UNIVERSITY OF SOUTHAMPTON

AN AUDITORY, AUDITORY ELECTROPHYSIOLOGICAL, AND PSYCHO-EDUCATIONAL STUDY OF A POPULATION OF HEARING-IMPAIRED CHILDREN

A DISSERTATION SUBMITTED TO
THE FACULTY OF ENGINEERING
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

BY
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NOVEMBER, 1987

We do not know in any detail why the
majority of deaf children find
speaking, reading, writing
and arithmetic so difficult

(Arnold, 1982)

ACKNOWLEDGMENTS

The author wishes to express her appreciation to the following people:

Dr. A. R. D. Thornton, for his guidance as the supervisor of this thesis

Drs. A. M. Martin and A. Salt, for their helpful comments, as the review board members for the thesis

Mr. R. Blunn, for his invaluable technical assistance

Mrs. B. Ingles, Principal, and other staff of The Sir Winston Churchill School for the Deaf, for their interest and co-operation in the study

Mr. E. Priddle, Director of Educational Services for the Hearing Handicapped, in Hampshire, for his help in identifying suitable subjects for the study,

Ms. A. Barks and Ms. S. Cunningham for their assistance in the assessments of the hearing-impaired children

My family and friends for their continual support in the preparation of this manuscript.

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ABSTRACT

FACULTY OF ENGINEERING

AUDIOLOGY

Doctor of Philosophy

AN AUDITORY, AUDITORY ELECTROPHYSIOLOGICAL, AND PSYCHO-EDUCATIONAL STUDY OF A POPULATION OF HEARING-IMPAIRED CHILDREN

by Elaine Saunders

The thesis is proposed that, when a child is assessed by behavioural measures and found to have a hearing loss, it is not implicit that the hearing acuity deficit is entirely peripheral in origin. Neither does it preclude the presence of any subtle central auditory dysfunction which has not resulted in further loss in acuity. However, the presence of central auditory difficulties may well affect a child's ability to code and process auditory, and, in particular, speech stimuli, in addition to the difficulties resulting from peripheral damage. Perceptual problems of this kind may therefore be present in hearing-impaired children who demonstrate excessive difficulty in the acquisition of oral language and related skills.

The aim of the this study was to examine the application of auditory electrophysiological (ep) measures to the differential diagnosis of children, already identified as hearing-impaired, and to investigate the stated hypothesis. A test population of 36 hearing-impaired children, consisting of subsets of "good" and "poor" oral achievers of oral language, were assessed in three main areas: audiometric, auditory eps, and psycho-educational. Preparatory studies were carried out to ascertain optimum recording parameters for the auditory ep recordings in the main study, and for the collection of normative data. An associated experiment, examining the relationship of high frequency hearing preservation and speech intelligibility, was also carried out. The high frequency experiment necessitated several, associated, preparatory experiments.

Qualitative and quantitative analysis of the data was carried out and discussed. The ep investigation gave equivocal results in the investigation of the site of auditory dysfunction in hearing-impaired children, as there were found to be unresolved difficulties in examining the locus, and effect, of additional central dysfunction in the presence of severe peripheral deficit. Some cases have been identified where there is a suspicion of central deficit, based on the ep findings, and compatible with the psycho-educational reports. Some unusual features in the ABR have been identified and their possible implications discussed. The results of the peripheral study on high frequency hearing support the notion that audiometric high frequency recovery contributes to speech intelligibility.

CHAPTER 1

TECHNIQUES AND APPLICATIONS OF AUDITORY, AUDITORY ELECTROPHYSIOLOGICAL, AND PSYCHO-EDUCATIONAL STUDIES WITH HEARING-IMPAIRED CHILDREN: A REVIEW OF THE LITERATURE

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1.1 INTRODUCTION

Children who are diagnosed as having a hearing loss are usually classified as being hearing-impaired, without regard to the site of the auditory dysfunction. The hearing loss is characterised by its extent, and possibly by the presence and degree of measured recruitment. A measure of speech discrimination may also be used to characterise the loss. There is now a body of evidence showing that children with normal or near normal acuity, but having a central auditory disorder, may have a resulting perceptual deficit sufficient to cause linguistic, cognitive, or educational difficulties (e.g. Lubert, 1981). This may, for example, arise as a result of difficulty in processing rapidly presented signals, such as occur in normal speech (Tallal and Stark, 1981), or in handling rapid intensity or frequency changes.

The central auditory pathway has been determined, but less is known about the neurological basis or the location of the central processes for speech. They could involve any structures in the brainstem and above, upwards of the locus of convergence of information from the two ears (Houtsma and Goldstein, 1972). Yet the therapist, dealing with communication disorders, must gain sufficient meaningful information about the status of the central auditory and speech processing mechanisms to implement an effective rehabilitation programme. Defects in the early stages of signal processing may be quantified by standard audiometric tests, but identification of a central dysfunction in the presence of a peripheral hearing loss is more difficult to evaluate. Further, tests to identify central auditory dysfunction are considered relatively experimental, and comprehensive, applicable normative data are not available. The current test batteries and the majority of the literature are designed for, and refer to, disorders of central processing occurring in the absence of impaired peripheral mechanisms. The group of patients so identified may be seen as belonging to a subgroup of the population of children who exhibit receptive language disorders, often of a severe nature, but perhaps manifesting as an educational problem if undetected before school entry. However, it can be argued that there is useful remedial, and possibly organic, distinction to be made between those with lower level central auditory disorders, who find difficulty in complex acoustic and auditory conditions, and those whose "hearing" is adequate, but whose comprehension begins to break down as linguistic complexity increases.

Studies of speech perception and the ageing process support the notion that central auditory dysfunction causes a more severe perceptual handicap when it occurs in the presence of a peripheral disorder. Central processes deteriorate with ageing, and the practical difficulties which result from the combination of peripheral loss and central degeneration in elderly people are well documented. The ageing studies support the theory that peripheral and central auditory processes seem to be potentially susceptible to dysfunction independently, although peripheral damage has the greater immediate impact. If the integrity of the processes may be independent, it would seem that the probability of impairment to both processes is rather small. However, it has been suggested that the integrity of central processes may be compromised by impairment of peripheral processes. Supporting evidence comes from animal development studies (Webster and Webster, 1979; Ruben, 1980) and from studies on children with long standing conductive hearing losses (Anteby et al., 1986). Thus it may be that children with peripheral impairment are more, rather than less, likely to have central auditory problems than normal hearing children. Where a hearing loss is adventitious, damage may also be more diffuse rather than a discrete peripheral problem as, for example, in meningitis caused hearing loss. Certainly, central involvement cannot be excluded simply because there is a peripheral auditory problem. Evidence for this comes from adult site of lesion studies and is discussed more fully later.

If a child with a pure tone acuity deficit has a central auditory site as the locus accounting for some or all of the dysfunction, he would be doubly disadvantaged for learning oral/aural language skills. The child is denied some of the physiologic and linguistic redundancy normally available to the child with a central deficit. Whilst it is known that many children fail to acquire good oral/aural language skills, even when that is a primary educational aim, little attention is given to ascertaining the complex perceptual basis for this. The focus of the literature is towards improving teaching techniques and audio input, although it is possible that physiologic differences account for some of the performance differences. As early as 1972, Downs proposed a "deafness management quotient", weighted on a 100-point scale, as an indicator of suitability for inclusion in an oral programme. She allocated 30 points to "central intactness", but the practical application has been limited, generally, to considering neurological signs, rather than perceptual components.

It may be possible to distinguish between two groups of hearing-impaired children, designated as making good or bad progress in oral/aural language skills on the basis of the site of auditory dysfunction, where this can be determined. It is a purpose of this dissertation to determine suitable tests from the range of auditory electrophysiological measures and to examine their application to the deeper audiological investigation of children with known hearing impairments. The hypothesis is proposed that auditory electrophysiological techniques may be used to identify and locate the site of auditory dysfunction in hearing-impaired children. It is further theorised that, in some cases, knowledge of the site of dysfunction may illuminate the reason for the failure of some hearing-impaired children to develop oral/aural skills comparable to those of their peers, with similar degrees and configurations of hearing loss, and having equal opportunity. This hypothesis will be examined in the following chapters.

1.2 THE ROLE OF AUDITORY ELECTROPHYSIOLOGICAL TESTS

The development of signal averaging computers has provided a technique which may prove useful in widening the assessment of hearing disorders in children. Computer averaging techniques enable recording of a range of electrophysiological measures which may be evoked by auditory stimuli. These may be used in conjunction with behavioural techniques to investigate hearing loss more thoroughly.

The auditory electrophysiological (ep) measures are commonly described as four different sets of responses that can be generated from auditory stimuli. Each separate waveform set reflects activity from different parts of the pathway. These four wave components are as follows:

1. The fast components - the auditory brainstem response (ABR), occurring in the first 10 ms following stimulus onset

2. The middle components - the middle latency response (MLR), occurring between 10 and 60 ms following stimulus onset

3. The slow components - the slow vertex response (SVR), occurring between 60 and 300 ms following stimulus onset

4. The late components - the contingent negative variation (CNV), occurring beween 300 and 600 ms following stimulus onset.

In an adult clinical population, auditory ep techniques are used successfully to detect the site of lesion causing an auditory disorder. At a time when there has been an increasing interest in auditory peripheral difficulties in children, it is appropriate to apply these ep techniques to seek the site of auditory dysfunction in hearing-impaired children.

The decision to attempt to utilise auditory ep measures is taken against a background of considerable development of behavioural investigation into central auditory function, and it is appropriate that a review of previous studies into the measurement of central auditory function and its affect on language skills be presented. The assessments in this area address the effects of central auditory dysfunction in terms of specific auditory skills, a deficiency which may contribute to the localisation of the auditory or language disorder, or illuminate functional reasons for failure. Many other factors contribute to the development of speech and language skills, as briefly described below. It is intended to minimise these influences in the present study, but it is recognised that they cannot be entirely eliminated.

In this introductory chapter, the essential issues in the investigation of auditory function are reviewed. These are:

factors affecting oral language skills in children;

effects of preserved high frequency hearing on speech production;

the current electrophysiological and behavioural methods of assessment.

1.3 FACTORS AFFECTING ORAL LANGUAGE SKILLS IN HEARING-IMPAIRED CHILDREN

It is a well established fact that many factors, inherent and environmental, affect the development of speech and language in hearing-impaired children. It is certainly too simplistic a view to suggest that central auditory dysfunction could be a major contributory factor in more than a few cases. The site of lesion causing a hearing loss is but one component among many. Other factors that should be considered are:--

1.3.1 The Degree of Hearing Impairment

The degree of hearing loss gives a very broad prognosis for future success in acquiring oral language. Assumptions are made concerning which features of the speech spectrum will be perceived, based on the audiometric configuration, but it is less easy to predict the effect on other perceptual aspects, such as frequency discrimination and resolution, temporal discrimination, intensity coding and central analysis. The quantification of the relationship between pure tone sensitivity, and receptive language goes back to Fletcher, in 1929, and a number of different summary measures of the pure tone audiogram have been devised to predict hearing for speech (e.g. Kryter et al., 1962; Erber, 1974; Bamford et al., 1981). However, even direct measures of speech hearing do not correlate well with spoken language ability in the deaf. There are few good experimental studies investigating the effect of degree of hearing loss on language, with different results probably being due to differing methods and sample selection. Davis et al. (1986) showed that language ability decreased with increasing hearing loss, in contrast to earlier studies which did not (Reynolds, 1955; Reich et al., 1977). Data on extent of hearing loss must be interpreted cautiously because of the difficulties in predicting the extent of the coding deficit caused by a particular hearing loss. For this reason a simple definition may be chosen. The simplest distinction is to categorise children according to whether they appear to have hearing for speech, as they then may be expected to achieve more in the oral language domain than a child who has clearly no hearing for speech.

1.3.2 Age at Onset of Hearing Loss

The most important reference points regarding the age of onset have traditionally been taken as birth and the establishment of language. It is now recognised that experience of language in the first year of life is critical to a normal child's speech and language development and that, equally, it can be expected that a child who is adventitiously deafened after some early language experience has an aural advantage over the congenitally deaf child.

1.3.3 Etiology

To a large extent, the effect of the etiology of the loss is determined by the extent of the loss, the site and spread of auditory dysfunction, and the age at which this causes a hearing loss.

1.3.4 Aural Habilitation (non-auditory factors)

In drawing a profile of a deaf child, many factors must be considered. For example, features of the home environment are examined, such as whether the language predominantly used is oral or manual; whether the language is the same as that of the current country of residence; and whether it should be regarded as normal, rich or impoverished. The home environment may be extremely supportive, with one or both caregivers participating in a home-based deafness early intervention programme, or there may be minimal support for the child. Important factors are the quality of the caregiver-child interaction (Kenworthy, 1986), the techniques used in spoken language interaction (Gregory and Mogford,1981; Chesbin, 1981), the age of identification and implementation of the programme of rehabilitation. The quality of the aural rehabilitation programme, including the attention given to the rigorous use of the most suitable amplification will have an influence on performance. The quality of aural input, and its continuity is known to vary widely. This occurs partly due to the difficulties in selecting the most appropriate amplifying devices for a child, at an age when sophisticated behavioural assessments cannot be carried out, and partly due to practical difficulties in maintaining a constant sound input. These difficulties arise from a child's dislike of the prosthesis, lack of education in recognition of instrument breakdown, and changes made in choice of hearing aid as the child gets older.

Outside the educational domain, the child himself provides a wide source of variability. His temperament, acceptance and understanding of his disability, his intellectual ability and social and emotional circumstances may all influence his ultimate progress. The addition of a handicapped child to a family is an additional strain which not every family can accommodate. Underlying weaknesses are frequently exposed, raising the incidence of emotional instability in the home to above the average.

These issues are presented to explain the proposal of this thesis to examine only one of many reasons causing a hearing-impaired child to fail to make adequate progress in spoken language. This particular area needs to be investigated because early intervention could then be tailored accordingly.

1.4 HIGH FREQUENCY HEARING AND SPEECH

The work of Berlin et al. (1978) and of Chasser and Ross (1979) strongly suggests that where a child has hearing in the frequencies above 4 kHz, which is better than his hearing at lower frequencies, then this may have a positive effect on his speech perception and the intelligibility of his speech.

Interest in assessment at higher frequencies revived, after a long lapse, in 1964 when Corso studied the high frequency range of hearing by air and bone conduction. However, it was a large study by Rosen et al. (1964) which reintroduced high frequency hearing assessment as a useful clinical technique. These authors tested in the range 12-24 kHz and their results suggested that the effects of ageing, noise, and urban lifestyle were detrimental to auditory acuity in the higher frequencies. Whilst their subject selection technique is perhaps doubtful, in that documentation supporting subject age was not available to the testers, most commonly encountered hearing losses are high frequency. Since several otological diseases may be expected to affect the basal area of the cochlea first, the technique is again finding a place in audiology because of its probable predictive importance as a more sensitive monitor of damage. There have been a number of attempts to provide standard reference threshold data of high frequencies since then, but differences in instrumentation and subject selection have led to results which differ considerably between studies. This has not, however, deterred the interest in clinical applications. In particular, causes of premature presbyacusis are of interest. For example, hypertensive vascular disease, elevated lipids, arteriosclerosis, heart disease, vestibular neuritis and diabetes have been identified as pathologies where hearing may be usefully monitored in this way (Cunningham and Goezinger, 1974; Osterhammel, 1980; Rhako and Karma, 1986). The technique has been examined as an early indicator of noise damage (e.g. Osterhammel, 1979; Fausti et al., 1981a; Dieroff, 1982) and to characterise the effects of impulse noise, such as gun fire (Fletcher and Loeb, 1967; Fausti et al., 1981b). High frequency hearing measurements are being used increasingly as a monitor of drug ototoxicity (Cunningham et al., 1983; Fausti et al., 1984; Rappaport et al., 1986).

Paparella et al. (1972) have reported that persistently recurring otitis media are associated with high frequency hearing loss, particularly at high frequencies. They attributed this to the permeability of the round window membrane during periods of middle ear effusion, permitting the infiltration of microbial toxins into the inner ear. High frequency audiometry has been of interest as a more rigorous and descriptive monitor of this process (Ahonen and McDermott, 1984) and as a monitor of cochlear damage following middle ear surgery (Laukli and Mair, 1985). High frequency audiometry may also be of use to give a broader profile of effects of disease on acuity. Fletcher (1967) demonstrated a decrease in high frequency acuity following meningitis. In each of these cases, measures at frequencies above 8 kHz were more sensitive to change than measures at other frequencies, and were considered to be an early indication of damage.

If hearing above 4 kHz is considered, the fortis/lenis fricatives and sibilants predominantly have energy in this range. Fig. 1.1 illustrates the principal energy bands and relative intensities of the sounds of spoken English. Fletcher (1929) lists their occurrence in spoken English as:
0.7 - θ; 2.5 - ð; 4.0 - s; 2.2 - z; 4.0 - ʃ; 0.3 - tʃ.
These figures indicate that usable hearing above 4 kHz enables perception of these commonly encountered sounds. The acoustic spectrum of the sounds clearly varies according to its phonetic environment, and according to speaker, but Heinz and Stevans (1961), attempting to provide an acoustical

theory of the production of fricative consonants, provide evidence of speech information above 10 kHz.

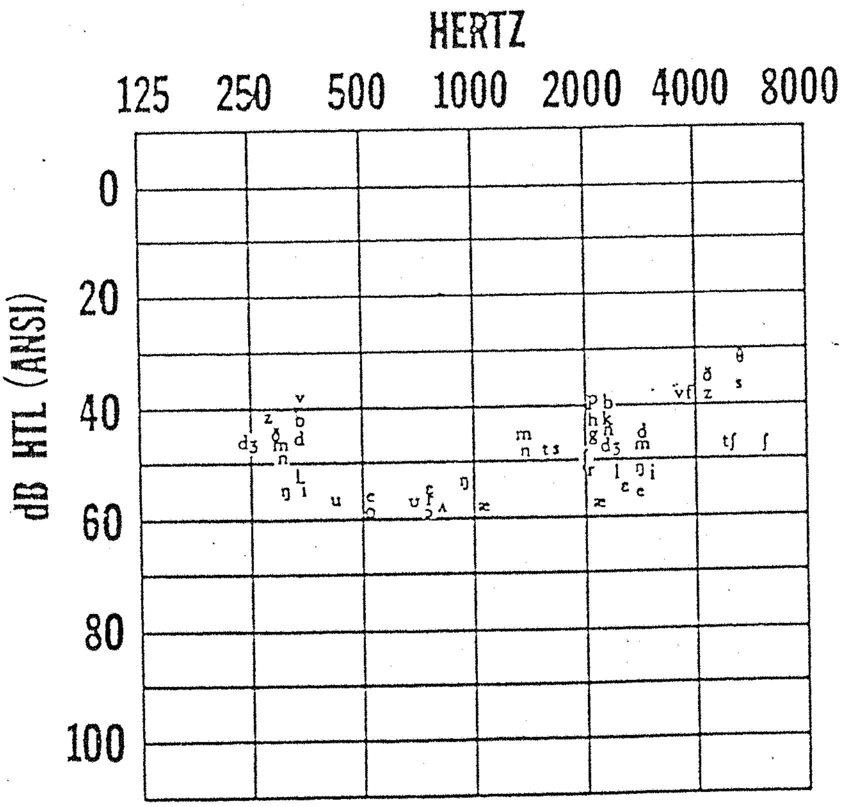


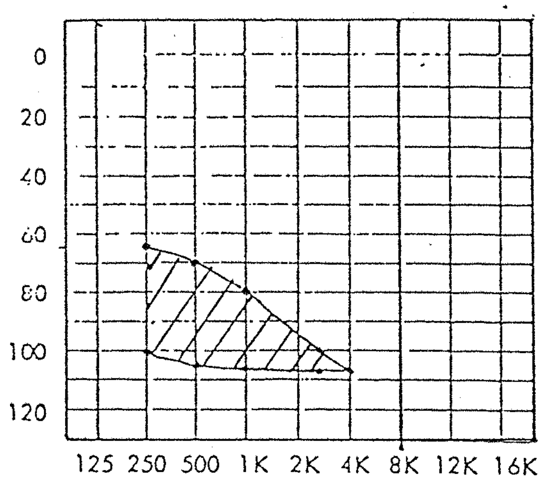
Fig. 1.1 (from Ling & Ling 1978)

The report by Berlin et al. (1976), of the relationship between speech intelligibility and the presence of hearing in the high frequencies, based on clinical observations, was of most relevance to this study. These authors reported the case of a patient whose speech quality was much better than would be predicted from audiometric information (0.25 - 8 kHz). This patient was able to detect speech presented to the free field at a lower sound pressure level than when the speech was presented through headphones, which have a limited frequency range. She was found to have usable hearing in frequencies above 8 kHz, i.e. outside the frequency range of TDH-49 headphones. Berlin's group investigated further. They presented speech recordings of 42 deaf children to a panel of experienced listeners, and asked the panel to grade each child's speech intelligibility on a seven point scale (A to F). The five deaf children who were awarded grades of B or better, all had measurable hearing about 4 kHz (Fig. 1.2) and the authors suggest a correlation between good speech and high frequency hearing. A second study was carried out by Chasser & Ross (1979). They recorded speech samples from 10 children, who had audiograms which rose at 10 dB per octave above 2 kHz bilaterally, and from a control group matched for age, sex and thresholds below 2 kHz, twenty six listeners were asked to rate each sample for speech intelligibility. They commented that individuals with similar pure tone average may have very different high frequency hearing, and found a high correlation between "ultra audiometric hearing" (Berlin et al., 1976) and speech intelligibility. Their experimental and control groups were significantly different ($p < 0.05$) on measures of speech intelligibility alone, although not all had superior high frequency hearing or speech intelligibility (Fig. 1.2). Both of these authors stress that it is important to identify those individuals with residual high frequency hearing as early as possible since:

i) Transposer hearing aids are now available which transpose the speech signal to a higher frequency range, where sensitivity is much improved (Collins et al., 1981)

ii) Lack of high frequency input could theoretically lead to sensory deprivation such that it would not be possible to use the high frequencies at a later date.

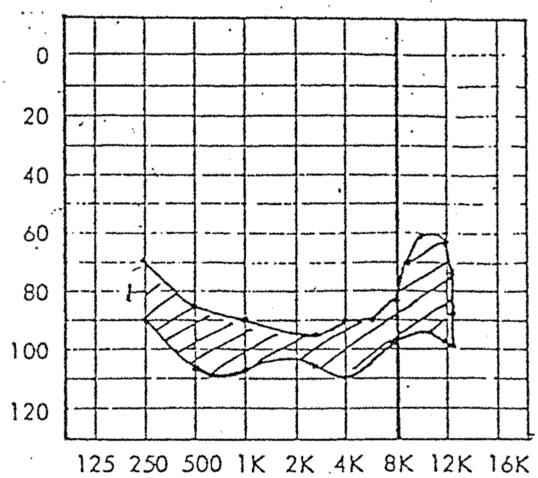
Although the speech spectrum extends above 8 kHz, the information conveyed in these frequencies is predominantly in frication. It is perhaps surprising



Poor Speakers

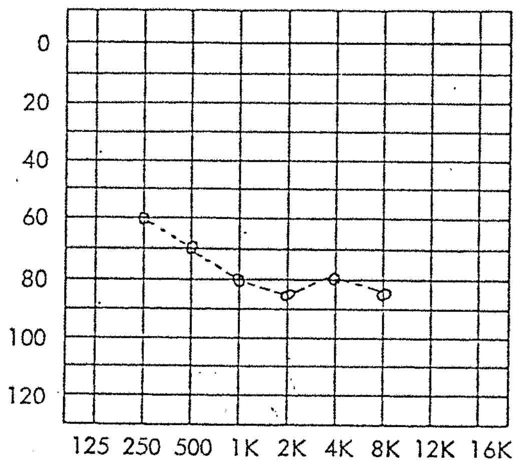
Composite audiogram of six worst speakers who received F grades from all judges

(from Berlin et al., 1978)

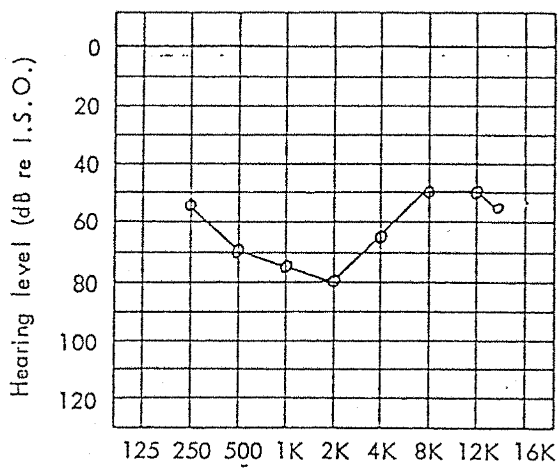


Good Speakers

Composite audiogram of five good speakers who received A or B grades, plus case report



Control Group



Experimental Group

Fig 1.2 (from Chasser & Ross, 1979)

that hearing information contained in the higher frequencies should make such a difference but this is, perhaps, one of the redundant areas of speech which the hearing-impaired listener is able to utilise where low frequency information is not available. Also, Berlin notes that there is more sound energy for some fricatives at 8 to 10 kHz than at 4 kHz.

High frequency hearing may be important for competence on psychophysical tasks at lower frequencies. Florentine (1983) addresses this by examining intensity discrimination at 1 kHz. Possibly recovery of acuity in the frequencies above 8 kHz is an indication of more widespread basal turn activity.

The Chasser and Ross study indicates that the presence of residual high frequency hearing may not be uncommmon, and this view is supported by Bergstrom and Morgan (1983) in a study of genetic hearing loss. They reported the audiometric findings from three families where ultra-audiometric thresholds were measured, and the audiograms showed an upward sloping high frequency in several cases. Their findings lead them to propose that hearing should be assessed in the high frequencies in all cases of congenital hearing loss, due to its possibly frequent occurrence.

1.5 BEHAVIOURAL ASSESSMENT OF CENTRAL AUDITORY FUNCTION AND AUDITORY PROCESSING SKILLS.

1.5.1. Historical Aspects and Theoretical Basis

There is an interdependence of signal language processing which complicates assessment for site of lesion investigation and remediation. In formulating assessments, it is a complex task to identify the fundamental auditory perceptual abilities and auditory language comprehension abilities. The early tests of central auditory function assumed that, since speech is the highest auditory function, tests of central auditory function should be based on speech material. Since the auditory system has high intrinsic neurological redundancy and speech material itself has high redundancy, the latter (extrinsic redundancy) is reduced to provide a more difficult task. The earliest attempt to assess central auditory function using speech with decreased message predictability was carried out by Bocca and his colleagues in 1954. Using lowpass filtered speech, they found that discrimination of bisyllabic words, with information above 500 Hz removed, was poor in a patient having a temporal lobe tumour on the side contralateral to the stimulated ear. Since then, other authors have devised monaurally presented speech tasks to assess cortical lesions, notably temporally-distorted speech (Calearo and Lazzaroni, 1957; Beasley et al., 1972; Quaranta and Cervellera, 1977; Baran et al., 1985); periodically interrupted speech (Bocca, 1958; Calearo and Antonelli, 1973; Korsan-Bengsters, 1973); low sensation level speech, where speech is presented at 5 - 10 dB sensation level (Jerger, 1960) and speech in a noise background (e.g. Morales-Garcia and Poole, 1972; Noffsinger et al., 1972; Heilman et al., 1973). Clinical investigation on adults using these tests generally shows impaired results in the contralateral ear of patients who have cortical lesions. Poor or variable results are also found for a variety of other intracranial and, sometimes, brainstem lesions.

Dichotic speech tests have been developed to evaluate auditory function in the brainstem. The most notable of these, the Matzker Test (1959) requires the binaural fusion of a speech message split such that a low frequency (0.50 to 0.80 kHz) band of spectral energy is presented to one ear and a higher frequency (1.82 to 2.50 kHz) band is passed to the other ear simultaneously. This test has been carried out on clinical populations by several authors (e.g. Lynn et al., 1972; Musiek et al., 1984) and the results suggest that the task is useful in differentiating brainstem from cortical lesions. Various other dichotic speech tasks have been used in the assessment of central auditory function, though not primarily brainstem functions (e.g. Kimura, 1961; Musiek et al., 1985). Essentially, in all these tests, the auditory system is assumed to be taxed by reducing the extrinsic redundancy of the stimuli, for example by filtering, or by temporal reduction of the message. It is thought that, in a dichotic situation, the stronger contralateral auditory pathway takes precedence over the weaker ipsilateral pathway unless there is hemispheric damage. However, ipsilateral deficits are expected if the left or dominant hemisphere is damaged. Although speech perception is unquestionably a high-order process, and hence degraded speech material may be a suitable material for the assessment of central auditory function in adults with normal language, it is important to identify the language and cognitive weighting. In the assessment of children with learning difficulties and/or delayed language, this weighting may be significant. In adults the tests are found to be demanding of the subject and the results variable. Thus, immature language skills will decrease further the extrinsic redundancy of the speech material when assessing children. Attention skills also affect these tests, to an extent dependent on the complexity of the task.

Although speech material is most commonly used, investigators have experimented with other methods to detect abnormal performance in individuals with central disorders, for example, sound localisation (Sanchez-Longo and Foster, 1960) and temporal ordering tasks with non-speech stimuli (Lackner and Teaker, 1973; Efton et al., 1985).

1.5.2 Neuroanatomical Basis of Central Auditory Dysfunction

The central auditory system consists of a series of neuroanatomical connections from the cochlear neuron to the cerebral cortex. The pathways are both crossed and uncrossed, but the majority of the complex array of pathways and synapses exciting the cochlear nucleus cross to the opposite superior olivary nucleus, and some groups of fibres decussate at each nuclei. Second-, third-, and fourth-order contralateral and ipsilateral fibres synapse at the inferior colliculus, from which fibres pass to the medial geniculate body and to the visual system's superior colliculus. Fibres from the superior olivary nucleus, the lateral leminiscus, and perhaps the cochlear nucleus travel ipsilaterally and contralaterally to the medial geniculate body, from which the majority of fibres project to the superior temporal lobes. There are further intersensory connections to the cerebellum, and to the reticular formation which interacts with higher levels in the central nervous system. In parallel to the afferent system, efferent fibres descend caudally from the cortical regions to the two cochleas, enabling some higher brainstem control upon the neural activity of auditory structures.

The pathways are complex, and have high intrinsic redundancy anatomically, physiologically and biochemically. This high redundancy is reflected in the hearing loss caused by lesions. A very small lesion in the peripheral auditory system causes a much bigger hearing loss in comparison with a lesion of similar magnitude in the central auditory pathway. Characteristically, mild brainstem and temporal lobe lesions cause minor losses in pure tone sensitivity, though there may be neurological symptoms.

