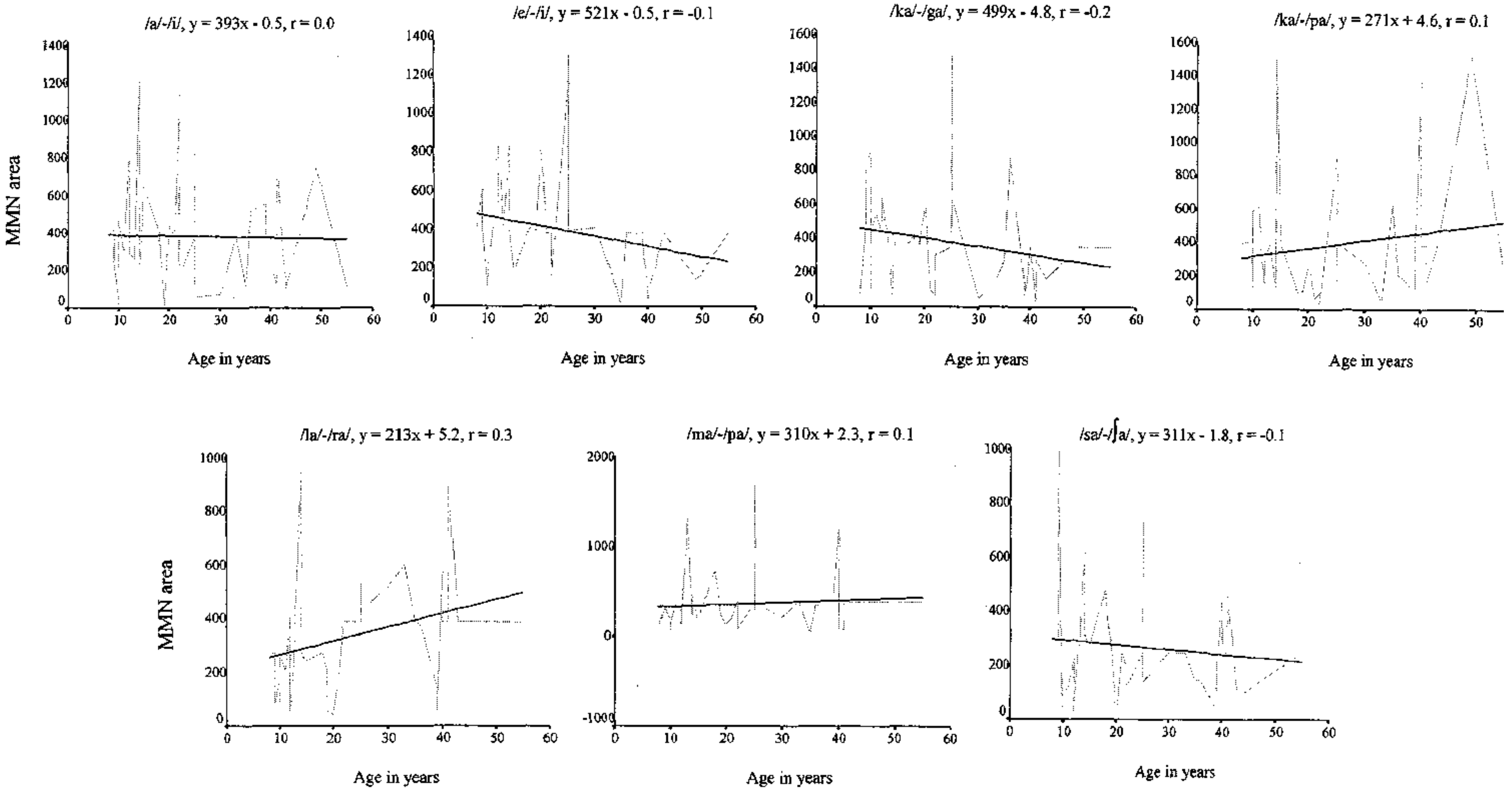


Figure R. 7. Effects of maturation on the MMN area (in ms X microvolts) recorded at the Cz site for different speech contrasts.

Table R.8

Estimated means and range for MMN area recorded at Cz in adults and children

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms X microvolts)
/a/-/i/	**Adults**	493.2	282.7	703.7	-6.6
	Children	617.6	362.7	872.6	
/e/-/i/	**Adults**	433.9	269.2	598.6	-21.3
	Children	531.9	332.4	731.4	
/ka/-/ga/	**Adults**	448.9	238.0	659.8	-68.0
	Children	594.5	339.1	849.9	
/ka/-/pa/	**Adults**	407.4	251.2	563.6	-13.6
	Children	437.1	247.9	626.2	
/ma/-/pa/	**Adults**	405.8	270.6	541.1	43.1
	Children	425.6	261.9	589.4	
/sa/-/Ja/	**Adults**	348.5	225.1	471.9	-49.3
	Children	363.9	214.4	513.4	
/Ia/-/ra/	**Adults**	553.9	453.2	654.6	115.5
	Children	425.3	303.3	547.3	

Note. Entries of the 'Difference' column are the result of'children group' values subtracted from 'adult group' values.

*p<0.05. **p<0.0l

Table R.9

Summary of changes in MMN parameters as a function of age across different electrode sites

Parameter	Maturational changes in MMN parameter	Electrode site
Peak latency	a. Decreased with increase in age for the /e/-*/i/* and /ka-/ga/ contrasts b. No change for the /a/-/i/, /ka/-/pa/, /sa/-/ a/, and /ma/-/pa/ contrasts c. Increased for the /la/-/ra/ contrast	a. At all scalp sites for /e/-/i/; at C_z and F_3 for /ka/-*/ga/* b. At all scalp sites c. At all scalp sites
Onset latency	a. Decreased for the /e/-/i/ contrast b. No change for the /a/-/i/, /ka-/ga/, /ka/-/pa/, /sa/-/Ja/, and /ma/-/pa/ contrasts c. Increased for the /la/-/ra/ contrast	At all scalp sites
Offset latency	a. Decreased for the /e/-*/i/* contrast b. No change for the *lal-lil*, *Ika-lgal*, */ka/-/pa/*, /sa/-/ a/, and /ma/-/pa/ contrasts c. Increased for the /la/-/ra/ contrast	At all scalp sites
Peak amplitude	a. Decreased for the/e/-*/i/* contrast b. No change for the *lal-lil*, *Ika-lgal*, /ka/-/pa/, /sa/-*/ a/*, */ma/-/pa/* and */la/-/ra/* contrasts	a. At F_3 and F_4 sites b. At all scalp sites
	No significant change for all the contrasts	At all scalp sites

II. c. Effects of degree of hearing loss on MMN

A linear regression analysis was done to find the effects of the degree of hearing loss on different MMN parameters across channels. The pure tone average was calculated to determine the degree of hearing loss. In this analysis, all the subjects were considered as one group. The y-intercept, slope and significance of the slope were obtained for each of the stimuli and across different channels on the scalp. The grand mean average waveforms obtained for different speech contrasts, as shown in Figure R.8, reflect the effects of hearing status on MMN.

1. Latency parameters

The latency parameters analysed included peak latency, onset latency, and offset latency. The effect of degree of hearing loss on each of these latency parameters was evaluated.

(i) Peak latency.

The effects of degree of hearing loss on peak latency varied with the type of stimulus contrast. Among the vowels, peak latency of MMN for the /a/-/i/ contrast increased with hearing loss which was statistically significant ($r = 0.6$; $p < 0.01$). In contrast, the peak latency for the /e/-/i/ contrast remained significantly unaffected ($r = 0.1; p > 0.05$) with increase in hearing thresholds (Figure R.9).

Peak latency for all the consonant contrasts was significantly affected ($r = -0.5$ to $0.6; p < 0.01$) by hearing loss at all the four scalp positions. An exception to this was the /sa/-/ a/ contrast, which was not affected ($r = 0.2; p > 0.05$) by hearing loss at all the scalp sites. The peak latency of MMN evoked by /ka/-/ga/, /ka/-/pa/, and /ma/-/pa/ contrasts increased (r - 0.3 to $0.7; p < 0.01$) with increasing hearing loss.

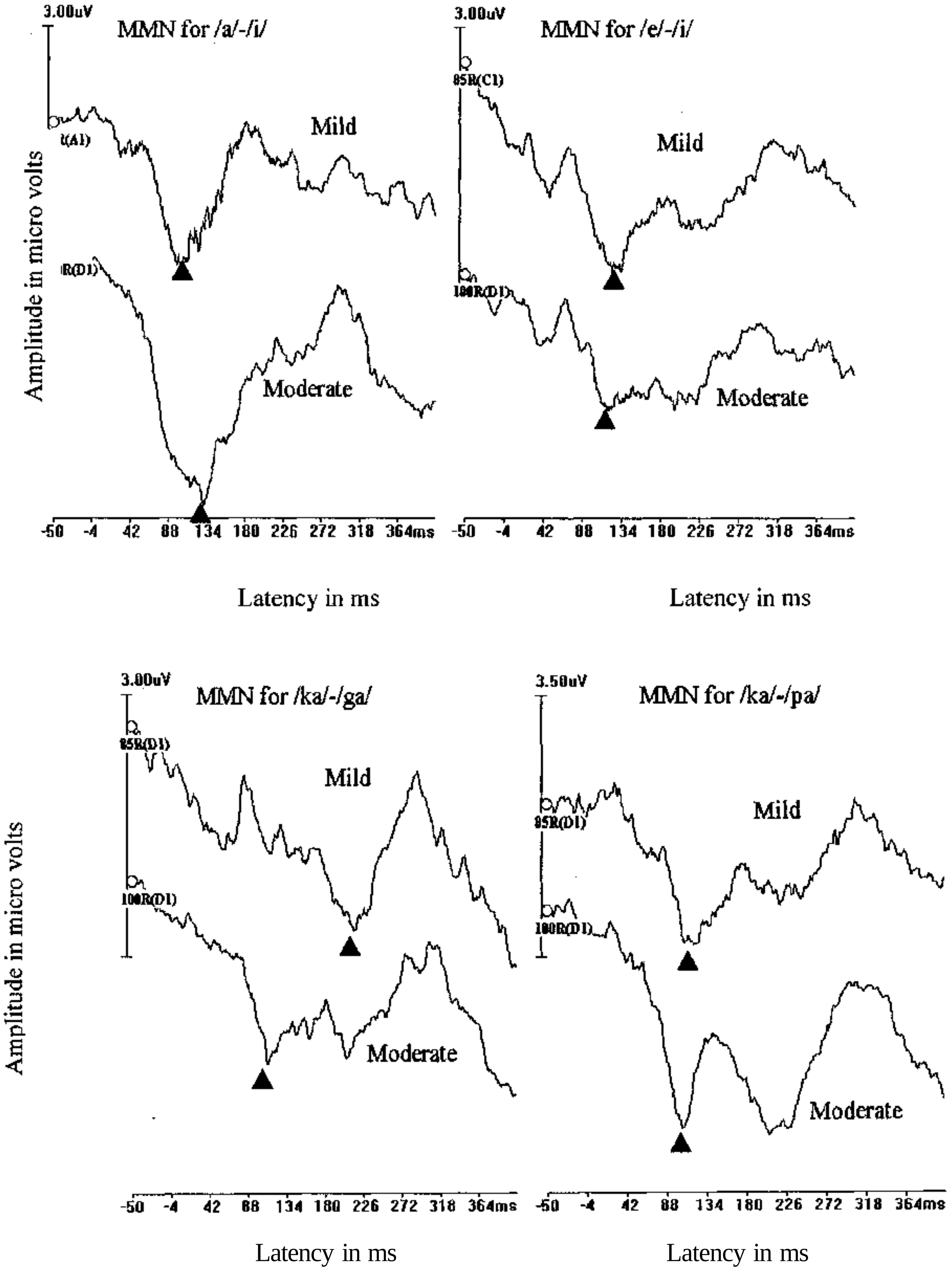


Figure R.8. Grand mean MMN waveforms recorded at Cz for different stimuli in mild and moderate degree hearing loss (arrow heads indicate the MMN peaks). (Continued...)

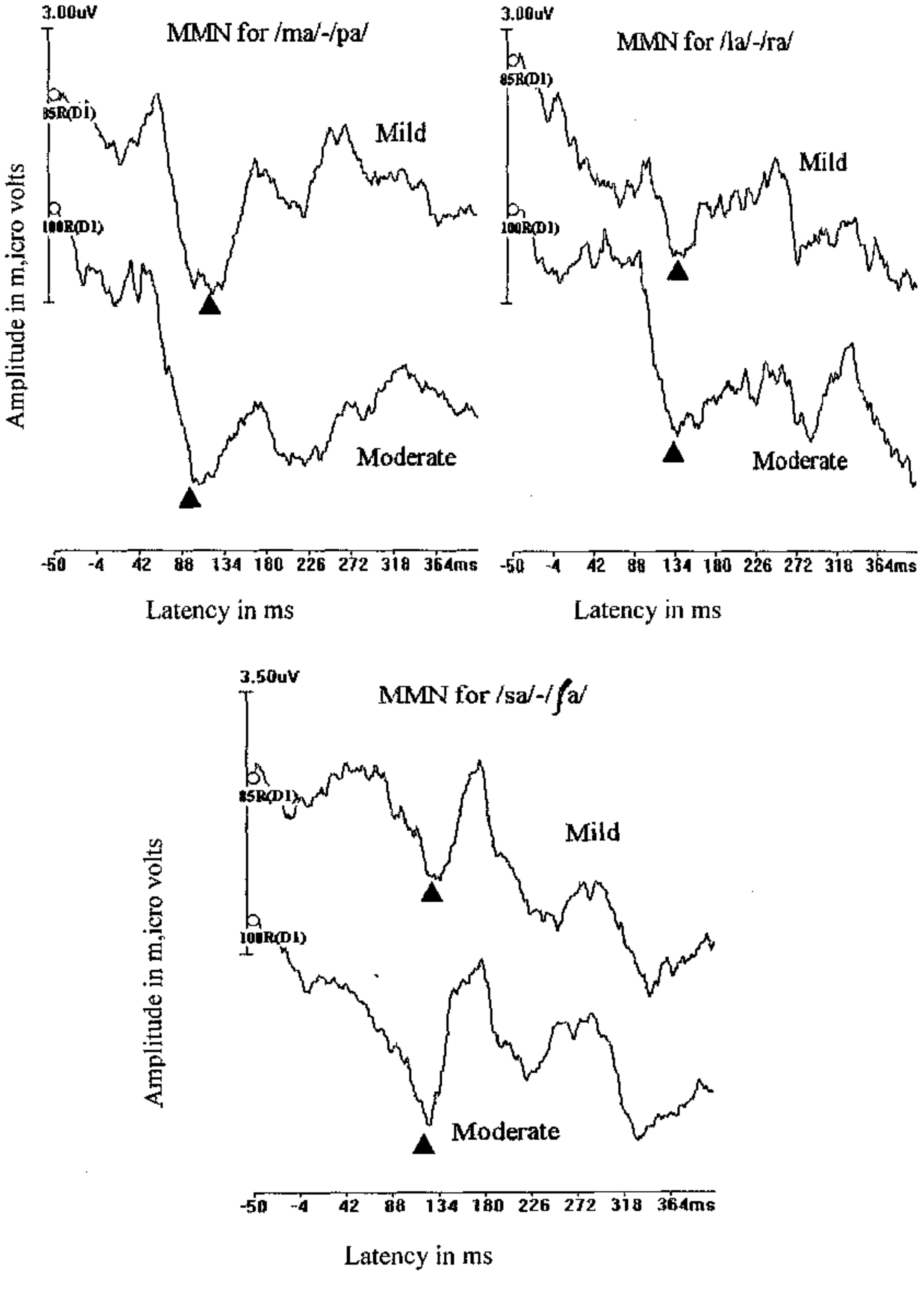


Figure R.8. Grand mean MMN waveforms recorded for different stimuli in mild and moderate degree hearing loss (arrow heads indicate the MMN peaks).

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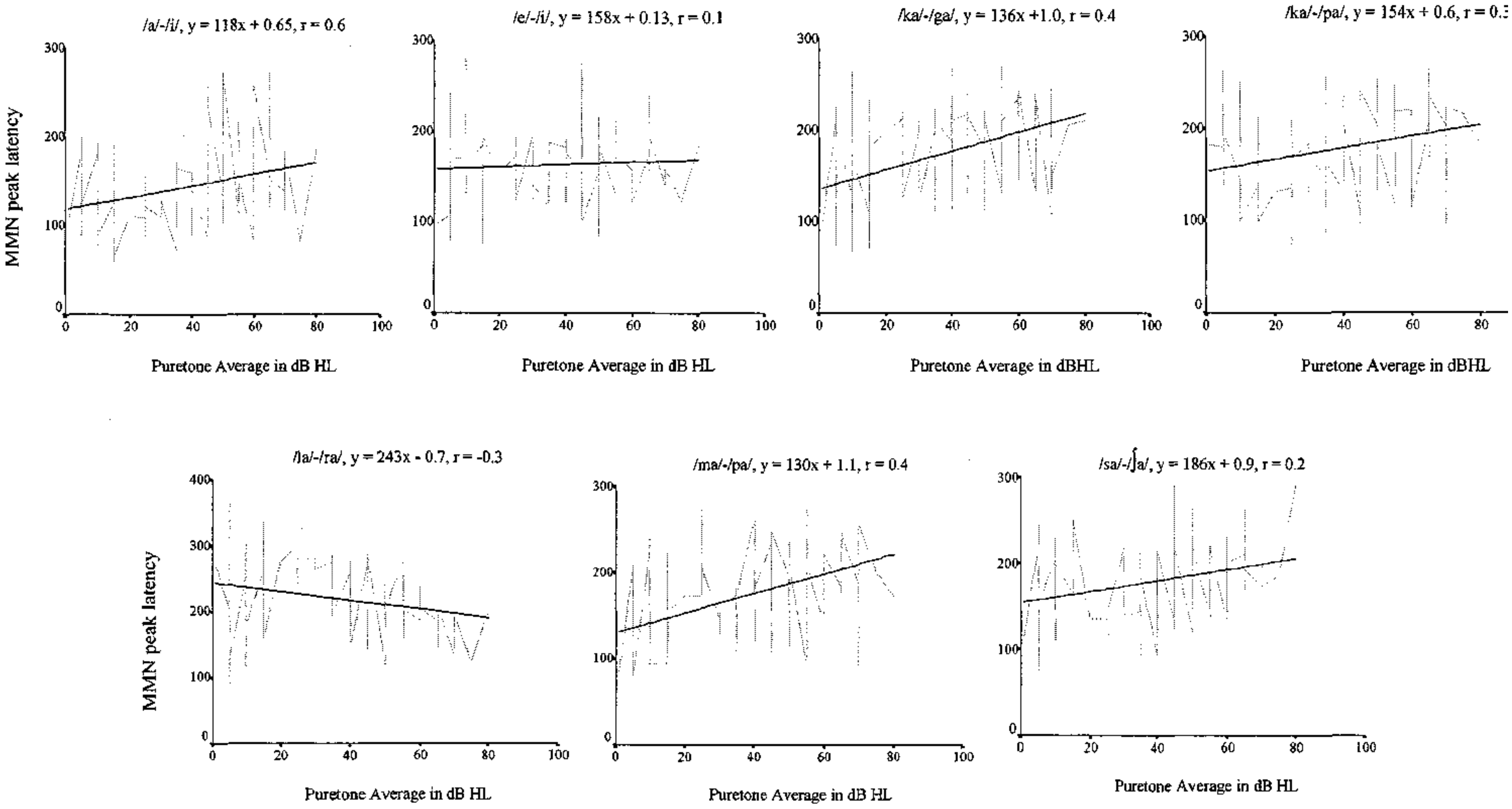

Figure R.9. Effects of hearing threshold level on MMN peak latency in ms recorded at the Cz site.

However, the MMN peak latency decreased (r = -0.4; $p < 0.01$) for the /la/-/ra/ contrast with increase in hearing loss (Figure R.9). The analysis revealed significant interaction effects between stimulus and degree of hearing loss [*F* (24, 57) = 14.7, $p < 0.01$]. The effects of stimulus contrast on peak latency were similar in adults and children of the experimental group.

Table R. 10

Estimated mean and range of MMN peak latencies recorded at Czfor different stimuli in msfor subjects with mild and moderate hearing loss

Stimulus	**Group**	Mean	**Lower Bound**	**Upper Bound**	Difference **(in ms)**
/a/- /i/	**Mild**	117.1	105.4	128.7	-40.1**
	Moderate	141.7	131.3	152.9	
/e/-/i/	**Mild**	168.1	153.1	183.0	-14.5
	Moderate	162.9	149.5	176.2	
/ka/-/ga/	**Mild**	162.3	148.5	176.1	-58.0**
	Moderate	193.8	181.4	206.1	
/ka/-/pa/	**Mild**	170.1	152.9	187.2	-35.4*
	Moderate	198.4	183.0	213.7	
/ma/-/pa/	**Mild**	147.6	129.2	165.9	-31.6*
	Moderate	185.8	169.3	202.2	
/sa/-/ a/	**Mild**	165.3	152.0	178.6	-36.2*
	Moderate	168.1	156.2	179.9	
/la/-/ra/	**Mild**	236.8	221.6	251.9	79.8**
	Moderate	193.1	179.6	206.7	

Note. Entries of the 'Difference' column are the result of 'moderate hearing loss group' values subtracted from 'mild hearing loss group' values.