The neuroanatomical evidence suggests that the development of language closely parallels neurological maturation of the auditory system. This has been inferred from study of the developing brain, in conjunction with studies of language development (Young 1983). This in turn has led to the study of central auditory function as a measure of maturation of the auditory pathways (Keith, 1981). Keith proposes that in immature pathways a plateau of language development is reached as the structural maturity begins to impose limitations, and he interprets measures of central auditory function accordingly.

Difficulty in processing auditory signals may underly some of the speech, language and learning difficulties which children demonstrate. This forms the basis of the perceptual deficit theory of language, reading and learning disorders (e.g. Keith, 1980). Opponents of this theory claim that auditory perceptual disorders may be related to disorders of language, but are not the cause (e.g. Rees, 1973, 1974; Lyon, 1977 and Sanders, 1977), and that verbal mediation deficiencies are fundamental to the problem.

In favour of the peripheral deficit model is experimental evidence showing that some children with language learning and reading disorders have difficulty in certain non-cognitive, non-linguistic auditory abilities, such as binaural fusion, binaural separation, dynamic auditory localisation (Devens et al., 1978), two tone auditory suppression (McGroskey and Kidder, 1980), perception of rapid transitions in acoustic signals (Tallal, 1976), and word recognition at favourable signal-to-noise ratios (Palanker, 1978).

These two theories of disorder derive from the Language Processing (Top Down) or Auditory Processing (Bottom Up) theories of language perception. The former view is that most language processing must be done using higher-level linguistic and cognitive knowledge, on an uninformative acoustic signal. The suggested paucity of information is used to argue for the role of abstract processing at the phonologic as well as the semantic and syntactic information levels. The auditory processing view shares the notion that listening is more effective using language knowledge, but that this is in conjunction with extensive auditory analysis. The acoustic signal must be processed through several steps before it becomes influenced by higher-level knowledge. Whilst some language processing advocates deny signal processing of language as being separable from higher auditory processing (Rees, 1975, 1981) and some auditory processing advocates consider language processing as building basically on processing skills (Katz and Illmer, 1972), a compromise view is possible. For example, Wiig and Semel (1976) suggest the concurrent existence in one child of both auditory and language processing problems, and deal with each type of problem independently. This synthesised view is relatively rare. Duchan and Katz (1983) suggest that in most situations there is a continual fluctuation between signal and cognitive or linguistic operations in the listener and that this interplay should be noted in assessment methods.

These issues are important to the practising clinician as they underlie the test procedures and therapeutic strategies currently in practice. The term "auditory perception" is aptly used to collectively define fundamental auditory abilities such as localisation, ability to perceive rapid acoustic transitions in speech, or manipulation of intersensory information. These skills are thought to be fundamental to language acquisition. The term is also used to define certain language-based skills, such as auditory blending and auditory closure, which emerge as one acquires language, rather than being fundamental to learning language. From these two categories arise many tests, the latter group being heavily weighted by language factors which are used in the assessment of central auditory function.

Tests of central auditory function used successfully in adult studies are rarely applicable to the assessment of children. Often the goal is different, being more functional than clinical in the paediatric assessments. Neither the test validity nor its reliability are transferable. Procedures currently in use specifically for assessment of central auditory function in children are discussed below.

1.6 ASSESSMENT OF CENTRAL AUDITORY FUNCTION IN CHILDREN

The assessment of underlying auditory capabilities must be as free as possible from language bias. A useful list of criteria essential to the design of a test of normal central auditory function has been formulated by Keith (1981). Tests should;

not be loaded with language comprehension items;

not require linguistic manipulation;

minimise cross-sensory input or response modality.
A selection of the common tests are reviewed in the following pages.

1.6.1 Localisation

This binaural task is free from language bias, being non-speech. The subject is asked to locate the direction of a sound source in space in the horizontal plane. Impaired ability to localise sounds has been shown for adult patients with temporal lobe, midbrain and brainstem lesions (Sanchez-Longo et al, 1957; Nordlund, 1964 and Jerger et al., 1969). However, it is now well documented that more peripheral impairments may reduce localisation ability, and this restricts the interpretation of this test for patients not shown to have symmetrical peripheral hearing sensitivity. Formal localisation testing is costly to set up and requires large test-room facilities. These tasks are difficult for children and, in this context, we are usually more interested in functional ability than site of lesion studies, so more informal tests of crude localisation ability are appropriate. A child older than four months with normal peripheral sensitivity should be able to localise sounds in the horizontal plane, and failure to do this where the neuromusculature system is normal may indicate immature auditory processes. More speceific diagnosis is currently not a realistic goal with a localisation task.

1.6.2 Binaural Synthesis.

Speech and non-speech tasks of binaural synthesis have been devised to assess brainstem function. The test message is somehow split, and presented to the two ears, such that it is a central process to reconstruct the whole signal. The test stimulus is either divided on the basis of frequency content of the signal, or temporally split between the ears.

1.6.2.1 Binaural Fusion tests are based on Matzker's 1959 work. Willeford (1977) developed a version using spondaic words presented at 30 dB SL. He has reported developmental age norms for this task, though he notes that individual ranges are wide, reducing the specificity of the test for young children. Further, the use of symbolic material, even for a test of functional ability, is dubious, since it is weighted by aspects of cognition and linguistic maturity.

1.6.2.2 The Rapidly Alternating Speech Test, in which a speech message is rapidly alternated between ears, is another procedure that Willeford (1977) used in his battery of tests. Normal scores have been reported by Bocca and Calearo (1963) from adult patients with lesions in the auditory cortex, and abnormal scores from patients with brainstem lesions (Calearo and Antonelli, 1968). In Willeford's version of the test for children, the sentences are presented (split into alternating bursts of 300 ms) first to one ear, then to the other, at a suggested level of 50 dB sensation level. Again, developmental normative data have been collected on children from five to ten years of age by Willeford (1978), and reported by Keith (1981), with a smaller range of results than for the previous test. The auditory memory component supplies an apparent confounding variable in completing this task, confusing the implications for differential diagnosis, as a disruption in normal auditory memory would suggest a higher-level disorder. A poor performance in this test as a measure solely of dichotic function would reflect a brainstem disorder. To try to compensate for this, tests of auditory memory could be administered in conjunction with the test (Protti, 1983), but both tasks are influenced by linguistic maturity, and it is doubtful whether measure of underlying auditory capabilities, as related to brainstem function, can be made in this way. The rapidly alternating sentence task itself requires mature processing of syntax in conjunction with an auditory memory load, making it primarily a test of language maturity.

1.6.2.3 The Masking Level Difference Test is based on the binaural effect which facilitates selective listening to a specified signal in a noise background, and the effect has been used as a central auditory test using both speech and non-speech stimuli. It has been used with some success in adult studies of central auditory problems. Matkin and Hook (1983) recommend its inclusion in test batteries of central auditory function. These authors presented a nonspeech version, using a 500 Hz pure-tone as the signal, and a speech version, using children's spondaic words. The performance scores did not, however, correlate well with difficulties in language or learning. Thus, while results to date from site of lesion studies suggest that this task may have some diagnostic significance, its value is not established as a functional measure in children.

1.6.3 Binaural Separation

Measures of binaural separation have been carried out primarily as tests for lesions in the auditory cortex.

1.6.3.1 The Staggered Spondaic Word (SSW) Test is perhaps one of the most well known of the central auditory tests (Katz 1962). A spondaic word is presented to each ear at 50 dB sensation level, and the listener must repeat both words. The words are staggered such that the second syllable of one stimulus is simultaneous with the first syllable of the other. The test is reportedly more effective in identifying cerebral lesions than brainstem lesions (Jerger and Jerger, 1975). Further, Katz describes a test maturational effect which reduces the test's specificity for brainstem dysfunction. Although the test was designed as a site of lesion test, several functional skills are assessed in the test and many factors are assessed independently. In general, children show a tendency to superior performance to the stimuli presented to the right ear; between the ages of six and eleven years children improve at the task, and variability is reduced.

1.6.3.2 The Dichotically Competing Sentences Test, devised by Willeford (1977), uses 25 different sentences, presented simultaneously to both ears. Willeford's reported developmental norms for children aged from five to nine years showed a right-ear dominance at the lower ages. There is, as with many of these tests, much variability, particularly from the weaker ear and the younger children. Probably this test has most use in monitoring attentional capabilities in children, although it may provide some comparative information on auditory neuromaturational levels where differences from the normal are marked. Adult studies have shown diagnostic application in the detection of brainstem and temporal lobe lesions (e.g. Musiek and Guerkink, 1982; Pinheiro et al., 1982)

1.6.4 Dichotic Listening Tests

Dichotic recall tasks of digit strings, word lists, nonsense syllables and phonemes have been used to demonstrate right ear advantage. and to relate speech-processing laterality to language problems. Porter and Berlin (1975) have criticised these studies on the grounds of the inappropriate weighting of memory load and acoustic factors, and the poor control of phonetic factors. Typically, a set of six CV nonsense syllables are presented simultaneously in pairs to the ears. The syllables generally used are /pa/, /ta/, /ka/. /ba/, /da/ and /ga/. Normal children seem to show a right ear advantage in this task (Keith, 1981) and with age both right and left ear performance improves (Berlin et al., 1973).

Several authors have attempted to investigate the confounding factors in this task. Teng (1981) proposed that an ear advantage could be identified and falsely ascribed to hemispheric specialisation if input asymmetries were allowed to occur in the test ear. Dwyer et al (1982) explored the extent to which asymmetry in stimulus parameters could affect results. They showed that the presence of an abrupt onset determines lateralisation for stop consonants. Transition information, including duration, also contributes, indicating a contribution of temporal processing and duration to demonstrable right ear advantage. Hiscock and Bergstrom (1982) found strong order effects in a dichotic digit task, and concluded that attentional biases may exert a strong and enduring influence in ear asymmetry.

Dichotic listening tasks are founded on the rationale that there is normally a right ear advantage or left hemisphere dominance for processing language, particularly for the information carrying phonetic contrasts of speech. The specificity of this laterality is not totally clear, and the implications of an inability to demonstrate this specificity are even less clear. Probably the right ear advantage on a dichotic listening task reflects a developmental process requiring the integration of several skills, including attention. Breakdown of any one of several areas may lead to poor performance, so that demonstration of left ear or no-ear advantage is a measure of central nervous system immaturity. This area of performance is still not fully understood.

1.6.5 Resistance to Distortion

This final category is an extension of tests in which redundancy in speech is reduced in order to tax the auditory system.

1.6.5.1 Auditory Figure Ground tests entail presentation of the speech signal against a background of noise. Comparison of the discrimination of (monaurally presented) speech in quiet against discrimination of speech in noise (also monaurally presented) has been used by several authors in the last 25 years (Dayal et al., 1966; Morales-Garcia and Poole, 1972; Noffsinger et al., 1972). In relation to site of lesion testing, poor discrimination in noise in patients with brainstem lesions, and poor discrimination in noise in the ear contralateral to a cortical lesion have been reported. As with other tests, there seems to be greater variability in the patients with brainstem lesions. In this test, typically, a performance-intensity function for monosyllabic words or sentences is obtained by presenting material at different intensity levels. Generally, the normal speech material is too highly redundant to reflect an ear advantage in the presence of a lateralised lesion in the auditory cortex; but, if the task is made more difficult by the addition of noise, then the shape of the function may be abnormal, with a maximum percentage score below normal. When the test is carried out on children, it is more usually as a functional measure, although Jerger (1981) lists it among tests for investigation of site of dysfunction in children under seven years. Variants of the task are incorporated into the speech pathologist's test batteries of auditory skills, where it is regarded as a test of selective attention. An example of this is the Goldman-Fristoe-Woodcock (GFW) Auditory Skills Battery (Woodcock, 1976), which contains the auditory selective attention subtest. Monosyllabic words are presented against a background of cafeteria noise, with steadily increasing signal-to-noise ratios. It is not strictly accurate to describe a task of this kind as a task of selective attention, which may be regarded as a two-component task. The first component is the brainstem-mediated process of binaural advantage; the second is a higher-level task. Presented monaurally with a high signal-to-noise mix, only the latter component is assessed. At its simplest, the task is thought to give some idea of how easily a child can attend amid distractions (Dempsey 1983; Brown, 1987). In this respect, the test has less language bias than Willeford's Competing Sentence Test.

The 'speech-in-noise' task is not, strictly, free of the confounding effects of receptive language ability. Elliott (1979) clearly demonstrates increasing proficiency with increasing age on speech-in-noise tasks, on a sample of children aged nine to seventeen. In a review of these tests, Mills (1977) emphasised the contaminating influence of receptive language levels on the task. Jerger and his colleagues (1980) devised a test which they called the Pediatric Speech Intelligibility Test, and which they recommend as appropriate for children aged between three and seven years. These authors report that their test incorporates the normal differences in receptive language function that characterise children in this age group. The word and sentence material were based on children's utterances in response to viewing a picture. They found it inappropriate for testing children with very low receptive language scores (as measured by the Northwestern Syntax Screening Test). It is also not sensitive enough to test children above six years old (Jerger et al., 1983). It was recognised that non-auditory factors, such as linguistic competence, may confound the results from this task and various strategies, which may be carried out to reduce the importance of these confounding factors, were suggested.

1.6.5.2 The Monaural Filtered Speech Test was included by Willeford (1977) as part of his test battery assessment. He presented monosyllabic words with the energy above 500 Hz removed. His normative data collected from children showed a maturational effect which was not complete by 9 years. This is comparable with the work of Elliott (1979), reported earlier. Again, widely varying individual scores were reported, suggesting that it is difficult to use this test as a 'clean' measure of auditory neuromaturational level. Dempsey (1983) reports that young children find this task very difficult. A variant on Willeford's original test is the Filtered Word Identification by Picture Test (WIPI, Willeford, 1977). Young children find this test easier and as a picture-pointing response is required, there is less tester bias introduced than when the tester must correctly identify the child's spoken response. However, the test adds visual-motor skills to the list of confounding variables.

1.6.6 Time Distorted Speech

Tests of time-compressed speech, as developed for adult subjects by Calearo and Lazzaroni (1957) and Bocca and Calearo (1963) yield much less conclusive results with children. For example, Beasley et al. (1972) report results from 60 children aged 4 to 8 years. These authors found intelligibility decreased as a function of increasing time compression, and decreasing age and sensation level. This effect was more pronounced with more difficult test material.

A time-compressed version of the WIPI test was presented by Freeman and Beasley (1976) in both a closed and open-set response format, to children with and without reading difficulties. Their results showed that, on at least one test condition, children with reading difficulties did not perform as well as children without reading difficulties. There is little agreement between authors of other studies, and this probably reflects the procedural differences and the different confounding factors which are involved. The diagnostic implications of this test for children are far from certain, and since the results are so equivocal even as a functional measure of disability, the test results on children must be regarded as having little significance.

Probably one of the most significant measures of auditory processing is the ability to perceive rapid transitions in acoustic signals (Tallal, 1976). In this discrimination task, Tallal presented pairs of non-speech and speech-sound stimuli to dysphasic children of six to nine years of age. The children were required to make a same/different judgement to stimuli presented with varying interstimulus intervals. Performance was affected by the size of the interval. A developmental effect was recognized, but the dysphasic group required longer interstimulus intervals than even the youngest normal subjects. Tallal argued that this test demonstrates a primary inability to analyse the rapid stream of acoustic information that characterises speech. She speculated that this is essential to normal speech perception and language development. Rees (1981), on the other hand, argues that since the test results demonstrated that phonetic distinctions could be discriminated if the interval between the stimuli were long enough, then clearly the child had sufficient auditory processing skills to learn this distinction. The precise relationship between difficulty on this task and language development is thus unclear, but as a functional measure it leads to predictions of difficulty in situations where rapid processing is essential -- for example, in reverberant acoustic conditions.

1.7 ASSESSMENT OF AUDITORY PROCESSING SKILLS IN CHILDREN

The discussion has so far centred on the measures of central auditory function which could be carried out as part of an audiological assessment. However, other assessments of auditory processing are carried out, usually by speech pathologists, which are thought to relate more directly to speech and language development. On the whole this delineation is rather arbitrary and exists for historical reasons. The basic abilities which are generally categorised as requisit to speech and language development are auditory discrimination, auditory memory, and auditory sequencing. Tests such as the GFW and the ITPA are used in their assessment. The overlap with the tests classified as 'central auditory tests' is apparent, particularly in the case of auditory discrimination. Auditory memory and auditory sequencing are complex tasks which are difficult to see as fundamental auditory skills.

1.7.1 Auditory Discrimination

Various tests of discrimination are commonly carried out by speech therapists/pathologists and it has not been uncommon for a child's failure to correctly make a discrimination to be ascribed to an auditory difficulty in discriminating between pairs of sounds, presented as test stimuli (Hammill and Larsen 1974). However the speech perception process is complex and interactive. Speech is not processed as a series of successive phonemes, but as a rapidly changing acoustic signal. Further, the development of speech and speech perception are probably interdependent processes, with the ability to carry out tests involving speech stimuli including numerous factors other than auditory skills. If a child fails to discriminate the difference between a minimal pair, the reason for this failure is not necessarily apparent.

1.7.2 Auditory Memory

Tests of auditory memory require a child to recall auditory stimuli, in terms of number and sequence. Auditory memory is often described as an intrinsic property. An individual is thought to have various levels of memory:

(i) Echoic memory, from which any utterance can be immediately reproduced.

(ii) Short-term memory, which may be regarded as a sort of short-term data store where, for example, several sentences could be retained and reproduced after several minutes.

(iii) Long-term memory, which may be thought of as a quasi-permanent store. Phonetic representations, syntactic and lexical information are stored to give a library of references.

Whatever view one takes of speech perception, it is evident that there must be some mechanism by which the units of language are stored and held in sequence. Intuitively, therefore, auditory memory appeals as an underlying component of the speech perception process. However, major problems with auditory memory tests arise in knowing why a child fails to do well, as there are several stages involved in the process. For example, if it is assumed that the message which is stored is coded, the question arises as to whether difficulties occur in the encoding processes, in storage processes, or in retrieval processes. So, poor performance on a standard memory task of the type employed in test batteries of auditory processing skills may, like so many other tasks discussed, only identify a test difficulty and not a specific underlying skill deficit, and may not localise the disorder.

Although it is appealing to assume storage of units for speech processing, it is not at all clear what these units are, and hence identification of the most appropriate test item is difficult. Even if a unit of perception could be delineated, a test requiring recall of a non-meaningful list of, for example, phonemes, does not give the same memory task as recall of a sentence containing the same number of phonemes. Rees (1981) notes that if an organisation can be imposed on material, recall or retrieval usually improves, both for short-term and for long-term memory. Drawing from the work of Olsen (1973), she suggests that memory ability is so linked to organization of material that it is the child's ability to organise the input that imposes and defines the limits of ability. Language development and performance on tasks of auditory memory may be mutually dependent, which further limits the usefulness of this measure as one of underlying auditory ability.

1.7.3 Auditory Synthesis

Sound blending, phonemic synthesis, and auditory synthesis are tasks in which a child is required to listen to words presented one phoneme at a time, with a silent interval between each. The rate of presentation varies between tests. The child is required to say the words (i.e. to 'blend' the phonemes). A major proponent of this test task is Katz (1983) who relates difficulty with phonemic synthesis to specific lesions. He reasons that a deficit in this area of language may cause subtle difficulties, not apparent during the years that speech is presented slowly and simply to a child, but becomes more obvious with increasing exposure to more complex language. Katz proposes that a test of phonemic synthesis is a form of distorted speech, and hence taxes the auditory system. This hardly appears as a unitary task of auditory function. Katz is correct in identifying this as a difficult task, but the origins of the difficulty must be complex. It is apparent that to complete this task, a degree of linguistic maturity is necessary; the conclusion that this ability is an auditory process fundamental to language must be considered to rest on very little evidence. Phonemic synthesis has long been associated with reading and spelling: there is rather more evidence for investigating this area in children with reading and spelling problems, but not necessarily for regarding it as an auditory deficit.

1.8 HEARING ACUITY DEFICIT AND CENTRAL AUDITORY DYSFUNCTION

This review of methods currently available for assessment of central auditory function highlights the difficulties inherent in using behavioural tests with children who have normal peripheral acuity. These deficiencies become more important when testing children known to have acuity deficits. Much of the debate surrounding auditory tests stems from differences in the so called "Top Down" or "Bottom Up" theories of speech processing discussed earlier. It seems that tests of central auditory function give little diagnostic information in the assessment of children's hearing. The difficulty lies primarily in finding a task which is sufficiently difficult to tax the highly redundant central auditory system, without increasing the weighting on cognitive factors and language maturity. At best, most of these tasks reflect a functional measure of difficulty in particular situations. The addition of any peripheral hearing impairment to the test situation renders interpretation of most of the tests described impossible, as was implicit in the descriptions of the individual procedures. In general, their suitability for the assessment of central auditory problems in children with acuity deficits seems minimal. The calibration and standardisation of each of these tests is at best fragile and their suitability for use with unquantified and asymmetric input is negligible. Some authors (e.g. Protti, 1983) firmly believe that use of these tests in this manner results in over interpretation. There is clearly room for a diagnostic, site of lesion assessment that can be used, independent of age effects, hearing loss, and linguistic bias, and for this reason attention turns to the application of auditory evoked potentials.

1.9 AUDITORY ELECTROPHYSIOLOGICAL RESPONSES AND CENTRAL AUDITORY DYSFUNCTION

Although ep responses may be used in site of lesion assessments, they do not provide functional evidence of a child's central auditory processes. The responses may be used currently as a demonstration of abnormality in the central auditory pathway. If ep responses are used to test the integrity of the central auditory pathway at different levels, some insight into the nature of the auditory difficulties confronting a child may be gained by deduction. This is particularly true for children with confirmed losses in auditory acuity where, as stated at the outset, little attention is given to the possibility of central auditory disorder, and where in any case, the behavioural tests are either invalidated or subject to questionable interpretation. Few studies have attempted to identify central auditory problems in this way, particularly with children with known pure tone deficits or normal hearing.

Ep measures have long been of interest to the cognitive psychologists, who have predominantly examined the relevance of the Contingent Negative Variation (CNV), particularly in the area of attention. (e.g. Cohen, 1974; Luria, 1973; Teece, 1972). There have been fewer studies on behavioural correlates of the earlier responses. Some of the more notable are discussed below.

The Slow Vertex Response (SVR) has been examined as a physiological correlate of selective attention (Hillyard and Kutas, 1983; Teyuing, 1978) and possibly short-term memory. Stanny and Elfner (1980) found a linear relationship between N1 amplitude and the accuracy of short-term recall for tonal sequences. They concluded that this component of the response might reflect central processing of briefly stored sensorimotor information. Naatan (1982) reached a similar conclusion based on a review of selective attention studies. Mittenberg et al. (1985) also supported the theory that N1 reflects the accuracy of the short-term memory image, based on experimental work with normal subjects and chronic alcoholics.

In an early series of experiments, Seitz (Seitz, 1972; Seitz and Weber, 1972; and Seitz et al., 1980) explored the use of the SVR, waves N1 and P2, to measure aspects of linguistic processing and hemispheric asymmetry as an initial step towards the development of a speech perception diagnostic procedure. He used the SVR as a monitor of the EEG activity of 24 subjects who had to locate a click superimposed on sentences using two different response methods. Their results supported the notion that different hemispheric activity occurred in syntactic processing, and that measurement of the SVR was a useful monitor of this.

There have been only a few attempts to utilise the ABR in the assessment of central auditory language and learning problems in children. (Lenhardt, 1981; Piggot and Anderson, 1983; Roush and Tait, 1984). Seitz and his colleagues also studied the relationship of the reported sex differences in the latency of the ABR to speech and language processing in humans (Seitz et al., 1980). Seitz relates the latency differences found to the female advantage documented in auditory processing, rather than to differences in pathway size. Females acquire language earlier than males, have better sound discrimination abilities and lower touch and pain thresholds than males. His theory is compatible with findings by Stürzebacher and Werb (1987) that there is a gender and age interaction for the Wave V latency, and that reported latency differences are due to the differing time courses of the development of the response in males and females. Morphologic asymmetry between left and right temporal lobes occurs earlier and is more efficient in females than males. Epidemiologic evidence indicates that male children are more susceptible to certain neurological disorders such as autism, some forms of cerebral palsy, reading disabilities and language disorders. They suggest that the ABR reflects events in the brainstem which lead to heightened perception of loudness, extra attention to auditory stimuli via delayed habituation, and shorter transmission time through the brainstem, and that these, in turn, might provide a small but substantial advantage in earlier language learning abilities.

Combined ep recordings have been used by Hecox and Hogan (1982) to examine the central auditory system in normal hearing children with language deficits. Their results from 50 children revealed at least one abnormality from across the response range, suggesting the technique has prognostic value in the assessment of speech and language problems, though the practical implications of this study are not yet clear.

Mason and Mellor (1984) studied a range of early to late ep responses in a group of children with severe language or motor speech disorders. These authors examined the topography of the responses and found significant inter-group difference, in amplitude but not latency, particularly in the early waves (ABR). They found the MLR to show site specific amplitude differences between the motor speech and the other groups, and the cortical responses to show hemispheric dysfunction in cases of language disorder. These results are convincing in that the ep responses have been successfully associated with language and other speech problems and suggest the possibility of underlying central auditory disorder.

The authors explain each of the following abnormalities. They attribute the ABR amplitude abnormalities to possible peripheral deficits, too small to cause acuity reduction, or to anomalies in the tissue conductivity. The former reason seems more probable. The high amplitude MLR responses recorded from the motor speech group could be a result of enhanced myogenic activity, from a group where the myogenic activity is not normal. The hemispheric differences observed in the language disordered group during recordings of the SVR are attributed to abnormal functioning of the left temporal lobe. Supporting evidence for this conclusion is taken from adult studies on acquired aphasia. They felt this measure to be the most useful in studying language disorders using ep methods.

A more specific comparative study of eps and psychoacoustic effects was carried out by Scherg and von Cramon (1986), who examined patients with confirmed cortical lesions. They used a dichotic psychoacoustic discrimination task and compared results with a map of dipole source activity, transformed from middle latency response data. Their test material was non-verbal and reportedly performed without difficulty by the patients. Two of their 21 cases demonstrated correlating deficits, according to the interpretation put on their psychoacoustic test results. According to these authors, a strong diagnostic technique lay in a combination of the test methods. The dipole lesion detection method distinguishes their work from that of Woods et al (1984), who were not able to demonstrate these specific associations.

Another study relating the ABR results to psychophysical studies was carried out by Hausler and Levine (1980), who made estimates of the just-noticeable difference (JND) for intra-aural time and intensity in patients with MS. In general, their results showed that patients with abnormal time JNDs had abnormal ABRs on at least one side, while those with normal time JNDs tended to yield normal ABRs. The authors suggest that these results indicate that the same auditory structure of the brainstem subserves intra-aural time discrimination and short latency click evoked potentials.

Researchers report use of ep responses to auditory stimuli to monitor some aspects of neural development. As the central auditory system develops, during the first two years of life, clear and well documented morphologic changes are seen (e.g. Hecox and Galambos., 1974). Therefore age related latency changes in the ABR are presumed to reflect neural maturation processes. The ABR latencies may indirectly measure the amount of brainstem myelination in the auditory system. The ABR responses have also been shown to increase progressively after birth in full-term healthy infants, but not in all pre-term infants (e.g. Salamy et al., 1980; Kaga et al., 1986). Although the clinical outcome and the neural basis for the amplitude discrepancies are uncertain, it is thought that there may be a correlation between ABR abnormalities and childhood disorders such as autism, minimal brain dysfunction, and psychomotor retardation. Correlative data in older children suggest that abnormal ABRs are associated with autism, muscular hypotonia, and severe language impairment. It is also thought that so-called sensitive tests using the ABR such as peak amplitude comparisons under differing stimulating conditions, may be suitable detectors of central pathology (Antonelli et al., 1986).

An investigation into central disorders using electrophysiologic measures was carried out by Protti (1983). She tested 13 children, referred for learning disabilities, on three behavioural measures (binaural fusion, rapidly alternating speech, and the SSW test) and with an ep measure (auditory brainstem responses). She found a strong positive relationship between abnormal performance on subjective and objective brainstem measures. This was the only ep measure she used and she did not, in fact, find the ABR measure to reflect functional ability. In assessment of children with hearing-impairment, the information sought is less subtle, so her caution may be of less relevance.

Kileny and Robertson (1985) found the ABR to be a sensitive indication of neurological involvement in the area of the midbrain and pons. In their investigation of the neurological aspects of infant hearing impairment, they used it to study the effects of hypoxia, anoxia, and asphyxia. They have also carried out one of the few studies to look at differential thresholds of ep responses to look for damage at higher neurological levels. These authors found that they were able to record normal ABRs from children later found to have significant delays in speech and language development. Each of these children was also found to have absent SVR responses. Their interest was from a clinical neurological angle, and the case studies they quote are associated with brainstem damage. However, this study provides further evidence that application of auditory ep measures to a group diagnosed as hearing-impaired, but with wide ranging speech and language abilities, is a logical investigative step.

The ABR has been recorded to examine the effect of recurrent conductive hearing impairment on the central auditory system. Anteby et el. (1986) demonstrated increases in inter peak latencies and inferred that a type of sensory deprivation phenomenon was occurring to increase central conduction time. This is interesting given the emerging evidence for educational disturbance resulting from recurrent serous otitis media.

There are sufficient reports in the literature of discrepancies between ABR findings and behavioural threshold measures, in the absence of clinical evidence of brainstem damage, to alert interest in the application of a series of ep measures to hearing-impaired children. Davis and Hirsh (1979) mention instances of absent ABR in children who behaviourally responded to moderate or low intensity sounds. They report a population incidence of 0.5%. Worthington and Peters (1980) published four case reports of patients with absent ABRs and severe, rather than profound, hearing loss. Lenhardt (1981) reported on a case in which only Wave I was obtained from a patient with normal pure tone hearing. Kraus et al. (1984) found a number of patients who had absent ABRs or no detectable Waves III or V, with no clinical signs of brainstem neuropathology and no more than a moderate hearing loss by behavioural measures. These studies have alerted interest in the application of ABR results to the investigation of communication skills. Absent ABRs may result from the disruption of the neural synchrony necessary for ABR generation. Minor degrees of myelination deficits, or destruction of cell bodies may result in loss of neural synchrony sufficient to retain sound perception, but insufficient to generate the ABR response. It has also been suggested that the ABR generation may only loosely be related to actual hearing sensitivity, and may be related more precisely to some highly specific aspect of auditory function, such as encoding of inter-aural time relationships (Rohrbaugh, 1987). In these cases of absent ABRs, it may still be possible to record later ep responses, as was indeed found in the study by Kraus and her colleagues.

A less optimistic view of the potential of serial examination of the eps is provided by Parving et al. (1981) who examined the ECoG and SVR responses from patients with and without neurological signs. These authors felt that the method foundered as a means of detecting central auditory problems on the unreliability of the SVR. They did not, however, utilise the ABR in their study, focusing instead on the ECoG..

There has been interest in the application of the technique in the investigation of infantile autism, a disorder where sensory deficits are particularly evident in the auditory modality (Bruneau et al., 1987). In an early study, Sohmer and Student (1977) tested three groups of children, 13 diagnosed as autistic, 16 diagnosed as having minimal brain dysfunction, and 10 having psychomotor retardation. The authors proposed the hypothesis that the auditory input in autism is sufficiently altered to account for the failure of autistic children to develop specific language skills. This, they thought, may be reflected in the ABR results. In their study, Student and Sohmer found the ABR to be absent in four of the children in the autistic group, suggesting that they also had a profound peripheral hearing loss. The ABR results of the remaining nine children were present to normal threshold levels, but significant delays of all the response peaks were observed. They found similar results for the group of minimally brain-damaged children and for the retarded group, and found these results to support their hypothesis.

Similar results were found in more recent studies by Rosenblum et al. (1980) and by Tanguay et al. (1983), although they caution that the dominant characteristics of autism may be a phenomenon additional to the disruption in the peripheral or lower brainstem auditory processing mechanisms. Tanguay et al. tested 16 autistic children from 2½ to 14 years of age. Their results were compared with 28 normal hearing children recruited from local schools, and of similar age range and mean age. These authors found moderate to severe delays in the latency of Wave I among the autistic group three of which were beyond 4 s.d.'s of the normal. This occurred at three supra-threshold intensity levels, but in other subjects the delay was only seen at the lowest test intensity of 42 dB re normal click threshold.

Tanguay et al. also found asymmetry in their results, the delay at low intensities only being present on right ear signal presentation. These results also suggest that there is physiologic evidence that autistic children do not process auditory stimuli in a normal fashion.

The diagnostic information that the ABR yields on site of dysfunction in the auditory pathway, is finding a role in the identification of a wide range of audiological, neurological, mental and behavioural impairments. Careful use of the technique in conjunction with good behavioural techniques, where possible, should yield a greater insight into the audiological and neurological status of the child with a severe hearing loss. These exploratory studies demonstrate an increase in interest in the application of auditory eps to the study of speech and language problems. It is a logical step to develop this work further with hearing-impaired subjects at risk for these problems.

1.10 OVERVIEW OF AUDITORY ELECTROPHYSIOLOGICAL MEASURES

The clinical recording of auditory evoked potentials is a comparatively recent technique. The first commercial system was produced in 1970, but this was discontinued only three years later due to inappropriate choice of recording paradigms. Yet the preparatory work could conceivably be dated back to Galvani's discovery of the electrical activity of biological tissue in 1790. A hundred years later, Caton demonstrated to the British Medical Association (1875) that electrical potentials could be recorded from the brains of rabbits and monkeys and that these potentials varied over time. The electrocortiograms, as these measurements became known, were first photographically recorded by Pravdich Neminsky in 1913, using a string galvanometer. A number of rapidly consecutive and parallel discoveries were then made, laying the foundations for today's knowledge of auditory evoked potentials.

In 1929, Berger demonstrated recordings of the first human electro-encephalogram (EEG) from scalp electrodes, and the following year reported a change in the rhythm from a sleeping subject following presentation of a loud noise. This "K" complex, as it was called, was renamed the "V" potential, by Hallowell Davis, because it is the most prominent wave recorded from the vertex. Around the same time (1926) Davis and his colleagues identified the important all-or-none characteristics of the auditory nerve impulse, and it was in 1930 that Wever and Bray impressively demonstrated the waveform replicating properties of the cochlear microphonic potential. Derbyshire and Davis, in 1935, were able to publish a study of action potentials in the auditory nerve, by which time the distinction between the cochlear potentials and the eighth nerve potentials had been identified.

Despite rapid advances in cathode ray oscilloscopes in the years following the 1930s, further developments in this area remained extremely slow until the advent of the electronic averager, because of the small size of the responses and the problems of extracting them from the background noise. Dawson (1954) is attributed with having described the first electronic averager which was in fact a photographic superimposition technique. The device could only handle a limited number of averaged signals. Clark (1958) laid the foundation for today's techniques. He developed a device which employed an analogue to digital converter and then averaged the digitally stored signal. This development opened the way for study into auditory evoked potentials. By this time, it was hoped that the technique could be used to make audiometry more objective and hence obtain auditory threshold data from populations previously found to be too hard to test. It was also becoming apparent that the integrity of various parts of the auditory system could be tested with auditory potential techniques.

The earliest recorded application of the evoked potentials to threshold qualification was made by Geisler (1958), who used clicks to evoke auditory potentials and collected data over the first 100 ms after signal onset over a 90 dB range of intensity levels. This important study demonstrated that a subject's psychophysical threshold could be determined using an auditory evoked potential technique. Following this work, controversy arose as to whether these potentials were myogenic or neurogenic in origin. Bickford et al. (1964) and Cody et al. (1964) showed, partly by the dramatic method of use of injected curare (a muscle paralyser), that the responses recorded by Geisler et al. were largely myogenic in origin, a finding which still affects the technique of recording neurogenic potentials at these latencies today.

Prior to Geisler's work, most attention had focused on cortical responses, since Pauline Davis' discovery of the "V" potential. This response proved to be less suited to the task of threshold determination than originally envisaged, as the underlying EEG is influenced by the effects of natural sleep and sedation, rendering response identification difficult. Interest in auditory evoked potentials was revived from a fairly slack period by the studies of Ruben et al. (1960, 1961 and 1963), who recorded clear cochlear and auditory nerve potentials during middle ear surgery, with the help of the recently developed averaging computer. This was followed by ear canal (Yoshie et al. 1967), earlobe and mastoid (Sohmer and Feinmesser, 1967), mastoid and scalp (Spreng and Feinmesser, 1967) and bony promontory (Portman et al., 1967) recordings. Comparison of auditory nerve and cochlear potentials, recorded from an ear canal or promontory active electrode, are now routine in many clinics of the world for site of lesion assessments and for determination of auditory threshold of the peripheral auditory system. It has been shown to be a safe (Crowley et al., 1975) and reliable procedure, and commercial instrumentation for the procedure is now readily available.

Today, the most commonly used auditory evoked potential is recorded from the brainstem via scalp electrodes. The response was described by Jewett and his collegues, in 1970, and by Lev and Sohmer, in 1972, as a series of five or more waves generated from sources in the brainstem and recorded in the first ten ms following stimulus onset. Hecox & Galambos (1974) applied the technique to a study on infants and adults and Thornton (1975) defined important statistical properties of the technique for clinical use.

A result of these early studies and of numerous, more recent, studies into the pathologic and non-pathologic characteristics of the responses, is that selective recording of potentials evoked by auditory stimuli from various locations along the auditory pathway can be made. The rapid development of the microprocessor has brought versatile and sensitive recording equipment into the clinical situation and the recording of auditory evoked potentials has become an accessible clinical tool. With appropriate choice of stimulating and recording parameters, auditory evoked potentials may be used to assess threshold in those patients who are otherwise difficult to assess. In many cases, this technique may indicate the location and pathophysiology of a disorder affecting the auditory pathway. The potentials used in the present study are classified as transient responses in contrast to the perceptual responses which were not considered approriate for use here, for reasons given below.

The most commonly recorded of the perceptual responses is the event related response, P300, so named as this main peak is a positive wave occurring about 300 ms after the stimulus. Three types of P300 are described by Courchesne (1979), the differences being in scalp distribution and type of stimulus event. The first is recorded maximally over the vertex and is elicited by non target events that are unrecognisable; the second is maximal over the parietal cortex and elicited by non target and easily recognisable events; the third is also maximal over the parietal cortex, but is elicited by any target event.

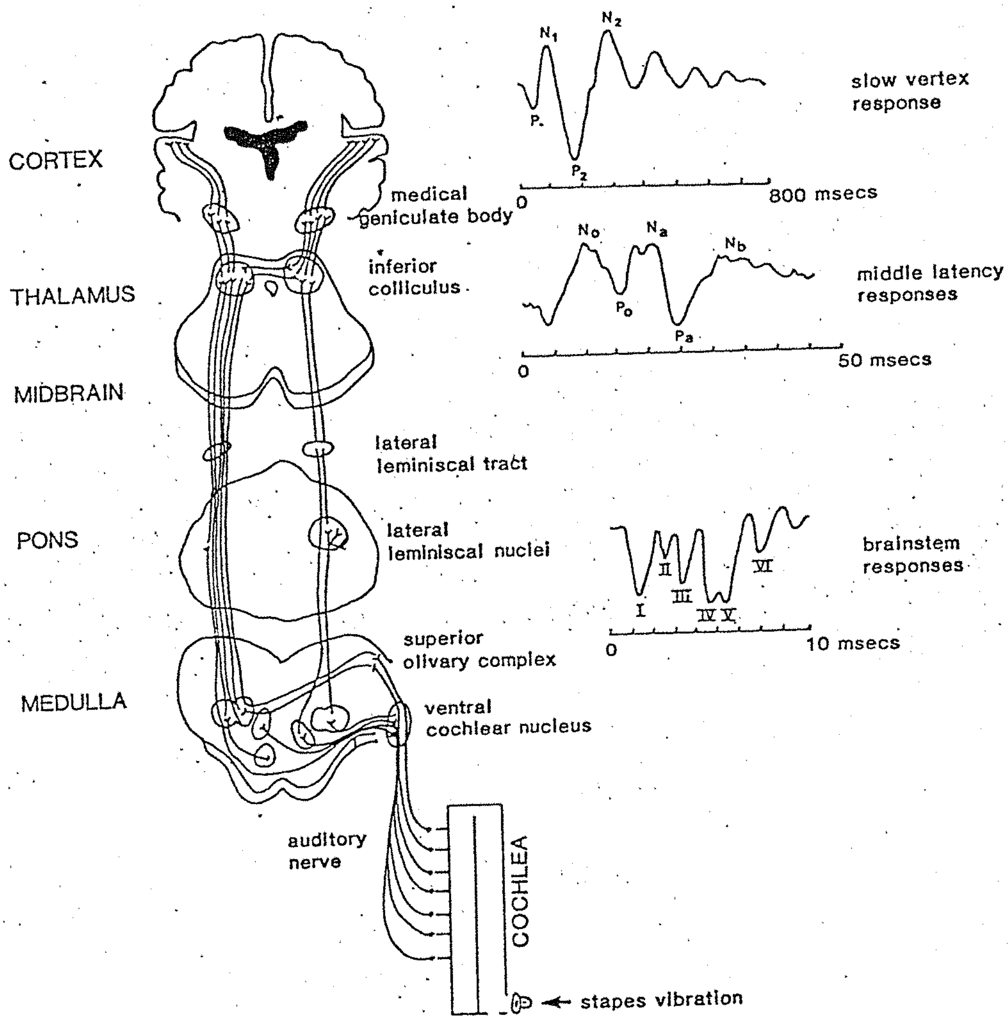
Another type of perceptual response is described as the Contingent Negative Variation (CNV). First described by Grey Walter in 1964, it appears as a slow DC shift in the baseline following one stimulus, when, as a result of conditioning, the subject expects a second stimulus,in response to which he is required (i.e. 'expects') to carry out a task. These responses have been found to be influenced by concentration and fatigue, subject age, health, and task difficulty (Lasky 1983).

The P300 was not considered suitable for use in the main study. An advantage of the perceptual responses is the high neurological level investigated, so that the entire pathway is tested, and for a positive response the subject must perceive the stimulus. With the test population in this study, however, a nil response would be difficult to interpret. The children are all severely hearing-impaired, and it is probable that they all have at least some cochlear damage, so that calibration of the test stimulus would be meaningless. The difficulty in distinguishing the phenomena "not processed peripherally" from "not perceived" reduces some of the advantage of ep testing over behavioural testing, but it does provide an objective measure of peripheral integrity. Use of the P300 response in conjunction with other techniques is not practical at this stage due to the extensive time required in the test procedure and in the preliminary development work necessary. These responses will not, therefore, be discussed further.

The remaining commonly used auditory evoked potentials will be described in more detail and a comparative summary of their main features is given in Table 1.1. A normal waveform for each response, related to its approximate generating site in the auditory pathway is shown in Fig. 1.4.

Response	Latency ms	Probable Source	Main Applications	Strengths	Weakness
Auditory nerve and brain stem (ABR) Waves I - VII	1.5 to 6	Auditory nerve Pons Midbrain Thalamus	Threshold evaluation Localisation of retrocochlear dysfunction	Repeatable Stable to sleep sedation etc. Rapid stimulus Presentation acceptable.	As a threshold measure, lack of frequency specificity is a disadvantage
Middle latency response (MLR) Po, Na, Pa, Pb	10-100	Thalmus Primary Auditory cortex	Threshold evaluation at all frequencies	Stable to sleep	Interference from post auricular muscle response in working state
Slow vertex	50-300	Cerebral cortex	Threshold evaluation at all frequencies	Frequency specific High amplitude response	Poor results during sleep Lengthy procedure Low signal to noise in children

The Transient Evoked Potentials Table 1.1



THE AFFERENT AUDITORY PATHWAYS AND AUDITORY EVOKED POTENTIALS

Fig 1.4

1.11 PROPERTIES OF THE SLOW VERTEX RESPONSE

The slow vertex response (SVR) is a triphasic waveform occurring between 90 and 250 ms after the stimulus. The waveform probably arises from several generating areas; notably, the auditory cortex, the temporal auditory association cortex, and the frontal association areas, as described by Vaughan and Ritter in their potential mapping study of 1970. There is some controversy surrounding this work, but the balance of evidence, including work on dipole source potentials (Scherg and von Cramon, 1986), supports the view that most of the SVR components are generated in the primary and secondary auditory cortex. Intracranial recordings have not resolved the dispute, but rather have shown that evoked potentials which appear to correspond to the slow vertex potential are recorded diffusely throughout the depth of the brain (Goff, 1978; Woods et al., 1987). Goff and his colleagues (1977) found a maximum amplitude of response in the mid central region at first, supporting the theory of a modality specific response area in the auditory cortex. They also found a very similar waveform to somatic stimulation, which they suggest could indicate a non specific origin in central sub-cortical structures. Studies on patients with temporal lobe lesions have provided conflicting results, again probably due to the differing extent of lesion (e.g. Auerbach et al., 1987; Woods et al., 1987) and are inconclusive.

The SVR is generated in response to a change in the auditory environment. Sayers et al. (1974) believe the response to be mainly due to a reorganisation or constraint of the phase spectra of the existing spontaneous activity of the EEG. They have been able to utilise this, more recently, in the development of automatic response recognition, a technique which has been explored by several methods (e.g. Barford and Saloman, 1978).

The response is widely recorded from frontal and central scalp areas and is maximal at the vertex, with bilateral symmetry around it. It is elicited at the on-set or the off-set of a tone, or to a modulation of the frequency or the intensity of a tone, with difference limens of the order of subjective detection.

The amplitude of the response increases with stimulus durations up to 25-30 ms. There is some debate as to whether or not the effects of temporal integration are reflected (Skinner & Jones, 1968; Hyde, 1976). It is therefore possible to elicit responses to pure tone stimuli. These features of the response suggest it to be an excellent tool for the assessment of threshold across the speech frequency range, but a number of technical and recording difficulties detract from its use. The signal-to-noise ratio may be low in recordings from younger children. Although the amplitude of response is in the same range in all age groups (3 to 20 µV), the amplitude background activity in children may be of the order of 50 to 400 µV, four times higher than for adults. The signal-to-noise ratio decreases with decreasing signal intensity, increasing the difficulty of response identification near threshold. Additionally, the response amplitude and morphology is unstable, even under constant stimulus conditions. This also reduces the strength of the technique as a threshold determinant as the response cannot always be identified, by visual inspection, at stimulus intensities near threshold. The recordings from children are often overlaid with artefacts, originating from transient EEG signals, DC potential shifts related to changes in brain activity, and myogenic activity (Barford and Saloman, 1978). The spectral energy of the response overlaps with the spectrum of the common EEG rhythms, most commonly alpha rhythms, and subject state is of great importance.

The response morphology is markedly altered during sleep or sedation, because of the variance and specific changes in the background EEG rhythms, which fall into the frequency range of the response. Response identification is more difficult during sleep. Sleep recordings and response identification have been successfully carried out by some authors (e.g. Skinner and Antinoro, 1969) but natural sleep is less commonly encountered than sedation, by drugs, which tend to increase the beta and theta activity in the background EEG. The response amplitude is increased by attention and, again, if levels change markedly during one recording, response identification is more difficult, although effects on response threshold are small.

Despite these reports, in co-operative adult subjects and older children, the SVR thresholds have been measured close to psychoacoustic thresholds. Davis et al. (1967) reported a mean discrepancy across frequencies of 2.2 dB (maximum 15 dB). Beagley and Kellogg (1969) found a difference of 2.6 dB; Mason et al. (1977) a difference of 1.7 dB. Coles and Mason (1984) did not report a mean discrepancy, since they found the mean SVR threshold to be within 15 dB of the mean psychoacoustic threshold in only 3.2% of cases. Most reports of threshold determination in children under 6 years give less close agreement, of the order of 20-30 dB (e.g. Jones et al., 1975). There is an interaction between the maturation of the response and sleep effects and Shucard et al. (1987) indicate the need for maturation studies with awake infants. These authors have shown that there are changes in the latency, amplitude and intersubject variability over the first 6 months of life.

The late, or slow, response appears as a useful determinant of pure tone thresholds, particularly at low frequencies, because frequency specific responses may be obtained. The objective estimate is based on a response originating at a high neurological level. The disadvantages to its wide adoption as a threshold estimator are the length of the procedure and the dependence on subject state and the presence of too many false positive statements of hearing loss (Parving et al., 1981). Clearly, both are major disadvantages in the assessment of children. Future trends to improve the technique, are likely to lie in objective response detection. As the response appearance changes so markedly with subject state, objective detection by phase analysis is the most promising alternative to make this a robust response.

1.12 THE MIDDLE LATENCY RESPONSE

The neurogenic middle latency responses are coincident in time with the sono-motor myogenic potentials recorded from the mastoid process. This has led to long controversy as to the origin of the potentials (Bickford et al., 1964; Cody et al., 1964) and certainly still leads to confusion (Sammeth and Barry, 1985; Scherg and von Cramon, 1985). The neurogenic nature of the response was demonstrated by Ruhm and Flanigan (1967) using electrodes in the dura of the brain. However, contamination from myogenic activity does occur, and is reduced by careful placement of the recording electrode. At high stimulus intensities, there may be contamination from several scalp muscles. These are the postauricular reflex, the temporalis reflex, and the inion and frontalis reflex. The middle potentials consist of a negative/positive peak complex (No-Po), which corresponds in time with the ABR IV/V complex (Kavanagh et al., 1983), followed by three more prominent peaks Na, Pa, Nb (Picton et al., 1977) in the time period 10-50 ms following the auditory stimulus. The latency of the response is quite consistent within the same subject (Kileny and Shea, 1987) with Pa probably being the most robust of the peaks. The response amplitude varies from about 0.7 to 3.0 μV, depending on stimulus and recording parameters. As studied in adults, the response is identifiable in natural sleep, or following sedation, though some amplitude reduction and response instability occurs, and the threshold estimate is reduced in sensitivity (Mendel et al., 1975; Prosser and Arslan, 1985). The responses are essentially unaffected by varying attention to the stimulus (Picton and Hillyard, 1974; Woldorf et al., 1987).

1.12.1 Middle Latency Response Origins

The neurogenic nature of the response is established, but the origin of the response is still a controversial topic. Picton et al. (1974) listed several possible generator sites in their review papers: the thalamus and the association cortex in the frontal, parietal or temporal lobes, ruling out a significant contribution from the primary auditory cortex. They cited the study of Celesia and Puletti (1971) who failed to detect a temporal correspondence between the scalp-recorded MLR and responses recorded from the exposed human primary auditory cortex. Goff et al. (1977) failed to be able to record the MLR from patients during barbiturate anaesthesia, and concluded that the primary auditory cortex could not be the generating source for the potential. However, Kaga and Tanaka (1980), and Buchwald et al. (1981), deduce from experimental data from animal studies that the primary auditory cortex and reticular thalamus projections are probably involved in their generation. Other animal studies (Gardi and Bledsoe, 1979) suggest that the substrate of the middle components is at several levels above, and including, the inferior colliculus. Further support comes from Erwin et al (1987) who concluded that the human and cat components of the response were differentially affected by several functional and parametric variables, suggesting different underlying mechanisms for the two species. Polich & Starr (1983) suggest that the early middle latency components (No, Po, Na) might arise from the medial geniculate and poly-sensory nucleus of the thalamus, while the later portions of the waveform are found over wide areas of association cortex (Picton et al., 1974; Davis, 1976). Human intra-cranial recordings from the superior surface of the temporal lobe have yielded a wave similar to the scalp recorded Pa (Celesia, 1976). Kavanagh et al., (1984), noting the latency correspondence of the ABR IV/V complex and

Po, found the energy spectrum of Po to extend from Wave II to Wave VI and controversially suggest its origin to represent a combination of several of the generator sites of the ABR. Thus, the precise substrate of the response complex is unclear but seems to include a component from the thalamus.

Support from patient studies for a temporal lobe locus is also variable, probably partly, because of the difficulties inherent in precisely defining the extent of the lesion, and partly, because of the small sample sizes in most studies. In a paper combining an informative review of previous studies of bitemporal patients, with the MLR and SVR recordings from five patients, Woods et al. (1987) inferred a multi-generator basis for the response. Their work does not support generators located exclusively in primary auditory cortex or auditory association areas. Parving et al. (1980) reported on a patient with auditory agnosia and documented bilateral temporal lobe lesions who showed normal MLRs. Ozdamer et al. (1982) reported on a patient with bilateral temporal lobe lesions, inconsistent awareness of sound, and impaired pure tone sensitivity whose MLRS were not normal. Kraus et al. (1982) found the response to be normal in the majority of patients whom they tested with cortical lesions.

Surface electric field studies of generator sites are promising. Vaughan and Ritter (1970) concluded that the orientation of the primary auditory cortex can account for the vertex response, because of the summation of the fields of the temporal lobes. The response is maximally recorded at the vertex (Wood and Wolpaw, 1982). Evoked magnetic field measurements support this view, showing vertically orientated dipoles located close to both Heschl's gyri and corresponding to the electric N_{100} activity (Elberling, 1982). Vaughan et al. (1980) extended their earlier work to attribute Pb and Na to sources in the lateral surface of the superior temporal gyrus. Scherg and von Cramon (1985) developed a spatio-temporal dipole model and identified two bilateral sources of the wave forms within the temporal lobe. The localisation, orientation and latency differences suggested that sequential activation of primary and secondary auditory cortex is the predominant source of the late auditory eps.

There is still some controversy as to the bilateral nature and the binaural interaction effects of the response. Peters and Mendel (1974) found the response configuration to be unaltered independent of stimulus ear and binaural or monaural stimulation. Wolf and Goldstein (1978), recording from infants, found a more identifiable response ipsilateral to the stimulus but, in contrast, Kraus et al. (1982) argue in favour of a bilateral generation theory, on the basis of the symmetrical distribution of the Pa amplitude over the temporal lobes. The dipole source potential work of Scherg and von Cramon (1986) supports this view.

In summary, the middle latency response has been shown to yield threshold information, under a range of conditions. This threshold probably represents activity at the level of the thalamus, and perhaps higher.

1.12.2 The Middle Latency Response in Site-of-Lesion Studies

The latency of the response decreases and the amplitude increases with increasing stimulus intensity. However, the Na-Pa complex is less sensitive to intensity change than the earlier potentials. There is a strong relation between amplitude growth and intensity increase, but only a small inverse relation has been found for latency and intensity, which is further complicated by a frequency interaction (Thornton et al., 1977). McFarland et al. (1977) found a stronger interaction with both normal and hearing-impaired subjects, but noted that some differences may be due to methods of peak identification.

The middle latency response has been examined for its efficacy as an estimator of auditory threshold. Evoked potential threshold estimates range from 10 to 30 dB with respect to behavioural measures (Goldstein and Rodman, 1967; Madell and Goldstein, 1972; Kupperman and Mendel, 1974; Mendel et al.,1975; McFarland et al., 1979), but the response threshold is thought to have large inter-subject variability, relative to behavioural indices (Polich and Starr, 1983).

Less attention in the literature has been devoted to the diagnostic application of the middle latency responses, in comparison to the ABR. The early work in this field was primarily directed towards threshold evaluation (Goldstein and Rodman, 1967; Mendel et al.,1975). Leading on from this, examination of the differential thresholds of the ABR and MLR responses has been used to determine the site of lesion. As an example, Fourcin et al. (1985) report on a patient who had very poor speech discrimination, following a car accident. Electrophysiological thresholds were recorded at progressively worse intensities, at successively higher neurological levels, and brainstem injury was determined. Threshold comparisons were used as a diagnostic measure in this case.

The MLR has appeared to be a less promising clinical tool because of the inter- and intra-subject variability, which has been found to be large in comparison with the ABR (e.g. Terkildson et al., 1981), although more recent reports have found the component Pa to be stable in adults (e.g. Ozdamer et al., 1982). Studies show Pa and Nb to be the most consistent features of the waveform, but with a large amplitude variability. It seems probable that the MLR is the result of activity at several generator sites, making correlation with behavioural measures and site-of-lesion studies difficult. In the 1981 study by Terkildson and his colleagues, the Pa-Nb component was found to be well preserved in the tumour ear in recordings from 33 patients with neuromas, and unilateral hearing losses of up to 80 dB. These authors found the mean Pa latency in these pathological ears to be more than 2 s.d.s beyond the normal mean, and that, interestingly, there was also a Wave V-Pa latency increase. Two interesting studies have been reported describing recordings from cases with bilateral temporal lobe lesions, but differing functional hearing. Parving et al. (1980) found only minor abnormalities in the response from a patient with symmetrical high tone deafness; in contrast Ozdamer et al. (1982) found the response to be absent in a patient displaying total functional deafness. In both cases, the ABR was in the normal range. These contrastive results probably arise from slight differences in the site of lesion.

A large study was carried out by Kraus et al. (1982), in which the ABRs and MLRs were recorded simultaneously from 24 patients with anatomically defined cortical lesions of the left and right hemisphere, and with and without aphasia. They found MLR components, Na and Pa with normal latency and morphology, but reduced amplitude, from patients with either right or left hemisphere lesions, who showed normal ABR recordings. Two cases with more widespread involvement resulted in a more abnormal result. These authors did not find any correlation between MLR abnormalities and receptive and expressive language processes.

It seems that, with the current state of knowledge of the generating sites of the MLR, the most promising use of the response in the context of this study is as a threshold comparator with other ep response thresholds. The response morphology should also be examined, as this has been shown to be useful (Parving et al., 1980).

1.12.3 Non-Pathologic Factors Affecting the Middle Latency Response

1.12.3.1 Stimulus and recording characteristics

A. Auditory Stimulus

A(i) Rate Effects

The presentation rate of the MLR has been of particular interest since Galambos et al. (1981) described a response that approximates a sine wave with a period of 25 ms. This response appears when stimuli are presented at approximately 40 Hz stimulation rate and is colloquially referred to as the 40 Hz test (e.g. Kileny, 1983). It is the result of sequential summing of subsequent portions of the MLR, which has a fundamental period close to 25 ms. This response is consequently of larger amplitude than the MLR at suprathreshold levels (Galambos et al., 1981; Stapells et al., 1984). A comparison of the MLR, recorded to stimuli presented at 9.1 s^{-1} and 39.1^{-1}, by Kileny and Shea (1986), showed equal efficacy in threshold identification in normals. They found the '40 Hz' presentation to result in larger amplitude responses at threshold when clicks were used as the stimulus, but a less marked difference when a 500 Hz tone presentation was used. There appear to be interactions of stimulus rate, recording parameters and maturation effects. Kraus et al (1987b) found that detectability of the waveform varied inversely with the rate of stimulation in immature subjects only, but Kileny's 1983 study suggests that this may be an effect of reduced response amplitude in the infant recordings. In infants, Jerger et al. (1987) found very slow stimulus presentation rates to be optimal. That is less than 4 s^{-1}. Fifer (1985) suggests that the stimulus itself might be a critical factor in response characterisation. The main point of agreement seems to be a difficulty in response recognition. Stapells suggests that this be best overcome by objective response detection and he has devised a technique based on phase coherence (Stapells et al., 1987).

A(ii) Clicks and Frequency Specific Stimuli

Clicks and tones have been used to elicit responses, and the literature suggests that the MLR is more robust than the ABR to the use of tone bursts gated with slow linear rise times Ozdamer and Kraus, 1983; Kavanagh et al., 1984). In comparative studies of the ABR and MLR responses, the latter has been found to have the lower mean threshold (Musiek and Geurkink, 1981; Kavanagh et al., 1984), particularly if the stimulating and recording conditions are optimised (Galambos et al., 1981; Sammeth and Barry, 1985). Discrepancies from this (e.g. Ozdamer and Kraus, 1983) are thought to be due to differences in recording bandwidth. The MLR may be evoked by stimuli with slower linear rise times and consequently better frequency specificity (McFarland et al., 1977; Thornton et al. 1977; Kodera et al., 1979). The early studies of Goldstein (1967) employed clicks to achieve the required neural synchrony, but tone pips with short rise times are now commonly used. Vivion et al. (1976) showed that identification was enabled due to increased peak amplitudes when shorter rise times were used. The shorter rise times also resulted in reduced peak latencies.

B. Recording Characteristics

The slope and cutoff of the filters affect the MLR waveform (Jerger, 1987; Kraus et al., 1987a). In children this can affect the wave detectability, particularly during sleep. As with ABR studies, a number of filter settings have been used in the reported studies, hindering inter-study comparison of data. Unlike the ABR, it is the effect of the lowpass filter which is more pronounced. Commonly the highpass filter is set at 15 to 25 Hz using slopes of up to 48 dB/octave, and the lowpass between 85 to 175 Hz. The highpass filter is employed to reduce high amplitude, low frequency biophysiological noise. This is well demonstrated in the study by Kraus et al.(1987), who employed a very low highpass filter of 3 Hz, 6 dB/octave.

In a review of the literature, Scherg (1982) noted that the reported values for Na, recorded to click stimuli, range from 16 to 26,9ms and for Pa the range is 25 to 40.6 ms. Scherg demonstrated that steep highpass analogue filter slopes can cause so much distortion of the waveform that new peaks and completely altered waveforms emerge. He found the order of the filter to affect the amount of oscillations in the filter response and the amount of phase shift, and to cause artefactual enhancement of later components. In general, the major peaks show longer latencies as lower frequency activity is added to the recordings (Scherg, 1982; Kavanagh et al., 1984). Lowering the low-frequency cutoff causes an increase in the MLR amplitude (McGee et al., 1987) and also allows increased levels of low frequency noise, thereby reducing detectability of human MLRs (Suzuki et al., 1983a,b,1984; Kraus et al., 1987b).