*p<0.05. **p<0.01

The mean and range (99% confidence interval) values for the mild and moderate hearing loss are shown in Table R.10. It may be noted that the peak latencies were more in the moderate hearing loss than that of the mild hearing loss (Table R.10). However, for the /la/-*/ra/* the peak latency reduced in the higher degree of hearing loss. For the phonetic contrasts /e/-*/i/,* /ka/-/pa/, /ma/-/pa/ and /la/-/ra/, the MMN peak latencies were prolonged in the group with moderate hearing loss. The latency was significantly different between the mild and the moderate hearing loss groups for the /a/-/i/, /ka/-*/gal,* /ma/-/pa/ and /la/-*/ra/* contrasts.

(ii) Onset latency.

The hearing threshold level affected the onset latency of MMN also. Among the vowels, MMN for the *lal-/i/* contrast showed a significant increase ($r = 0.3$; $p < 0.05$) in onset latency with increase in hearing loss at all the scalp sites. The onset latency of MMN for the /e/-*lil* contrast was not affected ($r = 0.2$; $p > 0.05$) by the degree of hearing loss at any of the scalp sites.

For the consonantal contrasts /sa/-/ a/ and /la/-*/ra/,* the onset latency of MMN was not significantly affected ($r = -0.2$ to $0.3; p > 0.05$) by hearing threshold levels at any of the scalp sites. The MMN onset latency was affected by hearing loss at all the four scalp positions ($r = 0.4$ to 0.6; $p < 0.01$) for the remaining consonantal contrasts *{IkaJ-lgal,* /ka/-/pa/ and /ma/-/pa/). There was an increase in onset latency with increasing degree of hearing loss for all these speech contrast. These trends in onset latency with increasing hearing loss are shown in Figure R.10.

The interaction effect between stimulus and degree of hearing loss [F (24, 57) = 6.1, $p < 0.01$] was significant. There were no differences in effects of stimulus contrast on onset latency between adults and children of the experimental group. As

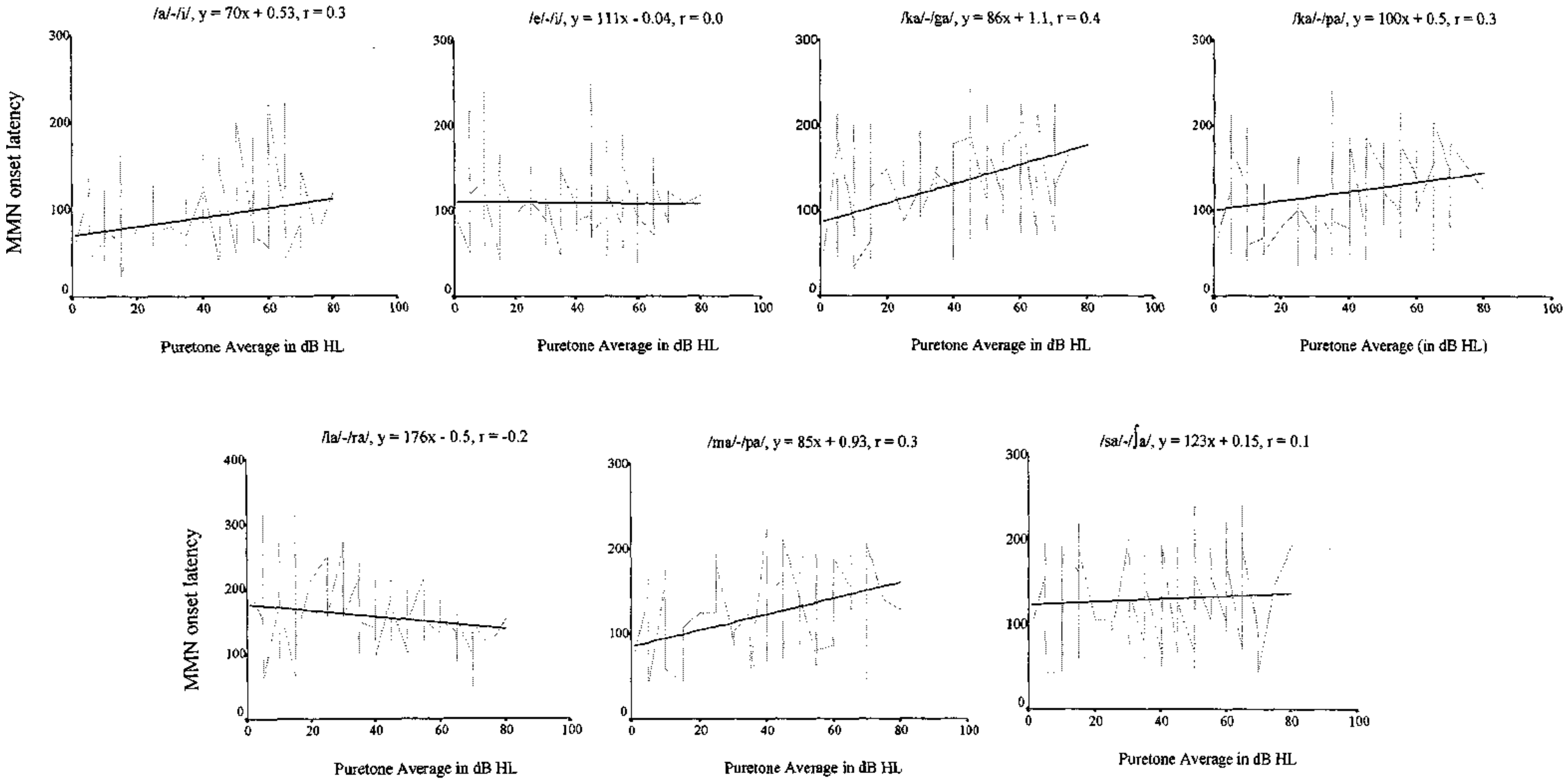

Figure RJ0. Effects of hearing threshold level on MMN onset latency in ms recorded at the Cz site.

mentioned earlier, the stimulus effects on MMN onset latency differed with the degree of hearing loss. Mean and the range (99% confidence interval) values of onset latency for the mild and moderate hearing loss are shown in Table R. 11.

Table R. 11

Estimated mean and range of MMN onset latencies recorded at Czfor different stimuli in ms for subjects with mild and moderate hearing loss

Stimulus	**Group**	**Mean**	**Lower Bound**	**Upper Bound**	Difference **(in ms)**
/a/-/i/	**Mild**	77.7	66.0	89.4	-2.4
	Moderate	85.2	74.7	95.6	
/e/-/i/	**Mild**	118.9	105.8	131.9	22.5
	Moderate	104.2	92.6	115.8	
/ka/-/ga/	**Mild**	105.4	90.4	120.4	-15.9
	Moderate	128.2	114.7	141.6	
/ka/-/pa/	**Mild**	115.8	99.1	132.5	-22.2
	Moderate	133.9	118.9	148.8	
/ma/-/pa/	**Mild**	95.9	79.7	112.2	-26.1
	Moderate	122.5	108.1	137.0	
/sa/-/ a/	**Mild**	121.2	104.9	137.5	-16.0
	Moderate	117.7	103.1	132.2	
/la/-/ra/	**Mild**	165.8	149.2	182.3	28.1
	Moderate	144.4	129.6	159.2	

Note. Entries of the 'Difference' column are the result of'moderate hearing loss group' values subtracted from 'mild hearing loss group' values.

*p<0.05. **p<0.01

Though it appears from Table R. 11 that the MMN onset latency in mild hearing loss group was shorter when compared to that moderate hearing loss, there was no significant difference between the groups for any of the speech contrasts.

(in) Offset latency.

The degree of hearing loss showed a mixed effect on the MMN offset latency. The MMN offset latency for the vowel contrast /a/-/i/ showed a significant increase $(r = 0.5; p < 0.01)$ in offset latency only at the frontal sites (F_3 and F_4). However, the MMN offset latency for the /e/-/i/ contrast was not affected (r = 0.01;/? > 0.05) by hearing loss at any of the scalp sites (Figure R.I 1).

The MMN offset latencies for the consonantal contrasts /sa/-/Ja/ and /ka/-/pa/ was not affected by hearing loss at any of the scalp positions. MMN offset latency was affected by hearing loss (r = -0.4 to 0.6; $p < 0.01$) for all other consonant contrasts at all the four scalp positions. There was an increase in offset latency with increase in hearing loss, for MMN recorded for the /ma/-/pa/ and /ka/-/ga/ pairs. In contrast, a decrease in offset latency was also observed for the /la/-/ra/ contrast with increase in hearing loss.

The analysis of variance was administered to find the effects of degree of hearing loss on stimulus effects. The stimulus contrast had a significant $(p < 0.01)$ effect on the offset latency. The interaction effects between stimulus and degree of hearing loss $[F(24, 57) = 17.9, p < 0.01]$ were significant. No differences were observed in the effects of stimulus contrast on offset latency between adults and children of the experimental group.

The stimulus effects on MMN offset latency differed with the degree of hearing loss. Mean and the range (99% confidence interval) values of offset latency for the mild and moderate hearing loss are shown in Table R.12. From Table R.12, it may be said that the offset latency values were more in the individuals with a moderate hearing loss than those with a mild hearing loss for specific contrasts. The differences in offset latencies obtained from the mild and moderate hearing loss

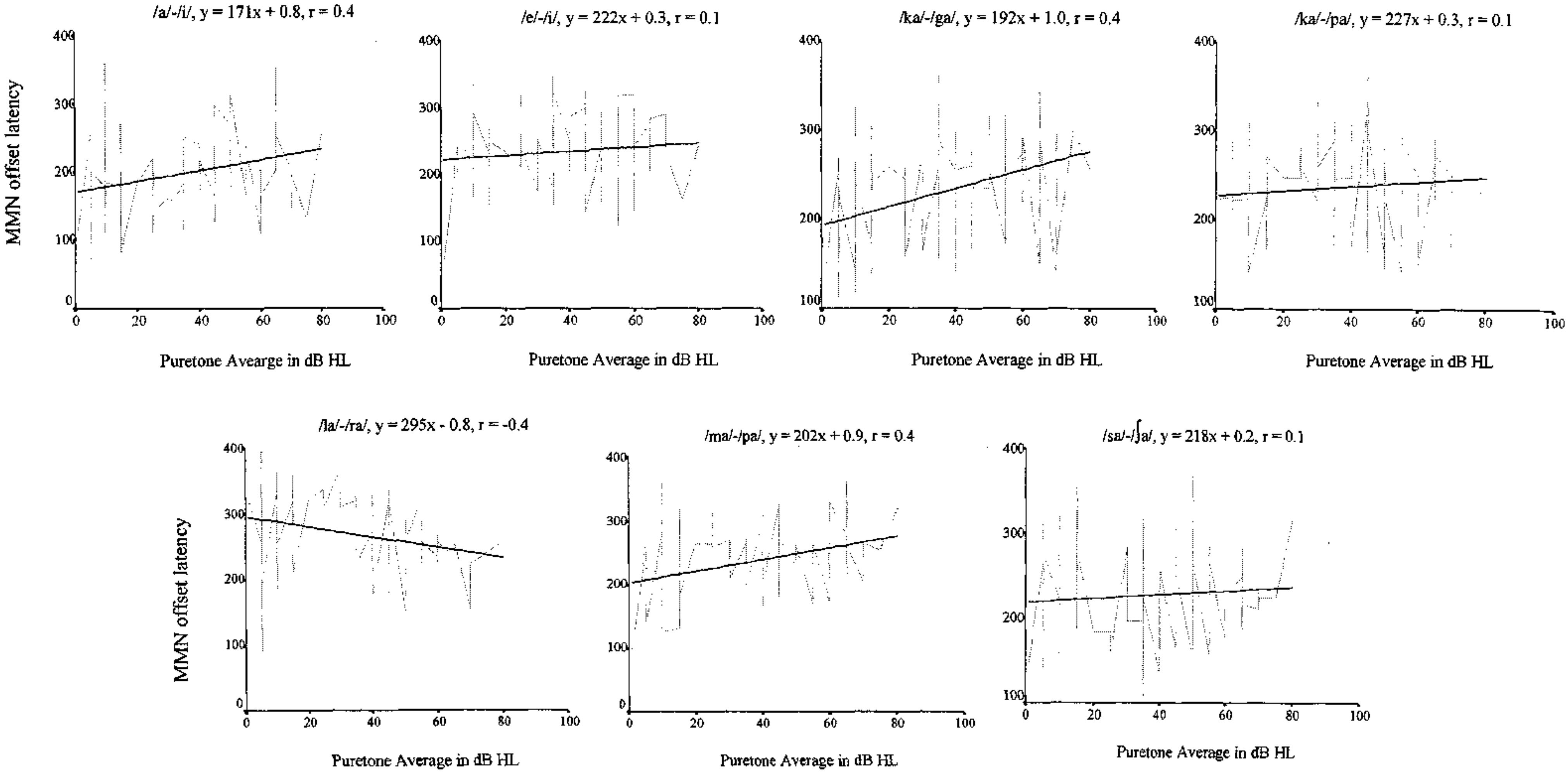

Figure R.11. Effects of hearing threshold level on MMN offset latency in ms recorded at the Cz site.

groups were significantly different for the contrasts *lal-/i/*, /ka/-/ga/, /ka/-/pa/, /ma/-/pa/ and /la/-/ra/.

Table R. 12

Estimated mean and range of MMN offset latencies recorded at Czfor different stimuli in msfor subjects with mild and moderate hearing loss

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms)
/a/-/i/	**Mild**	162.4	144.5	180.4	-48.1**
	Moderate	205.2	189.1	221.2	
/e/-/i/	**Mild**	227.3	211.7	242.9	-24.9
	Moderate	225.9	212.0	239.9	
/ka/-/ga/	**Mild**	213.4	200.2	226.6	-69.2**
	Moderate	257.6	245.8	269.4	
/ka/-/pa/	**Mild**	232.4	217.6	247.3	-39.7*
	Moderate	256.5	243.2	269.7	
/ma/-/pa/	**Mild**	219.1	203.7	234.5	-55.3**
	Moderate	245.6	231.8	259.3	
/sa/-/|a/	**Mild**	215.3	197.2	233.4	-13.7
	Moderate	211.1	194.9	227.3	
/la/-/ra/	**Mild**	293.6	278.1	309.2	77.5**
	Moderate	242.9	229.0	256.8	

Note. Entries of the 'Difference' column are the result of moderate hearing loss group' values subtracted from 'mild hearing loss group' values.

*p<0.05. **p<0.01

In summary, the present study showed that the MMN latency parameters are sensitive to the effects of hearing loss. Among the vocalic contrasts, latency parameters of MMN for the /a/-/i/ contrast consistently showed an increasing effect with increasing hearing loss. However, that of the /e/-/i/ contrast did not show any effect of hearing loss.

Among the consonantal contrasts, MMN latencies for the /sa/-/Ja/ contrast did not get affected with the presence of a hearing loss. The peak latency and the offset latency of MMN for the /la/-/ra/ contrast showed a decrease with an increase in hearing loss. The onset latency and the peak latency of the /ka/-/pa/ showed an increase with increasing hearing loss. All the MMN latency parameters for the /ka/-/ga/ and /ma/-/pa/ contrast showed an increase with increasing degree of hearing loss.

These results indicate that the way in which individuals with a hearing impairment perceive speech contrasts as a function of the degree of hearing impairment, varies. In general, the subjects required longer processing time as the degree of hearing impairment increased. MMN latencies for the /la/-/ra/ contrast violate this general trend.

The observed prolongations in latency for some of the contrasts may be explained based on the hypothesis given by Polen (1984). He reasoned that the presence of a sensorineural hearing loss might alter the event-related potential (ERP) parameters because of the loss of high frequency information, which can reduce the individual's ability to discriminate phonemes. Further, a loss of frequency resolution may compound discrimination difficulty and/or increased difficulty in a discrimination task. This may increase the latency of MMN.

Evidence also comes from the physiological studies, which showed that a peripheral hearing loss leads to response changes of the auditory cortical neurons (Rajan & Irvine, 1996) and in turn, functional reorganization of the auditory cortex (Irvine, 2000). This 'injury-related plasticity' (Irvine, 2000) might lead to speech perception difficulties and prolongation of MMN latencies.

The MMN latencies for the /sa/-/ a/ contrast did not get affect by the presence of any degree of hearing loss. This result was unexpected, given the fact that though the /sa/-/ a/ contrast has its differentiating cues concentrated at high frequency regions, MMN latencies were not affected by the degree of hearing loss. This may be explained based on the preserved spectral cues useful for the /sa/-/Ja/ discrimination. Revoile (1999) showed that the strong spectral peak at 4.2 kHz in the /s/ spectrum and a broad spectral peak in the frequency region of 2.5 to 3.5 kHz for *l\l* sound are helpful in their discrimination. He also showed that these cues are well preserved in the audibility spectrum of the individuals with a moderate hearing loss.

However, the results of the present study are in a disagreement with the findings of Oates et al. (2002), who showed no effect of degree of hearing loss on MMN peak latency for the speech contrast /ba/-/da/. The differences between the findings may be because of the small number of subjects included in their study (N=20) and high variability in the peak latency data at higher sensation levels (SL) reported in their study. However, Oates, Kurtzberg and Stapells (2002) showed that the MMN latencies were significantly affected at lower sensation levels. Based on the amount of change in latency and amplitude parameters, they concluded that latency could be a predictor hearing loss rather than the amplitude measures.

Overall, the statistical analysis also indicated that the control and experimental groups could be clearly differentiated between the control and experimental groups based on the latency parameters, for selective contrasts. Based on the peak latency of MMN for the consonantal contrast /ma/-/pa/ the control and moderate hearing loss group (of the experimental group) could be differentiated. MMN onset latency for the *Id-I'll* contrast was clearly different for the control and moderate hearing loss groups.

The control and the moderate hearing loss groups could also be clearly distinguished based on the MMN offset latency for the /ka/-*/pal* and /ma/-/pa/ contrasts.

Though the latencies were prolonged in the experimental group, the differential effects of phonetic contrasts as in the control group were preserved. The prolonged latencies could be attributed to the inherent perceptual deficits in subjects with sensorineural hearing loss. It is shown that the hearing-impaired persons use cues different from those of normal-hearing in discrimination and identification of speech sounds because of several perceptual limitations imposed by the inaudibility of speech. Such a report has also been given by Revoile et al. (1987). The limitations in availability of acoustic cues to discriminate sounds might have increased the complexity of the task and thus leading to prolonged MMN latencies.

2. Peak amplitude

The effects of degree of hearing loss on peak amplitude were different from those of the peak latency. For the vocalic contrasts, the peak amplitude was not affected by degree of hearing loss, at all the four scalp sites (r = -0.1 to -0.4; $p > 0.05$). The effects on MMN peak amplitude for the consonantal contrasts were however different. For the consonant contrasts /ka/-/pa/, /ma/-/pa/ and /sa/-/Ja/ a significant effect of hearing loss was observed.

The MMN peak amplitude for all these contrasts increased with an increase in hearing threshold levels, which was statistically significant (r = -0.4 to -0.6;/? < 0.01) only at the frontal sites (F_3 and F_4). The peak amplitude did not show any significant (r = -0.02 to 0.1; $p > 0.05$) effects of degree of hearing loss at any of the four sites, for the /ka/-/ga/ and the /la/-/ra/ contrasts. Figure R.I2 shows the trends in peak amplitude with increasing hearing loss.

The effects of degree of hearing loss on stimulus effects was found using ANOVA. The stimulus contrast had no significant ($p > 0.05$) effect on the peak amplitude, when analysed as a group. However, a significant interaction effects between specific stimulus contrasts and individuals with different degree of hearing loss [$F(24, 57) = 8.2$, $p < 0.01$] was seen for the peak amplitude.