Suzuki et al. (1983a,b) examined the frequency spectra of the MLR, and found the main power of the response to be located at the frequency range from 30 to 50 Hz, with a peak at 40Hz. The main power is in the 20 Hz region for children. Suzuki et al (1984) compared the effects of digital and analogue filtering on the response, and found analogue filtering of this degree to shorten the peak latency values, enhance the later components, and cause the artificial emergence of new components. He found that highpass filtering resulted in a reduction of the Na-Pa amplitude.

Selection of the MLR recording parameters should be made considering the stimulation rate and subject maturity, and in the knowledge of the introduced phase shifts. This may be particularly true in recordings from young children where the lower cutoff is coincident with the greatest peak in the response spectra.

1.12.3.2 Effects of subject variables

A. <u>Effects of Sleep</u>

Unlike the SVR, which is known to be susceptible to sleep and attention effects (Osterhammel et al., 1973; Graziani et al., 1974; Suzuki et al., 1976) and the ABR which is very stable under various levels of sleep conditions, evidence for the stability of the MLR response in sleep is uncertain (Mendel and Goldstein, 1969; 1971; Davis, 1976; Bobbin et al, 1979; Ozdamer and Kraus, 1983). The few studies on attention effects are not in complete agreement either (Linde et al., 1987; Woldorf et al., 1987). Some trends have been reported in each area but they must be interpreted with caution because of these inter-relationships. The studies indicate that there are large inter- and intra-subject variations during wakefulness, and this becomes more pronounced during sleep. Part of this controversy may be related to the parameters which are affected. Mendel and Goldstein (1971) studied latency effects, without placing emphasis on morphological or amplitude changes. Also, the study of sleep and age effects are inter-related and also dependent on the stimulating and recording parameters used. Similarly, the response appears to be unstable during sedation or anaesthesia (Prosser and Adams, 1985), although Smith and Kraus (1987), examining the effects of normal sedating agents on the response in guinea pigs, found response identification to be unaffected. Osterhammel et al. (1985) carried out simultaneous recordings of the ABR and the MLR response in the 40 s^{-1} recording condition, during conditions of natural sleep and full wakefulness. These authors found only minor changes in the ABR during sleep, but dramatic changes in the response morphology and latencies of the MLR. Their results appear to indicate that the 40 s^{-1} stimulus presentation mode of the MLR is not very effective during sleep due to the pronounced latency shifts of the different peaks in the MLR. Amplitude may be reduced, but Jerger et al. (1986), testing adults, found that the threshold values were not affected.

The response is differentially affected by sleep in children and adults. Okitzu (1984) found that sleep effects were of significance in children. He identified only one component, Po, as recognisable and this is probably the ABR Wave V. He considered the other waves to be largely unrecognisable. Okitzu and other authors (e.g. Picton et al., 1977) have also observed that the appearance of the response in sleep may be related to the depth of sleep. However, the adult response seems to be affected to a lesser degree (Mendel and Goldstein, 1971; Mendel, 1974; Kraus et al., 1980; Ozdamer and Kraus, 1983). It is the spectral content of the EEG, which is age related, and this affects the detectability of the SVR. High amplitude, low frequency EEG activity may obscure MLRs, most particularly in children. This is supported by the work of Suzuki et al.(1983a, 1984) who showed that the variability of MLRs in children can be reduced when low frequency EEG activity (below 20 Hz) is excluded by highpass filtering.

B. Effects of Age

The presence of a consistently obtained response is more open to question in children than in adults. From the foregoing sections it is apparent that this is, in part, due to the interaction effects of maturation, sleep, response morphology, stimulus rate and recording parameters (Sprague and

Thornton, 1982; Suzuki et al., 1983; Davis et al., 1983; Okitsu, 1984; Suzuki and Kobayashi, 1984; Prosser and Arslan, 1985; Kraus et al., 1985; Suzuki and Hirabayashi, 1987). Several reports exist of reliably obtained responses in children (Mendel et al., 1977; Wolf and Goldstein, 1978; Wolf and Goldstein, 1980; Mendelson and Salamy, 1981; Frye-Osier et al., 1982; McRandle et al., 1983). There are however other reports of unstable or absent responses (e.g. Engel, 1971; Skinner and Glattke, 1977; Hirabayashi, 1979; Davis et al., 1983; Okitzu, 1984). Engel tested 24 neonates, and found the response to be absent or unstable in the majority of his subjects. He detected the response in only 33% of his samples, although he was able to record the SVR in all subjects, confirming adequate hearing for the response to be elicited. Hirabayashi (1979) reported the detectability of Pa in 37 infants and children to be unstable. Okitzu (1984) found a similar rate of detectability of the Pa peak in a sample of 20 children tested asleep, but a higher rate of detectability of the Na peak (64 - 71%).

Suzuki et al. (1983a) found differences in the adult's and child's MLR response. Firstly, a different highpass filter setting was found to optimally record the Pa peak with the two subject groups. This indicated that the main power of the response was located around 20 Hz in children and they had previously found it to be around 30 to 50 Hz in adults (Suzuki et al., 1983). These authors also found that Pa, in adult subjects, was consistently followed by a positive peak, Pb. This peak was rarely observed in the assessment of the children, whatever filtering configuration was used. This is probably the phenomenon observed by Okitzu (1984) as a sleep related effect, as the children were tested in natural sleep or under sedation. The comparison adults were tested awake, relaxed or under sedation, but, as noted, sleep effects seem less pronounced in adult subjects.

Kraus et al. (1985), found age-related changes in the response. These authors tested 217 subjects ranging in age from 6 days to 20 years, all having normal brainstem responses, and they used a technique which had been used successfully to consistently record responses in adult subjects. Their patients classified into five categories; normal, mentally retarded, language delayed, post-meningitic, and miscellaneous. They used click stimuli and tested their subjects asleep, to reduce muscle artefacts, although this introduces sleep effects. These authors found that the chances of obtaining a response increased with age up to 10 years. From later studies (Kraus et al., 1987a,b) they infer that this is due to factors which influence the identification of components which are themselves affected by maturation, such as filter effects and stimulus presentation rate. Suzuki and Hirabayashi (1987) found a similar trend. They found the latency of Pa approached the adult value between 8 and 11 years, but that the later peaks of the response matured around 12 -14 years. In young children, they found the response to differ from the adult in having a broad and prolonged peak latency around 40 ms, in agreement with other authors. It is suggested that age-related changes may, however, be associated with maturation of non-specific thalamocortical pathways and sensory cortex, which is complete by the onset of puberty (Kraus et al., 1985).

1.13 THE AUDITORY BRAINSTEM RESPONSE

1.13.1. Auditory Brainstem Response Origins

The auditory brainstem responses occur as a series of distinct waves in the first 9 ms after stimulus onset, resulting from presentation of an acoustic transient. This is the most commonly and easily recorded of the auditory eps and the technique has become an established component of otoneurological investigations. The review of this response, given here, is in greater depth than for the other responses, reflecting the greater body of research, and its greater role in this thesis.

Clinical studies have favoured a theory of several generating sites along the auditory nerve and brainstem sites up to the midbrain. Experimental studies, however, have yielded conflicting results. Attempts to establish the sites of generation of the ABR have been made by three principal methods:

1) By comparison of in-depth electrode recordings in animal subjects, with surface recordings in human subjects (Jewett et al., 1970; Lev and Sohmer, 1972).
2) By study of the changes in the ABR recorded in non-human subjects, resulting from lesions; for example by transecting the brainstem or obliterating possible generating sites (e.g. Buchwald and Huang, 1975).
3) By intracranial recordings in human subjects and comparison with surface recording (e.g. Hashimoto et al., 1981, and Møller et al., 1981).

Each technique is subject to difficulties. For example, the correspondence between the animal auditory pathway in the brainstem and the human auditory pathway is not precise (Borg 1981). Secondly, lesions at a single brainstem auditory structure may affect only a single component of the ABR, but more typically the effect is on several components. This may occur by damage to fibre passing through the lesioned structure, or as a result of physiological disturbances to the generator remote from the lesion due to circulatory or pressure effects. Thirdly, the lesion may result in altered function of the remaining neural elements. Clinical studies are confused by the varying physiological extent of lesions, by the functional extent of lesions and by the lack of ipsi- or contralateral specificity. For example, it is known that the auditory pathways are predominantly crossed and yet lesions affecting the middle and upper part of the pons primarily produce ABR abnormalities ipsilateral to the lesions. Finally, the correspondence between human intracranial potentials and the scalp recorded wave is uncertain.

The generator theories that have evolved may be summarised along three lines of argument, with each being derived from a combination of techniques:

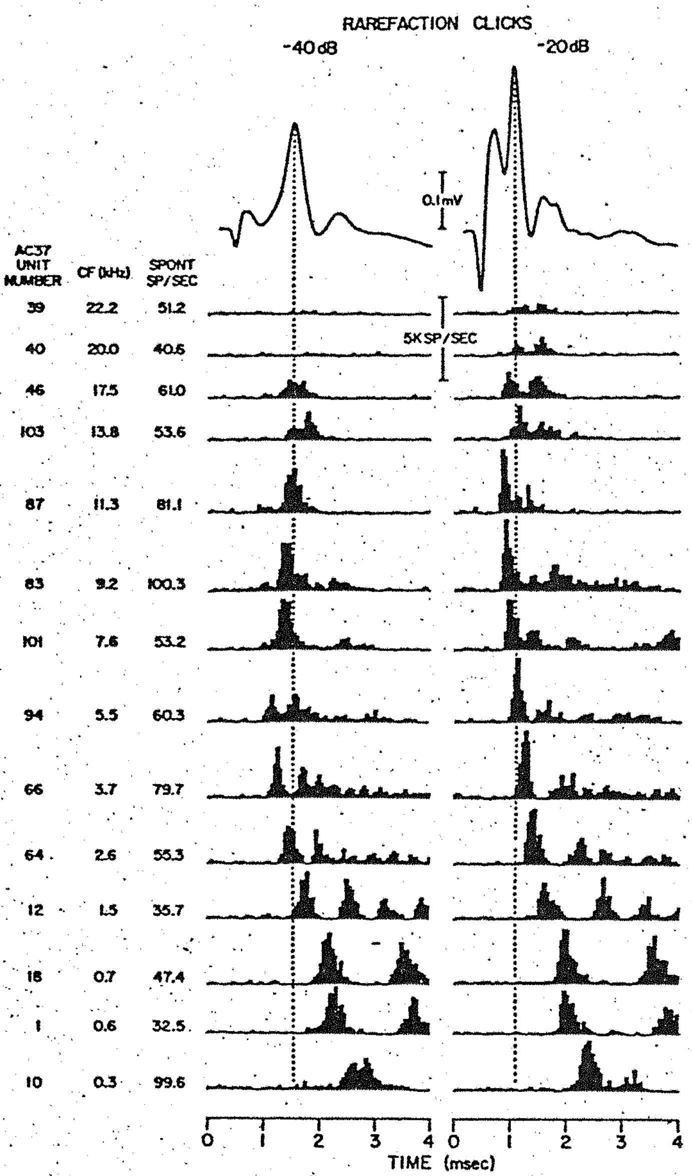
1) The response is composed of activity from multiple generator sites, with activity in different nuclear regions overlapping in time (e.g. Achor and Starr, 1980).

2) The response is due to sequential activity along the auditory pathway (e.g. Lev and Sohmer, 1972; Huang and Buchwald, 1979)

3) The response is due to a series of discrete sites, with second order activity not occurring before wave III. (e.g. Møller and Janetta, 1983)

The body of evidence indicates that N_1, as recorded by a transtympanic electrode from the promontory, reflects synchronised activity in a large number of simultaneously activated nerve fibres. Antoli-Caudela and Kiang (1978) recorded the post-stimulus time histograms (PST) from single fibre units with various characteristic frequencies (CF's), in cats. They demonstrated that the PST shows a best correlation to the N_1 waveform, with PST fibres with a CF between 4 and 10 kHz (Fig. 1.5).

It is the interaction of stimulus variables with the unit properties that determines how much each unit contributes to N_1. An example of this is provided by the relatively small contribution of units with CF above 10 kHz. This results probably from an interplay of factors such as the acoustic stimulus spectrum (Parker and Thornton 1978a), the characteristics of the sound generating system, the transfer function of the middle ear, and the



PSR histograms for 14 units in one animal to rarefaction clicks at two levels. All of these units had high spontaneous discharge rates and were selected to have a wide range of CF. The histograms are arranged in order of descending CF. Gross responses for the two click levels are shown at the top. dotted vertical lines are drawn form the N 1 peaks in the gross response (Antolie - Caudela & Kiang, 1978).

Fig 1.5

properties of the sensorineural apparatus. From the figure, it is seen that the units with the highest CF do not contribute at lower click intensities and the latency increases as the CF of the neuron decreases. This is reflected in the latency-intensity function of N_1 which shows an increase in latency for a decrease in intensity. On comparison of the latency-intensity functions to narrow (8 kHz) and standard broad band clicks, the latter is found to have a greater latency range (Elberling, 1976). The two stimuli were found to be equally effective in their excitation of the basal part of the cochlea; at high intensity the broad band stimuli activates the basal fibres as well as the more apical fibres. At lower intensities the standard click with peak energy at 2 kHz activates mid-cochlear fibres responding with long latencies (Fig. 1.6)

The single unit model provides a working hypothesis for the interpretation of the N_1 action potential, recorded from the round window, where the amplitude of the whole AP is proportional to the discharge rate and the number of fibres firing. The temporal characteristics of the Wave I of the ABR correspond to N_1 and the commonly accepted interpretation is that of the same generating site and mechanism as that of the whole nerve action potential (e.g. Lev and Sohmer, 1972; Achor and Starr, 1980b).

Controversy exists as to whether the major contribution to the surface recording comes from graded post-synaptic potentials or from synchronised action potentials.

Buchwald (1981) hypothesised that the ABR peaks, including Wave I, reflect graded post-synaptic potentials, rather than all-or-none action potentials discharged at the cell soma and transmitted along the axonal projections. This hypothesis runs through her understanding of the generation of the ABR. In the context of Wave I, she proposes that graded generator potentials in the dentritic terminals may be the physiologic and anatomic substrates most relevant to Wave I. In support, lesion studies have confirmed that it is activity in the distal area of the auditory nerve which generate Wave I. Section of the nerve at its exit from the internal auditory meatus has abolished subsequent ABR waves but Wave I was preserved (e.g. Buchwald and Huang, 1975). There is greater support for the whole nerve action potential as the basis for Wave I, and this is the best understood of the waves in the response. For clinical work, it is widely and long understood that a lesion

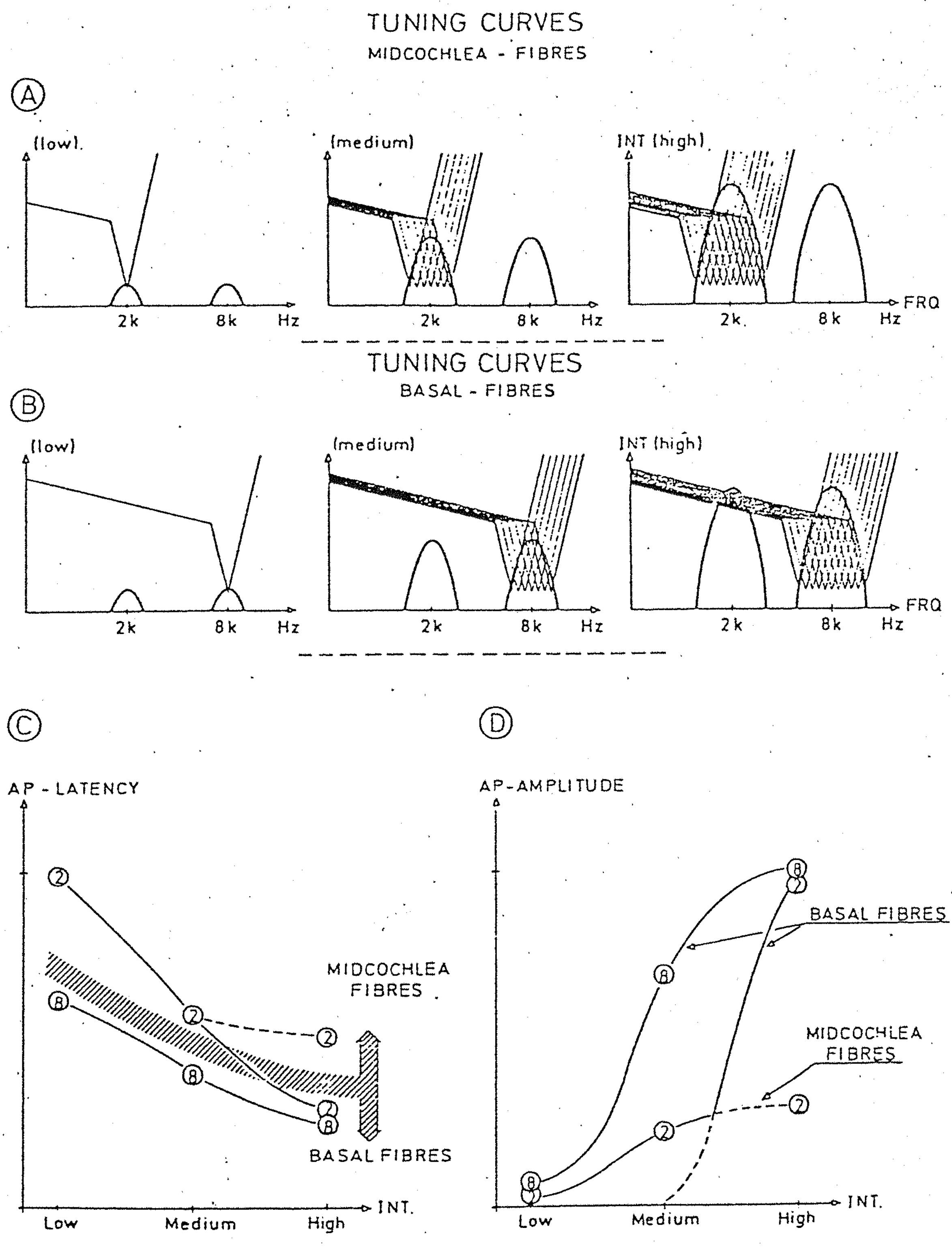


Fig 1.6

From (Eberling 1976)

affecting the auditory nerve may be reflected as a marked reduction or broadening of Wave I (Gibson and Beagley, 1976; Portman and Aran, 1974).

The origin of Wave II is more controversial. Increasing evidence points to the origin as the auditory nerve (e.g. Tait et al., 1987), rather than the cochlear nucleus as was thought at first (e.g. Lev and Sohmer, 1972; Buchwald and Huang, 1975)), though it may derive from a different mechanism (Buchwald, 1981). Buchwald (1981) denotes two components; a Wave IIA and a Wave IIB, the former having an equal or greater latency, depending on the species, the electrode derivation, and the subject maturity (Plantz, et al., 1974; Stockard et al., 1978; Achor and Starr, 1980a). She suggests Wave IIA may be generated at the unmyelinated central terminals of the acoustic nerve, whilst Wave IIB (equivalent to Wave II in the mature, human ABR) depends on, and has contributions from, the cochlear nucleus. Studies of single unit activity, and near field recordings of the whole nerve action potential, reveal the intensity dependence of the latency of Wave I. The later waves would appear to have a different underlying mechanism, as they do not relate to intensity in quite this way.

Analysing the ABR of cats in the spatial and temporal domains, Achor and Starr (1980a) determined the auditory nerve as the generator of the first two components of the response. Human intracranial recordings from the auditory nerve by Møller et al. (1982) and Hashimoto et al. (1981) support this finding. These authors attributed the increased latency separation of the waves to the time taken to reach the intracranial portion of the nerve, a distance of 1-1.5 cm. Garg et al. (1982) recorded from patients with motor sensory neuropathy, Type 1, which only affects the peripheral nerves, and found Waves I and II to be delayed, but Waves III to V to be normal. Also Wave II is occasionally recorded in brain dead patients (Stockard and Sharbrough, 1980b). The weight of evidence supports the intracranial extra-medullary portion of the auditory nerve as the generator of Wave II, or a composite of the activities of the auditory nerve, the cochlear nucleus and the trapezoid body, with the relative contributions being unclear (Hashimoto et al. (1981).

The source of Wave III is ascribed to the superior olivary complex (Lev and Sohmer, 1972; Buchwald and Huang, 1975;G ardi and Berlin, 1979; Achor and Starr, 1980a, b), though the relative contributions from the ipsilateral and contralateral complexes are less clear (Prasher and Gibson, 1980a; Robinson and Rudge, 1981; Buchwald, 1983). Essentially, available studies showed that lesions at the inferior colliculus and lateral leminiscus, not affecting the superior olivary complex, resulted in preservation of the waveform up to, and including, Wave III. Hashimoto et al. (1981), in intracranial recordings in humans undergoing intracranial surgery, found the response to originate from the pons, which, though less specific, does not conflict with other studies. The relative contributions of the various nuclei on the complex and the proportional ipsi- and contralateral combinations are less clear.

The superior olivary complex is an important point in the auditory pathway, as it is the first structure where both crossed and uncrossed projections meet; the bipolar neurons are uniquely suited for decoding binaural information and the superior olivary complex plays an important role in the localisation of sound sources. Huang and Buchwald (1977) found well synchronised units in both the medial and lateral superior olivary complex, ranging in latency from 2 to 5 ms. It is probable that more than one peak may arise from this complex, and that the observed response would originate from the most synchronised. It is possible that this is reflected in the electrode montage studies, which show some differences in the vertex ipsilateral and vertex contralateral recorded ABR (Picton et al., 1974; Thornton, 1978; Stockard et al., 1979; Prasher and Gibson, 1980), notably in the reduced amplitude and earlier latency of the ipsilateral condition. Buchwald (1981) suggests that this occurs because the ipsilateral mastoid, like the region lateral to the medial superior olive, is in a current field negative for Wave III, relative to the vertex and to the contralateral mastoid.

There is less evidence from human studies to identify the basis of the IV/V wave complex, but the body of data suggests that the waves originate in the high pons or low midbrain (lateral leminiscus or inferior colliculus). The IV/V complex is recorded maximally with a vertex contralateral configuration (Stockard et al., 1978); is reduced with binaural stimulation (Huang and Buchwald, 1978; Dobie and Berlin, 1979; Gardi and Berlin, 1979), and is recorded as a number of different configurations (Chiappa et al., 1979; Edwards et al., 1982), Fig. 1.7. Evidence from lesion studies in humans indicates that lesions in the high pons or low midbrain produce abnormalities in both waves. (Lev and Sohmer, 1972; Starr and Achor, 1975; Starr and Hamilton, 1976; Stockard and Rossiter, 1977; Epstein et al., 1980; Brown et al., 1981.) The intracranial recordings of Hashimoto et al. (1979) and

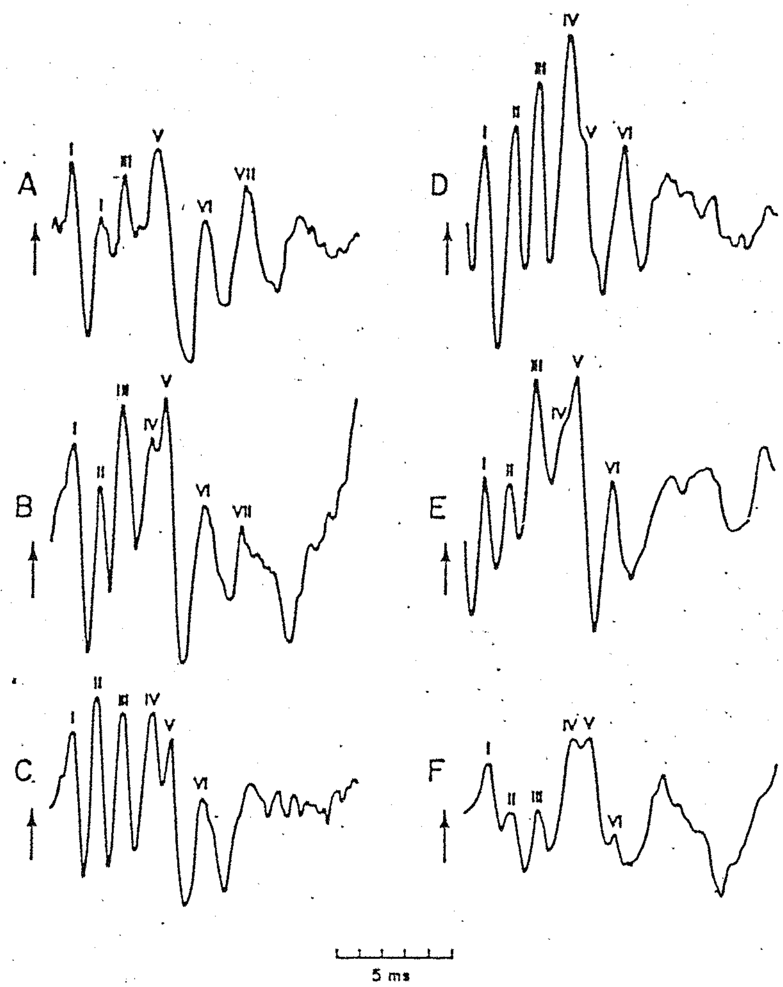


Fig 1.7 Different wave IV–V complex configurations at 10 clicks per second. From Chiappa (1983)

Hashimoto et al. (1982) recorded a large peak (P_4), generated in the pons, which they correspond to Wave V. They showed that the intracranial potential corresponding to Wave V is maximal at the midbrain and reverses polarity between the pontine and midbrain regions. By comparison with the mapping studies of Picton et al. (1974), where the peak was found to be maximal over the frontal regions and minimal over the occipital regions, they showed that the distribution of potential is almost a vertically orientated dipole set up in the brainstem, with a rostral positive and a caudal negative. They explained the large constant positive polarity that is recorded, as being related to the electrode locations, rostral and dorsal to the pontine generators.

Møller and Jannetta (1982) recorded directly from the surface of the inferior colliculus during surgery and also recorded a large positive wave at about 7 ms. They deduced that this was too early to be originating in the inferior colliculus and favoured the lateral leminiscus as the generator of Wave V. As stated earlier, the comparison with animal studies is more difficult for this wave complex, but the IV/V complex is thought to correspond to the large positive Wave 4 (Arabic numerals are commonly used to denote the principal peaks elicited in recordings from animals) recorded in animal studies. (Lev and Sohmer, 1972; Starr and Achor, 1978; Stockard et al., 1978). Animal studies have been used to provide evidence that the complex is generated independently of the inferior colliculi. Bilateral destruction of the inferior colliculus in the cat (Gardi and Berlin, 1979; Buchwald and Huang, 1975) did not reduce Wave 4. The body of evidence from animal studies suggests that the wave form is generated below the level of the inferior colliculus and that there may be more than one generating source.

Lesions including the ventral acoustic stria reduce the Wave 4 amplitude by 50% (Buchwald and Huang, 1975; Achor and Starr, 1980b; Gardi et al. 1979). Achor and Starr also found Waves 3 and 4 to be reduced by a lesion to the superior olivary complex and the trapezoid body; if only the superior olivary complex is affected, then only Wave 3 is reduced. This demonstrates that the wave is dependent both on fibres crossing the midline in the trapezoid body and a component which is not dependent on crossed projections. Further animal studies (e.g. Buchwald and Huang, 1975) point to the ventral region of the lateral leminiscus in response generation.

Wave IV would also appear not to be dependent on the inferior colliculus, the lateral superior olive of the medial superior olive. Direct recordings from the lateral leminiscus yield responses to ipsilateral and contralateral stimulation where Wave IV is compatible with the binaural properties reported (Jewett, 1979; Huang and Buchwald, 1978). Achor and Starr (1980b) also noted the necessity for the integrity of the contralateral lateral leminiscus for the generation of the complex. Wave IV has some different properties to the earlier waves. Drawing from these animal studies, and others, Buchwald (1981) hypothesises that the ventral nucleus of the lateral leminiscus is not only the generator of Wave IV/V, but also an essential relay in the production of Wave V. The evidence, she argues, is primarily the binaural interaction effects which parallel those seen for the IV/V complex. In summary, the body of evidence suggests that the IV/V complex depends on input from crossed and uncrossed projections from the anteroventral cochlear nucleus to the ventral nucleus of the lateral leminiscus.

From their thalamus depth recordings in humans, Hashimoto et al. (1981) and later Veal et al. (1982) proposed that Wave VI is generated in the medial geniculate body and supported by some animal studies, though not all, (e.g. Henry, 1979b). In these studies, Wave 5 was not affected by complete transection of the brainstem rostral to the inferior colliculus (Achor and Starr, 1980b). There is further evidence, from lesion studies, that the Wave 5 is generated from the deep ventrolateral portion of the inferior colliculus. Achor and Starr (1980b) showed that bilateral destruction of the central nucleus of the inferior colliculus in the cat brain stem did not markedly reduce Wave 5, whereas compression of the lateral and ventral extent of the nucleus (Buchwald and Huang 1975) or a lesion affecting the input to the inferior colliculus from the lateral leminiscus (Lev and Sohmer, 1972; Henry, 1979a,b) markedly reduce Wave 5.

A more recent approach to the problem of the source of the scalp potentials derives from succinctly and comprehensively expressing the information from multichannel auditory ep measurements. Complementary evidence is obtained from scalp distribution studies of electrical fields, analysis of equivalent dipole sources and by comparison with intracranial recordings. A number of possible combinations of generators may explain a given surface potential. Two general approaches are followed: to create contour maps of potential (Grandori, 1982, 1984; Starr and Squires, 1982; Scherg, 1984), or to combine several channels of data into a vector presentation (Pratt et al., 1983). Approximate solutions have been proposed using various analysis techniques. Scherg and von Cramon (1985b) used a spatio-temporal dipole model, which simulated surface wave forms due to overlapping activity from multiple dipolar sources within a 3 shell head model. The modelled surface activity resulting from the dipole source was compared with the normal ABR waveform. When the temporal course of dipole strength was modelled according to a triphasic compound action potential, 6 dipolar sources were sufficient to fit all ABR waveforms. The locations of the dipoles were interpreted as roughly corresponding to the neuroanatomical sites of the auditory structures at the distal end of the auditory nerve; in, or near, the cochlear nucleus; in the trapezoid body, the superior olivary complex and the lateral leminiscus. This raises a question regarding the contribution of third order neurons and of the amount of ipsilateral and contralateral input. Ino and Mizoi (1980) and Pratt et al. (1984) recorded simultaneously from 3 orthogonal electrode montages and plotted the 3 voltage time records on 3 dimensional (V-V-V) coordinates, giving a 3-dimensional Lissajous trajectory. Ino and Mizoi (1980) attempted to explain the surface potentials by a specific sequential generator theory, with controversial results. Pratt et al. found planar processes rather than linear segments, suggesting more complex processes. Similar observations were made by Williston et al. (1981). These studies show great promise in elucidating the origins of the ABR waveform.