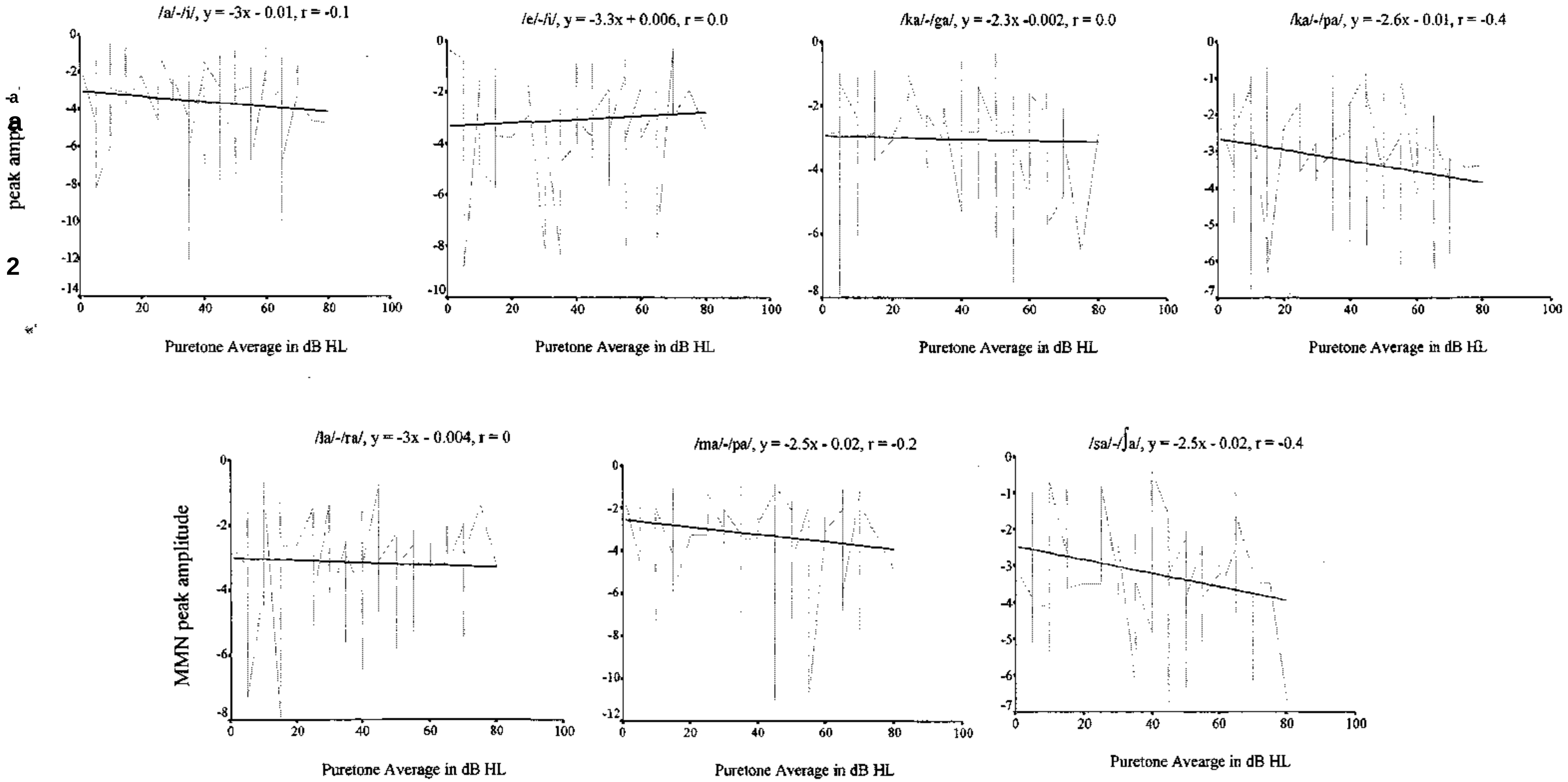

Figure R.I 2. Effects of hearing threshold level on MMN peak amplitude in microvolts recorded at the Cz site.

Table R.I3

Estimated mean and range of MMN peak amplitude recorded at Czfor different stimuli in msfor subjects with mild and moderate hearing loss

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in microvolts)
/a/-/i/	**Mild**	**-3.6**	**-4.7**	**-2.5**	-0.4
	Moderate	**-4.1**	**-5.0**	**-3.1**	
/e/-/i/	**Mild**	**-3.8**	**-4.5**	**-3.2**	-1.0
	Moderate	**-2.9**	**-3.5**	**-2.3**	
/ka/-/ga/	**Mild**	**-3.2**	**-3.7**	**-2.6**	0.6
	Moderate	**-3.9**	**-4.4**	**-3.5**	
/ka/-/pa/	**Mild**	**-2.7**	**-3.4**	**-2.1**	0.2
	Moderate	**-4.4**	**-5.0**	**-3.8**	
/ma/-/pa/	**Mild**	**-3.4**	**-4.2**	**-2.6**	0.4
	Moderate	**-3.9**	**-4.6**	**-3.2**	
/sa/-/ a/	**Mild**	**-3.2**	**-3.8**	**-2.7**	0.6
	Moderate	**-3.9**	**-4.4**	**-3.4**	
/la/-/ra/	**Mild**	**-4.1**	**-4.8**	**-3.5**	-0.9
	Moderate	**-3.4**	**-3.9**	**-2.8**	

Note. Entries of the 'Difference' column are the result of 'moderate hearing loss group' values subtracted from 'mild hearing loss group' values.

*$p<0.05$. ** $P<0.01$

No differences in stimulus effects were seen in children and adults of the experimental group. The stimulus effects on peak amplitude differed with the degree and slope of hearing loss. Mean and the range (99% confidence interval) values of offset latency for the mild and moderate hearing loss are shown in Table R.13. It may be said from the Table R.I3 that the peak amplitude of MMN is more in the individuals with a moderate hearing loss than those with a mild hearing loss. There was no significant difference in peak amplitude obtained from mild and moderate hearing loss groups for any of the speech contrasts.

The cochlear pathology is known to cause abnormal loudness growth at suprathreshold intensity levels. Broadened frequency characteristics of cortical neurons may increase the loudness of the stimulus (Harrison, Smith, Nagasawa, Statnton & Mount, 1992; Irvine, 2000). Though a constant 40 dB above threshold was maintained in the present study, the intrinsic physiological aberrations would have lead to increased loudness perception in the subjects with a hearing loss. It is shown that the MMN peak amplitude is larger at higher stimulus levels for pure tones with an intensity deviance in individuals with normal-hearing (Shroger, 1996) and hearing loss (Sivaprasad, 2001).

Increased peak amplitude at higher stimulus intensities has been attributed to the better representation of the memory trace responsible for the generation of the MMN (Shroger, 1996). However, larger peak amplitude has not been reported for subjects with a hearing loss for intensity deviance of pure tone stimuli (Sivaprasad, 2000). The difference may be attributed to the complex stimuli (speech sounds) used in the present study while pure tones were used in recording MMN in Sivaprasad (2000) study.

The results are not in agreement with Oates et al. (2002) study which showed significant decreasing trends in MMN peak amplitude with increasing hearing loss, for the /ba/-/da/ contrast. The differences could be because of the differences in stimulus intensity levels used in recording the MMN. While the intensity level was 40 dB above the pure tone average in the current study, it was 60 and 85 dB SPL (equivalent to 40 and 65 dB HL) in the study by Oates et al. (2002). The increase in peak amplitude for some of the speech contrasts with increasing hearing loss may be the result of increased loudness of the stimuli for high degree of sensorineural hearing loss rather than the increased accuracy in speech perception. It may also be noted that the MMN latency parameters were more affected by the degree of hearing loss when compared the peak amplitude. Hence, it may be said that the latency parameters are more sensitive to degree of hearing loss rather than the peak amplitude.

3. Area

Hearing threshold levels had a mixed effect on the MMN area. MMN area for the vocalic contrasts was not affected ($r = 0.00$; $p > 0.05$) by degree of hearing loss at any of the scalp sites. MMN area for the syllabic pairs, /ka/-/ga/ and /ma/-/pa/ also did not show any significant change ($r = 0.00$ to -0.2; $p > 0.05$) at any given scalp site with increase in hearing loss. The /ka/-/pa/ and /sa/-/ a/ contrasts resulted in significant ($r = 0.6$; $p < 0.05$) increase in area with increase in hearing loss. As observed with other MMN parameters for the /la/-/ra/ contrast, MMN area also showed a decreasing trend ($r = -0.4$;$p < 0.01$) with increase in degree of hearing loss. These significant changes were observed at all four scalp sites. Figure R.13 shows the trends in area with increasing hearing loss.

The change in MMN area with variations in degree of hearing loss in the experimental group was analyzed using ANOVA. The stimulus and degree of hearing loss had significant interaction effects [F (24, 57) = 10.0,/; < 0.01]. The mean and range values (99% confidence interval) MMN area obtained in different degrees are shown in Table R.I4. The MMN area was generally more in the group with a moderate hearing loss than that with a mild hearing loss. This kind of a trend was seen with MMNs for all the contrasts except for the /e/-/i/ and /la/-/ra/ contrasts

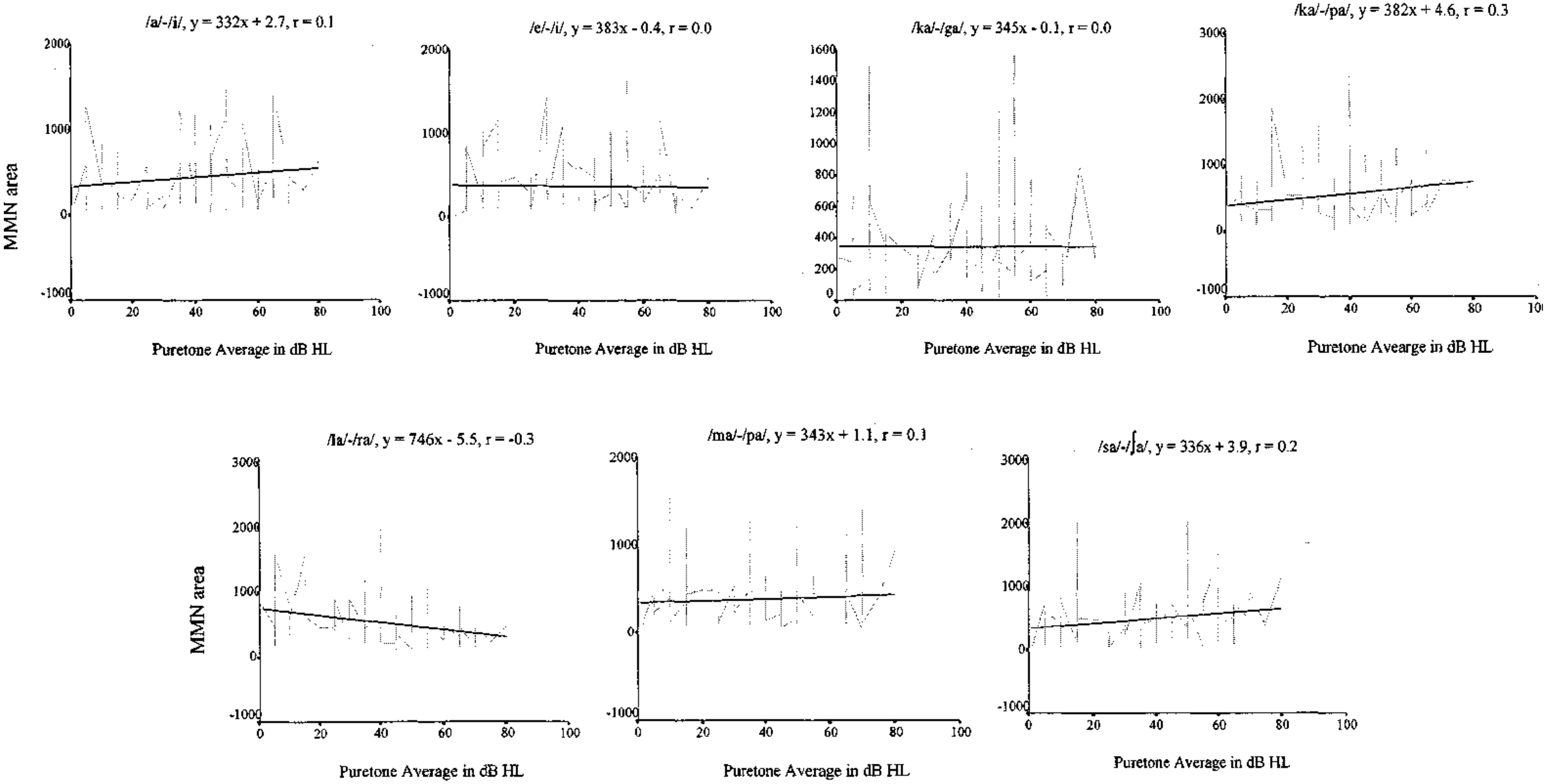

Figure R.13. Effects of hearing threshold level on MMN area in ms X microvolts recorded at the Cz site.

(Table R.I 4). The /e/-/i/ and /la/-/ra/ contrasts showed larger MMN area in the mild hearing loss group. The difference in area between the mild and the moderate groups was not statistically significant for any of the speech contrasts except for that of the /ka/-/ga/ contrast.

Table R. 14

Estimated mean and range of MMN area recorded at Cz for different stimuli in ms for subjects with mild and moderate hearing loss

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms X microvolts)
/a/-/i/	Mild	330.7	140.9	520.3	-146.7
	Moderate	540.1	370.6	709.5	
/e/-/i/	Mild	446.1	344.5	547.7	-75.9
	Moderate	336.1	245.3	426.8	
/ka/-/ga/	Mild	362.1	258.6	465.5	-189.9*
	Moderate	557.3	464.9	649.8	
/ka/-/pa/	Mild	350.6	186.7	514.5	-7.4
	Moderate	630.2	483.8	776.6	
/ma/-/pa/	Mild	434.4	348.3	520.4	-79.0
	Moderate	464.3	387.5	541.2	
/sa/-/{a/	Mild	328.1	232.3	423.9	-26.8
	Moderate	413.4	327.8	498.9	
/la/-/ra/	Mild	584.4	485.2	683.6	127.0
	Moderate	347.6	258.9	436.2	

Note. Entries of the 'Difference' column are the result of 'moderate hearing loss group' values subtracted from 'mild hearing loss group' values.

*$p<0.05$. **$p<0.01$

From the above findings it may be construed that the MMN area was not significantly affected by the degree of hearing loss for any of the vocalic contrasts.

The summary of effects of degree of hearing loss on different MMN parameters is summarised in Table R.I5.

Table R. 15

Effects of degree of hearing loss on MMN parameters across scalp sites

Parameter	Effects of hearing threshold level on MMN parameters	Electrode site
Peak latency	a. Decreased with increasing degree of hearing loss, for the /la/-/ra/ contrast b. No change for the /e/-*/i/* and /sa/-/ a/ contrasts c. Increased for the and /a/-/i/, /ka/-/ga/, /ka/-/pa/, and /ma/-/pa/ contrasts	At all scalp sites
Onset latency	a. No change for the /e/-/i/, /sa/-/ a/ and /la/-/ra/ contrasts b. Increased for the /a/-*/i/*, /ka-/ga/, */ka/*-/pa/ and /ma/-/pa/ contrasts	At all scalp sites
Offset latency	a. Decreased for the /la/-/ra/ contrast b. No change for the /e/-/i/, /ka/-/pa/, and /sa/-/ a/ contrasts c. Increased for the /a/-/i/, /ka-/ga/, /ma/-/pa/ contrasts	At all scalp sites (At F_3 and F_4 sites for the/a/-*/i/* contrast)
Peak amplitude	a. No change for the *lal-/i/*, */e/-/i/*, /ka-/ga/, and /la/*-/ral* contrasts b. Increased for the /ka/-/pa/, /sa/- */ al*, /ma/-/pa/ contrasts	a. At all scalp sites b. At F3 and F4 sites
Area	a. Decreased for the /e/-/i/ and /la/-/ra/ contrast b. Increased for the *lal-/i/*, */ka/-/gal*, */ka/-/pal*, /ma/-/pa/ and /sa/-/ a/ contrasts	At all scalp sites

II. d. Effects of audiogram slope on MMN

To find the effects of audiogram slope on MMN parameters across channels, simple linear regression analysis was used. In this analysis, subjects of the experimental group were studied with respect to the slope of their audiogram i.e., average of the differences in pure tone thresholds between adjacent octaves, for each of the subject. The Pearson's correlation coefficient, y-intercept, slope and significance of the slope effects were obtained for each of the stimuli and across different locations on the scalp. The grand mean waveforms of MMN recorded for different phonetic contrasts are shown in Figure R.I4 in individuals with sloping and flat hearing loss.

1. Latency parameters

The effects of audiogram slope were studied on different latency parameters viz. the peak latency, onset latency and offset latency.

(i) Peak latency.

The effects of audiogram slope on peak latency were almost uniform across the stimuli. MMN peak latency recorded for vocalic and consonant contrasts did not change with increasing slope of the audiogram ($r = 0.002\text{-}0.2; p > 0.05$) except for the /ka/-/ga/ contrast. The MMN for the /ka/-/ga/ contrast showed a significant ($r = 0.5; p < 0.01$) increasing shift in peak latency with increase in slope of the audiogram. These trends were observed at all the four scalp positions (Table R.I6).

Table R. 16

Estimated mean and range of peak latencies for different stimuli in ms for individuals with flat and the sloping hearing loss at C_z *site*

Stimulus	**Group**	**Mean**	**Lower Bound**	**Upper Bound**	**Difference (in ms)**
/a/-/i/	**Sloping**	131.6	120.4	142.7	4.7
	Flat	127.2	116.2	138.1	
/e/-/i/	**Sloping**	158.4	144.1	172.7	11.5
	Flat	172.6	158.5	186.6	
/ka/-/ga/	**Sloping**	208.1	194.9	221.2	77.1**
	Flat	148.0	135.0	160.9	
/ka/-/pa/	**Sloping**	178.5	162.1	194.9	-27.1
	Flat	189.9	173.7	206.0	
/ma/-/pa/	**Sloping**	178.1	160.5	195.6	19.6
	Flat	155.3	137.9	172.6	
/sa/-/ a/	**Sloping**	171.5	158.8	184.2	**-3.2**
	Flat	161.8	149.4	174.3	
/la/-/ra/	**Sloping**	224.8	210.3	239.3	10.5
	Flat	205.1	190.8	219.4	

Note. Entries of the 'Difference' column are the result of the 'flat hearing loss group' values subtracted from 'sloping hearing loss group' values.

$*p<0.05$. $**p<0.01$

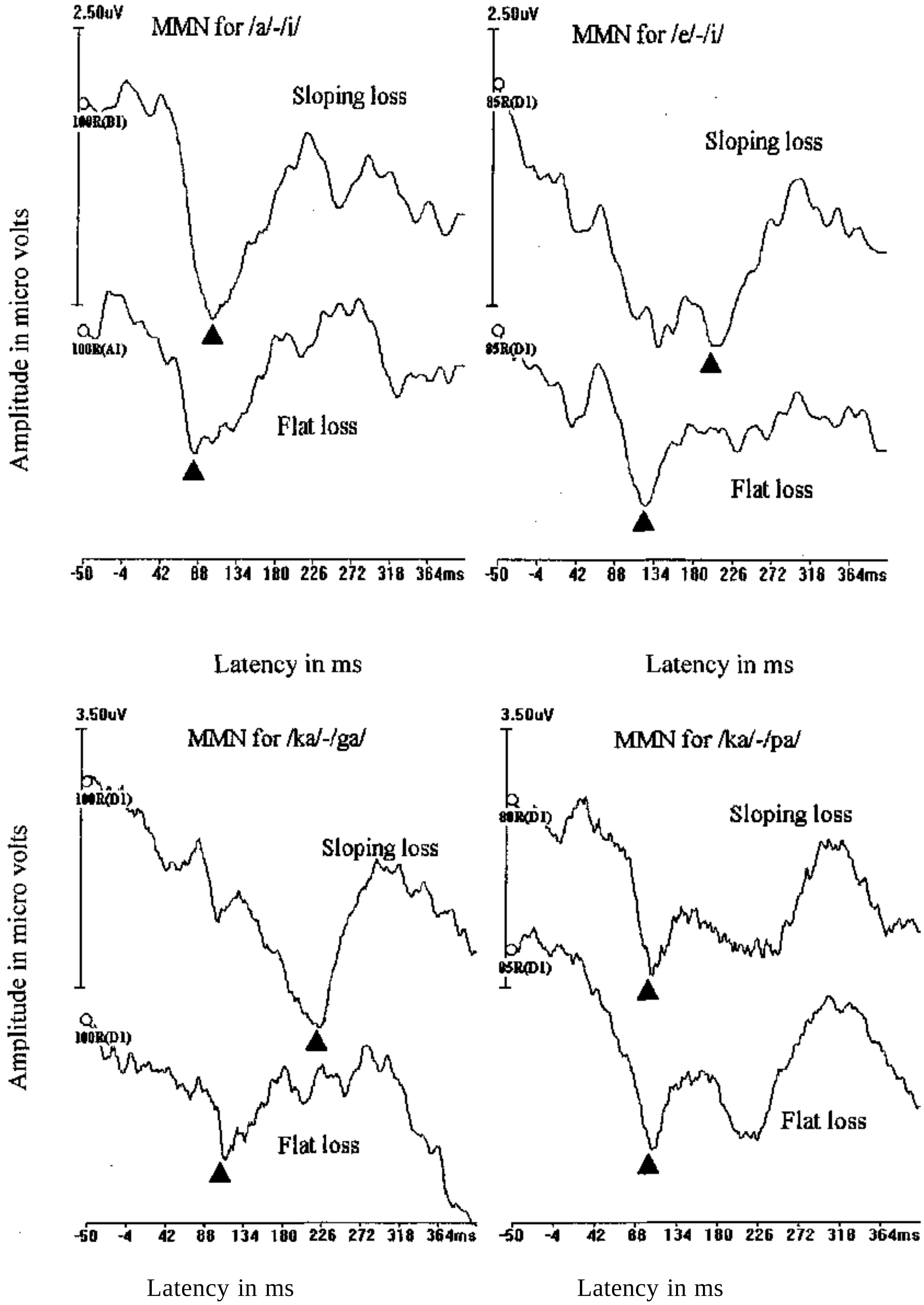

Figure R.14. Grand mean MMN waveforms recorded at Cz for different stimuli in sloping and flat type of hearing loss (arrow heads indicate the MMN peaks). (Continued...)