In summary it can be said that the ABR arises from the vectorial sum of oscillating potentials arising from multiple local field potentials in generators in the auditory nerve and brain stem, up to and including the inferior colliculus. It is apparent from the evidence of temporal overlap in the evoked potentials occurring in the individual brain stem structures (Wicklegreen, 1968), and the disparities between studies, that a single generator substrate for the response waves is unlikely. Further, our understanding of the auditory evoked potentials is about to increase rapidly as studies on multiple generator sites, the spectral composition of the response and the properties of the response, as studied by vector analysis are drawn together (Møller, 1983; Martin et al., 1986). This has practical and clinical implications, which are now reviewed.

1.13.2 Auditory Brainstem Responses in Site-of-Lesion Studies

The aim in the main study is to use the evoked responses to investigate the site of auditory dysfunction in children with known hearing deficiencies. Accordingly, a brief review is presented to discuss the evidence that auditory evoked potentials are of clinical value in site-of-lesion studies. The areas to be discussed here are drawn from otoneurology, where a hearing loss may be a symptom of some underlying condition. Evidence is presented which demonstrates that the technique is used, with some success, to identify retrocochlear disorders and central auditory disorders.

Auditory brainstem responses have now been in use for several years in site-of-lesion studies, and the specificity with which they can be used has been improving with clinical experience, with improved stimulus and recording techniques, and with more advanced instrumentation. The earliest popular use of the ABR was in the identification of acoustic neuromas, and ABR testing has now become a routine part of audiological investigation in that area. Although we cannot specifically attribute abnormalities in particular parts of the waveform to pathologies at specific generating sites, because of the complex response mechanism, abnormalities in the response do enable some conclusions to be made regarding the status of the auditory pathway. The discovery that cochlear hearing disorders, unless they are so severe as to abolish the early waves of the ABR, do not affect the response interpeak latencies as much as retrocochlear disorders, was of paramount importance. It is upon this finding that the diagnostic differentiation of cochlear and retrocochlear disorders rests. As long as Wave I can be identified, the general assumption is made that increases in the interpeak latencies reflect increases in conduction time that have localising value. The ABR may then be used to test the peripheral hearing system in conductive and sensorineural hearing disorders, and the brainstem auditory pathway in CNS disorders.

The diagnostic value of the ABR was predicted by Thornton (1975), who later developed a graphical presentation for his statistical data. This is based on comparative latency and amplitude analysis of normal and pathological cases. Since then, a large body of clinical data has been acquired, allowing refinements in diagnostic interpretation and method to be developed (e.g. Pijl, 1987; Kamath et al., 1987; Tackman and Vogel, 1987). For some time, the most commonly reported diagnostic application was the identification of acoustic neuroma and cerebellopontine angle tumours. Numerous clinical studies have been reported giving the identification rate using specified diagnostic criteria, and describing response characteristics. A large study of House and Brackman (1979) reports on 150 cases. A complication in the identification of retrocochlear disorders is the cochlear contribution to the response. The ABR depends on the state of the cochlea, and the output from the damaged cochlea has a complex effect on the response waveform (e.g. Gorga et al., 1985). Data from derived response studies (Don and Eggermont, 1978) yield a workable model for the ABR which allocates an intensity dependent weighting of the the contribution from various cochlear regions to the overall response. At high intensities, Wave V appears to have contributions extending to the more apical turns, whilst Wave I has a more basal weighting. Using this model one would predict that cochlear damage may affect each wave differently, and indeed this is supported by clinical data. Hyde (1985) summarises three complicating factors in the interpretation of the ABR in the presence of cochlear hearing loss. These are:

1) The effect may be different on each peak of the waveform. For example, the I-V interval would be predicted to shorten, and this does occur (Coats, 1978).
2) Loss of tuning will affect the cochlear source pattern, and does not correlate well with pure tone threshold.
3) It is possible for neural synchrony to become reduced in the presence of normal pure tone thresholds. Hyde suggests that in some unrecognised disorders of the cochlea, timing may underlie some of the reported cases of ideopathic ABR absence.

Commonly, studies use either the absolute Wave V latency, or the interaural Wave V latency (ITV) as the diagnostic criteria (e.g. Starr and Hamilton, 1976; Clemis and McGee, 1979; Hashimoto et al., 1979; House and Brackmann, 1979; Saloman et al., 1980; Eggermont et al., 1980; Parker et al., 1980; Shanon et al., 1981; and Maurer et al., 1982). The latency of the click evoked Wave V, and hence the other measures, is dominated by contributions from the 2 to 4 kHz region of the cochlea. Accordingly, low frequency hearing loss has little effect on the ABR morphology. In general, the latency of Wave V increases and the I-V interval decreases as the high frequency hearing loss increases (Coats and Martin, 1977; Rosenhamer et al., 1981).

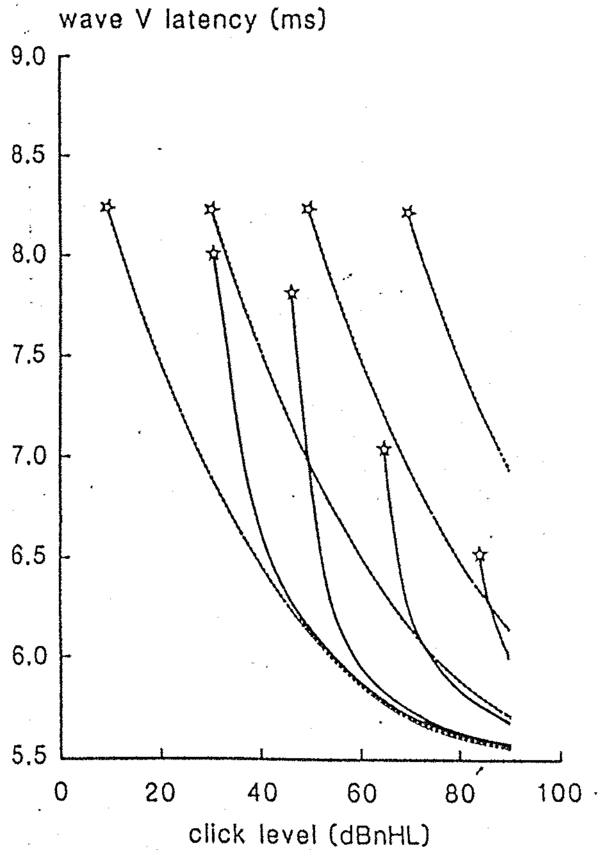
The ITV value has a relatively broad distribution due to the effect of cochlear mechanics on the response, and diagnosis based on this criterion alone has the disadvantage that the degree of loss and auditory configuration between ears affects the interpretation. The ITV tends to be shorter in patients with low frequency hearing impairment (Thomsen et al.,1978). The latencies of Wave V in patients with flat sensory hearing loss are predominantly the same as for normal hearing subjects, 5 to 10 dB above response threshold, giving an ITV as for normal subjects. The Wave V latency delay in cases of high frequency hearing loss, depends on the slope and extent of the loss above 2 kHz (Yamada et al., 1978). Because a cochlear hearing loss affects the latency of the whole waveform, correction factors have been suggested in an attempt to attribute changes in wave latency to the correct pathology (e.g. Selters and Brackman, 1977; Jerger and Maudlin, 1978). The ITV value is a commonly used diagnostic measure, and some studies have shown hit rates of above 90% using this method (e.g Bauch et al., 1982; Clemis and McGee, 1979; Selters and Brackman, 1977; Terkildson et al, 1981).

The inter-peak intervals, I-V, I-III and III-V form another common diagnostic criterion (Selters and Brackman, 1977; Clemis and McGee, 1979; Glasscock et al., 1979; Eggermont et al., 1980 and Chiappa, 1983). Musiek et al. (1986) demonstrate that both the I-III and III-V intervals are affected. When an ear canal electrode is used, Wave I can often be successfully recorded in the presence of quite severe cochlear damage. In diagnostic work, Elberling (1978) and Saloman et al. (1979) have suggested combined use of surface recorded ABR and transtympanic ECOG techniques, to obtain waves I, III and V. But in practice, the "butterfly" electrode (Coats, 1974) used in ear canal placement allows good, non-invasive recording of Wave I. A similarly effective method is described by Yanz and Dodds (1985), who use an ear canal electrode which consists of a stainless steel wire in a foam ear tip. These authors report an enhanced Wave I amplitude with no loss in the amplitude of Wave V. Again, of course, the cochlear status as reflected by the audiometric configuration affects the recorded interpeak latency, and the effects of cochlear hearing loss on this measurement are not well understood (Bauch and Olsen, 1986). Stockard and Stockard (1983) found the I-V interval to decrease as click intensity decreases in normal hearing subjects.

Normal values have been obtained and correction factors proposed for some types of audiometric configuration. Keith and Greville (1987) found that notch shaped hearing losses caused an increases in the I-V interval, due to the first wave being at a shorter latency than normal, and the Wave V being at a longer latency than normal. They attribute this to the absence of the usual early contributions to Wave V, with its latency being dominated by later occurring activity from further along the basilar membrane. The reverse is then true for Wave I, the longer latency components being absent. Coats (1978) reports a reduction in the I-V latency in the presence of high frequency hearing loss. The I-V interval has been found to be a powerful diagnostic measure, with Eggermont (1980) reporting a 95% hit rate, and a 5% false positive rate, in the detection of 45 cerebellopontine angle tumours.

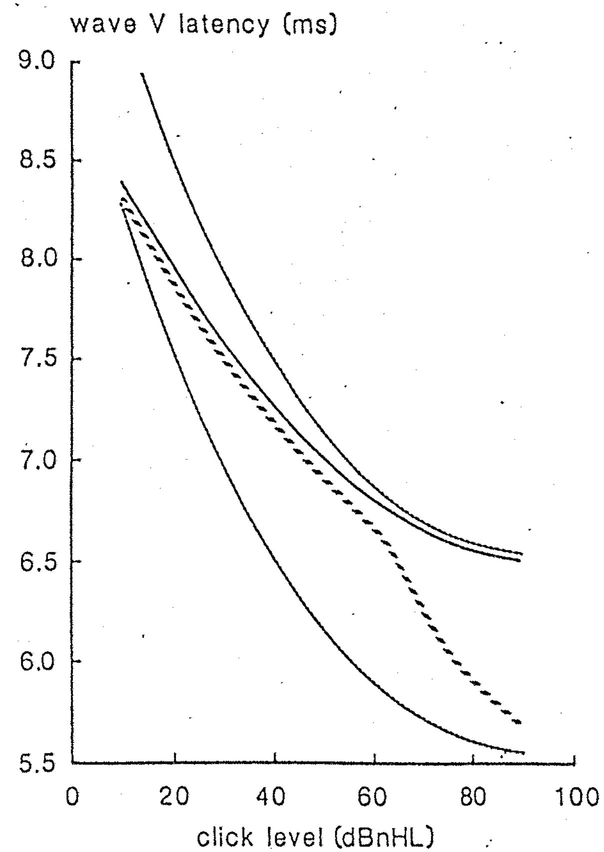
In the clinical application of ABR recordings to the differential diagnosis of sensorineural hearing loss, the criteria described here are best used in combination (Elberling and Parbo, 1987). The measurement parameters available depend on the extent of the hearing loss. A retrocochlear lesion is identified by an increase in the conduction time, following the generation of Wave I. Recent information on multiple generator sites makes it more practical to examine only the more robust components of the waveform. The clinician usually makes diagnostic deductions based on some simple measures of relative latency. A delay in the I to III interval indicates a disorder in the lower part of the pathway, below the superior olivary complex, and a delay only between the third and fifth waves indicates a disorder in the higher brainstem pathway. Amplitude measures are also rarely used, due to its wide variance.

The latency-intensity function is of particular interest, as the functions for the individual peaks of the waveform are not found to be exactly parallel. A schematic by Hyde (1985), based on work of Picton et al. (1981), illustrates the non-linearity. (Fig. 1.8a) This study compared the latency-intensity function generated in response to a high intensity click, with responses to the same stimulus but in the presence of 20, 40, 60 and 80 dB flat conductive hearing loss. Hyde notes that the slopes of the solid curves (cochlear losses) increase immediately above the ABR threshold; for mild to moderate losses the latency is normal at high stimulus levels. The ABR threshold moves closer to the hearing loss value as the latter increases, and the latency at threshold is reduced with increasing loss. An implication of this is that latency correction procedures for retrocochlear lesion detection will be intensity dependent. Where the loss is steep, latency increases of



A model of the effects of flat hearing loss on the click intensity-latency function for wave V. Dotted curves (left to right): normal ears and ears with 20, 40, and 60 dB of flat conductive hearing loss. Solid curves (left to right): ears with 20, 40, 60, and 80 dB of flat cochlear hearing loss. ABR thresholds are starred.

Fig 1.8a



A model of the effects of high-frequency hearing loss on the click intensity-latency function for wave V. Lower dotted curve: normal hearing. Upper dotted curve: a constant latency increase associated with precipitous high-frequency loss. Solid curve: an alternative form which incorporates a basal shift in cochlear excitation weighting with increasing click intensity. Heavy broken curve: a possible effect of moderate high-frequency loss.

Fig 1.8b

Pickn et al (1981); from Hyde (1985)

Wave V will occur due to the suppressed basal contribution. Another schematic by Hyde demonstrates four possible effects (Fig. 1.8b).

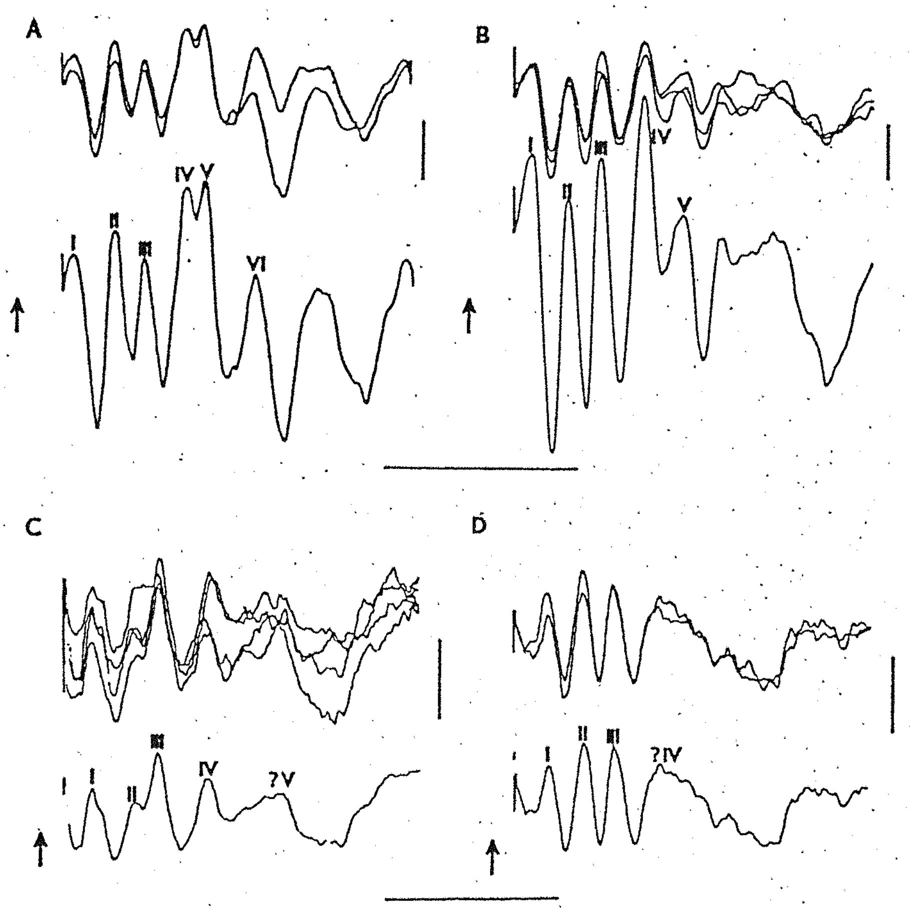
Studies on patients with retrocochlear lesions have proved that the ABR is a reliable detector of disorders affecting the auditory nerve and lower brainstem, even in the presence of cochlear hearing loss (Eggermont et al., 1980; Parker et al., 1980; Deka et al., 1987). This sensitivity is better than that recorded for any other audiological test (Musiek et al., 1983a), false positive results usually being the results of the confounding effect of high frequency cochlear loss (Musiek et al., 1983b). The success of the technique occurs because, in order for waves of normal amplitude and latency to be recorded, a synchronous response is required at the generating sites. Slight pressure on the auditory nerve, any reduction in the number of fibres, or a disorder affecting the conducting myelin sheath of even some nerve fibres are disorders sufficient to cause marked abnormalities in the response.

Abnormal latency patterns enable some deductions regarding site of lesion to be made. The resultant morphology of the waveform depends on the nature and location of the retrocochlear lesion, and on the output from any primary or secondary cochlear damage. It is partly because several factors affect the morphology, that definitive identification of the site of lesion is rarely possible. Further reasons are internal electrical radiation from response generators, the complexity of the auditory pathway and uncertainties regarding generating sites. However, a retrocochlear disorder may be reliably detected. Several authors report false positive rates of around 10% (Selters and Brackman, 1979; Glasscock et al. 1979; and Terkildson et al. 1981). Some inferences regarding the site of lesion may be made. Several authors have reported abnormal findings contralateral to the lesion (Parker et al.,1980; Selters and Brackman, 1977; Zappulla et al.,1985; Stockard and Sharbrough, 1980). It is thought to be caused by distortion and cross-compression of brainstem structures. Zappulla et al. (1985) studied rats subjected to graded compression in the brainstem and demonstrated progressive degrees of abnormality with increasing structural distortion. The ABR has proved to be a very valuable technique in the diagnosis of acoustic neuromas because of the characteristics described.

The technique has also been used in neurological studies, and is now in common use as part of the diagnostic assessment for multiple sclerosis (MS). If this demyelinating condition affects the auditory pathway, there will be a loss in the synchrony of the response. This results in less precise morphology, reduced amplitude of the later waves and possible latency delays of the later waves. Findings include abnormality of symmetry, delay in latency, fragmented responses, decreased amplitude, and poor response reliability (e.g. Robinson and Rudge, 1978; Chiappa et al., 1980; Shanon et al., 1981 and Keith et al., 1987) and differences in ipsi- and contralateral stimulation (e.g. Quaranta et al., 1986). When the system is stressed by more complex tasks, other changes are found, including abnormal responses to change in rate and abnormal latency-intensity functions (e.g. Antonelli et al., 1986). Fig. 1.9 shows examples of the various types of waveforms that are recorded from patients with MS (Chiappa, 1984). The characteristics signifying abnormalities are more diverse for this patient group than for the previous group discussed. Various manipulations of stimulus and recording parameters are used in an attempt to stress the central nervous system and detect subtle abnormalities. For this reason, attention is given to both monaural and binaural stimulation effects (Prasher and Gibson, 1980b) and the responses to stimuli presented at greater rates than normal (Stockard et al., 1977).

Results from other demyelinating and degenerative conditions have been reported upon, and are generally as expected from a first principles treatment of the response mechanism, that is there are delays in the later waves, or reduced amplitude of the response, if the auditory pathway, as tested by the ABR, is affected. For example, abnormal responses have been reported in patients with Friedrich's Ataxia, some patients with progressive supranuclear palsy, hereditary cerebellar ataxia, cerebral-cerebellar atrophy and olivopontocerebellar degeneration. Normal responses have been reported in several groups of patients with amyotrophic lateral sclerosis, Parkinson's disease, Batten's disease, Charcot-Marie-Tooth disease, and other patients in the aforementioned groups (Chiappa, 1983).

Auditory brainstem responses have become more frequently used in the investigation of central disorders, and hence their application in this study. The responses have been shown to consistently reflect the presence of brainstem tumours. In the majority of reported cases, peripheral hearing is at least partly preserved and the response abnormality caused by a higher disorder is then easily detected. The effect on the ABR depends on the size and site of the tumour, and may result in prolongation of the interpeak interval, amplitude reduction or an incomplete waveform. A brainstem glioma,



Spectrum of IV-V complex abnormalities seen in MS. **A and** B are following stimulation of the same ear of the same patient; B 2 months after A. The IV-V separation increased from 0.5 msec to 1.1 msec and the I/V amplitude ratio percentage went from 90% to 204%; both measures in B are at the upper limit of normal. **C and** D are from different patients, showing further progression of the abnormality. In **C**, wave IV is clearly visible but wave V is difficult to recognize—note poor reproducibility in repeated trials. In **D**, wave V is absent and wave IV is not present as a distinct peak. In **A, B, and C** the superimposed trials have N = 1,024 clicks each; in D N = 2,048 clicks each. The single trace below each is the sum of the superimposed trials. Calibration marks are 0.25 μV and 5 msec.

Fig 1 .9 The ABR response in multiple sclerosis, from Chiappa et al, 1980.

for example, may abolish the ABR, whilst hearing acuity is still measurable, or even unaffected (Stockard et al., 1977). The complexities of the auditory pathway restrict clinical interpretation, but the clinician is alerted to the need for further investigation.

Among the earlier reported investigations, Starr and Achor (1975) showed markedly abnormal ABR recordings in five cases with tumours of the midbrain and brainstem. Starr and Hamilton (1976) reported on a case with a focal lesion in the midbrain where only the first three waves of the ABR were clear, and on three patients with more widespread brainstem lesions, resulting in marked alterations to the ABR, and clarity of wave I only. Similarly, Stockard and Rossiter (1977) recorded an abnormal III-V delay in a patient with a tumour in the upper third of the pons. More recently, Hashimoto et al. (1979) recorded abnormal ABRs in each of three patients who had brainstem gliomas. Lynn et al. (1981) tested patients with a thalamic glioma, an invasive pineleoma, a cerebellar hemangioblastoma, and a lateralised pontine glioma, respectively, and the ABRs were abnormal in all cases. Other cases reported support these findings. The ABR is also sensitive to vertebrobasilar vascular pathology, though not necessarily more sensitive than a good neurological investigation.

In the last few years, there have been reports of ABR findings with numerous pathologies, as the equipment has become more commonly available. In general, it is most commonly used either as part of a neurological investigation; as part of an otoneurological diagnosis, or for threshold determination. It is clear that an examination of the central auditory pathways may be made using this technique, but the procedure becomes more difficult in the presence of a peripheral hearing loss. However, it is hypothesised that a comparative study of the behavioural threshold, the ABR response threshold, and the response morphology should indicate the presence of a disturbance in the central auditory system by revealing discrepancies between these measures. This comparison has been carried out to detect neurological disorders. In a follow up study of the applicability of the ABR in infant neurological screening, Kileny et al.,(1985) demonstrated the presence of several central neurological disorders by comparison of ABR and SVR records. In these cases a normal ABR was found, even though the subjects were not responsive to auditory stimuli.

1.13.3 Non-Pathological Factors Affecting the ABR

In order to ensure utilisation of optimal recording and stimulatory conditions in the main experiment in the present study , the non-pathological factors which affect the response were considered. A brief review is presented below.

1.13.3.1 Stimulus characteristics

(i) Clicks and Frequency Specific Stimuli

The ABR is dependent on the stimulus waveform, its frequency and envelope. Using brief tonal stimuli (tone bursts or filtered clicks), the latency of Wave V decreases with increasing frequency (Coats et al., 1979; Picton et al., 1979; Suzuki and Horiuchi, 1981). This is not unexpected if one considers the cochlear response to the applied stimuli. The acoustic click has been shown to elicit activity predominantly from fibres between 4 and 10 kHz (Fig.1.5) The gross action potential, Wave I, is generated by the "wave front" of the short latency action potentials in the auditory nerve. Brinkman and Scherg (1979), in their studies of the ABR to bursts of white noise, introduced the concept of "virtual trigger time", which they describe as the period in the rise time of the stimulus when the majority of fibres, fundamental to the ABR, are activated. This trigger time is a function of the rise time, frequency and intensity of the stimulus (Picton et al., 1981). The action potential latency increases with decreasing stimulus intensity, due to an increase in neural firing latency and a shift of the peak of excitation on the basilar membrane. This was clearly demonstrated by Elberling (1976), who compared the latency-intensity function of the responses elicited by an 8 kHz stimulus and a broadband click. The action potential latencies were the same at high intensities, but the click had a significantly increased latency, compared to the 8 kHz stimulus at levels lower than 80 dB.

If tone pips are used as the stimulus, instead of broadband clicks, the latency of the response increases with decreasing stimulus frequency. Frequency specific stimuli can be satisfactorily used to record the ABR at frequencies above 2 kHz; but at lower frequencies, inappropriate latencies are obtained, indicating that the responses are dominated by a more basal response. Davis et al. (1985) described frequency specific thresholds obtained using tones of rise time 2 periods, a plateau of one period and a fall time of 2 periods (2-1-2). This slower rise time gives a reduced spread of energy into other frequencies, but the response is a result of less synchronous activity and different morphology to the typical ABR. The vertex negative peak at 10 ms is prominent and has been called SN_{10} (Davis and Hirsh, 1979). It has been suggested that this peak, maximally recorded with low highpass filter cutoff, with steep (24 dB/octave) slopes, is the No component of the MLR (Hawes and Greenberg, 1981; Sohmer and Kinarti, 1984). In contrast to the behaviour of the ABR to tone pips, where the latency shift resulting from the use of increasingly lower frequencies is too short to account for appropriate shifts on the basilar membrane, the latency shift resulting from frequency decrease of the SN_{10} seems too long (Klein, 1983; Sohmer and Kinarti, 1984). Klein (1983) presented tone pips in the presence of varying pure tone stimuli, as maskers. These masking studies indicated frequency specificity in response to 0.25 and 0.50 kHz tone pips to be good. The sequence has also found a clear response to be absent in a proportion of adult subjects (Hawes and Greenberg, 1981). Thus, study of the ABR in response to tone pips illustrates the frequency dependence of the response and also the difficulty in combining a frequency specific response with a clinically viable method.

Use of filtered clicks, whilst appealing, does not solve the frequency specificity problem. Although a short rise time is used, it has been found (Kinarti and Sohmer, 1982), that the recorded ABR, to filtered clicks centred at 0.6 kHz, is less than 1 ms longer than the response to 4 kHz filtered clicks, being 1.60 and 1.90 ms respectively. This is shorter than the theoretical value calculated on the basis of place of activity on the basilar membrane. The reason for this is thought to be the spread of the spectrum of acoustic energy to a wider range of frequencies than is normal. The onset response is essentially seen to dominate the spectrum. Interestingly, the simultaneous presentation of pink noise, masking the responses from the basal turn, resulted in more appropriate low frequency latency values. Thresholds more closely correlate with low frequency psycho-acoustic thresholds in subjects with sensorineural low frequency hearing loss. Presumably, the masking exposes the low frequency components of the response which are otherwise obscured by the more dominant basal fibre response. Kinarti and Sohmer note that, even in the presence of pink noise, the latency of the response increases with decreasing intensity. Since this cannot be explained by the recruitment of basal fibres, Kinarti and Sohmer favour the theory that, as click intensity increases, the latency of firing decreases, expressed as PST histograms.

A number of studies have reported the effect of stimulus rise time on response amplitude (e.g. Bauch et al., 1980; Stapells and Picton, 1981). Suzuki and Horiuchi (1981) recorded the ABR to tones using six tones of fixed slope and different duration. They found that there was a critical rise time beyond which there was no increase in amplitude. But in general, the longer the rise time the less synchronised the response.

To partially overcome the difficulties of using a frequency specific response, two procedures have been devised. The first technique utilises derived brainstem responses. The method, developed by Don and Eggermont (1976) and Parker and Thornton (1978a), entails recording the ABR to clicks presented, simultaneously, with highpass masking noise at different cutoff frequencies. Subtraction of responses recorded at different filter frequencies enables derivation of frequency specific responses. The frequency selectivity of the method is mainly determined by the filter slope of the masker (Don and Eggermont, 1978; Parker and Thornton, 1978a).

Experiments support the hypothesis that the derived technique elicits responses which are initiated at discrete frequency specific loci along the cochlear partition (Sohmer and Kinarti, 1984). Experiments simulating sensorineural hearing loss, (Parker and Thornton, 1978b) and round window recordings of single unit activity in the cat, in which the effect of highpass masking on the PST histograms is examined (Evans and Elberling, 1982), suggest that there is less support for the hypothesis at low frequencies. As a threshold procedure, it is frequency specific at frequencies above 2 kHz. Further evidence regarding the lower test frequencies is required for the derived response technique, but the major clinical difficulty with regard to its adoption in threshold determination, is the length of the procedure. A variation on this method was proposed by Pantev and Pantev (1982), who used a pure tone masker. This provides a method more readily available to most clinics, and similar results were obtained to those using a noise masker.

The second and alternative approach to this problem was made by Picton et al. (1979). These authors presented tones (5 ms/0.01 ms/5 ms) in the presence of notched noise masking, with steep cutoff slopes. The central frequency of the notch matches the nominal frequency of the tone pip. The latency-intensity functions of Wave V are similar to those obtained with derived responses, and hence probably result from the same mechanism. The notched noise method takes less than half the time of the derived response technique as, theoretically, the frequencies above and below the notch frequency are fully masked, but there are reported to be some technical difficulties.

(ii) Stimulus Polarity

The ABR is sensitive to stimulus intensity, frequency, envelope, and click polarity. Several studies have reported changes in response to click stimulation when the polarity is reversed (Borg and Lofquist, 1982; Hoult, 1985; Hughes et al., 1981; Kevanishvilli and Aphonchenko, 1981; Ornitz and Walter, 1975; Stockard et al., 1979). The response to rarefaction stimuli was found, in earlier studies (Ornitz and Walter, 1975; Stockard et al, 1978) to precede the response to condensation stimuli, and based on single unit studies of Peake & Kiang (1962) and Pfeiffer and Kim (1972), this is explained as the rarefaction stimulus phase causing upward movement of the basilar membrane and resulting in excitation. However, later studies show longer latencies for later waves (Hughes at al., 1981; Sand and Sulg, 1984) and the resulting morphological changes in waveform suggest a more complex physiological mechanism, involving central processes (Coutin et al., 1987).

Reported estimates on the latency of Wave I in response to condensation and rarefaction clicks vary from 0.04 ms in normals (Picton et al., 1981) to 1.0ms (Coats and Martin, 1977) in subjects with high frequency hearing loss. Picton et al. (1981) relate this to the slower rate of basilar membrane oscillation in the more apical region. In general, Wave IV is reported as more susceptible to change than peaks III or V and, generally, a latency decrease is reported for rarefaction clicks, compared with condensation clicks (Ornitz and Walter, 1975; Stockard et al., 1978). Wave I latency is reported to be of shorter latency in response to rarefaction clicks, and the latencies of Waves III and V to be unaffected (Coats and Martin, 1977; Stockard et al., 1979; Ornitz et al., 1980). However, Kevanishvilli and Aphonchenko (1981) found the condensation click stimuli to reduce the latency of Wave V. Different effects have been observed in children (Ornitz and Walter, 1975) and infants (Stockard et al., 1979), where the response morphology appears different for different polarities.

Debruyne (1984) compared the ABR recorded as a result of several condensation and rarefaction stimuli. They presented a click (0.10 ms rectangular pulse), 1 kHz sine wave and a 0.5 kHz wave. Condensation stimuli were found to cause latency increases relative to rarefaction stimuli. These delays were proportional to the stimulus phase shift, suggesting that the early part of the waveform is phase locked to the stimulus. This is compatible with observations on the compound action potential (Elberling and Saloman, 1971). This phenomenon was not observed for Waves IV and V, suggesting that different components of the brainstem response derive from independently activated brainstem pathways (Picton et al., 1981); or from different portions of the cochlear partition (Coats et al., 1979; Kramer and Teas, 1979; Gerull et al., 1987) or that a neural reorganisation may occur in the higher brainstem where Waves IV and V are generated (Debruyne, 1984).

Debruyne's study suggests that the simple explanation of the rarefaction phase being excitatory and the condensation phase being inhibitory may not apply to the auditory brainstem response. More convincing evidence is supplied by Salt and Thornton (1984), who thoroughly explored the effect of rise time on the latency differences caused by different polarity stimuli. They found that the latency increase tended to occur only for components Wave I and Wave II. As the rise time of the stimulus increased, the amplitude changes observed were not consistent in direction throughout the waveform, nor to click polarity. A dependence upon rise time was demonstrated. Comparison of waveforms to rarefaction and condensation stimuli, with differing rise times, showed polarity sensitive components which increased in amplitude with rise time, and in which Wave V was least affected. Salt and Thornton propose that the ABR results from two components, the dominant being insensitive to polarity changes and the second varying when the polarity of the auditory stimulus is inverted. The latter component makes a bigger contribution at longer stimulus rise times and with greater low frequency content. The polarity insensitive component is found to be more dependent on the high frequency elements of the stimulus. The implication of their work is that a choice of whether to use a single polarity or alternating stimulus depends on the information required and the clinical purpose. The alternating click yields a simpler response than a single polarity stimulus, even though polarity specific information may be lost. Coutin et al. (1987) supported the complexity of the phenomenon, using a three channel recording and vector analysis technique. These authors demonstrated differences in the course of the propagation of afferent activity to different phase components and alterations in the presence of pathology.

An advantage of the alternating click lies in the reduction of any stimulus artefact. This is a particular asset in studies, such as the present, where very high stimulus levels must be used. Until the understanding of the abstraction of the phase-sensitive components is complete, studies of central problems may best be completed with alternating stimuli.

(iii) Duration and Interstimulus Interval

Decreasing the interstimulus interval (ISI) has generally been found to result in an increase in Wave V latency (Chiappa, 1979; Stockard et al., 1979) and decreased and more variable response amplitude (e.g. Thornton and Colman, 1975; Don et al., 1977; Rowe, 1978; Stockard et al., 1978; Chiappa et al., 1979; Picton et al., 1981; Paludetti et al., 1983; Lasky, 1984). These effects are probably only significant at rates above 20 s^{-1}. There are disparities in the literature regarding the extent of waveform changes, and hence the underlying mechanism is only partially understood. A central neurological basis is favoured where a progressive increase in latency with decreasing ISI, greater with each successive wave is found (e.g. Hyde et al., 1976). There is some supporting clinical evidence from patients with brainstem neuropathology (Stockard and Rossiter, 1977; Scott & Harkins, 1978) and from the detection of central abnormalities in infants (Hecox et al., 1981; Stockard & Stockard, 1982). However, the shift in later components has also been ascribed to peripheral nervous system effects (Don et al., 1977). An additional central component may be due to changes in conductive velocities of neural elements (Harkins et al., 1979).

Don et al. (1977) observed a change of 0.9 ms in the latency of Wave V, as the repetition rate increased from 10 s^{-1} to 100 s^{-1}, and was independent of intensity. Thornton and Colman (1975) found a similar shift and amplitude reduction, but found that the early waves could not be recorded at fast repetition rates. The difficulty in wave identification at high stimulus rates (above 20 s^{-1}), due to peak amplitude reduction was also recognised by Sand and Sulg (1984) and is of importance to the clinician The frequency of recognisability of waves at 60 dB SL, from Chiappa's rate study on 50 normal ears, is summarised in Table 1.2.

Table 1.2

FREQUENCY OF RECOGNISABILITY OF INDIVIDUAL WAVES

(from Chiappa,1983)

Wave	$10\ s^{-1}$ n=100 ears	$30\ s^{-1}$ n=36 ears	$70\ s^{-1}$ n=80 ears
I	97	92	76
II	96	92	61
III	100	97	85
IV	88	67	57
V	100	97	99
VI	84	67	34

It would appear that little information is lost by stimulating at repetition rates of up to 20 s^{-1}, and this rate may be useful in threshold recording, due to the time reduction factor.

(iv) Effects of Intensity

The peaks of the ABR waveform increase in latency as the stimulus intensity is decreased. The waveform morphology at the different intensity levels depends partly on the stimulus recording conditions (Stockard et al., 1978). The latency of Wave I, the action potential, shows this characteristic, and the delay in the other waves is predominantly a direct result. The latency decrease of the response, with increasing stimulus intensity, is thought to be the result of the gradual rise of the generator potential (Voller, 1985). Until the work of Stockard et al. (1979), there was a widespread assumption that the I-V interval was constant across intensities. They demonstrated a highly significant decrease in the I-V and I-III interpeak intervals with decreasing stimulus intensity. This is thought to be due to changes in the Wave I action potential, with change in stimulus intensity, and by the variable contributions to Waves I and V from the more apical regions of the cochlea. The standard deviation of the latency measures increases with decreasing intensity, (Picton et al., 1981), though this may partly reflect a combination of subjective response identification and reduced signal-to-noise ratio at lower intensity levels.

The latency and amplitude changes occurring with stimulus intensity changes are affected by the presence of cochlear hearing loss. In analysis of data for differential diagnosis, this is a recognised difficulty, and several studies have provided data on the effect of extent of cochlear loss and audiogram shape on peak latency (e.g. Selters and Brackman, 1977). This topic will be covered more completely, in Experiment 2: normal subject study of rate and intensity effects.

1.13.3.2 Effects of subject variables

(i) <u>Age</u>

Several studies indicate that interpeak intervals reach adult values by age three (Salamy and Mckean,1976; Ochs and Markand, 1978) to five (Mochizuki et al.,1982) years. In general, latency decreases and amplitude increases with increasing age, up to maturity and the ABR may serve as a maturation index for the human auditory pathway (Despland, 1985). The absolute latency of Wave I reaches normal values by about two months (Salamy and McKean, 1976; Collet et al., 1987). The I-V interval continues to decrease for some years after that. An adult response configuration is reached between three and six months of age (Hecox and Galambos, 1974; Salamy and McKean, 1976; Zimmerman et al., 1987). The peak latencies decrease slowly until approximately three years of age (Salamy et al., 1978; O'Donovan et al., 1980), when they reach normal adult values. A reduction in interpeak interval occurs in this period and is ascribed to increasing myelination and more efficient transmission across the synapses (Starr et al., 1977). These values then remain constant in young adults, but show some changes in elderly subjects. Latency increases of the order of 0.10 to 0.25 ms have been reported in subjects of older than 55 years (Rowe, 1978; Rosenhamer et al., 1980; Stürzebacher and Werbs, 1987), with latency ranges of about 0.20 ms over the age range from 25 to 55 years (Jerger and Hall, 1980; Rowe, 1978; Rosenhamer et al., 1986). A slightly smaller effect was reported in the study by Beagley and Sheldrake (1978). Jerger and Hall also report lower amplitude responses from older subjects, but this is not a consistent finding across other studies. Age and the effects of cochlear damage are likely to be interacting factors in older subjects. Age effects need to be considered in ABR studies but, after maturity, the effect is not important below 55 years of age.

Amplitude changes have been observed in studies of auditory brainstem responses recorded from young infants, and the enhanced amplitude commonly observed may result from smaller head size (Stockard et al., 1978), but is perhaps also related to increased response variability. The influence of different types of recording situation may cause the appearance of greater subject variability (Lasky et al., 1987). Houston and McClelland (1985) also demonstrated, in their studies of the amplitude spectrum, that there is less energy in the neonatal response than in the adult response. They indicate that this is seen as a depression of the second and third wave components and a relative broadening of the fourth and fifth wave complex.

(ii) Gender

Several authors have demonstrated that the absolute and interpeak latencies obtained in female subjects are shorter than those obtained in males (Stockard et al., 1978; McClelland and McCrea, 1979; Jerger and Hall, 1980; O'Donovan et al., 1980; Rosenhamer et al., 1980). The difference is small, varying from 0.06 ms to 0.27 ms for the I-V interval, arising predominantly from an increase in the absolute latency of Wave V (Thivierge and Coté, 1987). Thornton (1987), in a review of this topic, compares a mean gender difference of 0.14 ms with an inter-laboratory range of 0.39 ms. There are several laboratories that have not found significant gender differences, though these findings may not all be published (Thornton, 1987) but where differences are found it has always been in the same direction.

The earliest age at which the adult difference is reported is eight years (O'Donovan et al., 1980). Houston and McClelland (1985) show gender differences from birth onwards, and attribute this to different head sizes, the growth patterns being consistent with the relative changes. An age and gender interaction was found by Stürzebacher and Werb (1987). They propose that age and gender dependence is not caused by different mechanisms, but that the ABR latency differences between males and females are the result of a less pronounced age dependence of the ABR for females. This difference they ascribe to faster neural development and slower neural degeneration in the females. Re-analysis of some other studies (Allison et al., 1983; Hecox and Gallambos, 1974) can be used to support this interpretation. They suggest that it is important to have separate normal values for gender at all ages. Thornton's conclusion, based on the published data on latency differences between genders, is that the increased hit rate in diagnostic identification will be very small (1.8%) if gender differences are observed.

1.14 SUMMARY

This concludes the review of the literature published in the principal areas which are involved in this dissertation, where the working hypothesis is that auditory electrophysiological techniques may be used to identify and, perhaps, locate central auditory dysfunction in children with known acuity deficits. Methods available for the investigation of central auditory problems have been discussed, concluding with the application of auditory evoked potential studies. Since the auditory evoked potentials are to be examined closely in a group of severly hearing-impaired children, their properties have been closely reviewed, with special attention to factors relating to the selection of stimulating and recording conditions. A discussion on the generating sites of the responses was included to investigate the theory that the responses could be usefully applied in this way. The range of topics discussed has necessarily been broad, as examination of the hypothesis required several supporting studies and work in multi-disciplinary areas.

CHAPTER 2

DESIGN OF AN INVESTIGATION INTO THE SITE OF AUDITORY DYSFUNCTION IN A GROUP OF HEARING-IMPAIRED CHILDREN

CONTENTS

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2.1 INTRODUCTION

In Chapter 1 it was suggested that the site of the auditory dysfunction causing a child's hearing loss may affect his ability to acquire spoken language. Following a review of methods available to investigate the presence, or otherwise, of a central component in a child's auditory deficit, it was proposed that auditory electrophysiological measures would provide a suitable means of detecting site of auditory dysfunction in hearing-impaired children. It may then be possible to establish a relation between a child's spoken language ability and, or, his educational progress, and his site of auditory dysfunction. A combination of evoked potential techniques is thus used, in an attempt to determine the site of auditory dysfunction, and the results are then related to the child's functional progress in the acquisition of speech and language, and related psycho-educational measures.

Two hypotheses are proposed for investigation in this dissertation:

1) A combination of auditory evoked potential techniques may be used to investigate the site of auditory dysfunction in children with auditory acuity deficits

2) There is a relationship between a child's ability to develop oral/aural skills and the site of auditory dysfunction, as determined by auditory evoked potential techniques

In the present study, auditory electrophysiological responses were used to establish the site of dysfunction in 36 children with known hearing impairment. The children were also assessed on a combination of audiometric and psycho-educational measures, and by the qualitative assessment of their teachers. The study then has two main areas:

1) Collection and analysis of auditory eelectrophysiological data from a population of severely hearing-impaired children. Comparison of sensitised measures were made against a normal population.

2) Examination of the entire data array of audiometric, electrophysiological and psycho-educational measures to

seek underlying relationships in the data. Supporting studies were carried out in areas thought to be particularly important to speech and language ability.

In this chapter, the experiments carried out to investigate the above stated hypotheses are outlined and the structure of the remainder of the thesis is explained.

2.2 SUBJECT SELECTION

The main test population in the study comprised 36 hearing impaired children. These were treated as two groups of 25 and 11 children. The experimental study had two distinctive components: that of devising and applying the most appropriate array of auditory electrophysiological measures, and that of selecting and carrying out a suitable psycho-educational and spoken language evaluation. Comparisons between the results of the two areas of investigation were then sought. The investigation was designed to investigate the effect of areas in the auditory domain which can be quantified, and did not dwell on the effect of non-auditory factors.

Twenty-five hearing-impaired children took part in the study initially. They were all pupils at a residential school, in the London area, for severely to profoundly hearing impaired children. The selection of the children was not random and was carried out in close co-operation with the school staff. The children were selected across a wide age range. Six years was taken as the lower age limit, since below that age it may be difficult to enlist sufficient co-operation to reliably carry out the evoked potential techniques. This is not a necessary limitation in clinical work, where it is permissible, and often desirable, to use sedation during recording of auditory evoked potentials. The upper age limit was 16 years, with a mean subject age of 11 years 10 months. Approximately equal numbers of children were selected from two categories as described below. Selection was based on teachers' qualitative judgements. The categories were:

1) Children considered to have average or better ability with oral/aural skills

2) Children considered to have below average ability with oral/aural skills.

The school used as the subject source for this study was chosen because it had a tightly controlled oral/aural programme, devised by a school staff member. This programme is based around a spoken language teaching course, called "Guidelines", through which every child progresses in a systematic way. It provides written, spoken, and listening assessments in a thematic structure. The use of formal manual communication or gesture is strongly discouraged and, as most of the children (and all of the children in this study) are in residence at the school, this allows minimal opportunity for the development of manual communication from outside influences. Whilst many of the children do, of course, use some signing, this is probably low in comparison to children with similar degrees of hearing loss in most other environments.

All the participating children had been hearing aid users since infancy. Their hearing aids are checked frequently by a specially trained staff member to ensure continuous sound input. It is an aim of the aural teaching programme for the children to instantly report hearing aid malfunction. The children's audiometric status is regularly reviewed at special centres, and audiometric records are kept at the school. Regular visits by an ENT specialist are made to check middle ear status in the children.

It is not the purpose of this dissertation to evaluate the teaching technique of the school, nor to enter into the oralist/manualist/total communication debate. This is a complex issue and beyond the scope of the present study. Rather, the school was chosen, without criticism of their particular oral/aural programme, and of their decision to prohibit a signed support language, because of the comparatively tightly controlled communication training environment which it provided. The children in the study then came from as homogeneous a background as possible.

In the selection of the test group of 25 children, the following criteria were also applied.

1) Each child must be a native speaker of English, with English as the principal language in the home environment.

2) Each child should have been in the school programme at least since the age of six years old.

3) No child should be included where there were thought to be dominant social, emotional, or psychological disturbances, which may have proved disruptive to the child's general progress.

It was decided that a requirement for the hearing loss to be congenital would not be applied. Four children were included where the cause of hearing loss was early childhood meningitis (the earliest occurring at two weeks, and the latest at two years). This possibly confounding issue is discussed in the data analysis. A background summary of all the subjects is given in Appendix 2. This summarises for each child subject age, cause of hearing loss (if known), age at which the child was detected as hearing-impaired, educational management prior to attendance at the residential school and hearing aid history.

Subject selection and assessment took place in several stages. Detailed discussion with several staff members, the heads of the junior and senior schools, and the overall school principal, resulted in the formulation of a preliminary list of subjects. This was reduced to the selected 25 children by the author, after detailed examination of the pupil's individual school records, to which access was given. These files covered the relevant medical history and family history and circumstances; audiological records and hearing aid history; scholastic achievement; and progress reports, from both formal and informal assessments of speech, language and reading ability. Background information pertinent to the investigation was then compiled from these records.

Following the assessments on this group of children a second group of children was selected. Whilst most of the assessment procedures were common to both groups the selection criteria were slightly different. Children in Group 2 were selected because they were children demonstrating difficulties in the acquisition of oral/aural skills, or in related areas, and where the group mean hearing loss was less severe than that of Group 1 subjects. Since children with hearing losses which are of lesser extent than severe-to-profound rarely attend special schools for the deaf, and even more rarely residential schools for the deaf, these children were not from a less homogeneous environment than children in Group 1. Although there are advantages to selecting children from one school, the restricted sampling may limit the implications of the findings, since particular linguistic skills and deficits in hearing-impaired children are heavily influenced by the quality, style and method of teaching. Incorporating a study with a second group of children is introduced as a partial solution.

Children in Group 2 were selected as a result of detailed discussion with the Director of Educational Services for the Hearing Handicapped in Hampshire, who agreed to provide a group of children, with known hearing losses, all in oral/aural programmes, who were considered to be achieving less well than their peers with similar hearing losses. Selection criteria (1) and (3), as described above, for Group 1 were applied to this group. Ten of the eleven children in this group were thought to have congenital hearing losses, although detection was fairly late in three cases (more than two years old) and very late in three cases (more than five years old). The age range of the children in Group 2 ranged from 7 to 15 years (mean age 10 years 8 months).

In Appendix 2 the relevant background, including current educational situation is given for each child. Five of the children were attending partial hearing units attached to normal schools, five of the children were attending normal schools with support from either a remedial teacher or from a teacher of the deaf, and one child (the only child with a post-lingual hearing loss) had recently transferred to a special school for the deaf, from a partial hearing unit (P.H.U)

2.3 ASSESSMENTS ON THE HEARING-IMPAIRED CHILDREN

The assessments carried out on the children fell into three main areas, which are listed below, with the individual test procedures used in each category. The figure in parenthesis indicates that the procedure was unique to that experimental subgroup.

1) Audiometric assessments

(a) pure tone audiometry at frequencies of 0.25 to 16 kHz,

(b) measurement of uncomfortable loudness level (ULL),

(c) measurement of abnormal adaptation (tone decay test),

(d) tympanometry,

(e) measurement of acoustic reflex thresholds (ART).

2) Psycho-educational tests

(a) Raven's Progressive Matrices (Coloured Progressive or Standard; an intelligence test designed to have a low verbal weighting)

(b) English Picture Vocabulary Test

(c) Schonell Vocabulary Test (1)

(d) Southgate Reading Test (Test 1, Word Identification) (1)

3) Samples of running speech were recorded from each child and judged for intelligibility by a panel of naive listeners. (1)

4) Teachers' grades for "Speech and Hearing" were recorded. (1)

5) Auditory electrophysiological tests

These assessments clearly required a considerable time to be spent with each subject. This necessitated splitting the test sessions to minimise the fatigue factors which would otherwise affect the data collection. The test sessions for Group 1 were arranged as described below.

1) The psycho-educational tests were carried out at the children's school, each child leaving class to be tested singly, in a quiet room.

2) The collection of teacher's assessments were carried out at the school.

3) Audiometric and ep testing was carried out in a quiet, two room, test suite in the University wing of the General Hospital in Southampton. The children attended for assessment in pairs, accompanied by a school teaching assistant. The assessments

were spread over a 10.00 a.m. to 5.00 p.m. day, and several of the children were required to return for a second assessment. A child was not required to be tested for more than 1½ hours, without a rest period.

4) The children in Group 2 were assessed in the test suite at the General Hospital only. In most cases they attended singly and the test procedures were spaced over the whole day.

Following data collection with the children, extensive data analysis was carried out on all areas of the investigation. The ep data were compared qualitatively and quantitatively to normal data, and the types of responses obtained in cases of severe-to-profound hearing losses examined. The ep data were examined to investigate the site of auditory dysfunction. All relevant features of the data array were subjected to a factor analysis procedure in order to seek any underlying order in the data. The hypothesis that the site of auditory dysfunction, as determined by auditory ep techniques, has an effect on the acquisition of oral/aural skills was investigated. Other factors, as revealed by the behavioural audiological and psycho-educational assessments, which may have contributed to the childs speech and oral language related skills were examined.

2.4 PRELIMINARY EXPERIMENTS

The study undertaken was multi-disciplinary covering areas of psycho-educational, audiometric and electrophysiological testing. In the latter two of these areas some preliminary experimentation had to be carried out in order to provide comparative data from normal hearing subjects. This lead to the design and implementation of three subsidiary experiments:

1) (a) A study of high frequency hearing in normal and hearing-impaired children,

(b) The relationship of high frequency hearing to speech intelligibility,

2) An investigation into the recording parameters which would be optimal for the purposes of this study; that is, study of the whole waveform at suprathreshold levels, and study of the most robust component (Wave V) to threshold.

3) Collection and analysis of ep data (auditory brainstem and middle latency responses) from a population of young, normal hearing adults. Data was examined to investigate intensity effects, monaural/binaural effects and gender effects. Some clinical examples of known lesion site were compared with the normal data.

This dissertation summarises the implementation and analysis of all these areas. The remainder of the report is laid out as described below.

2.5 STRUCTURE OF THE DISSERTATION

The different aspects of the investigation are dealt with, for clarity, in separate chapters in this report.

Chapter 1is a review of the literature, in all the areas important to the overall study.

Chapter 3 describes the audiometric and psycho-educational data collection and analysis. The rational for choice of tests selected is discussed and the manner of test presentation reported. The collection of speech recordings and the judgement of these samples for intelligibilty by a panel of naive listeners is described. A summary of the data collected is reported for all the measures, and the results of inter-test comparisons, using appropriate statistical procedures, are reported and their implications discussed.

Chapter 4 describes the experiment examining the relationship of high frequency preservation of hearing to speech intelligibilty. It has been found that in some cases of hearing loss, where audiometric configurations have shown an upward trend from 4 kHZ, such that a high frequency island of hearing is retained, the subject's speech production is better than would be predicted on the basis of the conventional audiometric information. It was therefore decided to investigate this possible contribution to speech production. The auditory acuity of each child in the main study was assessed at 12 and 16 kHz, and comparisons were made with measures of speech intelligibility. The selection of a suitable transducer, its physical calibration and the study carried out on normal hearing children, as a biological calibration, is described. Test repeatability was also investigated.

Chapter 5 describes the ep experiments on normal subjects. Firstly, an experiment to determine the optimum recording parameters to be used in the main study is presented. Secondly, the normal data collection of auditory brainstem and middle latency responses to click stimuli is described and the results analysed and discussed.

Chapter 6 describes the auditory ep assessment of the test population. The data are discussed, predominantly qualitatively, because of the nature of the responses recorded, but quantitatively where possible, in comparison with the normal data. The efficacy of these techniques in ascertaining the site of dysfunction in hearing-impaired children is discussed.

Chapter 7 provides an overview of the entire experiment and a summary and discussion of the results.

CHAPTER 3

AUDIOLOGICAL AND PSYCHO-EDUCATIONAL STUDIES ON THE TEST POPULATION OF HEARING-IMPAIRED CHILDREN

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3.1 PROCEDURES

3.1.1 Audiometric Evaluation

3.1.1,1 Test Selection

Several audiometric measures were carried out, selected because of their possible association with speech intelligibility or because of their role in site-of-lesion investigations. A normal audiometric profile was determined, with the addition of threshold determination at two frequencies above the conventional upper limit of 8 kHz. These additional threshold measures were included because other studies have suggested that hearing in the frequencies above 8 kHz may contribute to speech perception and intelligibility. This aspect of the investigation is described and discussed fully in Chapter 4. Other measures were included for reasons given below. In general, investigative literature in this area, particularly on children with the less severe hearing deficits, is scant, and there is a paucity of recent contributions.

A measure of abnormal adaptation was included since abnormally fast adaptation of the auditory system to a near threshold stimulus has been shown to be an indicator of central disorder (e.g. Olsen, 1974; Fourcin et al., 1985). Further, it is probable that the presence of extensive tone decay, irrespective of its diagnostic value, may have adverse affects on speech processing. Costello and McGee (1967) reported on two patients whose speech and language began to deteriorate at three years old, apparently in the absence of any known illness. Despite normal pure tone acuity, both children demonstrated extremely poor results in tests of speech discrimination. They also both showed a marked and rapid tone decay. The associated results led to the inference that a pathology had occurred which interfered with the normal transmission of neural impulses in the auditory pathways. The possible association between oral language ability and the presence of abnormal tone decay is the principal reason for the inclusion of this test in the assessment procedure. The extent of the tone decay is also related to the extent of hearing loss, and some tone decay might be expected in those subjects with severe to profound losses (Saunders, 1976).

Various tests of tone decay have been devised, but there is general agreement that the character, or rate, of the tone decay is as important as the extent (e.g. Hood, 1956; Carhart, 1957; Rosenberg, 1958; Sorenson, 1960; Green, 1963; Owens, 1964; Olsen, 1974; Jerger and Jerger, 1975). The main differences between the tests are the presentation level above threshold, the required time of tone perception, the preservation of tonality, and the presence or absence of recovery intervals during the task. The most clinically popular tests in the U.K. are the Carhart test and its modified forms (e.g. I.S.V.R, Southampton University and Rosenberg); the Owens test; and the Jerger and Jerger test, which is carried out at high sound pressure levels. In the present study, the full Carhart procedure was used, in order to ensure that both the rate of decay and the full extent of decay were measured. Hearing losses were so severe in the subject sample, there was seen to be no reason to choose a modification which is designed to reduce the test time of the procedure, since the extent of loss would impose the ceiling limits in most cases. The Carhart procedure is uncomplicated and can easily be used with children (Saunders, 1976).

3.1.1.2 Instrumentation

Audiometric measures were made using a Peters AP6 pure tone audiometer, with TDH-39 headphones. Middle ear measurements were made on a Damplex portable impedence meter. Calibration was carried out, by the author, in the conventional manner, and to the required British Standards (2497 Part 2, 1969) for pure tone audiometry. High frequency thresholds (12 kHz and 16 kHz) were measured via the Peters audiometer, with specific additions as described in detail in Appendix 4.

3.1.1.3 Methods

There were differences between the tests carried out on the two subject groups. The ULL procedure was not attempted with Group 1 due to the extent of hearing loss of these subjects.

i) Pure tone air conduction thresholds were measured on each child, using the Hughson-Westlake procedure, masked as necessary, at the following frequencies: 0.25, 0.50, 1, 2, 4, 8, 12, and 16 kHz.

ii) Pure tone bone conduction thresholds were measured, masked where possible, at the following frequencies: 0.25, 0.50, 1, 2, and 4 kHz.

The test sequence of air and bone conduction depended on the individual audiometric circumstances and the conventional rules were observed. The high frequency thresholds were measured after the bone conduction thresholds for logistic reasons.

iii) Uncomfortable loudness levels (ULL) were measured at 0.5, 1, and 2 kHz, where possible. The child was carefully instructed to indicate as soon as he found the tone uncomfortably loud (Group 2 only).

iv) A full Carhart tone decay test was carried out at frequencies 4, 2, and 1 kHz, testing in that order and proceeding to successively lower test frequencies only if decay of 10 dB or more was measured at the last frequency. The test was started 5 dB above threshold, and acknowledged tone perception was required for 60 seconds for the test to be terminated. Testing was abandoned in some cases if the child found the task too difficult, or the test could not be completed due to audiometric limits. Testing began at a lower frequency if there was insufficient hearing at 4 kHz.

v) A tympanogram was recorded from each child in the conventional manner, and middle ear pressure and middle ear compliance were noted.

vi) Contralateral and ipsilateral acoustic reflex thresholds were sought at 0.50, 1, 2, and 4 kHz. An ascending technique from 80 dB HL was used.

3.1.2 Psycho-educational Tests

The choice of test material was made following a thorough literature search, and after consultation with a number of specialists in deaf education and educational psychology. The purpose of the psycho-educational tests was to provide an oral-language related description of each child, that could be quantified, allowing inter-subject comparison. It was also intended to examine the inter-test relationships in the data. A feature of the selected test instrument was that it be applicable to the whole age span of the test population for each area of assessment.

Descriptions of the selected test instruments are provided in the following pages; procedural details are reported and the basis for their selection explained.

Reading and vocabulary tests were the only measures of academic achievement included. It was considered beyond the scope of the present study to implement more widely ranging achievment tasks. However, previous studies have shown these measures to correlate highly with other academic measures such as maths, when children are tested on one of the wide range achievement scales (Quigley and Thomure, 1968).

In the analysis, the relationships between the tests will be examined, and later, in Chapter 7, they will be compared with data from the site of auditory lesion studies across the data array. There were some differences in the test battery applied to each group, as indicated below. Restrictions on total test time available were more limiting with subjects in Group 1, than Group 2. Further, the tests on Group 2 subjects were carried out with the benefit of some preliminary examination of the data from the assessment of Group 1 subjects. It was felt adequate to carry out this reduced range of procedures, as an inter-subject comparison on heavily language biased tests is less valid on the test group with the wider range of hearing ability. A number of studies suggest that hearing loss is the biggest influence on tests of verbal ability. For example, the work of Hine (1970), who carried out a factor analytic procedure on results of psychometric tests on deaf and hearing children, showed that hearing loss was the demographic variable with the highest loading on the first principal factor. This indicates that hearing loss would be the major contaminating variable in a factor analysis, where tests have a high verbal loading. The situation differs with Group 1 subjects because of the limited auditory range across subjects.

3.1.2.1 Raven's Progressive Matrices (Standard or Coloured, according to subject age)

This instrument was used as a measure of cognitive function. The tests are designed to have a low verbal weighting (Raven, 1977a, 1977b, 1977c). It was also a requirement of this study that the test should be of short duration and applicable to a wide range of subjects. Long tests can cause subjects, especially the younger children, to lose interest (Levine, 1974).

It was also desirable to select assessments which were as short as possible, because the subjects were to undertake several different procedures. Raven's Progressive Matrices are one of the shortest assessment instruments in this subject domain.

Assessments used to examine the mental ability of hearing-impaired children should not discriminate against their lower verbal ability. There is some controversy surrounding the psychometric evaluation of hearing-impaired children using standard instruments yielding IQs and their equivalents. The basis for this controversy is the theory that IQ is a compound of inherent ability *and* environmental effects. The experiences of the hearing-impaired child are different to those of the normal hearing child, and this has led people to postulate that there is some influence of language on cognitive development (e.g. Furth, 1966, Conrad, 1979). The relationship between language and intelligence has long concerned philosophers and psychologists, and is not yet clear.