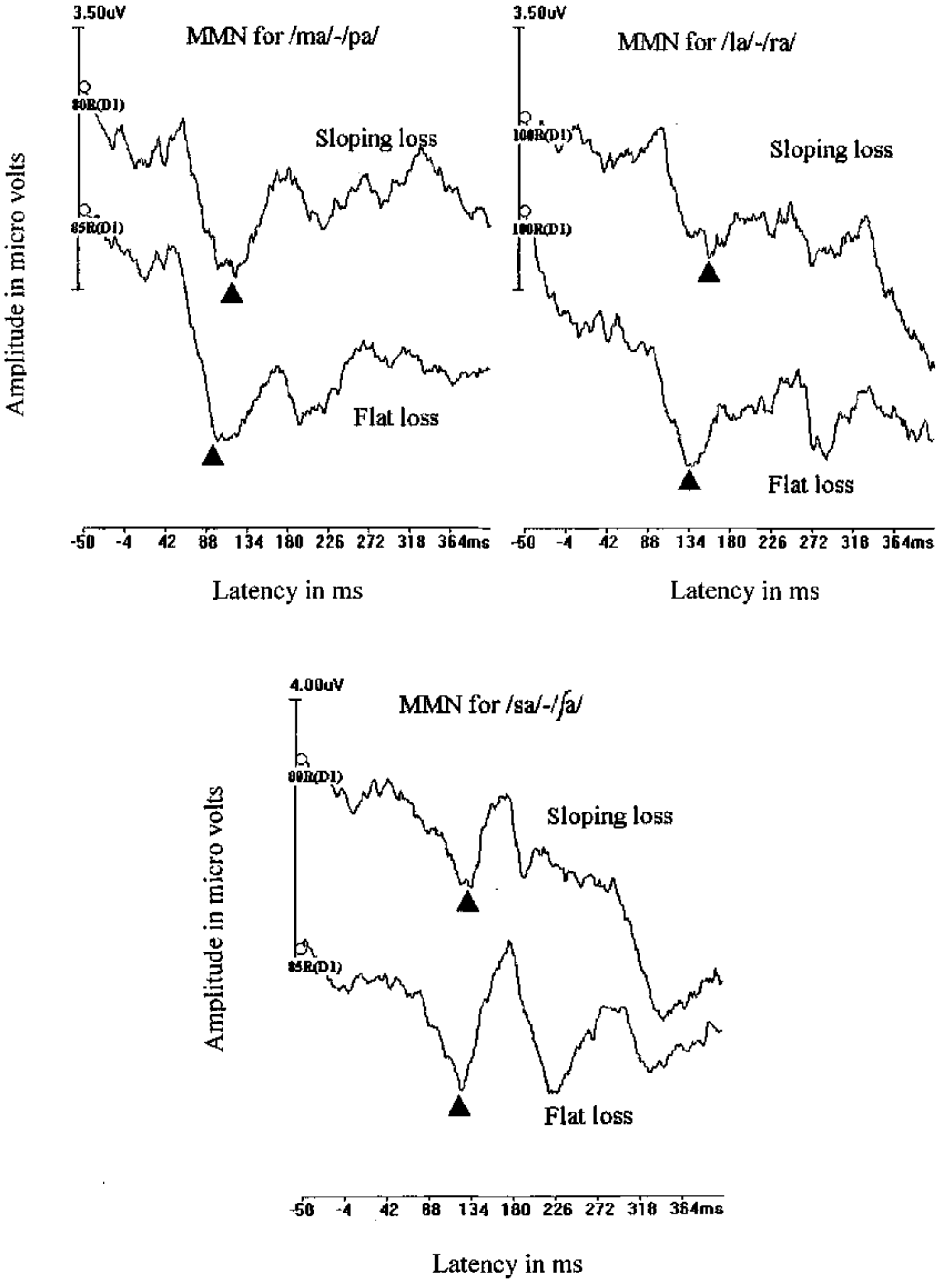

Figure R.14. Grand mean MMN waveforms recorded at Cz for different stimuli in sloping and flat type of hearing loss (arrowheads point the MMN peak).

The mean MMN peak latency values were not significantly different for other contrasts between both the groups. The group with a sloping hearing loss generally had prolonged peak latencies compared to those with a flat hearing loss, though this difference was not statistically significant for the majority of contrasts.

(ii) Onset latency.

The effects on MMN onset latency were similar to that of the peak latency. MMN onset latency for vocalic and consonant contrasts did not change with the slope of the audiogram ($r = -0.1; p > 0.05$) except for the /ka/-/ga/ contrast, as shown by the regression analysis. Once again the /ka/-/ga/ contrast showed a significant increase ($r = 0.2; p < 0.05$) in onset latency with an increase in audiogram slope. These trends were seen only at the frontal (F3 and F4) scalp sites. The MMN onset latencies between the flat and the sloping groups were significantly different ($t < 0.01$) for the /ka/-/ga/ and the /la/-/ra/ contrasts at C_z site, as shown by t-test (Table R.17). The MMN onset latency values overlapped for other contrasts between both the groups.

(Hi) Offset latency.

The MMN offset latency was not significantly affected ($r = 0.3$;/? > 0.05) at any of the four scalp sites, by the slope of the audiogram for all speech contrasts, except for the /e/-/i/ and /ka/-/ga/ contrasts. While the /e/-/i/ contrast showed a decrease ($r = -0.3; p < 0.05$) in offset latency, the trend for /ka/-/ga/ contrast was a significant increase ($r = 0.4; p < 0.01$) in offset latency with an increase in audiogram slope. These trends were observed at all the scalp sites except at the Pz site.

Table R. 17

Estimated mean and range of onset latencies for different stimuli in ms for individuals with flat and the sloping hearing loss at C_z site

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms)
/a/-/i/	**Sloping**	84.9	73.7	96.0	8.1
	Flat	78.0	67.0	89.0	
/e/-/i/	**Sloping**	105.0	92.5	117.5	19.4
	Flat	118.1	105.8	130.3	
/ka/-/ga/	**Sloping**	137.4	122.9	151.7	54.1**
	Flat	96.2	82.1	110.3	
/ka/-/pa/	**Sloping**	111.4	95.4	127.4	-25.7
	Flat	138.2	122.5	154.0	
/ma/-/pa/	**Sloping**	114.9	99.5	130.4	28.4
	Flat	103.5	88.3	118.8	
/sa/-/ a/	**Sloping**	122.1	106.5	137.7	-17.2
	Flat	116.7	101.4	132.1	
/la/-/ra/	**Sloping**	170.5	154.6	186.4	54.6**
	Flat	139.7	124.1	155.2	

Note. Entries of the 'Difference' column are the result of 'flat hearing loss group values' subtracted from 'sloping hearing loss group' values.

$*p<0.05$. $**p<0.01$

Table R.18 shows the MMN offset latency for different speech contrasts in the flat and the sloping loss groups. The audiogram slope resulted in a significantly different offset latency for only two of the contrasts i.e., /ka/-/ga/ and /ma/-/pa/. The clients with a sloping hearing loss had longer offset latencies.

Table R. 18

Estimated mean and range of offset latencies for different stimuli in msfor individuals with flat and the sloping hearing loss at C_z *site*

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in ms)
/a/-/i/	**Sloping**	181.7	164.6	198.9	5.8
	Flat	185.8	168.9	202.7	
/e/-/i/	**Sloping**	216.2	201.3	231.2	13.9
	Flat	237.1	222.4	251.7	
/ka/-/ga/	**Sloping**	272.4	259.8	285.0	94.0**
	Flat	198.6	186.2	211.0	
/ka/-/pa/	**Sloping**	240.1	225.9	254.3	-11.6
	Flat	248.8	234.9	262.8	
/ma/-/pa/	**Sloping**	244.9	230.3	259.7	34.9*
	Flat	219.8	205.3	234.2	
/sa/-/ a/	**Sloping**	219.9	202.7	237.3	-13.0
	Flat	206.4	189.4	223.4	
/la/-/ra/	**Sloping**	277.7	262.9	292.6	8.4
	Flat	258.8	244.2	273.5	

Note. Entries of the 'Difference' column are the result of'flat hearing loss group' values subtracted from 'sloping hearing loss group' values.

*p<0.05. *p<0.01

Overall it can be said that the audiogram slope had no significant effect on MMN latency parameters for all the speech contrasts except for the /ka/-/ga/ contrast. All MMN latencies for the /ka/-/ga/ contrast were prolonged with an increase in slope of the audiogram. Among the vocalic contrasts, only the MMN offset latency for the /e/-/i/ contrast decreased with an increase in audiogram slope.

The loss of spectral resolution in the auditory system results as a consequence of a sloping hearing loss (Marronroge & Diefendorf, 1984), which leads to poor speech perception scores. Polen (1984) also hypothesised that inaudible high frequency information, as a result of sloping hearing loss may lead to prolonged latencies in ERPs. However, the results of the present study does not support Polen's hypothesis, based on MMN parameters. The present study did not find any effects on MMN evoked for speech contrasts other than the voicing one i.e., /ka/-/ga/. The effects on the voicing contrast may be explained by the reduced availability of temporal cues to a mild-to-moderate loss listener (Fitzgibbons & Wightman, 1982), which are helpful in voicing distinction.

Martin et al. (1999) used ipsilaterally presented high-pass noise with varying cut-off frequencies from 8000 Hz to 500 Hz in octaves, to simulate the effects of sloping hearing loss on MMN. They used the /ba/-/da/ contrast in a flip-flop method. In this method both the stimuli were used as deviants in alternative recordings. They found no effects on of high-pass noise on MMN till the cut-off frequency of noise was 2000 Hz. The effects became significant and the peak latencies prolonged, only when the cut-off frequency of high-pass noise was lowered to 1000 Hz and below. The major limitation of the study by Martin et al. (1999) was that the high-pass noise had a very steep attenuation of the speech energy, which is not seen in a clinically presented sloping hearing loss. The findings of their study contradict with those of the present study. In the present study, though the sloping hearing loss clients had a loss starting from 1000 Hz, they had some audible information at that frequency. The present study did not include any subject whose hearing loss started sloping from frequencies below 1000 Hz, hence no effect was found. Further, increased critical bandwidths (Moore & Glasberg, 1990) and reduced temporal processing (Moore, 1995), which are affected in the subjects with a hearing loss may not be simulated well with filtered noise. Hence, the MMN findings in subjects with a hearing loss may be different from that of the simulated studies.

2. Peak amplitude

Like the peak latency, MMN peak amplitude was also not affected by the audiogram slope. MMN peak amplitude recorded for vocalic and consonant contrasts did not change at any scalp site, with increasing slope of the audiogram ($r = -0.1; p > 0.05$).

Table R. 19

Estimated mean and range of peak amplitude for different stimuli in ms in individuals with flat and the sloping hearing loss at C_z site

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in microvolts)
/a/-/i/	Sloping	-3.4	-4.5	-2.4	0.8
	Flat	-4.2	-5.3	-3.2	
/e/-/i/	Sloping	-3.6	-4.3	-2.9	-0.5
	Flat	-3.1	-3.7	-2.5	
/ka/-/ga/	Sloping	-4.2	-4.7	-3.7	-1.8*
	Flat	-2.9	-3.5	-2.5	
/ka/-/pa/	Sloping	-3.6	-4.3	-2.9	0.6
	Flat	-3.6	-4.2	-2.9	
/ma/-/pa/	Sloping	-3.8	-4.6	-3.1	-1.0
	Flat	-3.5	-4.2	-2.7	
/sa/-/ ja/	Sloping	-3.7	-4.2	-3.1	-1.0
	Flat	-3.5	-4.0	-2.9	
/Ia/-/ra/	Sloping	-3.5	-4.2	-2.9	0.7
	Flat	-3.9	-4.6	-3.4	

Note. Entries of the 'Difference' column are the result of'flat hearing loss group' values subtracted from 'sloping hearing loss group' values.

$^{*}p<0.05$. $^{**}p<0.01$

An exception to this was the MMN for the /ka/-/ga/ contrast which showed a significant decrease ($r = -0.3; p < 0.05$) in peak amplitude with an increase in audiogram slope at all the scalp positions. The /ka/-/ga/ contrast resulted in an MMN with peak amplitude that was significantly different between the subgroups based on the audiogram slope (shown in Table R.I 9). The peak amplitudes of other speech contrasts were not significantly different in flat and sloping loss clients.

Thus, it may be construed that the MMN peak amplitude is not altered on account of the slope of the audiogram. This was shown for all the speech contrasts, except for the /ka/-/ga/ contrast, which showed a decrease in MMN amplitude with increase in hearing loss. Changes in the peak amplitude of MMN for the /ka/-/ga/ contrast may be explained based on the altered temporal cue processing leading to difficulties voicing perception in individuals with sloping hearing loss (Fitzgibbons & Wightman, 1982).

In a study to simulate the effects of sloping hearing loss, Martin et al. (1999) found that the mean and peak amplitude of MMN decreased with a cut-off frequency of 1000 Hz and below. As mentioned earlier, none of the subjects in the present study had such steeply sloping hearing loss and a loss that started below 1000 Hz. Due to methodological differences, the results of their study cannot be compared with that of the present study.

3. Area

Trends for the MMN area were also in the same line as the other parameters. MMN area was not affected ($p > 0.05$) by slope of the audiogram for all the vocalic and consonantal contrasts, except for the /ka/-/ga/ contrast, which showed an increase ($r = 03; p < 0.05$) in MMN area for an increase in audiogram slope. Similar trends were observed at all the four scalp sites. As shown in Table R.20, generally larger MMN area was seen in the group with a sloping hearing loss when compared to those with a flat hearing loss. This was seen for all the contrasts except for /a/-/i/ and /la/-/ra/. However, with the exception of /ka/-/ga/ there was no statistically significant difference seen for the MMN area between the two groups having different audiogram slopes.

Table R.20

Estimated mean and range of MMN area for different stimuli in ms in individuals with flat and the sloping hearing loss at C_z site

Stimulus	Group	Mean	Lower Bound	Upper Bound	Difference (in microvolts)
/a/-/i/	**Sloping**	361.3	179.9	542.6	-34.2
	Flat	509.5	331.1	687.8	
/e/-/i/	**Sloping**	414.4	317.2	511.5	173.6
	Flat	367.8	272.3	463.3	
/ka/-/ga/	**Sloping**	581.2	482.3	680.1	282.9*
	Flat	338.3	240.9	435.6	
/ka/-/pa/	**Sloping**	522.0	365.3	678.7	-192.1
	Flat	458.7	304.6	612.8	
/ma/-/pa/	**Sloping**	502.8	420.5	585.0	159.7
	Flat	395.9	315.0	476.8	
/sa/-/ a/	**Sloping**	395.8	304.2	487.4	92.1
	Flat	345.7	255.6	435.7	
/la/-/ra/	**Sloping**	409.8	314.9	504.6	-151.2
	Flat	522.3	428.9	615.5	

Note. Entries of the 'Difference' column are the result of'flat hearing loss group' values subtracted from 'sloping hearing loss group' values.

$^*p<0.05$. $^{**}p<0.01$

Comparing the effects of degree and slope of audiogram on MMN parameters, it can be noted that the degree of hearing loss poses a greater difficulty in the task rather than the audiogram slope. The audiogram slope effects on MMN parameters is summarised in Table R.21.

Table R.21

Changes in MMN parameters with increasing audiogram slope

Parameter	**Effects of audiogram slope on MMN parameters**	**Electrode site**
Peak latency	a. No significant change for the /a/-*/i/*, */e/-/i/*, /ka/-/pa/, /ma/-/pa/, *lsal*-*l\al* and /la/-/ra/ contrasts with increasing audiogram slope b. Increased for the *Ikal*-*lgal* contrast	At all scalp sites
Onset latency	a. No change for the /a/-*/i/*, */e/-/i/*, /ka/-/pa/, /ma/-/pa/, /sa/-/ja/ and /la/-/ra/ contrasts b. Increased for the *Ikal*-*lgal* contrast	a. At all scalp sites b. At $F_3$and F_4 sites
Offset latency	**a.** Decreased for the /e/-/i/ contrast c. No change for the /a/-/i/, /ka/-/pa/, /ma/-/pa/, */la/-/ra/* and /sa/-*/ a/* contrasts c. Increased for the /ka-*/ga/* contrast	At C_z F_3 and F4 sites
Peak amplitude	a. Decreased for the /ka/-*/ga/* contrast b. No change for the /a/-*/i/*, */e/-/i/*, */ka/-/pal,* /ma/-/pa/, /sa/-/ a/ and /la/ *-/ra/* contrasts	At all four scalp sites
Area	a. No change for the /a/-*/i/*, */e/-/i/*, */ka/-/pa/*, */ma/-/pa/*, */sa/-/ a/* and /la/-*/ra/* contrasts b. Increased for the *Ikal*-*lgal* contrast	At all scalp sites

IIe. Variations inMMN as a function of the phonetic contrast

MMN parameters differed with the type of phonetic contrast used in eliciting it. This pattern was observed both in normal-hearing and hearing loss groups. A repeated measures mixed ANOVA was administered to verify this objective. Analysis was done in the control and experimental groups separately. Age effects in the control group and the degree of hearing loss effects in the experimental groups with respect to phonetic contrasts were also studied.

1. *Latency parameters*

Peak latency, onset latency and offset latency of MMN were studied with respect to different speech contrasts and electrode sites both in the control and the experimental groups.

a. Peak latency.

In the control group, the repeated measures ANOVA showed that peak latency was different for different stimulus contrasts ($p < 0.01$) in the control group. Table R.22 shows the estimated mean peak latencies for different speech contrasts and Table R.23 shows the significance of difference in peak latency values between the speech contrasts in the control group. Analysis also showed that the effects of type of stimulus contrast on peak latency were significantly different ($p < 0.01$) in children and adults in the control group.

From the Tables R.22 and R.23, it may be said that, the vocalic contrast /a/-/i/ and the consonantal contrast /ma/-/pa/ resulted in an MMN with the shortest peak latency. These differences were statistically significant ($p < 0.01$). MMN for the /ma/-/pa/ contrast had shorter peak latency on par with the vocalic contrasts. The /la/-/ra/ contrast resulted in an MMN with the longest peak latency. However, it was not different from that of the /sa/-/ a/ contrast. The /e/-/i/, /ka/-/ga/ and the /ka/-/pa/ contrasts resulted in MMN peak latency with no significant difference.

Table R.22

Estimated mean peak latencies for different speech contrasts in the control group

Stimulus	**Mean**	**Lower Bound**	**Upper Bound**
/a/-/i/	131.3	118.9	143.6
/e/-/i/	168.7	152.8	184.5
/ka/-/ga/	155.7	139.5	171.9
/ka/-/pa/	162.5	146.2	178.7
/ma/-/pa/	129.9	119.7	140.3
/sa/-/ a/	186.7	169.8	203.5
/Ia/-/ra/	213.4	198.9	227.8

Table R.23

Significance of differences between estimated peak latencies across speech contrasts in the control group

Stimulus	**/a/-/i/**	**/e/-/i/**		/ka/-/pa/	/ma/-/pa/	**/sa/-/Ja/**	/la/-/ra/
lal-/i/		0.000	0.030	0.001	1.000	0.000	0.000
Id-IM			1.000	1.000	0.000	0.911	0.000
/ka/-/ga/				1.000	0.016	0.091	0.000
/ka/-/pa/					0.002	0.153	0.000
/ma/-/pa/						0.000	0.000
/sa/-/ a/							0.157
/la/-/ra/							

The peak latencies recorded at the four scalp sites did not show a significant difference ($p > 0.05$) for any of the speech contrast in this group. This lack of difference in peak latency to electrode site on the scalp was seen both children and adults which is evident from Figure R.15.