In a review published by Levine, in 1974, Raven's Progressive Matrices were reported as being among the most widely used instruments for intellectual measurement of the hearing-impaired (in the U.S.A.). Other popular tests are the Weschler Intelligence Scales for Children - Revised (WISC -R) (1974), the Hiskey-Nebraska Test of Learning Aptitude (1966), the Lieter International Performance Scale (1969) and the Snidjers-Oomen Non-Verbal Intelligence Tests for Deaf and Hearing Subjects (1970). More recently, Davis et al. (1981) report the WISC-R and the Stamford-Binet Scales to be the most popular for use with mild to moderately hearing-impaired children in normal schools. The latter is, however, not particularly suitable for use with hearing-impaired children, as it allows for a single estimate of intelligence based on both verbal and non-verbal items.

The standardisation of the Raven's Matrices is open to criticism. It was carried out on a comparatively small sample (735) for the individual administration of the test, and confined to one geographical region. Reliability is quoted in the manual from 0.83 to 0.93, increasing with increasing subject age for normally hearing children. The validity of IQs obtained on the deaf with test instruments standardised on hearing children has been questioned. Vernon published a review of 31 psychometric studies, involving a range of test instruments, in 1967. He concluded that the IQs of deaf children are comparable to those of normal children. This view was supported by Levine et al. (1971) and Willis et al. (1972). Earlier findings, showing that deaf people performed poorly relative to hearing controls, were attributed to the language requirements inherent in many tasks.

Hearing loss variation has been shown to predict language related achievements more accurately than any other demographic variable, including IQ (Trybus, 1980), although, as stated earlier, experimental design constraints have caused limitations in exploring this area. A significant non-intellectual variance exists in some comparative studies on deaf subjects, which, by definition, is eliminated from the hearing samples in the standardisation study. It is vital that tests of cognitive function have a low verbal input, and are not language related. Having a low range of hearing losses may reduce the effects of language bias.

Raven's Progressive Matrices were ranked in the top-ten for frequency of use by Levine in the 1974 study. The Raven's scale has a major advantage over the other tests mentioned, in that it takes only about 20 minutes to deliver, as against 60 minutes for the WISC-R. It is a matter of importance that the relative measurement merits of this shorter test are examined against the others. A few studies have investigated the relationship between the WISC-R and Stamford-Binet Scale and the Raven's Matrices, including Levine and Iscoe (1955), Barratt (1956), Hall (1957), Evans (1966), Wilson et al. (1975) and James (1984). Correlation coefficients ranged from +0.54 to +0.87 between the compared instruments.

The most recent study, by James, is of particular interest since the audiometric profiles and subject age range are similar to the present study. He administered the WISC-R and the Raven's Coloured or Standard Matrices to 84 hearing-impaired children, and found strong correlation coefficients (0.87) between them. Closer examination of his data led him to conclude that the Raven's Matrices provide a reasonable indicator of the subject's current functioning level, but less in-depth information than could be obtained with the WISC-R. The Matrices are divided into a number of task types, listed below. Some reviewers (e.g. Borton, 1965) found that the subcategories suggested by Raven are not of great diagnostic value, but that the test is best regarded as a whole to be used with other performance measures. Evans (1966), comparing the performance of deaf and hearing children on the Coloured Matrices and the WISC-R, found that the deaf children gave normal results with the WISC, but below average results for the Matrices.

Wilson et al. (1975) found good correlation between the two tests for deaf and hearing subjects, but found the distribution of the Raven's test scores to be atypical, being a bimodal distribution with the two greatest frequencies at either end of the distribution. The authors suggest that this may be due to the children's handling of complex cognitive problems in very different ways, and with different strategies. Dividing the subjects into a "good" group and a "poor" group, they found a number of other perceptual differences between the groups (tapping, stereognosis, the Embedded Figures, the Bender-Gestalt, the Benton Visual Retention Test, and the Purdue Pegboard). The authors suggest that there is an underlying difference in perceptual response strategy. The possibility exists that the structures underlying this equal performance could be qualitatively dissimilar.

Taken together, these studies indicate support for the use of Raven's Matrices in the present study, given that the the comparison of the test scores with normal values is not of major importance.

The tests in the series comprising the Raven's Progressive Matrices represent an attempt to measure intellectual functioning within the context of Spearman's concept of "g" intelligence. This is defined as relational thinking, via perceptual reasoning. The tasks consist of designs which require completion, and the testee has multiple choice options for the design which best fits. An answer may: complete a pattern; complete an analogy; systematically alter a pattern; introduce systematic permutations or systematically resolve figures into parts. The number of items correctly scored is converted into percentile rank. No feedback is given to the child as this has been shown to significantly increase performance, depending on the extent of the feedback (Carlson and Dillon, 1978).

Test Method:

The test is presented as a series of diagrams, in a book, and the child is required to carry out a matching task on each. They become progressively more difficult through the book. There are five sets of 12 tasks. The younger children (11 years or less) were asked to complete tests A, B and C

(Coloured Progressive Matrices, CPM) and the older children, tests C, D and E (Standard Progressive Matrices, SPM). A score out of 36 was then achieved. This was converted to a percentile rank (Raven, 1977a) and to placement in one of seven categories (Raven, 1977b; Raven, 1977c).

3.1.2.2 The English Picture Vocabulary Test, EPVT (1973)

This test was used to obtain a measure of listening vocabulary. The test is designed for use with children in the five to eleven year age range, and appears to correlate well with other vocabulary measures in normal hearing children. The manual reports a correlation of 0.76 with the WISC vocabulary test, and 0.80 with the Schonell Graded Word Reading Test. The standardisation studies indicate that there is a consistent difference in raw scores in favour of boys.

Criticisms of the test relate mostly to the standardisation method (e.g. Lovell, 1972), as this was carried out in rural Wiltshire, which is not very representative of the current English population. The test reliability is reported as 0.88 (EPVT manual). The authors report that the test is relevant to the understanding of reading difficulties and other verbal learning handicaps. They suggest that it provides a reading-free predictor of future language attainment, but it is essentially a test of word knowledge rather than assessing more comprehensive language skills. For this reason it is commonly used in the assessment of children with hearing difficulties. The reliability of the test is reported in the manual as having a high correlation with other measures of intelligence.

The EPVT is derived from the Peabody Picture Vocabulary Test, which is an American Test based on 2055 words from the Webster New Collegiate Dictionary, and standardised on white children in Nashville, Tennessee. It is commonly used as a quick language check with hearing-impaired children, but studies indicate that extrapolation to academic prediction should not be based on this test alone (Beck et al, 1985).

Test Method:

The child sees four line drawings presented on a page, each depicting a familiar object, and is asked to point to the test word by verbal instruction. The test becomes progressively more difficult. It consists of

120 items, divided into three equal parts, with different recommended age levels, and the child works through in order. The score may be expressed as a raw score, a standardised score, where the mean is 100 and the s.d. is 15, or as a percentile rank. The raw score, or a transformation of the raw score was used in the analysis in the present study. As the standardised score is derived from work with normal hearing children its use would produce an unquantified bias.

3.1.2.3 The Southgate Reading Test (Test 1, Word Selection).

Each child in Group 1 completed the Southgate Reading Test. This is a reading test, devised by Vera Southgate (1959), which is commonly used to assess hearing-impaired children. It was originally devised as a group reading test, with the child using written responses, from a multiple choice selection. The whole test consists of two sections; a word selection test and a sentence completion test, and each is available in three forms of equal difficulty. The aim of the test is to provide a simple and quick method of making a preliminary assessment of a young child's reading ability.

The manual suggests that the test is suitable for average children in the 6 to 7½ years age range, or for older slow readers. The reading age of deaf school leavers is rarely in excess of 8 years (Redgate, 1972; Morris, 1978; Conrad, 1977, 1979), so it was thought to be an appropriate assessment tool for the test population.

Whilst widely used as an assessment procedure with the deaf, Test 2, the Sentence Completion task, is too advanced for the younger children in this sample. The only other test of reading which is widely used with the deaf is the Brimer Wide-Span Reading Test (Brimer, 1972). This test consists of 80 items of increasing difficulty which provide a range of reading ages, standardised on normally hearing children of between seven and sixteen years. Each item consists of a pair of written sentences from which one word is missing. The testee's task is to choose a word from the other sentence which is appropriate to the incomplete sentence. Again, this test was considered too difficult for the younger group of children in the present test population.

The Southgate Test (Test 1) was therefore carried out as an individual test.

Test Method:

There are 30 test items, consisting of lists of 5 words each. Sixteen items have an accompanying picture. The tester reads a word, and the child is asked to indicate which word from the list has been spoken. Some words have accompanying illustrations. The child is assigned a score out of 30. The children in Group 1 carried out this task.

3.1.2.4 The Schonell Vocabulary Test

This test is part of the Schonell Reading Test (Test R1) and comprises a list of 100 words, increasing in difficulty (Schonell, 1942). The recommended age range for use with normal hearing children is 5 to 15 years. The list is organised as a gain of 10 words per reading age year. This test is commonly used with hearing-impaired children, but a limitation imposed on the scoring is the tester's comprehension of the testee, due to his speech intelligibility.

The Crichton Vocabulary Scale and the Mill Hill Vocabulary Test are recommended by Raven to be used in conjunction with the Matrices. These tests require the child to explain a vocabulary item in his own words. It was felt that this task was too difficult to score in the context of this experiment, partly due to the poor speech intelligibilty of the test group, and partly due to the reliance of the test on compatible expressive language skills, which is not a valid assumption with hearing-impaired subjects.

The word order of the Schonell test is such that the words should become progressively less familiar to the child as the test progresses. Andrews (1965) and Linfoot (1967), in critical studies of the test demonstrated the need for restandardisation, as frequency of word use has changed in the years since the test's publication. Adjacent words in the test do not increase in difficulty by a constant amount. Linfoot noted two other difficulties. Firstly, that children commonly make errors with early words in the test, but get later ones correct, and secondly, that older children do worse, in relation to their chronological age, than do younger children.

Schonell's standardisation used the relation:

Reading Age = 5 + (Raw score/10)..........(Schonell and Schonell, 1965)

A general criticism of the test is the possibility that the result may be influenced by the method used to teach the child to read. Kellmer Pringle wrote in a review of the test (1953) that it favours children taught by a phonic method. Most, but not all, of the subjects in the present study were at the same school when they were taught to read, so the problem is almost, but not quite, eliminated.

Test Method

Each child is asked to read the test word to the tester. Ten successive failures signal the conclusion of the test. The children in Group 1 carried out this test.

3.1.2.5 Visual Discrimination

A simple visual discrimination task was presented to each child to check that reading difficulties were not caused by visual discrimination difficulties. The child was presented with a series of four simple pictures, where three were identical, and the child was asked to identify the odd picture in the set. In the second part of the test, the child had a similar task, but the test items were groups of four letters. In three presentations the test item was identical, and it differed in the fourth in letter order only. The child was asked to identify the odd item. This was regarded as a screening test and it was not intended to incorporate any formalised score in the assessments.

3.1.2.6 Measures of Speech Intelligibility

Accurate assessment of speech intelligibility in hearing-impaired children is a multiple component task, requiring specific skills. It involves evaluation of several different parameters of speech, which have largely been developed with oral training and rehabilitation aspects as an ultimate goal. The main areas of investigation are: speech intelligibility; measures of the physiologic parameters of speech (e.g. respiration); measures of voice; measures of articulatory accuracy

Measures of speech intelligibility obtained from oral reading and conversational samples have long provided the principal base line and ultimate index of therapeutic effectiveness. Two major strategies have commonly been used to assess speech intelligibility of deaf subjects, and both involve ratings by panels of judges. In the first, the recorded stimuli produced by the subjects are played to the judges, and intelligibility is judged as the number of words understood, expressed as a percentage of the total number of words spoken (John and Howarth, 1965). In the second, the judges are asked to listen to recorded samples and rate the intelligibility according to an equal appearing interval scale (Subtelny, 1977; Geffner et al., 1978). Monsen (1978) has indicated the importance of using simple material, an over complex task being a major contaminating factor in studies of speech intelligibility of deaf children.

It was felt appropriate to use a measure of speech intelligibility as the major speech description in this study. Since the aim was inter-subject and inter-test comparison, detailed descriptions of the speech process, as would be required for therapeutic work, were not considered necessary. Further it was considered to be an area of work requiring specialist skills, beyond the scope of this experiment. As additional information, the teacher's report summary for speech skills was obtained.

<u>Method</u>

Speech samples, consisting of a short familiar reading passage were collected from each child in Group 1. The material chosen was simple and familiar, being drawn from classroom material forming the basis of their language development and reading programme. The material was shown to the panel prior to listening.

The recorded samples were re-recorded in three different random orders, each sample being cut to 20 seconds duration. A panel of naive listeners was then asked to listen to the speech samples, and to judge them for intelligibility on a five point scale, 1 to 5, where 1 was "very clear" and 5 was "completely unintelligible speech". This was based on the equal interval speech intelligibility scale and is typical of intelligibility scales used with the hearing-impaired. The panel attended for each of three sessions, the first being counted as a practice session, and the sessions were each one week apart. Thus, each panel judged the speech complex in different random orders on three different occasions. The script of the passage was read by the panel members before the session, to ensure that all the listeners had a standard familiarity with the passage.

Comparisons of the panel data from the sessions using a one-way analysis of variance showed there to be no significant differences in the variance of the last two sessions. A mean speech intelligibility grade was then taken over panel members from these two sessions and assigned to each child.

The logistics of the study did not permit this analysis to be carried out in the same way for Group 2 children. As a guide to speech intelligibility the tester noted a value judgement on the child's speech intelligibility, and this was later compared to a teacher's appraisal

3.1.2.7 Teacher's Grades

The most recent annual report on each child was studied. This covered scholastic areas and communication and social skills. An overall grade was assigned for several areas, and the grade assigned for "hearing and spoken language" was used as part of the comparative assessment procedure. Notes were taken from the reports for qualitative examination of the data, and summaries of these are available in Appendix 2

The tests described were all conducted interactively with the author, and no written responses were required from the child, although this is an option with some of the tests. The test environment was a quiet room, and the children were tested with their hearing aids on. The child was seated face to face with the tester under favourable lighting conditions to ensure the best possible listening conditions. At no time were the assessments treated as a test of auditory acuity and every effort was made to ensure that the child had understood the task and test item.

3.2 RESULTS

3.2.1 Audiometric Assessments

3.2.1.1 Audiometry

The average pure tone audiograms for both Groups are shown in Figure 3.1. It is apparent that the range of hearing of subjects in Group 2 is greater than that of Group 1, and that the average hearing loss is less severe. Individual thresholds which were greater than audiometric limits were taken as 130 dB HL in these and other calculations. Bone conduction thresholds could not be recorded for any subject in Group 1 and no significant air bone gap was detected for any subject in Group 2. High frequency thresholds were recorded from only 5 subjects in Group 2. Full treatment of this topic is postponed to Chapter 4.

The audiometric information was summarised for each subject as a six frequency average, and an index for slope was calculated by a method described by Bamford et al. (1980). Several methods of data reduction had been considered. It was felt appropriate to select a method which best correlated with a speech discrimination method. For example, the three frequency pure-tone average at 0.50, 1 and 2 kHz, although this is limited, as is Kyle's five frequency summary (1977). Neither of these methods takes account of the slope of the audiogram, although this appears to affect speech perception ability. Methods have been devised which categorise audiometric information, but have either too little data reduction (e.g. Carhart, 1945) or result in loss of information (e.g. Wedenberg, 1954, and Risberg and Martony, 1970). Bamford et al. (1980) arrived at a summary aimed to cause minimal loss of information. This was derived following analysis of the better ear audiograms of 200 hearing-impaired children. Bamford and his colleagues used a principal factoring method to identify sources of variation in the data, and noted that the main source of variability is related to an averaging measure of extent of loss in the audiogram, but that this accounts for only 60% of the variance. This leaves 40% of the variance unexplained. The second component in the analysis, accounting for 26% of one variance, reflects the slope. Factor weightings are maximal in the extremes of the frequencies, indicating the importance of the mid speech frequencies. This led Bamford et al. to the following summary for slope:

$$1/\sqrt{70}\,(-5x_{250} - 3x_{500} - x_{1000} + x_{2000} + 3x_{4000} + 5x_{8000})$$

This index is zero for a flat audiogram, positive if the hearing loss increases at higher frequencies and negative if the hearing loss decreases at higher frequencies. The combined use of this index, with a six frequency average, as suggested by Bamford et al. (1980) has been chosen as the audiometric summary for this study.

A better/worse ear audiometric comparison was made using a linear regression model. The results are summarised in Fig 3.2.

3.2.1.2 Uncomfortable Loudness Levels

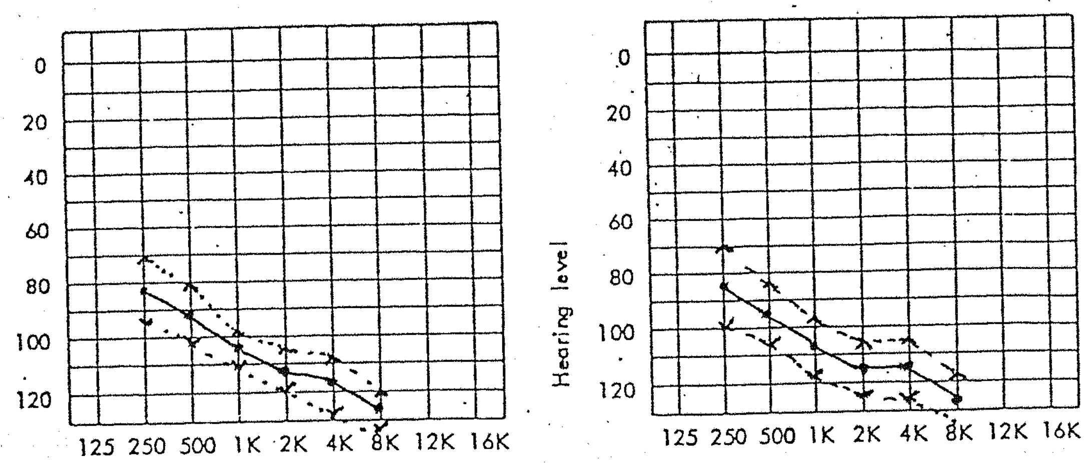
These were measured from Group 2 subjects and converted to a dynamic range measure by comparison with the pure tone thresholds. The figure listed in Table 3.2 is the dynamic range measure at 1 kHz. The mean dynamic range ($n = 10$) is 28.0 dB for the worse ear (s.d. 15.0 dB) and 26.5 dB for the better ear (s.d. 12.9 dB). This is markedly reduced from the normal range of 90-100 dB. As expected, the dynamic range is significantly related to the extent of loss ($p < 0.01$) as shown using the Spearman rho rank correlation test.

One subject in Group 2 causes some difficulty in the analysis in that there is a suspicion that her hearing loss may be, at least, exaggerated (LT). Her behavioural audiometric results have been entered into the data array. This suspicion arose from behavioural observation and later test results (ABR). Her audiometric profile was consistent with previous assessments in showing a moderate to severe sensorineural loss. This case is discussed at length in Chapter 6.

3.2.1.3 Tone Decay Test.

Measurable tone decay of 15 dB or more, was found in only six ears; although 12 other ears registered decay of 5 dB or more, the full extent could not be determined due to audiometric limits. No case of very rapid decay was observed, the greatest being 2 dB s^{-1}. The extent of decay was in excess of 20 dB (subject DaL). There was no significant correlation between the extent of tone decay and hearing loss ($p < 0.01$, Spearman rho).

Group 1



BETTER EAR

WORSE EAR

Group 2

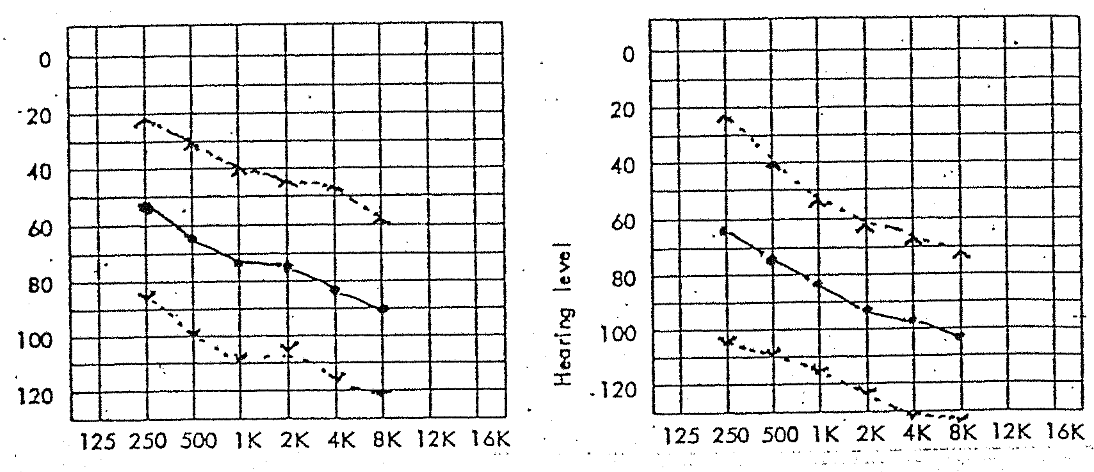


Fig 3.1

3.2.1.4 Tympanometry

This revealed that no child had an active middle ear condition at the time of testing.

3.2.1.5 Acoustic Reflexes

These were not elicited from any subjects in Group 1, and were within the range expected for each subject in Group 2.

All the audiological data is summarised in Tables 3.1 and 3.2.

Fig 3.2

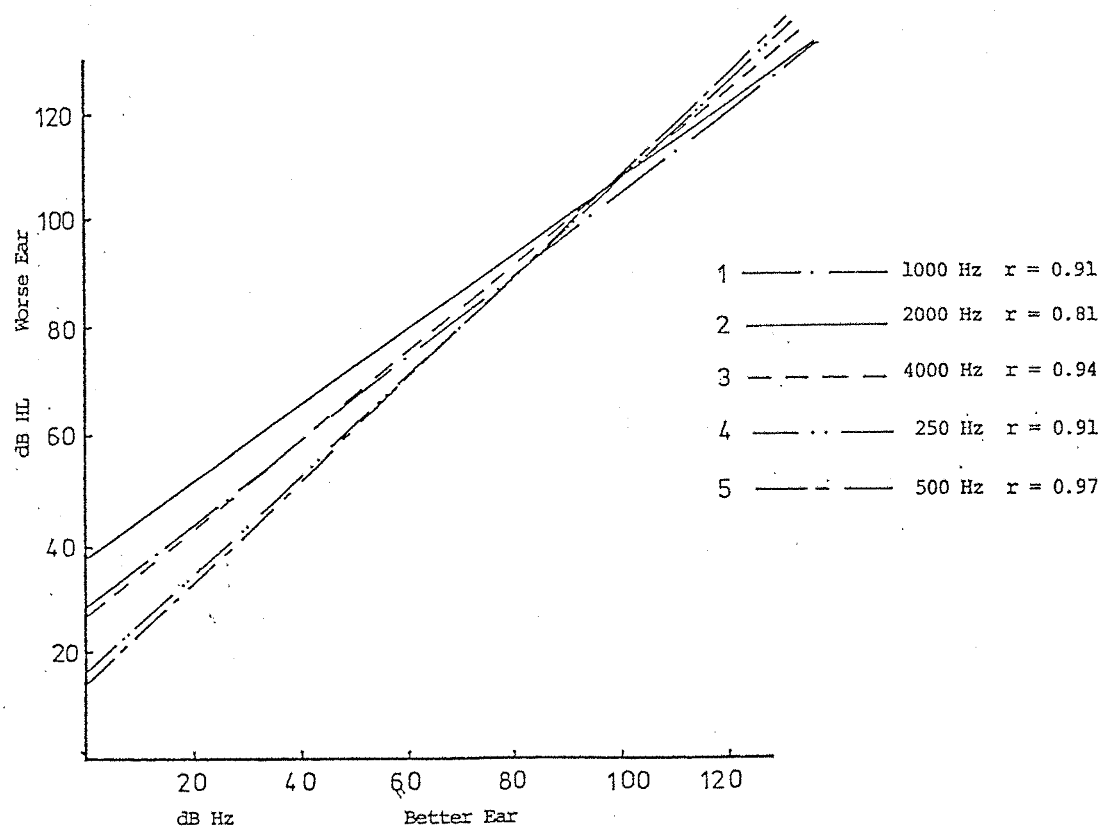


Fig 3.2 Best Ear Versus Worse Ear by Frequency

Table 3.1

SUMMARY TABLE OF AUDIOLOGICAL DATA FOR GROUP 1

Subject	Ear	Audio Ave. (6 freq.) dB HL	Audio Slp. (6 freq.)	High Freq. (12 kHz) dB	Tone Rate dBs^{-1}	Tone Degree dB
DL	B	104	42.5	75	2	>20
	W	104	41.8	85	nt	nt
ELM	B	110	36.4	-	0.1	5
	W	111	34.1	-	nt	nt
AD	B	100	34.6	-	nt	nt
	W	100	40.0	-	nt	nt
GP	B	101	43.6	-	0.3	15
	W	104	26.9	-	nt	nt
MCa	B	93.3	43.6	-	0.3	15
	W	85.8	35.8	-	0.1	10
KN	B	106	35.2	-	0.9	>10
	W	110	34.6	-	1.0	>5
HD	B	118	35.6	-	nt	nt
	W	118	28.1	-	nt	nt
SH	B	100	44.8	-	nt	nt
	W	109	25.2	-	nt	nt
AC	B	104	59.2	-	0.4	10
	W	110	25.1	-	0	0
BW	B	100	46.6	-	0	0
	W	105	40.0	-	0	0
DeL	B	104	42.4	75	0	0
	W	104	41.2	85	0	0
MC	B	100	45.4	-	0	0
	W	103	41.8	-	0	0
CN	B	112	40.0	-	0.4	>10
	W	112	27.0	-	0.3	>5
MP	B	116	25.7	-	0.5	>5
	W	123	17.3	-	0.3	>10
AS	B	111	43.6	-	0	0
	W	113	43.6	-	0	0
LL	B	98	40.6	95	0.7	15
	W	100	41.2	90	0	0
JW	B	102	47.8	-	0.1	>5
	W	103	44.2	-	0.2	>5
ZK	B	113	20.9	60	0	0
	W	114	34.1	-	0	0
JH	B	113	22.7	-	0.1	5
	W	118	18.5	-	0.1	5
PB	B	110	41.8	-	0.9	>5
	W	113	37.0	-	0.9	>5
EM	B	100	8.4	-	0.1	5
	W	107	22.0	-	0	0
CT	B	103	43.0	-	0.3	15
	w	108	35.2	-	0.2	5
DG	B	112	45.0	-	0.9	>5
	W	112	39.4	-	0.9	>5
BG	B	104	38.8	-	0.4	20
	W	117	21.5	-	0.5	10
PG	B	95	19.1	90	0.4	10
	W	96.7	27.5	-	0	0

Table 3.2

SUMMARY TABLE OF AUDIOLOGICAL DATA FOR GROUP 2

Subject	Ear	Audio Ave, (6 freq.) dB HL	Audio Slp, (6 freq.)	High Freq, (12 kHz) dB	High Freq, 16 kHz dB	Tone Rate dBs^{-1}	Tone Degree dB	Dynamic Range dB
MM	B	89	31,7	-	-	-	0	15
	W	99	3,0	-	-	-	0	10
MW	B	41	43,6	-	-	-	0	50
	W	50	21,5	-	-	-	0	45
SP	B	57	34,7	75	70	0,3	5	10
	W	63	31,7	75	75	-	0	5
JL	B	102	35,0	-	-	-	0	25
	W	105	31,1	-	-	0,14	5	20
AD	B	33	38,2	-	-	0,3	10	nt
	W	78	107,5	-	-	0,3	15	nt
LT	B*	69	9,0	80	-	-	0	>45
	W	74	19,7	80	-	-	0	40
NH	B	76	-22,1	40	65	0,3	5	10
	W	86	-10,8	85	60	0,2	5	20
CS	B	77	8,4	-	-	-	0	30
	W	96	6,6	-	-	-	0	>45
DS	B	36	44,8	70	70	0,2	5	35
	W	38	46	-	-	0,2	5	45
PS	B	78	-21,5	65	65	0,2	5	30
	W	85	6,0	85	-	0,2	5	30
MO	B	123	21,5	-	-	nt	nt	10
	W	127	11,9	-	-	nt	nt	20

Table 3.3

AUDIOMETRIC DATA FROM GROUPS 1 AND 2

The percentage of the total variation ascribed to each component.

Component	Percentage	Cumulative Percentage
1	39.5	39.5
2	22.4	62.0
3	16.2	78.2
4	9.1	87.3
5	5.7	92.9
6	3.9	96.8
7	2.3	99.1
8	0.7	99.8
9	0.2	100

3.2.1.6 Statistical Analysis

A factor analysis procedure was used to seek an underlying order in the audiological data. To meet the requirement of a normally distributed data input, the tone decay data was transformed according to the formula

$$y = \frac{1}{2}\ln(1+x/1-x)$$

where $x = (20-i)/i$ and i is the data point. The uncomfortable loudness levels were entered as measures of dynamic range. The factor analysis was carried out on an IBM 2970 computer, using the SPSS package. The procedures used throughout this study are fully explained in Appendix 3.

Examination of the initial correlation matrix revealed only a strong correlation between better and worse ear threshold data. There was no significant correlation between any other variables. In particular, it is noted that there was no significant correlation between the slope index and extent of loss, nor between the rate or extent of decay and extent of loss, nor between the presence of high frequency thresholds and either extent or slope of loss.

Principal factors were extracted from the intercorrelation matrix. Factors with eigenvalues of greater than 1.0 were retained for analysis. Only three factors emerged meeting this criterion, accounting for 78% of the total variance in the data. Table 3.3 shows the percentage of total variance ascribed to each of the 9 original factors which emerged from the principal component analysis.

The proportion of total variance accounted for by Factor 1 is 39.5%: the proportion of the common variance accounted for by Factor 1 is 34%. Calculation of the communalities of each variable indicates that no variable has a proportion of the unique variance greater than 0.31. The greatest degree of uniqueness belongs to the worse ear slope index (0.31), the worse ear ULL (0.27) and the worse ear tone decay rate (0.29).