Table R.24

Estimated mean peak latencies for different speech contrasts in the experimental group

Stimulus	Mean	Lower Bound	Upper Bound
/a/-/i/	129.4	121.6	137.2
/e/-/i/	165.5	155.5	175.5
/ka/-/ga/	178.0	168.8	187.3
/ka/-/pa/	184.2	172.7	195.7
/ma/-/pa/	166.7	154.3	178.9
/sa/-/ a/	166.7	157.8	175.6
/la/-/ra/	214.9	204.8	225.1

Table R.25

Significance of differences between estimated peak latencies across speech contrasts in the experimental group

Stimulus	/a/-/i/	/e/-/i/	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	/sa/-/ a/	/la/-/ra/
/a/-/i/		0.000	0.000	0.000	0.000	0.000	0.000
/e/-/i/			0.443	0.068	1.000	1.000	0.000
/ka/-/ga/				1.000	0.999	0.480	0.000
/ka/-/pa/					0.044	0.024	0.000
/ma/-/pa/						1.000	0.000
/sa/-/ a/							0.000
/la/-/ra/							

For the experimental group, table R.24 shows the estimated mean peak latencies of MMN evoked for different speech contrasts and Table R.25 shows the differences in peak latency values between different stimulus contrasts and their

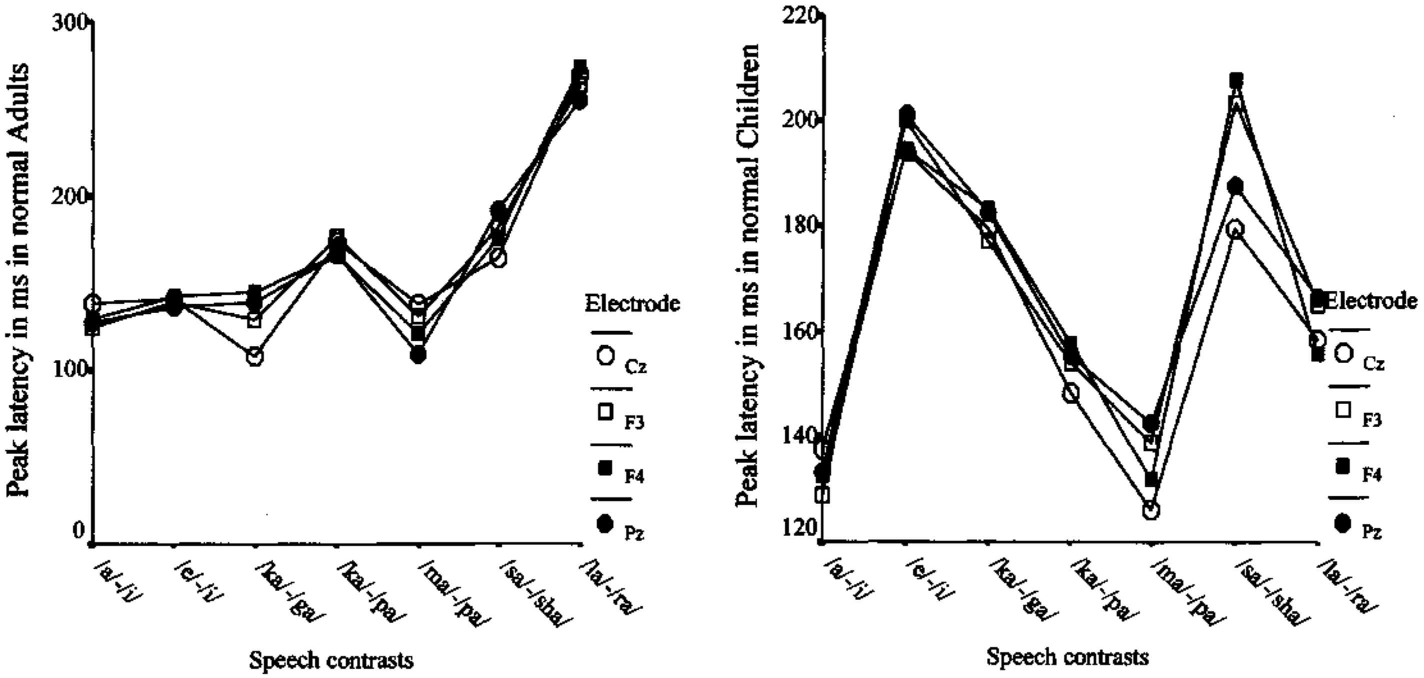

Figure R.15. Mean peak latencies for different speech contrasts recorded at the four scalp sites in the control group.

significance values. The /a/-/i/ contrast resulted in an MMN with the shortest peak latency. There was no significant ($p > 0.05$) difference in peak latencies evoked by the /ka/-/ga/ and /ka/-/pa/ contrasts. MMN peak latency evoked by the /e/-/i/, /ma/-/pa/ and /sa/-/ a/ contrasts was not different ($p > 0.05$) from one another and lower than the other contrasts. The MMN peak latency for the /la/-/ra/ contrast was the longest one ($p < 0.05$). The analysis also revealed that the effects varied with degree of hearing loss ($p < 0.05$). ANOVA revealed that the effects of phonetic contrast on peak latency were significantly different ($p < 0.01$) in different degrees of hearing loss.

The analysis also showed that there was no difference ($p > 0.05$) between the electrode sites in terms of the stimulus effects for any of the stimulus contrasts in the experimental group. Figure R.I 6 shows the peak latencies of stimulus contrasts across different scalp sites. The effects of degree of hearing loss on peak latency in control and the experimental hearing loss are summarized in Table R.26.

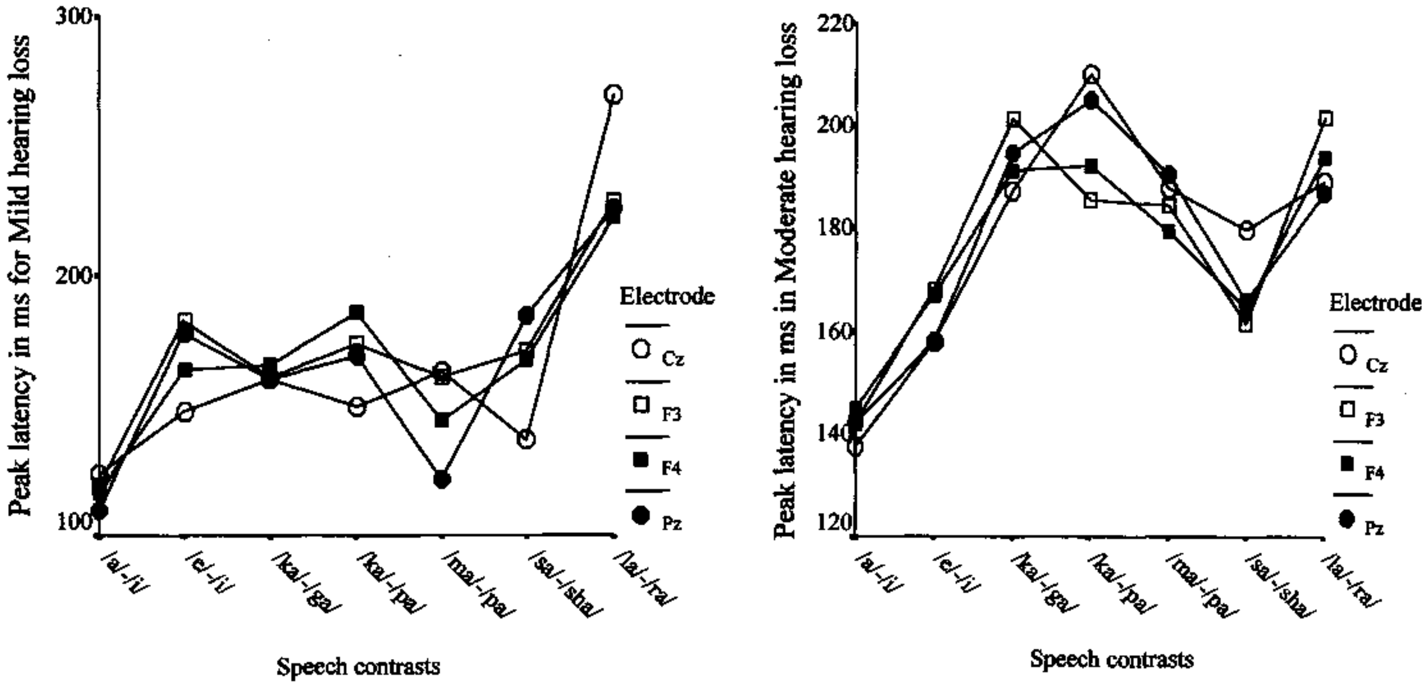

Figure R.16. Mean peak latencies of MMN for different speech contrasts recorded at the four scalp sites in the experimental group.

Table R.26

The effects of type of stimulus contrast on the peak latency (PL) seen in the control and the experimental groups

Control Group	Experimental Group
a. Type of stimulus had a significant effect on PL	a. Type of stimulus had a significant effect on PL
b. The shortest PL for the /a/-/i/ and /ma/-/pa/ contrasts	b. The shortest PL for the/a/-/i/ contrast
c. The longest PL for the */\a/-/xa/* contrast	c. The longest PL for the */lal-/ral* contrast
d. Interaction effects of stimulus on age were significant	d. Interaction effects of stimulus on degree of hearing loss were significant
e. The PL was significantly different for adults and children for the /e/-/i/, */ka/ /ga/* and /la/-/ra/ contrasts	e. Prolonged PL in the moderate degree of hearing loss for all the contrasts
f. No difference in PL across the scalp sites	g- The */lal-lral* contrast showed prolonged PL in the mild hearing loss group
	h. The PL for the */ka/-/ga/, /ka/-/pal, /ma/-/pa/* and */lal-/ral* contrasts between the mild and moderate hearing loss was significantly different
	i. No difference in PL across the scalp sites

b. Onset latency.

The repeated measures ANOVA was administered to see the differences in onset latencies evoked by different speech contrasts. In the control group, the estimated mean onset latency values of MMN for different speech contrasts is shown in Table R.27 and in Table R.28. They differed significantly as a function of the phonetic contrast.

Table R.27

Estimated mean onset latencies for different speech contrasts in the control group

Stimulus	**Mean**	**Lower Bound**	**Upper Bound**
/a/-/i/	75.9	65.0	86.8
/e/-/i/	109.6	94.2	125.0
/ka/-/ga/	95.9	80.6	111.3
/ka/-/pa/	105.8	88.9	122.8
/ma/-/pa/	79.5	71.2	87.8
/sa/-/ a/	134.9	116.7	153.3
/la/-/ra/	135.9	117.4	154.4

Table R.28

Significance of differences between estimated onset latencies across speech contrasts in the control group

Stimulus	**/a/-/i/**	**/e/-/i/**	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	**/sa/-/ a/**	/la/-/ra/
/a/-/i/		0.002	0.032	0.003	1.000	0.000	0.000
/e/-/i/			1.000	1.000	0.002	0.210	0.077
/ka/-/ga/				1.000	0.207	0.007	0.001
/ka/-/pa/					0.011	0.058	0.088
/ma/-/pa/						0.000	0.000
/sa/-/ a/							1.000
/la/-/ra/							

In the control group, As shown in Tables R.27 and R.28, the MMN onset latency was unique to a given speech contrast. Overall, the contrasts /a/-/i/ and /ma/-/pa/ resulted in an MMN with the shortest onset latency. MMN for the /la/-/ra/ and /sa/-/ a/ contrasts resulted in the longest onset latency. The contrasts /e/-/i/, /ka/-/ga/ and /ka/-/pa/ resulted in MMNs with onset latencies with no significant difference between each other. Similar trends were observed for peak latency also as mentioned in the earlier section. The analysis also showed that the phonetic effects on onset latency were significantly different in children and adults (*p* < 0.01).

Analysis also showed that there was no significant difference (*p* > 0.05) in MMN onset latency for any of the speech contrast recorded at the four scalp sites. This was seen in both adults and children. The onset latency values recorded at different scalp sites across stimuli are shown in Figure R.I7.

For the experimental group, the estimated mean onset latencies are shown in Table R.29, and the differences in onset latency values between different stimulus contrasts, and their significance values are shown in Table R.30. ANOVA showed that the phonetic effects on onset latencies were significantly (*p* < 0.01) different in varying degrees of hearing loss

Table R.29

Estimated mean onset latencies for different speech contrasts in the experimental group

Stimulus	**Mean**	**Lower Bound**	**Upper Bound**
/a/-/i/	75.9	65.0	86.8
/e/-/i/	109.6	94.2	125.0
/ka/-/ga/	95.9	80.6	111.3
/ka/-/pa/	105.8	88.9	122.8
/ma/-/pa/	79.5	71.2	87.8
/sa/-/ a/	134.9	116.7	153.3
/la/-/ra/	135.9	117.4	154.4

The /a/-/i/ contrast resulted in an MMN with the shortest onset latency. There was no significant (*p* > 0.05) difference in onset latencies evoked by the /e/-/i/, /ka/-/ga/, /ka/-/pa/, /ma/-/pa/ and /sa/-/ a/ contrasts. MMN onset latency for the /la/-/ra/

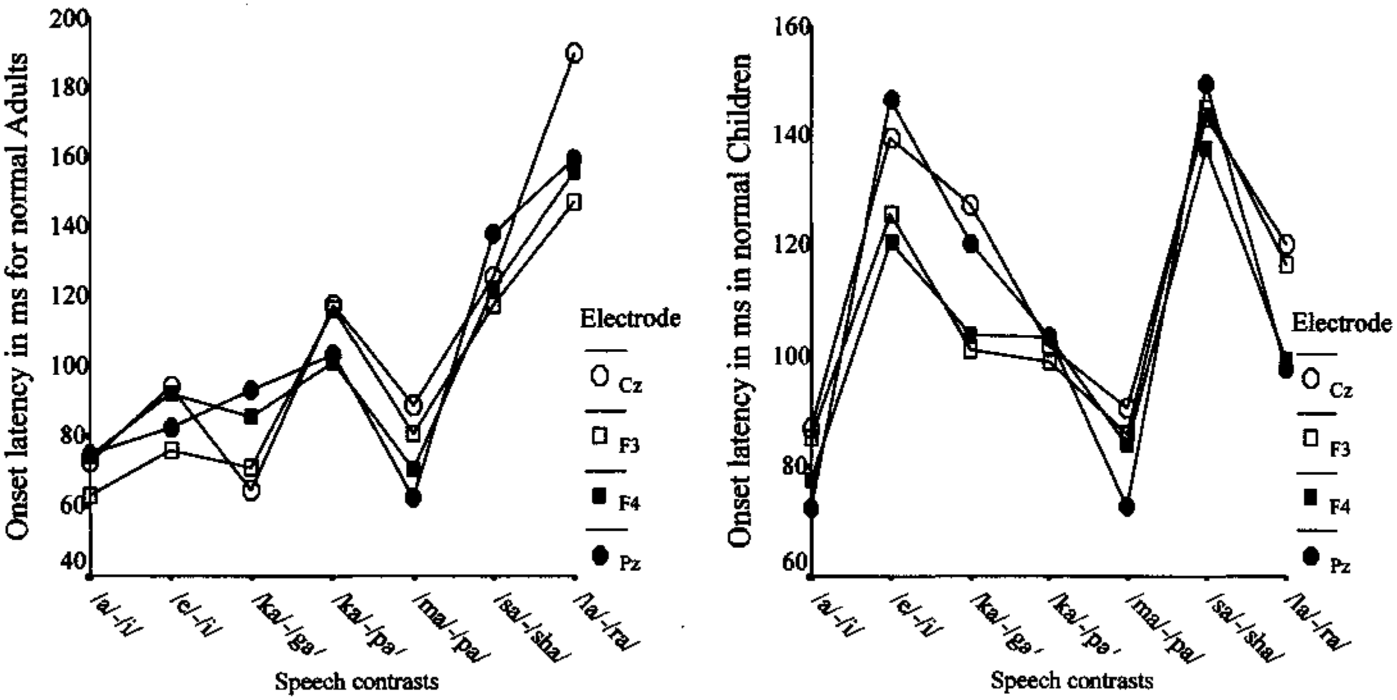

Figure R.17. Mean onset latency of MMN for different speech contrasts recorded at the four scalp sites in the control group.

contrast was the longest one (*p* < 0.05). Similar effects were seen in children and adults of the experimental group (*p* > 0.05).

Table R.30

Significance of differences between estimated onset latencies across speech contrasts in the experimental group

Stimulus	**/a/-/i/**	***/e/-/i/***	**/ka/-/ga/**	**/ka/-/pa/**	**/ma/-/pa/**	/sa/-/ a/	**/la/-/ra/**
/a/-/i/		0.000	0.000	0.000	0.000	0.000	0.000
/e/-/i/			1.000	0.444	1.000	1.000	0.000
/ka/-/ga/				1.000	1.000	1.000	0.000
/ka/-/pa/					0.058	1.000	0.000
/ma/-/pa/						1.000	0.000
/sa/-/ a/							0.000
/la/-/ra/							

In the experimental group, ANOVA showed that there was no difference between the electrode sites in terms of the stimulus effects on onset latency in the experimental group. The MMN onset latencies for stimulus contrasts across different scalp sites are shown in Figure R.18. The effects of phonetic contrast on the onset latency obtained in different main and sub groups are summarized in Table R.31.

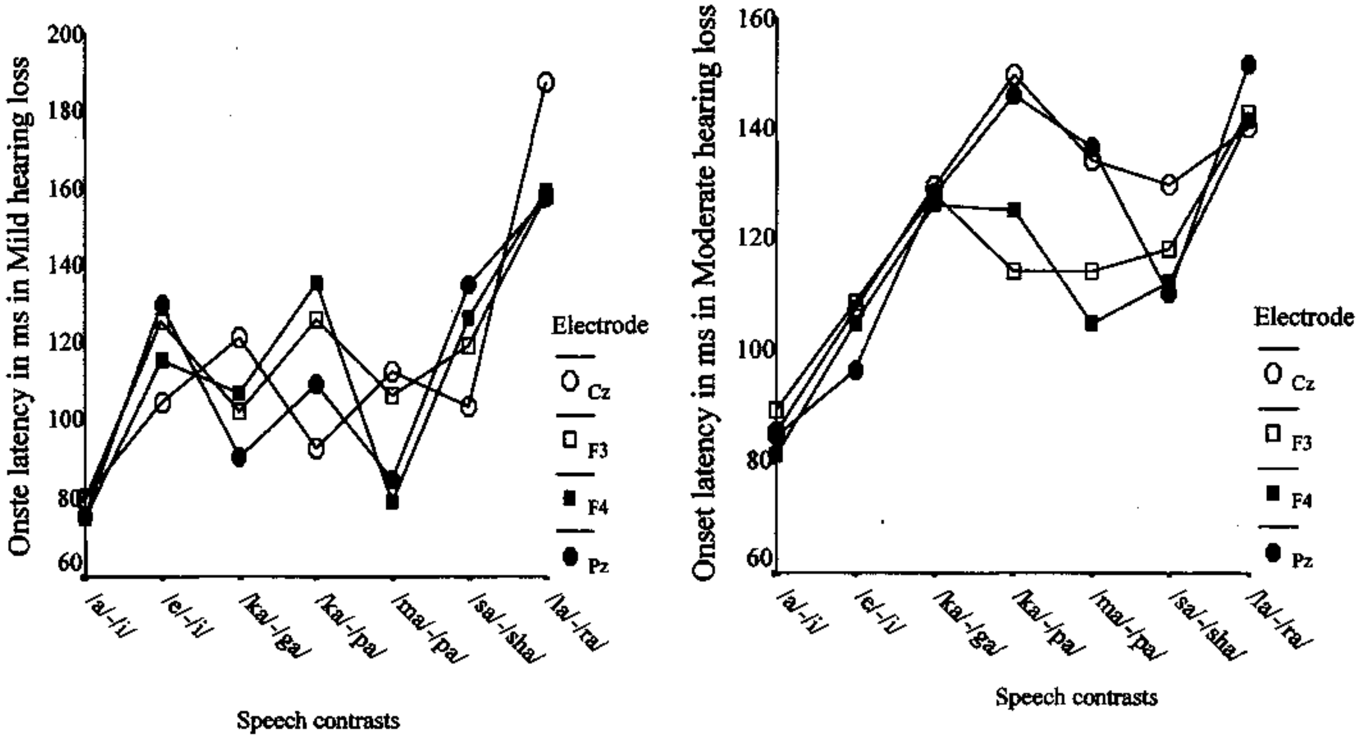

Figure R.18. Mean onset latencies of MMN recorded at four scalp sites for different speech contrasts in the experimental group.

Table R.31

The effects of type of stimulus contrast on the onset latency (OnL) seen in the control and the experimental groups

Control Group	Experimental Group
a. Type of stimulus had a significant effect on OnL	a. Type of stimulus had a significant effect on OnL
b. The shortest OnL for the /a/-/i/ and /ma/-/pa/ contrasts	b. The shortest OnL for the /a/-/i/ contrast
c. The longest OnL for the /la/-/ra/ and /sa/-/ a/ contrasts	c. The longest OnL for the /la/-/ra/ contrast
d. Interaction effects of stimulus and age were significant	d. Interaction effects of stimulus and degree of hearing loss were significant
e. The OnL between adults and children for the /e/-/i/, /ka/-/ga/ and /la/-/ra/ contrasts was significantly different	e. The OnL for none of the contrasts was significantly different between the mild and moderate hearing loss
f. No difference in OnL across the scalp sites	f. No difference in OnL across the scalp sites

c. Offset latency.

In the control group, the offset latency values were analysed with reference to different speech contrasts. The estimated mean offset latency values of MMN for different speech contrasts are shown in Table R.32, which indicates that they were significantly different for different phonetic contrasts in the control group. The differences in offset latency between speech contrasts is shown in Table R.33. The ANOVA also showed that the interaction effects between stimulus and age were significant ($p < 0.01$) indicating that the children and adults showed a different phonetic effect on the offset latency of MMN.

Table R.32

Estimated mean offset latencies for different speech contrasts in the control group

Stimulus	**Mean**	**Lower Bound**	**Upper Bound**
/a/-/i/	197.2	178.2	216.3
/e/-/i/	220.5	206.6	234.6
/ka/-/ga/	215.6	197.3	233.9
/ka/-/pa/	225.6	209.0	242.1
/ma/-/pa/	192.5	174.8	210.1
/sa/-/ a/	233.3	216.2	250.3
/la/-/ra/	261.5	252.4	270.7

Table R.33

Significance of differences between estimated mean offset latencies across different stimuli in the control group

Stimulus	**/a/-/i/**	**/e/-/i/**	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	**/sa/-/ a/**	/la/-/ra/
/a/-/i/		0.139	0.821	0.045	1.000	0.023	0.000
/e/-/i/			1.000	1.000	0.011	1.000	0.000
/ka/-/ga/				1.000	0.425	1.000	0.000
/ka/-/pa/					0.006	1.000	0.000
/ma/-/pa/						0.001	0.000
/sa/- a/							0.014
/la/-/ra/							

The speech contrasts /a/-/i/ and /ma/-/pa/ showed the shortest offset latency. The offset latencies were indifferent (*p* > 0.05) for the /a/-/i/, /e/-/i/, /ka/-/ga/ and /ma/-/pa/ contrasts. The longest offset latency was shown by the /la/-/ra/ contrast. The MMN offset latency for all the consonant contrasts also remained significantly unchanged (*r* = -0.1 to *0.l;p* > 0.05) at all the scalp sites, except for the /la/-/ra/ contrast. This contrast had an increase in offset latencies with maturation (*r* = 0.6;

$p < 0.01$) at all the four scalp sites. The ANOVA also showed that there was no difference ($p > 0.05$) in the offset latency of MMN recorded at the four scalp sites. Figure R.I9 shows the offset latency values recorded at the four scalp sites.

Table R.34

Estimated mean offset latencies for different speech contrasts in the experimental group

Stimulus	Mean	Lower Bound	Upper Bound
/a/-/i/	183.8	171.8	195.8
/e/-/i/	226.7	216.2	237.1
/ka/-/ga/	235.5	226.6	244.4
/ka/-/pa/	244.5	234.5	254.4
/ma/-/pa/	232.4	222.0	242.7
/sa/-/Ja/	213.2	201.1	225.3
/la/-/ra/	268.3	257.9	278.7

The phonetic contrasts resulted in different offset latencies in the control group. ANOVA revealed that the effects varied with degree of hearing loss ($p < 0.05$). The estimated mean offset latencies in the experimental group are shown in Table R.34 and the differences in MMN offset latency values for different stimulus contrasts, and their significance values in the experimental group are shown in Table R.35. The /a/-/i/ contrast resulted in an MMN with the shortest offset latency. There was no significant ($p > 0.05$) difference in offset latencies evoked by the /e/-/i/, /ka/-/ga/, and /ma/-/pa/ contrasts. MMN offset latency for the /la/-/ra/ contrast was the longest one ($p < 0.05$).

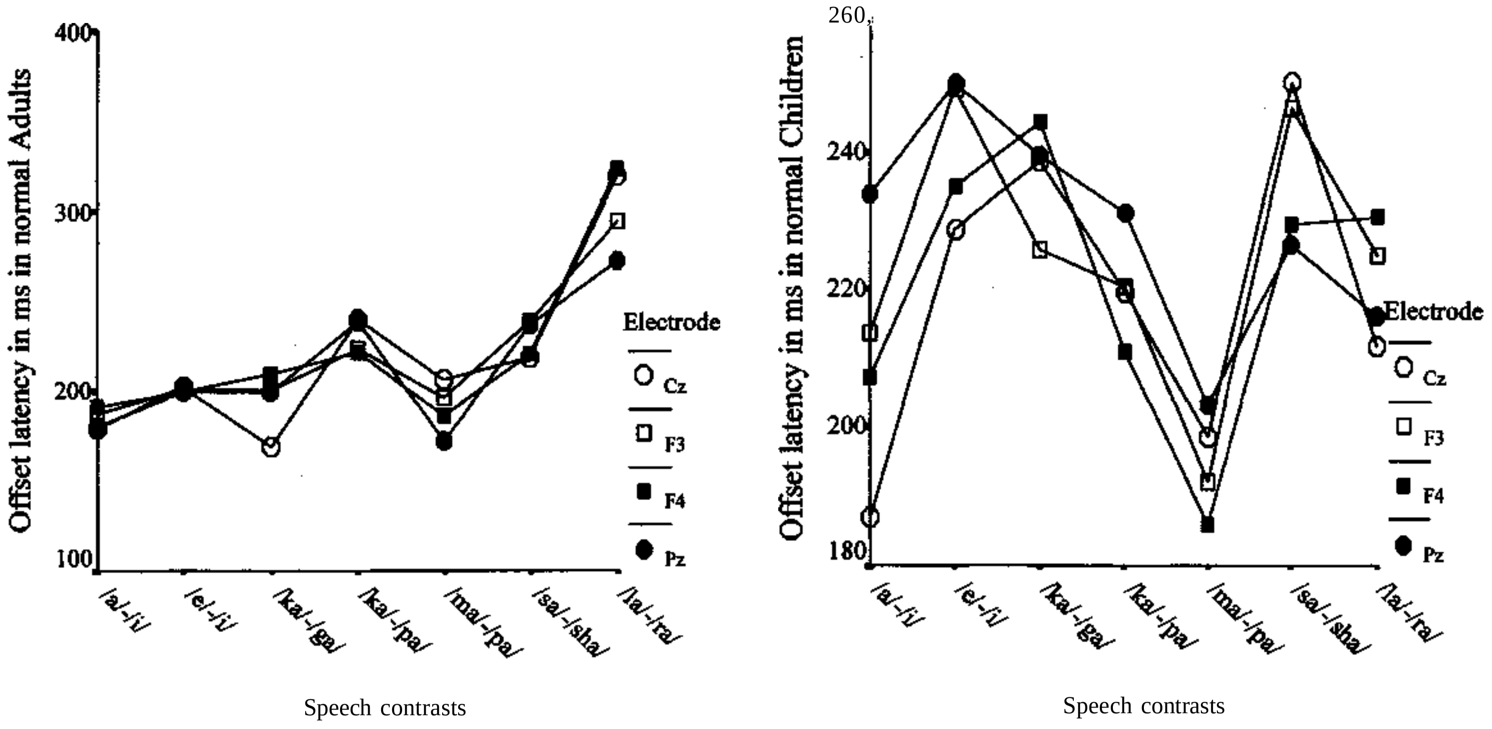

Figure R.19. Mean offset latencies of MMN recorded at four scalp sites for different speech contrasts in normal hearing adults and children.

Table R.35

Significance of differences between estimated offset latencies across speech contrasts in the experimental group

Stimulus	/a/-/i/	/e/-/i/	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	**/sa/-/Ja/**	/Ia/-/ra/
/a/-/i/		0.000	0.000	0.000	0.000	0.002	0.000
Id-lil			1.000	0.041	1.000	0.440	0.000
/ka/-/ga/				1.000	1.000	0.003	0.000
/ka/-/pa/					0.496	0.000	0.000
/ma/-/pa/						0.031	0.000
/sa/-/Ja/							0.000
/la/-/ra/							

The analysis also showed that the interaction effects between the electrode and the degree of hearing loss were insignificant (*p* > 0.05). The offset latencies recorded at different scalp sites are shown in Figure R.20. The effects of hearing loss on the offset latency obtained in different groups and sub groups are summarized in Table R.36.

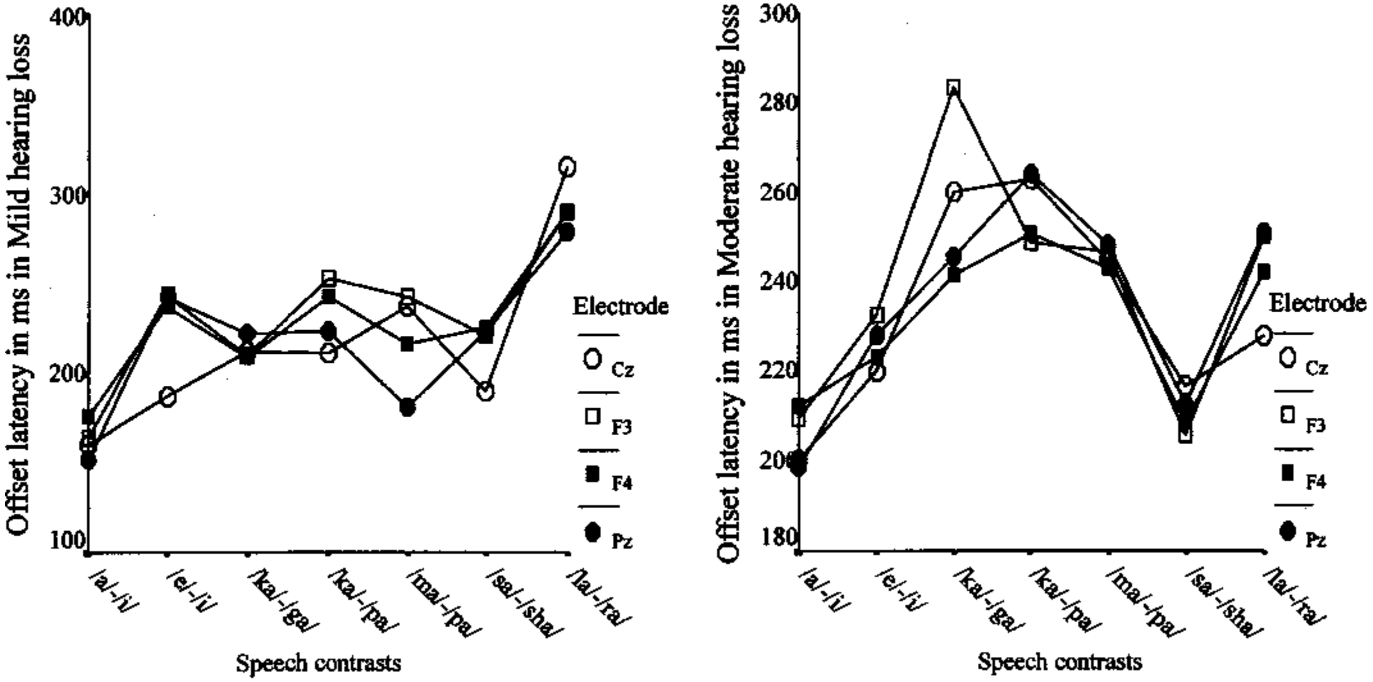

Figure R.20. Mean offset latencies of MMN recorded for different speech contrasts at different scalp sites in the experimental group.

Table R.36

The effects of type of stimulus contrast on the offset latency (OffL) seen in the control and the experimental groups

Control Group	Experimental Group
a. Type of stimulus had a significant effect on OffL	a. Type of stimulus had a significant effect on OffL
b. The shortest OffL for the /a/-/i/ and /ma/-/pa/ contrasts	b. The shortest OffL for the /a/-/i/ contrast
c. The longest OffL for the /la/-/ra/ contrasts	c. The longest OffL for the /la/-/ra/ contrast
d. Interaction effects of stimulus and age were significant	d. Interaction effects of stimulus and degree of hearing loss were significant
e. The OffL for adults and children for the/e/-/i/,/ka/-/ga/ and /la/-/ra/ contrasts was significantly different	e. The OffL for the /a/-/i/, /ka/-/ga/, /ka/-/pa/, /ma/-/pa/ and /la/-/ra/ contrasts between the mild and moderate hearing loss was significantly different
f. No difference in OffL across the scalp sites	f. No difference in OffL across the scalp sites

From the current study, it may be said that even among the speech stimuli, there may be feature specific MMN generators that show specific maturational effects. The decreasing trends of MMN latencies for the /e/-/i/ and /ka/-/ga/ contrasts and the increasing trends for the same parameters in case of the /la/-/ra/ contrast shows that the MMN generator could show differential effects of maturation.

The age effects on MMN latencies may be because of the developing auditory memory skills in children, compared to the well-developed auditory memory in adults (Pisoni, 1973). This is also evident from the observation that adults are better able than children to switch their response mode from one that relies on phonemic processing to that based on acoustic processing (Foss & Blank, 1980). Several neuro-developmental processes may also be attributed to these changes in MMN latency parameters. Maturation of the primary and secondary auditory cortices (Steinschnieder & Dunn, 2004) specific to an acoustic contrast could lead to such changes. Improved connectivity and transmission may also contribute to the maturational changes in the event-related potentials, and these changes are expected to occur throughout the individual's lifespan (Dustman, Shearer & Emmerson, 1993). However, neuro-maturational processes specific to latency of the event-related potentials are yet to be identified.

To summarise the effects of speech sound contrasts in the experimental group, they were similar on all the latency parameters. The effects were also uniform across the control and experimental groups and also between their subgroups. The vocalic contrasts yielded an MMN with shorter latencies than those of the consonantal contrasts. The /a/-/i/ contrast resulted in MMN with shortest latencies among the vocalic contrasts. Of all the consonantal contrasts, the /ma/-/pa/ contrast yielded MMN with shortest latency parameters. MMN for the /la/-/ra/ contrast had the longest latency values.

These differences in phonetic effects on latencies could be because of the spectro-temporal differences between the contrasts that have increased the complexity of the discriminating tasks. Shorter latencies as seen with the /a/-/i/ and /ma/-/pa/ contrasts may be explained by the low frequencies useful in discriminating these contrasts. The vowel /a/ has clearly distinguishable and equally strong first, second and third formants (Fl, F2, F3), in contrast, the vowel *IV* has a very low Fl (302 Hz) which is widely separated from F2 and F3. The F2 and F3 are merged for the vowel *I'll.* While a strong nasal murmur at low frequencies (below 1000 Hz) and a weak first formant (Fl) characterize the nasal sound /ma/, absence of the murmur and a strong Fl are seen in the spectrum of/pa/ (Pickett, 1999).

On the other hand, the /la/-/ra/ contrast have cues in F3 and F4 which are available only at very high frequencies. The onset of F3 was at 3317 Hz for /la/ it was at 2218 Hz for /ra/. The onset of F4 was also at very high frequency (4272 Hz for /la/ and 3460 Hz for /ra/). Since the cues are available only at high frequencies, resulting increased task complexity might have lead to prolongation of the MMN latencies for the /la/-/ra/ contrast. Thus, when compared to others, the /a/-/i/ and /ma/-/pa/ contrasts have cues at low frequencies which are easily audible for both the groups.

Based on the latency parameters, it appears that the present study supports the hypothesis of 'the phonetic MMN', the MMN unique to a speech contrast and is evoked for its unique spectro-temporal differences. However, this hypothesis has suffered much criticism. Sharma, Kraus, Me Gee, Carrell and Nicol (1993) and Shrama and Dorman (1998) have shown that MMN could be evoked by different exemplars of the same phoneme and concluded that MMN is sensitive to acoustic differences rather than the phonetic contrasts.

In contrast, other studies find phonetic contributions to MMN. Aaltonen et al. (1994) have recorded MMN in Finnish listeners for vowels, which correlated with the psychophysical data of magnet effect. Phillips (2000) used an innovative stimuli paradigm to record MMN for /da/-/ta/ contrast. It was concluded that MMN is more sensitive to phonetic and phonological information rather than the simple acoustic differences. From these studies it may be said that MMN is sensitive to both acoustic and phonetic information in the stimuli.

2. Peak amplitude

The peak amplitude of MMN was analysed for examining the effects of phonetic contrasts. As shown in Table R.37, the peak amplitude for all the contrasts was the same and statistically there was no significant difference between them as shown in Table R.38. Estimated means for peak amplitudes were obtained for different contrasts. Though not significant ($p > 0.05$), from Table R.38 it may be said that among all the phonetic contrasts, the /a/-/i/ and /la/-/ra/ contrasts resulted in an MMN with the largest peak amplitude. MMN peak amplitude was higher for the /ka/-/pa/ and /ma/-/pa/ contrasts. It may also be said that MMN for the vowels had more peak amplitude than that of the consonants. The effects of phonetic contrast on peak amplitude was not significantly different ($p > 0.05$) between adults and children.

Table R.37

Estimated mean peak amplitudes for different speech contrasts in the control group

Stimulus	**Mean**	**Lower Bound**	**Upper Bound**
/a/-/i/	**-4.1**	**-5.1**	-3.1
/e/-/i/	**-4.0**	**-4.8**	-3.2
/ka/-/ga/	**-3.9**	**-4.8**	-3.2
/ka/-/pa/	**-3.3**	**-4.0**	-2.6
/ma/-/pa/	**-3.5**	**-4.0**	-2.9
/sa/-/ a/	**-3.5**	**-4.2**	-2.9
/la/-/ra/	**-4.1**	**-4.8**	-3.4

Table R.38

Significance of differences between estimated mean peak amplitudes across different stimuli in the control group

Stimulus	/a/-/i/	/e/-/i/	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	**/sa/-/ a/**	/la/-/ra/
/a/-/i/		1.000	1.000	1.000	1.000	1.000	1.000
/e/-/i/			1.000	1.000	1.000	1.000	1.000
/ka/-/ga/				1.000	1.000	1.000	1.000
/ka/-/pa/					1.000	1.000	0.251
/ma/-/pa/						1.000	0.583
/sa/-/ a/							1.000
/la/-/ra/							

The peak amplitude showed significant differences ($p < 0.01$) between the scalp sites irrespective of the stimulus. Similar differences were observed in the children and adults for these electrode site differences. The highest peak amplitude was seen at the frontal sites and was greater than the peak amplitude at the midline electrode site by -1.0 to -1.5 microvolts. Among the frontal electrodes the highest MMN peak amplitude was recorded at the F3 site. Amongst the midline electrodes, the C_z site registered the highest peak amplitude. Figure R.21 shows the differences in peak amplitude across scalp sites in the control group.

The mean peak amplitudes for different speech contrasts in the experimental group are shown in Table R.39 and the differences in MMN peak amplitude for different stimulus contrasts, and their significance values, in the experimental group are shown in Table R.40. The peak amplitude for the /a/-/i/ contrast was the largest one, though not statistically significant.

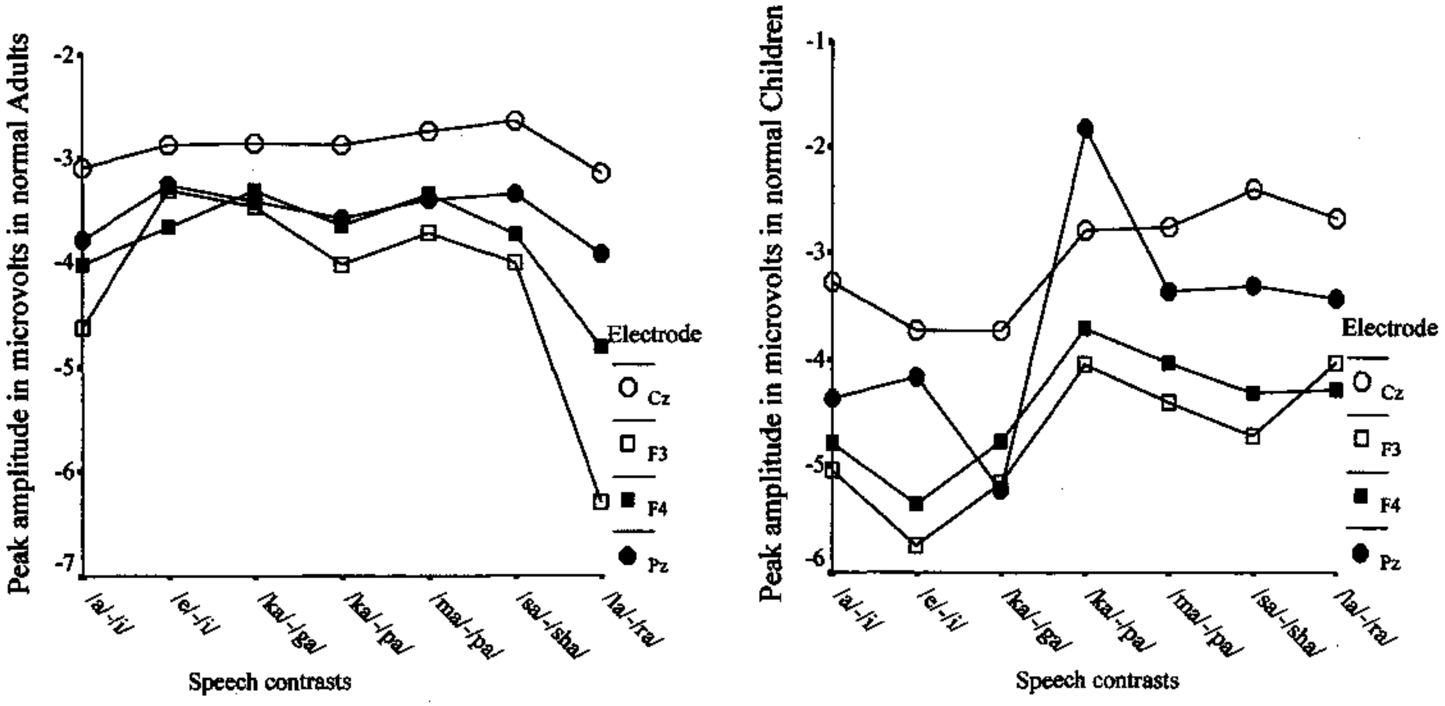

Figure R.21. MMN peak amplitude recoded for different speech contrasts recorded from the four electrode sites in the control group.

Table R.39

Estimated mean peak amplitudes for different speech contrasts in the experimental group

Stimulus	Mean	Lower Bound	Upper Bound
/a/-/i/	**-3.8**	**-4.6**	-3.1
/e/-/i/	**-3.4**	**-3.8**	-2.9
/ka/-/ga/	**-3.6**	**-3.9**	-3.2
/ka/-/pa/	**-3.6**	**-4.0**	-3.1
/ma/-/pa/	**-3.7**	**-4.2**	-3.1
/sa/-/ a/	**-3.6**	**-3.9**	-3.2
/la/-/ra/	**-3.8**	**-4.2**	-3.3

Table R.40

Significance of differences between estimated peak amplitude across speech contrasts in the experimental group

Stimulus	/a/-/i/	*/e/-/i/*	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	/sa/-/ a/	/la/-/ra/
/a/-/i/		1.000	1.000	1.000	1.000	1.000	1.000
/e/-/i/			1.000	1.000	1.000	1.000	1.000
/ka/-/ga/				1.000	1.000	1.000	1.000
/ka/-/pa/ :					1.000	1.000	1.000
/ma/-/pa/						1.000	1.000
/sa/-/ a/							1.000
/la/-/ra/							

The /la/-/ra/ contrasts resulted in an MMN with the smallest peak amplitude. There was no significant (*p* > 0.05) difference in peak amplitudes of MMN evoked by the /e/-/i/, /ka/-/ga/, and /ma/-/pa/ contrasts. The interaction effects between the electrode and the degree of hearing loss were shown to be not significant (*p* > 0.05) in the experimental group. The peak amplitude of MMNs recorded at different scalp sites are shown in Figure R.22.

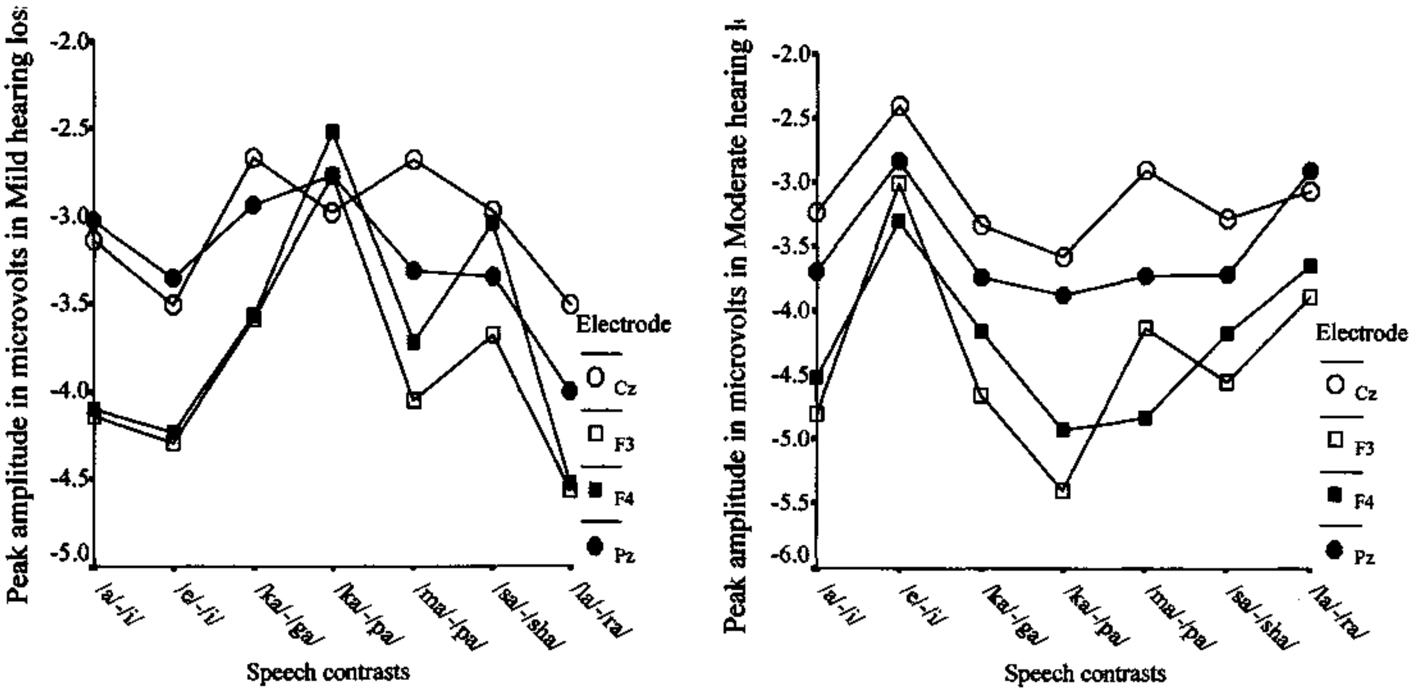

Figure R.22. Mean peak amplitudes of MMNs for different contrasts recorded from four electrode sites in the experimental group.

The summary of effects of degree of hearing level on MMN evoked for different speech contrasts is given in Table R.41. In summary, MMN peak amplitude for neither of the vocalic contrasts was affected by the degree of hearing loss. Among the consonantal contrasts, the MMN peak amplitude for the /ka/-/pa/, /ma/-/pa/ and /sa/-/ a/ showed decreasing trends with increasing hearing loss. It was not affected by the degree of hearing loss for the /ka/-/ga/ and the /la/-/ra/ contrasts.

Table R.41

The effects of type of stimulus contrast on the peak amplitude (PA) seen in the control and the experimental groups

Control Group	**Experimental Group**
a. Type of stimulus had no significant effect on PA	a. Type of stimulus had no significant effect on PA
b. Interaction effects of stimulus and age were significant	b. Interaction effects of stimulus and degree of hearing loss were significant
c. Significant differences in PA across the scalp sites	c. More PA in the group with moderate hearing loss
d. Larger PA was recorded at the frontal sites (F3 and F4) rather than at the central sites (C_z and P_z)	d. Larger PA was recorded at the frontal sites (F_3 and F4) rather than at the central sites (C_z and P_z)
e. F3 recorded the highest PA irrespective of the stimulus contrast	e. F3 recorded the highest PA irrespective of the stimulus contrast

The peak amplitude analysis indicated that MMN with similar peak amplitude could be obtained irrespective of the phonetic contrast. This is true even in the subjects with a hearing loss also. It may also be noted that the MMN peak latency was affected by the degree of hearing loss, for more speech contrasts than the number of contrasts with affected MMN peak amplitude. Hence, it may be said that the latency parameters are more sensitive to the degree of hearing loss rather than the peak amplitude.

However, there was a definite effect of the scalp electrode site on peak amplitude of MMN. The frontal electrode F_3 recorded an MMN with the largest peak amplitude, irrespective of the speech contrast and the hearing status. Several studies reported that the frontal cortex was more sensitive to speech contrasts as reflected by the amplitude over the frontal sites using the scalp current source density analysis. Sharma and Kraus (1995) showed that the MMN amplitude was more over the left hemisphere especially in the frontal sites, for the /ba/-/da/ contrast in adults. Naatanen and Alho (1997) also found left-hemisphere dominance in terms of MMN amplitude for native language prototypes of vowels in adults and children.

3. Area

All the stimuli evoked similar MMN areas in this group. In the control group, the estimated mean MMN areas for different speech contrasts are shown in Table R.42 and the table R.43 shows the differences in MMN areas evoked for several stimulus contrasts. Though not significant, it may be said that /a/-/i/ evoked MMN with the largest area among other contrasts and the /la/-/ra/ contrast evoked an MMN with the shortest area.

Differences in MMN area were statistically significant ($p < 0.01$) across the four electrode sites irrespective of the control group subject population. The analysis showed that the highest MMN area was recorded at the F_3 site followed by the F_4 site for any of the phonetic contrast. The C_z site registered higher MMN area when compared the P_z site but it was lower than that at the frontal sites. The frontal sites registered MMN with an area more than the midline sites by 150 ms X microvolts. These differences are shown in Figure R.23.

Table R.42

Estimated mean areas for different speech contrasts in the control group

Stimulus	Mean	Lower Bound	Upper Bound
/a/-/i/	555.4	390.1	720.7
/d/-/i/	482.9	353.6	612.3
/ka/-/ga/	521.7	356.1	687.3
/ka/-/pa/	422.2	299.6	544.9
/ma/-/pa/	415.7	309.5	521.9
/sa/-/Ja/	356.2	259.2	453.1
/Ia/-/ra/	489.6	410.5	568.7

Table R.43

Significance of differences between estimated mean MMN area across different stimuli in the Control group

Stimulus	/a/-/i/	/e/-/i/	/ka/-/ga/	/ka/-/pa/	/ma/-/pa/	/sa/-/ a/	/la/-/ra/
/a/-/i/		1.000	1.000	1.000	0.899	0.110	1.000
/e/-/i/			1.000	1.000	1.000	0.231	1.000
/ka/-/ga/				1.000	1.000	0.065	1.000
/ka/-/pa/					1.000	1.000	1.000
/ma/-/pa/						1.000	1.000
/sa/-/ a/							0.044
/la/-/ra/							

The estimated mean areas of MMN for different speech contrasts are shown in Table R.44 and the differences in MMN area across stimulus contrasts in the experimental group are shown in Table R.45.

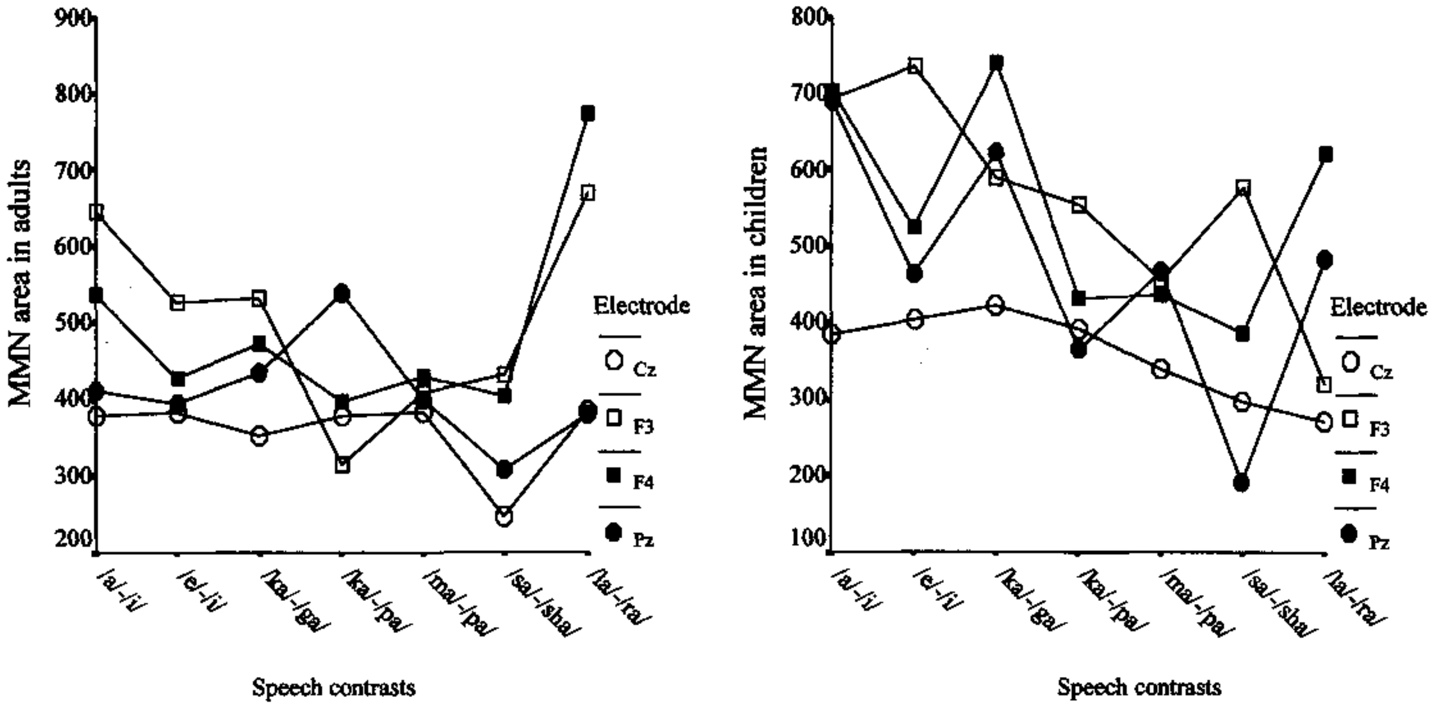

Figure R.23. MMN area recorded from the four scalp sites with for different speech contrasts in the control group.

Table R.44

Estimated mean areas for different speech contrasts in the experimental group

Stimulus	Mean	**Lower Bound**	**Upper Bound**
/a/-/i/	435.4	308.2	562.5
/e/-/i/	391.1	322.9	459.2
/ka/-/ga/	459.7	390.3	529.1
/ka/-/pa/	490.4	380.5	600.2
/ma/-/pa/	449.3	391.7	507.0
/sa/-/ a/	370.7	306.5	434.9
/la/-/ra/	466.0	399.5	532.5

Table R.45

Significance of differences between estimated mean MMN area across different stimuli in the Experimental group

Stimulus	*/a/-/i/*	***/e/-/i/***	**/ka/-/ga/**	**/ka/-/pa/**	**/ma/-/pa/**	/sa/-/ a/	**/la/-/ra/**
/a/-/i/		1.000	1.000	1.000	1.000	1.000	1.000
/e/-/i/			1.000	0.903	1.000	1.000	1.000
/ka/-/ga/				1.000	1.000	0.355	1.000
/ka/-/pa/					1.000	0.119	1.000
/ma/-/pa/						0.161	1.000
/sa/-/ a/							0.086
/la/-/ra/							

The MMN area showed significant *(p* < 0.01) differences with respect to the electrode site in the experimental group. The interaction effects of electrode site and the degree of hearing loss and were however not significant *(p* > 0.05). It was shown that the highest MMN area was recorded at the F3 site followed by the F4 site irrespective of the phonetic contrast. Among the midline sites, C_z registered a higher MMN area when compared the P_z site but it was lower than that at the frontal sites.

The frontal sites registered MMN with an area more than the midline sites by 150 ms X microvolts.

Figure R.24 shows these patterns in MMN area with the electrode site. These trends are similar to the once shown in the control group. The hearing level affected MMN area differently for different speech contrasts. The summary of these effects is given in Table R.46.

Table R.46

The effects of type of stimulus contrast on the area seen in the control and the experimental groups

Control Group	Experimental Group
a. Type of stimulus had no significant effect on area	a. Type of stimulus had no significant effect on area
b. Interaction effects of stimulus and age were not significant	b. Interaction effects of stimulus and degree of hearing loss were significant
c. Significant differences in area across the scalp sites	c. More area in the group with moderate hearing loss
d. Larger area was recorded at the frontal sites (F_3 and F_4) rather than at the central sites (C_z and P_z)	d. Larger area was recorded at the frontal sites (F3 and F4) rather than at the central sites (C_z and P_z)
e. F_3 recorded the highest area irrespective of the stimulus contrast	e. F3 recorded the highest area irrespective of the stimulus contrast

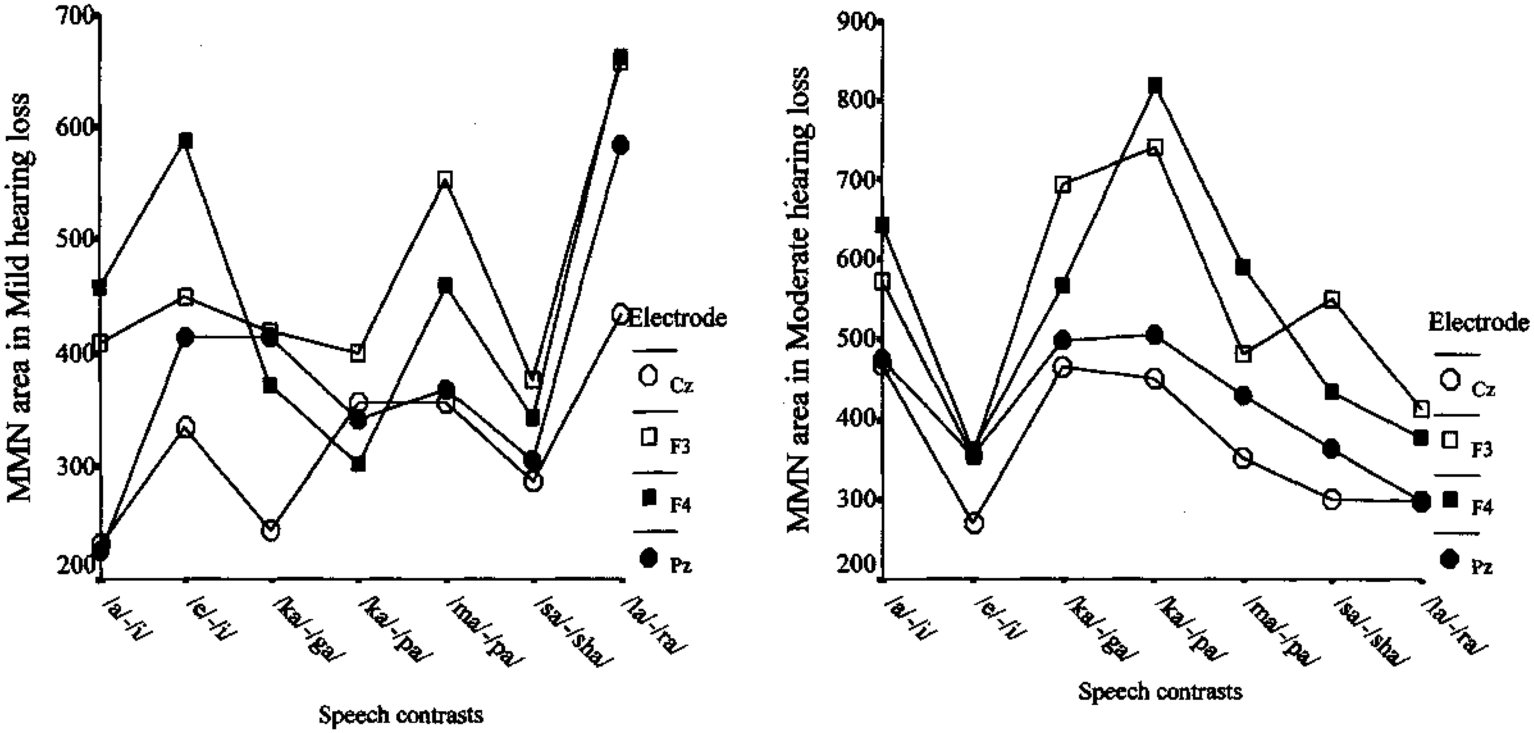

Figure R.24. MMN area recorded from the four scalp sites with for different speech contrasts in the experimental group.

III. Correlation between Mismatch Negativity and Behavioural Speech perception tests

A regression analysis was used to find the relation between behavioural speech perception scores (Table R.I) and all the five MMN parameters (Tables R.4, to R.8 and Tables R.10 to R.14) obtained in both the control and experimental groups. This was done for different speech contrasts at each of the four scalp locations (C_z, P_z, F3, F4). Data from the subjects of all the groups was used in computing regressions between the MMN parameters and the behavioural speech perception scores.

III a. MMN Peak latency vs. Behavioural speech perception scores

The peak latency values showed consistent and statistically significant correlation with the behavioural speech perception scores, using Pearson's correlation. This correlation was observed only for some of the speech contrasts. The correlation values for these parameters are shown in Table R.47.

The regression line slopes indicated decreasing/increasing trends in speech perception scores with an increase in peak latency. A significant correlation between the speech perception scores and the MMN peak latency existed for all but the vocalic contrasts and the /sa/-/ a/ contrast. It may be also noticed that the correlations were however lower but statistically significant. Hence, MMN by the vocalic and the /sa/-/ a/ contrasts may be the poor predictors of the behavioural scores. The poor correlation between the MMN for vocalic contrasts and the behavioural scores may be explained by the good vocalic perceptual abilities (compared to consonantal perception) in individuals with SN hearing loss (Richie et al., 2003). Though the fricative perception was shown to be affected (Pittman & Stelmachowicz, 2000) in those with SN hearing loss, no correlation was found between the MMN for the /sa/-/ a/ contrast and the behavioural speech perception scores. This could be because of the material used in behavioural speech perception scores, which had relatively a few words with sibilants. The overall findings indicate that poorer the speech perception scores, longer the peak latency.

Table R.47 shows that the peak latency of MMN for the consonantal contrasts was a better predictor of the behavioural speech perception scores when compared that predicted by vocalic contrasts. The speech perception scores decreased significantly with an increase in MMN peak latency for all the consonantal contrasts except for the /la/-/ra/ contrast. Thus, these stimuli showed an inverse relation between the MMN peak latency and the speech perception scores. The three behavioural speech perception scores tended to increase significantly with an increment in peak latency of MMN evoked by the /la/-/ra/ contrast. This was the only contrast that indicated a direct relation between the MMN peak latency and the speech perception scores.

From Table R.47, it may also be said that MMN recorded at C_z has better predicting capacity when compared to the other scalp locations. Table R.48 shows the regression parameters (y-intercept and slope) obtained from the regression analysis between MMN peak latency and different speech perception scores at C_z electrode site for different speech contrasts. The good correlation at this site may be explained by the dipole orientation to Cz site resulting in the best morphology (Lang etal., 1995).

It may also be noticed that the correlations were observed between MMN peak latency and all speech perception tests. Though the MMN recording essentially is a passive discrimination task, the peak latency of MMN showed correlations even with speech identification tests. MMN could predict speech identification scores obtained for the nonsense syllables as well as words. These correlations between the behavioural test scores and MMN latencies obtained in individual subgroups based on age and degree of hearing loss and slope of hearing loss were not significant *(p > 0.05)*.

Table R.47

Pearson's correlation coefficients computed between the behavioural speech perception scores and MMN peak latency across electrode sites

Stimulus	**Scalp location**	**SDS**	SIS-N	**SIS-M**
/a/-/i/	Cz	0.118	0.038	-0.009
	Pz	0.031	-0.039	-0.093
	F$_3$	-0.02	0.01	-0.09
	F$_4$	-0.01	-0.07	-0.09
/e/-/i/	Cz	-0.1	-0.08	-0.1
	Pz	0.04	0.04	-0.01
	F$_3$	0.04	0.1	-0.01
	F$_4$	-0.001	0.03	-0.004
/ka/-/ga/	C$_z$	-0.2**	**-0.3** **	-0.3**
	Pz	-0.3*	**-0.3***	-0.2**
	F$_3$	-0.2**	**-0.2****	-0.2**
	F$_4$	-0.12	-0.17	-0.16
/ka/-/pa/	**C$_z$**	-0.27*	-0.16	-0.2*
	Pz	-0.2*	-0.15	-0.13
	F$_3$	-0.1	-0.07	-0.1
	F$_4$	-0.01	-0.05	-0.1
/ma/-/pa/	**C$_z$**	-0.3**	**-0.2***	-0.2*
	Pz	-0.15	-0.15	-0.2*
	F$_3$	-0.16	-0.15	-0.17
	F$_4$	-0.1	-0.15	-0.2*
/sa/-/ a/	**C$_z$**	-0.1	-0.13	-0.17
	Pz	-0.07	-0.01	0.02
	F$_3$	0.06	0.04	0.11
	F$_4$	0.08	-0.02	0.00
/la/-/ra/	C$_z$	+0.2*	**+0.2***	+0.2*
	Pz	0.07	0.09	0.06
	F$_3$	0.09	0.13	0.12
	F$_4$	0.12	0.1	0.11

*p < 0.05; **p< 0.01

Table R.48

The y-intercept and slope values of regression analysis between peak latency and different speech perception scores at C_z*site*

Speech Contrast	**SDS**		SIS-N		**SIS-M**	
	y-intercept	***Slope***	***y-intercept***	***Slope***	***y-intercept***	***Slope***
/ka/-/ga/	21.6	-0.006	11.5	-0.005	51.8	-0.02
/ka/-/pa/	21.5	-0.005	-	-	51.3	-0.01
/ma/-/pa/	21.8	-0.008	11.3	-0.003	51.1	-0.01
/Ia/-/ra/	19.4	0.004	10.0	0.002	46.2	0.011

IILb. MMN Onset latency vs. Behavioural speech perception scores

Statistical analysis indicated that the onset latency is a poor predictor of the speech perception measures. There was no significant correlation ($r = 0.1$; $p > 0.05$) between the MMN onset latency and all the three the speech perception scores, at all scalp locations. This was found for all the speech contrasts at all the four scalp locations. The same was observed even in the individual subgroups based on the age, degree of hearing loss or audiogram slope. Thus, onset latency does not predict behavioural speech perception scores.

III.c. MMN Offset latency vs. Behavioural speech perception scores

The regression analysis between the MMN offset latency and the speech perception tests (SDS, SIS-N, and SIS-M) also indicated no significant ($r = 03;p > 0.05$) correlation between them. This observation was noted for all the speech contrasts at all the four scalp sites. The same results were observed even at the subgroups that were formed based on the age, degree of hearing loss and audiogram slope. It may be said that the MMN offset latency is also a poor predictor of the behavioural speech perception scores.

III d. MMN Peak amplitude vs. Behavioural speech perception scores

The regression analysis showed no significant ($r = 0.2; p > 0.05$) correlation between the peak amplitude and all the three speech perception scores. The same results were seen for all the stimuli at all the four scalp locations. No significant correlation (r = O.\;p > 0.05) between the MMN peak amplitude and the speech perception scores was seen even in the individual subgroups based on the age, degree of hearing loss or audiogram slope. It may be inferred that the MMN peak amplitude is also a poor predictor of the behavioural speech perception scores.

III .e. MMN Area vs. Behavioural speech perception scores

The MMN area was also a poor predictor of the speech perception scores both at the group and the subgroup levels. There was no significant correlation ($r = -0.3; p > 0.05$) between MMN area and the behavioural speech perception scores. This was seen for all the phonetic contrasts at all the four scalp sites.

In summary, the MMN peak latency alone showed significant correlations with the speech perception scores. Despite the fact that MMN is essentially a task involving discrimination, the MMN peak latency showed correlations even with speech identification scores. Only MMN evoked for consonantal contrasts correlated with the behavioural speech perception scores. This indicates that the more affected consonantal perception than the perception of vowels is mirrored by the affected MMN peak latencies for the consonantal contrasts.

Studies on correlation between MMN and behavioural measures till date have reported that such correlations existing between MMN peak amplitude and a behavioural measure. MMN peak amplitude is shown to correlate with difference limens in intensity (Iyengar, 1999) and frequency (Naatanen & Alho, 1997), categorical perception of stop consonants (Maiste et al., 1995), the fine-grain speech discrimination in the learning disabled (Kraus et al., 1999) and the effects of auditory training (Naatanen et al., 1993). However, in the present study, peak amplitude did not correlate with the behavioural discrimination or the identification scores. These differences with the earlier studies may be because of the stimuli used. The earlier studies used a series of stimuli differed in fine stimulus characteristics such as the intensity and VOT. The MMN amplitude was shown to be sensitive to the deficits in perceiving the fine acoustic cues. The present study used gross stimulus differences in behavioural tests, and that might have reduced correlation with the peak amplitude of MMN. It is possible that the peak latency be more sensitive to gross stimulus differences than the peak amplitude of MMN. Hence, it is recommended to use the peak latency as the MMN measure to predict the behavioural speech perception scores in subjects with a hearing loss. The results of the present study can be summarised as follows:

- Sensorineural hearing loss showed an effect on all behavioural speech perception scores. The speech perception scores reduced with increasing hearing loss. Similar effect was seen on both speech identification (meaningful and nonsense material) and speech discrimination scores.
- Age related changes on MMN latencies were clearly seen in the control group. The age effects were seen in terms of prolonged peak latencies in children for most of the speech contrasts.
- The hearing loss reduced the recordability of MMN. The percentage of normal-hearing subjects showing an MMN was higher than that seen in individuals with a hearing loss.

- With an increase in degree of hearing loss, prolongation of MMN latencies and increase MMN peak amplitude was seen for the majority of consonantal contrasts. No such effect was seen for the vocalic contrasts.
- The audiogram slope did not affect MMN latencies and amplitudes for most of the phonetic contrasts.
- MMN peak latency for consonantal contrasts /ka/-/ga/, /ka/-/pa/, /ma/-/pa/ and /la/-/ra/ were the best predictors of the behavioural speech perception scores.
- MMN peak latency not only correlated with behavioural speech discrimination, but also with behavioural speech identification scores.
- MMN peak latency was shown to be more sensitive to hearing loss, when compared to other MMN parameters that were studied, and it was the only parameter that correlated with the behavioural speech perception scores.
- MMN from the C_z scalp site, correlated the maximum with behavioural speech perception scores, when compared to the other sites studied.
- Hence, MMN was found to be an useful tool in predicting behavioural speech perception.

SUMMARY AND CONCLUSIONS

MMN has been used effectively to determine discrimination abilities in normal-hearing individuals (Sams et al., 1985; Oades, 1991; Lang et al., 1995; Iyengar, 1999, 2000; Naatanen and Escera, 2002). Its utility on the individuals with hearing loss has been researched by relatively few authors (Oates et al., 2002; Sivaprasad, 2000). The present study was taken up to examine the effects of age, degree of hearing loss and audiogram slope on speech perception measured using behavioural and electrophysiological tests. It also aimed at finding correlations between the behavioural and electrophysiological measures. 121 child and adult subjects were included in the study. Of them, thirty-seven had normal-hearing while eighty-four had a mild to moderate sensorineural hearing loss. They were studied for behavioural speech perception scores and mismatch negativity recorded for seven speech contrasts. The following conclusions are drawn from the study:

a. Effects of age on behavioural and electrophysiological speech perception:

Age had no significant effect on behavioural speech perception scores. Adult-like scores were achieved by children as young as 8 years. Hence, the behavioural speech perception tests [speech discrimination test (SDS), speech identification for nonsense syllables (SIS-N) and speech identification for words (SIS-M)] employed in the study, can be used from children as young as 8 years without using normative data obtained on adults.

The age of the subjects showed significant effects on different MMN parameters. This effect however was specific to a speech contrast used to elicit the MMN. The peak-, onset- and offset-latencies of MMN evoked for the *Id-I'll* contrast showed a systematic decrease with increasing age. On the other hand, all the latency parameters of MMN evoked for the /la/-/ra/ contrast showed an increase with increasing age. MMN latency parameters for the other speech contrasts (/a/-/i/, /ka/-*/ga/, /ka/-/pa/,* /ma/-/pa/ and /sa/-/ a/) were not affected by age.

The peak amplitude showed a decrease with increasing age recorded for the /e/-/i/ contrast. It did not show any change with age, when recorded for the other speech contrasts. MMN area recorded for all the phonetic contrasts did not show any change as a function of age.

Though, behaviourally no developmental changes were noted for the speech perception scores, such developmental changes were observed for the MMN latency parameters. These results indicate that peak latencies of MMN, evoked for certain speech contrasts, measure more subtle neuro-maturational changes which are not reflected in the behavioural speech perception.

b. Effects of degree of hearing loss on behavioural and electrophysiological speech perception:

The degree of hearing loss had a significant effect on all the behavioural speech perception tasks used in the study. The SDS, SIS-N and SIS-M scores decreased with increasing hearing threshold levels. The scores were significantly lower in the moderate hearing loss group when compared to that seen in the mild hearing loss group. These results have reflected speech perception difficulties in individuals with hearing loss, even at suprathreshold levels.

The peak, onset and offset latencies of MMN for the /a/-/i/, /ka-/ga/, /ka/-/pa/ and /ma/-/pa/ contrasts showed an increasing trend with increasing hearing threshold levels. However, the peak and offset latencies decreased with increasing hearing loss for the MMN evoked for the /la/-/ra/ contrast. The latencies of MMN for the /e/-/i/ and /sa/-/ a/ contrasts did not show any changes with increasing hearing loss. These effects were same across the scalp sites (C_z, P_z F_3 and F_4) used in the study.

The peak amplitude of MMN evoked for the /ka/-/pa/, /sa/-/Ja/, /ma/-/pa/ contrasts increased with increasing hearing loss at the frontal sites (F3 and F4). The MMN peak amplitude recorded for the /a/*-/i/*, */e/-/i/,/ka/-/ga/*, */*la/-/ra/ contrasts did not change with hearing loss. The MMN area evoked for the /la/-/ra/ contrast showed decreasing trends while that of the /ka/-/pa/ and /sa/-/ a/ contrasts increased with increasing hearing loss. No change was seen in MMN area for the /a/-/i/, /e/-/i/, /ka/-/ga/, and /ma/-/pa/ contrasts.

The results revealed that MMN for the vocalic contrasts when compared to those for the consonantal ones do not show any differences between individuals with normal-hearing and those with hearing loss. This is in consonance with behavioural studies shown in the literature that vowels are simpler to perceive when compared to the consonants. As shown in many other clinical populations in the literature, the MMN latencies show significant delays, which may be because of the complexity of the task for individuals with a hearing loss.

c. Effects of audiogram slope on behavioural and electrophysiological speech perception:

The audiogram slope did not show any significant effect on the behavioural speech perception scores. The SDS, SIS-N and SIS-M scores did not change with increasing audiogram slope. Neither did the individuals with a flat audiogram configuration, nor those with a sloping configuration showed a significant difference in these scores.

The audiogram slope also did not significantly affect all the MMN parameters, recoded for all the speech contrasts used in the study except for that of the *Ikal-lgal* contrast. While the latencies and the peak amplitude of MMN for the *Ikal-lgal* contrast decreased with increasing audiogram slope, the MMN area increased with increasing audiogram slope. The prolonged MMN latencies for the *Ikal-lgal* contrast may be explained by the loss of voicing cues for those with sloping hearing loss.

d. Effects of type of phonetic contrast on electrophysiological speech perception:

MMN results from the individuals with normal-hearing and hearing loss revealed that even among the speech stimuli, there may be feature specific MMN generators that show specific maturational effects. The decreasing trends of MMN latencies for the /e/-*/i/* and /ka/-*/ga/* contrasts and the increasing trends for the same parameters in case of the /la/-*/ra/* contrast shows that the MMN generator could show differential effects of maturation. These differences in MMN for different speech contrasts may be because of the spectro-temporal differences between them.

e. Correlation between behavioural and electrophysiological speech perception:

The correlation between the behavioural and the electrophysiological measures of speech perception revealed that only MMN peak latency showed a significant correlation with all the behavioural tests. MMN peak latency evoked for the consonantal contrasts /ka/-*/ga/*, */ka/-/pa/, /ma/-/pa/* and /l*a./-/ra/* showed significant correlations with SDS, SIS-N, and SIS-M scores. These correlations were more significant when recorded at the C_z site when compared to that at other scalp sites. However, no significant correlations were seen between the behavioural and electrophysiologic measures in individual subgroups (normal-hearing adults or children, individuals with a mild or moderate degree of hearing loss, children with a hearing impairment, and individuals with a flat or sloping hearing loss).

This study highlights the following characteristics of MMN that may have major implications in its clinical use:

- The presence of mismatch negativity is more relevant diagnostically rather than its absence. As some normal-hearing individuals also showed an absent MMN, there is a need to improve the technology in terms of its recordability in normal-hearing individuals.
- Mismatch negativity evoked by phonetic contrasts, as shown by its parameters is affected by the presence of sensorineural hearing loss; however, the effects are specific to a given contrast. The effects vary with the degree of hearing loss. Hence, its use as a tool to study the central auditory processing in this population is sceptical.
- Speech evoked mismatch negativity, especially its peak latency, can reflect the behavioural speech perception performance i.e., speech discrimination and speech identification in sensorineural hearing loss. Hence, it may be used as a tool to predict the behavioural scores
- This study showed that the MMN evoked for consonantal contrasts rather than the vocalic contrasts correlated with the behavioural speech perception scores. Hence, it is recommended to use consonantal contrasts to record MMN as it has more clinical value in case of sensorineural hearing loss. MMN for the contrasts - /ka/-/ga/, /ka/-/pa/, /ma/-/pa/ and /la/-/ra/ were able to predict behavioural speech perception more accurately.

- For an audiologist, in a clinical setup, recording MMN in two to three channels may be sufficient. The study recommends the use of C_z as non-inverting electrode places on the scalp.

Implications of the study

- The study provides a protocol for recording and analysing MMN for speech contrasts in both children and adults. This protocol helps in obtaining reliable MMN waveforms for speech contrasts.
- Normative data for MMN parameters for several vocalic and consonantal contrasts has been developed.
- The effects of age on MMN parameters are delineated. This information will be useful to make decisions on age-appropriate speech perception performance.
- The study provides information regarding the specific speech contrasts that give a better indication of the performance in behavioural speech perception.
- The effect of a peripheral hearing loss on MMN is highlighted.
- The findings are useful in evaluating speech perception abilities of difficult-to-test children, on whom behavioural tests would be difficult to administer. Knowing the specific speech perception problems of a child, would help in providing more appropriate amplification devices.
- Suggestions can be made regarding the kind of rehabilitation that the child would require. Those children with good speech perception abilities, which can be determined based on the MMN findings, can be recommended an auditory mode of training. In contrast, those with poor speech perception can be recommended an audio-visual mode of training.

- With the information from the present study as a basis, research can be carried out on perception of speech contrasts through listening devices such as hearing aids and cochlear implants.
- MMN for speech contrasts may be used for evaluating speech perception for other clinical population, such as those with a long-standing conductive hearing loss, dysphasia, and auditory maturational delay.

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Appendix A. Material for eliciting SDS

1. /a/-/i/
2. /la/-/ra/
3. /*kaJ-lpal*
4. /sa/-/ a/
5. /ma/-/pa/
6. /ka/-/ga/
7. /e/-/i/
8. /sa/-/ a/
9. /ma/-/pa/
10. /ka/-/ga/
ll./la/-/ra/
12. /a/-/i/
13./ka/-/pa/
14./d/=/i/
15./ma/-/pa/
16. /ka/-/ga/
17./la/-/ra/
18. /a/-/i/
19. /sa/-/ a/
20. /e/-/i/
21./ka/-/pa/

Appendix B. Material for eliciting SIS-N

1. **/a/**
2. /i/
3. ***Id***
4. **/ka/**
5. **/ga/**
6. **/pa/**
7. **/ma/**
8. **/sa/**
9. **/ a/**
10. **/la/**
11. **/ra/**

Appendix C. Material for eliciting SIS-M

1. /kannu/
2. /hu:vu/
3. /ka:ge/
4. /kappe/
5. /mola/
6. /e:ni/
7. /male/
8. /lo:ta/
9. /da:ra/
10. /cha:ku/
11. /mane/
12. /nalli/
13. /o:le/
14. /bassu/
15./kattu/
16. /gu:be/
17. /chatri/
18. /me:ke/
19./se:bu/
20. /bi:ga/
21. /la:ri/
22. /mu:gu/
23. /ka:ge/
24. /gini/
25. /tatte/
26. /sara/
27. /ka:ru/
28. /pennu/
29. /ni:ru/
30. /bale/
31./a:ne/
32. /chendu/
33./hallu/
34. /mara/
35. /mi:nu/
36. /na:yi/
37. /ko:li/
38. /kivi/
39. /ili/
40. /su:rya/
41. /ka:su/
42. /ka:lu/
43. /ele/
44. /chi:la/
45. /me:dzu/
46. /su:dzi/
47. /gante/
48. /railu/
49. /tale/
50. /ha:vu/