Principal factoring with iteration was carried out. (See Appendix 3). Factor 1 shows a strong negative loading on the average threshold data for the better and worse ears and a strong positive loading on the dynamic range measure. Hence, a common factor in the data is primarily responsible for the underlying variance of these two features. The slope index for the better and worse ears loads most heavily on Factor 2. This finding is expected from the deviation of the two audiometric indices, accounting for different aspects of the audiometric configuration. The third factor is loaded most heavily by the tone decay rate as measured in the better ear. It is not clear why the underlying variance should differ from the worse ear. Factor 1, following iteration, now accounts for 53% of the total variance, so the largest underlying effect is extent of hearing loss, as recorded by audiometric average, in both ears.

Oblique rotation of the factors was carried out. This method of rotation can lead to a more flexible and realistic representation of the data cluster than an orthogonal solution, and allows correlations between factors to be examined. The technique revealed that none of the factors correlated with each other to a significant extent. The factor pattern matrix was further simplified to load audiometric average on Factor 1 and audiometric slope index on Factor 2. The factor structure matrix shows correlations between each variable and each factor supporting the above described pattern. (Table 3.4a and b). Examination of an orthogonal rotation (Varimax) did not lead to observations different to those stated above.

Table 3.4a FACTOR PATTERN MATRIX

	Factor 1	Factor 2	Factor 3
Average Audio (BE)	-0.93	-0.06	-0.10
Average Audio (WE)	-0.95	0.00	0.10
Slope Index (BE)	-0.25	0.84	0.02
Slope Index (WE)	0.12	0.71	-0.14
High Frequency (BE)	0.62	-0.27	0.13
Dynamic Range (BE)	0.52	0.51	0.44
Dynamic Range (WE)	0.43	0.36	0.36
Tone Decay Rate (BE)	-0.21	0.02	1.04
Tone Decay Rate (WE)	0.15	-0.21	0.50

Table 3.4b FACTOR PATTERN MATRIX

	Factor 1	Factor 2	Factor 3
Average Audio (BE)	-0.90	-0.11	-0.20
Average Audio (WE)	-0.92	-0.53	-0.22
Slope Index (BE)	-0.19	0.82	-0.08
Slope Index (WE)	0.11	0.71	-0.12
High Frequency (BE)	0.65	-0.24	0.34
Dynamic Range (BE)	0.69	0.53	0.60
Dynamic Range (WE)	0.56	0.38	0.49
Tone Decay Rate (BE)	0.13	-0.01	0.97
Tone Decay Rate (WE)	0.29	-0.21	0.55

3.2.2 Psycho-Educational Measures

One subject in Group 1 was unavailable to complete the full range of procedures. The full data summary is reported in Tables 3.5a and 3.5b.

3.2.2.1 Raven's Progressive Matrices

Raw scores ranged from 8 (subject EM) to 59 (subject CN) in Group 1. The Group 1 mean was 31.17 (s.d. 13.70). Group 2, raw scores ranged from 19 (subject MW) to 50 (subject DS). The Group 2 mean was 33.10 (s.d. 10.92). These scores were converted to Raven's Group classification (Category IQs) and to percentile rank. The distribution of results for both Groups is shown in Figure 3.3. Only one child scored below the 10th percentile.

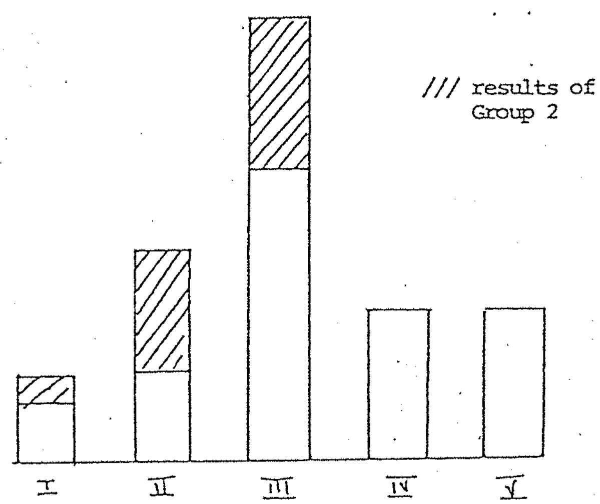
James (1984) compared the IQ categories, as determined by the Raven's Matrices, with the WISC-R IQ scores from a population of similarily hearing-impaired children, using the Pearson -r correlation coefficient. His results are summarised in Table 3.6, enabling a comparison of the childrens' results in this study with the WISC -R IQ. James found that children at the lower age range of his sample had lower categorised scores than the older children. This age relationship was not as marked in the present study, but a scatterplot of age against raw score (Fig. 3.4) demonstrates some improvement of raw score with age for the hearing-impaired subjects and a significant ($p<0.01$) correlation ($r=0.69$). Analysis of the audiometric data and both the raw score and standardised results did not show a significant correlation between hearing loss and test results ($r=0.04$).

3.2.2.2 English Picture Vocabulary Test (EPVT)

Raw scores ranged between 9 (subjects LL and ZW) and 71 (subject TG). The mean score was 34.17 (s.d. 19.32) for Group 1. The Group 2 range of scores was from 7 (subject MM) to 66 (subject DS). The mean score was 45.55 (s.d. 27.33). There is a significant correlation between subject age and raw score for this hearing-impaired group ($r=0.39$).

If the Group data was analysed separately, a significant correlation between subject age and raw score still emerges for both Groups. Also, three of the four highest scores belong to subjects at the top of the age range (15+). There is no significant correlation between hearing threshold and raw score for either group. Conversion to standardised score and percentile rank was attempted, but 92% of the children in Group 1 and 82% of the children in Group 2 fell below the first percentile (Tables 5.6a and 5.6b). When the test results are compared with the results of the Schonell Test, a significant correlation of 0.78 emerges. This improves to 0.85 if one subject (HD) is removed from the analysis. The EPVT manual reports a correlation of 0.80 with Schonell, for normal hearing children.

Fig 3.3 Histogram of RPM Scores



Ravens Progressive Matrices (Scored by Grade)

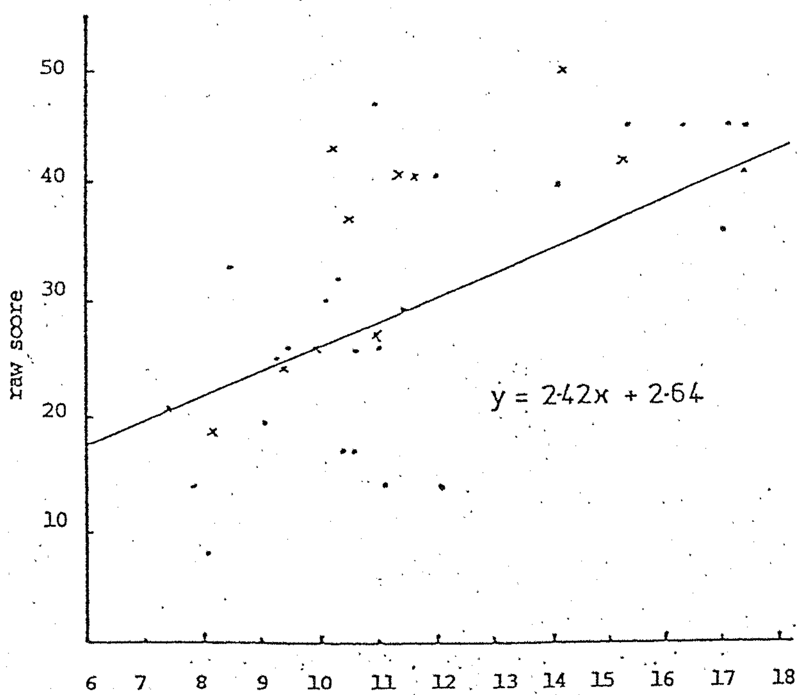


Fig 3.4 Ravens Progressive Matrices
Raw score versus subject age

Table 3.5a

GROUP 1 TABLE OF RESULTS OF PSYCHO-EDUCATIONAL TESTS

	EPVT rs	EPVT %ile	Ravens rs	Ravens %ile	Speech Grade	Schonell Vocab	Southgate Reading	Intellig. Rating	Rank	Age (years)
DL	17	<1	14	10	C	21	22	4	19	7,9
ELM	26	<1	18	<5	C	25	22	5	22	8,1
AD	23	<1	33	90	B	32	23	-	8	8,5
GP	nt	-	-	-	-	-	-	2	(10)	8,8
MCa	19	<1	19	25	C	23	21	3	18	9,1
KN	21	<1	25	50	C	34	24	4	16	9,3
HD	24	<1	26	50	C	30	18	4	17	9,4
SH	39	<1	30	75	B	33	30	3	11	10,1
AC	45	<1	32	95	C	38	30	1	7	10,2
BW	17	<1	17	5	C	30	23	4	14	10,4
DeL	19	<1	17	5	C	34	30	2	24	10,6
MCh	58	3	27	50	B	49	29	5	5	10,6
CN	65	7	47	95	B	40	30	3	2	10,9
MP	50	<1	26	25	B	40	26	4	4	11,0
AS	18	<1	14	<5	D	25	13	4	25	11,1
LL	4	<1	29	50	C	20	15	4	23	11,4
JW	29	<1	41	50	C	31	21	5	13	12,0
ZK	9	<1	14	<5	C	27	24	4	20	12,1
TH	22	<1	40	25	C	27	19	nt	15	14,1
PB	63	<1	45	50	B	25	30	2	12	15,3
EM	63	<1	45	50	B	41	30	2	3	16,3
CT	29	<1	36	10	C	nt	27	nt	21	17,0
DG	54	<1	45	50	C	51	28	4	6	17,1
BG	30	<1	41	25	C	42	30	3	9	17,4
TG	71	<1	45	50	B	50	30	2	1	17,4

Table 3.5b

Group 2 TABLE OF RESULTS OF PSYCHO-EDUCATIONAL TASTS

	EPVT		Ravens		Age
	rs	%ile	rs	%ile	(years)
MW	7	1	21	75	7.4
MW	34	1	19	50	8.2
SP	38	1	24	25	9.4
JC	41	1	26	50	9.9
AD	86	95	43	95	10.2
LT	96	99	37	75	10.5
NH	24	1	27	25	10.8
CS	39	1	42	75	11.6
DS	66	1	50	75	14.2
PS	14	1	42	25	11.3
MO	46	1	42	75	15.2

Table 3.6

CATEGORIES CORRESPONDING TO MATRIX PERCENTILES AND WISC-R IQ's

	Category	Matrice %ile	WISC-R IQ
Intellectually Superior	1	95	>125
Definately above average	2	90-94	120-124
Above average	3	75-89	110-119
Intellectually average	4	23-74	90-109
Below average	5	10-22	80-89
Definately below average	6	5-9	70-79
Intellectually defective	7	5	>69

3.2.2.3 Schonell Vocabulary Test

Scores in this test ranged from 21 to 51, with a mean of 33.13 (s.d. 9.32). The test score distribution is shown in Fig 3.5, where a considerable clustering in the mid range is seen. There is a low, but significant correlation of raw test score with age, although the two highest scores were obtained by the two oldest subjects. There is a strong correlation of this test with the Southgate reading test of 0.96.

3.2.2.4 Southgate Reading Test

Results of the Southgate test appear to suffer a ceiling effect, indicating that the reading age of some of the children in the sample was in excess of the test maximum of 7½ years. Fig. 3.6 shows the test score distribution. A comparison of subject age and test score showed a low but significant correlation of r=0.39 ($p<0.05$). Scores ranged from 13 (AS) to 30 (DL, CN, TG, BG, AC AND EM). The mean score was 24.54, (s.d. 5.06) However, the s.d. is small in comparison with the age span. There was no significant correlation between extent of hearing loss and reading test score for either test Group. A scatter plot of the test scores against age is shown in Figure 3.7.

3.2.2.5 Speech Intelligibility

There is no clear relationship between speech intelligibility and any of the psycho-educational variables. There was a poor correlation between the teachers' grades for speech and the judgement of speech intelligibility. In

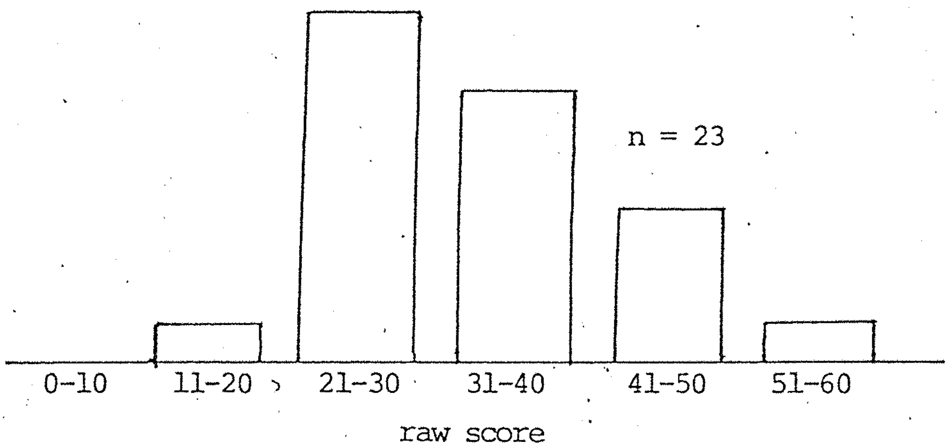


Fig 3.5 Histogram of raw score data of Schonell Graded Vocabulary Test

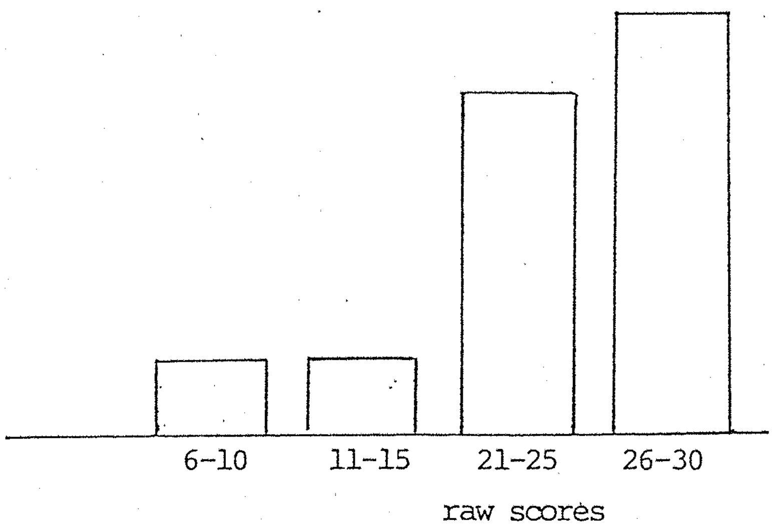


Fig 3.6 Histogram of raw scores of Southgate Reading Test

two cases, teachers' and the panels' grades were at opposite ends of the available scales. Where good agreement was found there was a tendency for this to be among the older subjects. The relationship of speech intelligibility and high frequency acuity will be examined in Chapter 4.

Each child was assigned an overall rank, based on all the scores described. There is a small, but significant correlation between age and rank, (r=0.44) but not between hearing loss and rank, (r=0.09). A scatter plot of hearing loss and speech inteligibility is shown in Figure 3.8, and the lack of correlation is apparent.

3.2.2.6 Visual Discrimination

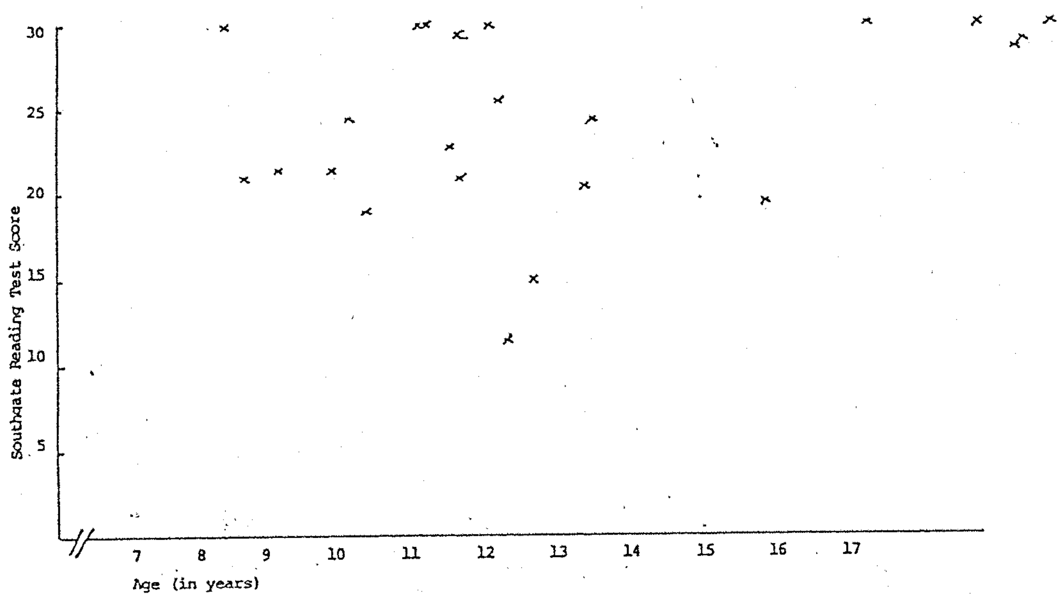
No child in the study showed a disorder on this assessment.

3.2.3 Audiological and Psycho-Educational Assessments

Examination of the two categories of tests did not reveal any obvious relationships. In reported correlations, only hearing levels from the better ear have been used. This was considered satisfactory, because of the close agreement in better/worse ear data (Fig. 3.2). When the 6 frequency average hearing loss, expressed in 5 dB steps from 90 to 120 dB HL was related to speech intelligibility rank in a 35 cell contingency table, a significant relationship between the variables was not found (χ^2) = 0.32)

Table 3.7 shows a summary of all the inter-test correlations that have been made using the Spearman Rho, non parametric, rank correlation method. It is clear that the Raven's Matrices, (a test of IQ) and the EPVT, reported to be related to measures of intelligence, correlate highly at 0.94. As may be expected, the Schonell Vocabulary and Southgate Reading tests also correlate highly at 0.96. This suggests that the ceiling effect suspected in the Southgate results may not be of importance. The correlation of the EPVT and the Schonell tests is comparable with that suggested in the manual, based on results obtained from normal hearing children.

Fig 3.7 Scatter Plot of Southgate Reading Test Scores against Age



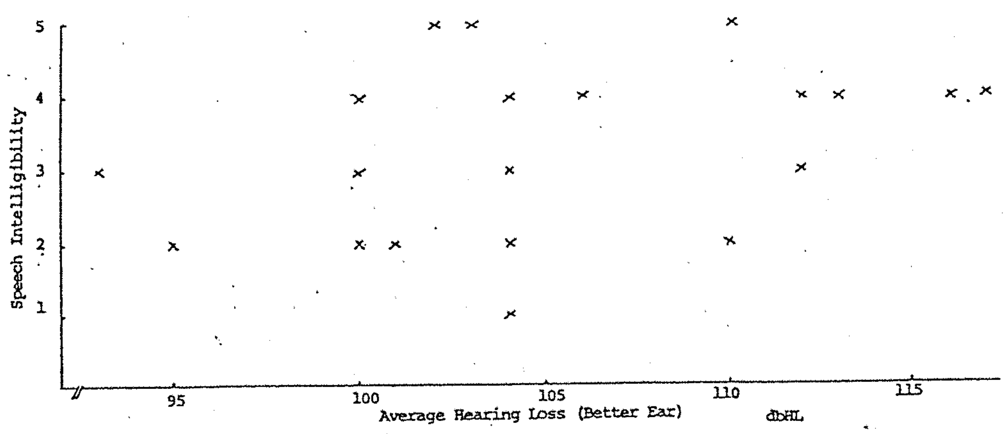


Fig 3.8 Scatter plot of Hearing Loss and Speech Intelligibility Grades (Group 1)

Table 3.7

CORRELATIONS BETWEEN TESTS

Spearman Rho (rank order correlation method)

EPVTand Raven's Matrices (Groups 1 &2)	r = 0.94
Schonnel and Southgate Reading (Group 1)	r = 0.96
EPVT and Schonnel (Group 1)	r = 0.78
Subject age and EPVT (Groups 1 & 2)	r = 0.39
Subject age and Southgate Reading (Group 1)	r = 0.37
Subject age and Schonnel (Group 1)	r = 0.33
Subject age and Raven's Matrices (Groups 1 & 2)	r = 0.65
Better ear HL and EPVT (Groups 1 & 2)	r = 0.04
Better ear HL and Raven's Matrices (Groups 1 & 2)	r = 0.04
Better ear HL and Southgate Reading Test	r = 0.06
Better ear HL and Schonnel	r = 0.17

Kendall Coefficient of Concordance

Raven's Matrices
EPVT — W = 0.803 (significant at $p < 0.001$)
Southgate Reading — $\chi^2 = 70$
Schonnel

Table 3.8

CORRELATION COEFFICIENTS OF PSYCHO-EDUCATIONAL TESTS

	EPVT	Raven's	Schonnel	Speech Intellig	School Grade	Southgate
EPVT	1,00	-	0,65	-	0,61	0,67
Ravens	-	1,00	-	-	0,63	-
Schonnel	0,65	-	1,00	-	-	
Speech Intellig.	-	-	-	1,00	-	-
School Grade	0,61	0,62	-	-	1,00	0,61
Southgate	0,67	-	-	-	0,61	1,00

(only ± correlations greater than 0,60 included)

Table 3.9

PSYCHO-EDUCATIONAL DATA : GROUP 1

The percentage of the total variation ascribed to each component.

Factor	Percentage	Cumulative Percentage
1	53.9	53.9
2	19.0	73.0
3	12.7	85.7
4	6.1	91.8
5	4.7	96.5
6	3.5	100

Table 3.10

SUBSET OF AUDIOMETRIC AND PSYCHO-EDUCATIONAL DATA : GROUPS 1 AND 2

The percentage of the total variation ascribed to each component.

Factor	Percentage	Cumulative Percentage
1	28.6	28.6
2	27.0	55.5
3	18.4	73.9
4	8.6	82.5
5	8.1	90.6
6	5.1	95.8
7	4.3	100

Table 3.11

FACTOR MATRIX, USING PRINCIPAL FACTORS

	Factor 1	Factor 2
EPVT	0.83	-0.20
Raven's Matrices	0.68	0.22
Schonnel	0.69	-0.62
Speech Intelligence	0.39	0.81
School Grade	0.85	0.14
Southgate Reading	0.86	0.01

Table 3.12a

FACTOR PATTERN MATRIX

	Factor 1	Factor 2
EPVT	0.86	-0.09
Raven's Matrices	0.60	0.31
Schonnel	0.85	-0.52
Speech Intelligence	0.15	0.86
School Grade	0.78	0.24
Southgate Reading	0.83	0.13

Table 3.12b

FACTOR STRUCTURE MATRIX

	Factor 1	Factor 2
EPVT	0.84	0.04
Raven's Matrices	0.64	0.40
Schonnel	0.77	-0.40
Speech Intelligence	0.28	0.89
School Grade	0.82	0.37
Southgate Reading	0.85	0.25

TABLE 3.13

CORRELATION MATRIX OF PSYCHO-EDUCATIONAL TEST RESULTS

	EPVT	Raven's Matrices	Ave Audio	Audio Slope Index	Dynamic Range	Tone Decay Extent	Tone Decay Rate	High Freq.
EPVT	1.00	0.35	0.41	0.10	-0.41	0.20	0.31	-0.07
Raven's Matrices	0.35	1.00	0.28	0.16	-0.10	0.28	0.33	-0.14
Ave. Audio	0.41	0.28	1.00	0.15	-0.58	-0.04	-0.09	-0.43
Audio Slope Index	0.10	0.16	0.15	1.00	0.31	-0.05	0.09	-0.39
Dynamic Range	-0.41	-0.10	-0.58	0.31	1.00	0.03	0.44	0.15
Tone Decay Extent	0.20	0.28	-0.04	-0.05	0.03	1.00	0.79	0.14
Tone Decay Rate	0.31	0.33	-0.10	0.09	0.44	0.79	1.00	0.07
High Frequency	-0.07	-0.14	-0.43	-0.40	0.16	0.14	0.07	1.00

Table 3.14

FACTOR MATRIX, PRINCIPAL FACTORS, NO ITERATION

	Factor 1	Factor 2	Factor 3
EPVT	0.75	0.00	-0.23
Raven's Matrices	0.66	0.22	0.06
Average Audio	0.71	-.50	0.02
Audio Slope Index	0.25	0.05	0.85
Dynamic Range	-0.45	0.65	0.53
Tone Decay Extent	0.42	0.73	-0.26
Tone Decay Rate	0.39	0.88	0.02
High Frequency	-0.42	0.37	-0.60

Table 3.15a

FACTOR PATTERN MATRIX

	Factor 1	Factor 2	Factor 3
EPVT	0.63	0.44	0.02
Raven's Matrices	0.30	0.53	0.24
Average Audio	0.78	-0.03	0.31
Audio Slope Index	-0.24	0.06	0.88
Dynamic Range	-0.93	0.22	0.27
Tone Decay Extent	-0.01	0.87	-0.21
Tone Decay Rate	-0.24	0.94	0.02
High Frequency	-0.23	0.16	-0.75

Table 3.15b

FACTOR STRUCTURE MATRIX

	Factor 1	Factor 2	Factor 3
EPVT	0.65	0.47	0.14
Raven's Matrices	0.36	0.56	0.32
Average Audio	0.82	0.03	0.41
Audio Slope Index	-0.11	0.12	0.85
Dynamic Range	-0.88	0.20	0.15
Tone Decay Extent	0.00	0.85	-0.15
Tone Decay Rate	-0.019	0.93	0.06
High Frequency	-0.32	0.10	-0.77

Since the better and worse ear audiometric results show a strong correlation, the better ear thresholds were used to compare audiometric and psycho-educational data. There is no correlation between average hearing threshold levels and any of the tests in this series.

A measure of the overall correlation of the Raven's Matrices, the EPVT, the Southgate Reading Test and the Schonell Vocabulary Test was determined using Kendall's coefficient of concordance, for Group 1 subjects (Table 3.7). The data revealed a significant correlation ($W=.803$, $p<.001$)

A factor analysis procedure was used to examine the relationships between the variables. Pyscho-educational data was transformed to fit the data entry requirements by the following strategy: a data transform of the score was carried out. This was regressed with age, and the residual entered in the factor analysis array. In this way, the data was internally standardised by age. This was felt to be a more appropriate method than using standardised norms obtained on hearing children. The correlation matrix obtained in this way is shown in Table 3.8. Only the larger correlations (greater than 0.60) are shown for clarity. Principal factors were extracted from the inverse of the correlation matrix. Factors with eigenvalues of greater than 1.0 were retained for analysis.. As shown in Table 3.9, these factors accounted for 73% of the total variance. Principal component factor analysis, without iteration showed the EPVT, the school grade and the Southgate Reading Test to load heavily on Factor 1. Less weight, but still notable loading comes from the Raven's Matrices and Schonell Vocabulary test.

Speech intelligibility loads onto Factor 2, with a less, but notable, negative loading from the Schonell Test (see Table 3.11). Rotation, using an oblique solution, was applied to the factor matrix (Table 3.12a and b). The rotated matrix more clearly demonstrates the clustering of the EPVT, the Schonell Vocabulary Test, the school grade and the Southgate Reading Test. Speech intelligibility mostly accounts for the variance from Factor 2. There is no significant correlation between the factors (0.15). There is still speculation as to the source of the remaining 27% of the variance in the data, unaccounted for by these factors. This is spread over four factors and may perhaps be attributed to the individual differences in each child, which it was not possible to control.

A factor analysis procedure was also used to examine the structure of the audiometric and psycho-educational data together. In order to fully utilise the audiometric data, the subset of audiometric and psycho-educational tasks common to both groups was entered into the data array. Given the strong relationship between the EPVT, the school grade, the Southgate Reading Test and the Schonell score, for Group 1, representation of this data by the EPVT results alone, was predicted to be useful. The major loss in data entry arose from the loss of the speech intelligibility data. Hence data from 36 subjects and eight variables comprised the data array. Only better ear audiometric data was used.

The initial correlation matrix yielded by this procedure is shown in Table 3.10. However, note that the only correlation in excess of 0.60 is between the better ear rate and extent of tone decay. Correlations between the other audiometric and psycho-educational measures are small.

Principal factors were extracted from the inter-correlation matrix. Factors with eigenvalues of greater than 1.0 were retained for analysis. This yielded three principal factors accounting for 74% of the total variance (See Table 3 10). This leaves unaccounted 26% of the total variance. Analysis of the factor matrix of the principal factors, obtained without iteration showed the EPVT and the better ear audiometric average to load most heavily on Factor 1, the tone decay data to load on Factor 2 and the index of slope of hearing configuration to load on Factor 3. Most of the variance underlying the Raven's Matrices is also accounted for by Factor 1. The factor matrix is shown in Table 3.14 with the variables which load most heavily on each factor underlined. Oblique rotation of the factor matrix did not, in this case, greatly simplify the data. The factor pattern and factor structure matrices are shown in Tables 3.15a and 3.15b. From the factor pattern matrix, Factor 1 is seen to contribute most significantly to the variance of the audiometric average and the dynamic range. Factor 1 also contributes more to the variance of the EPVT than the other factors. Factor 2 principally accounts for the variance in the tone decay data, and Factor 3 accounts for the variance in the audiometric slope and the high frequency data.

There is no significant correlation between the factors. The factor structure supports the clustering described. The inverse relation between dynamic range and average threshold, and between the slope and the high frequency threshold is notable.

In summary, the audiometric investigation has provided a profile on each child, and analysis of the data has shown some sources of common variance. The psycho-educational test battery has provided a comparative measure of educational communicative progress between the children. Certain features of, and inter-relations between, the tests were drawn from analysis of group data. Some observations were made on the structure of the audiometric and psycho-educational data considered as a whole.

3.3 DISCUSSION

3.3.1 Audiometric Data

The audiometric profiles confirmed that Group 1 subjects all had severe to profound hearing losses, with small inter-aural differences and a small range across subjects. The audiometric profiles of Group 2 subjects varied widely in extent, configuration and asymmetry.

The uncomfortable loudness levels measured indicated that the smaller dynamic ranges were present with the greatest degree of hearing loss, as might be expected. This factor was only measured with Group 2 subjects. It was not possible to form any relation between teachers' judged speech intelligibility (See Chapter 4) and dynamic range, as the relation between extent of hearing loss and dynamic range obscured this. Further study into this aspect would be of interest. The mean ULL threshold of 108 dB HL, at 1 kHz falls within the range of results recorded by Kawell et al. (1986), who was testing moderately hearing-impaired subjects.

It has been suggested that ULL's could be predicted using the equation;

ULL = 100 + 1/4HL (dB HL) (Cox, 1985)

to avoid the difficulties in measuring the ULL. He cautions that this might cause over-estimates of the ULL but here the level at 1 kHz is over-estimated by only 5 dB, favourably comparable with audiometric threshold accuracy. However, there are large variations from this in the individual data, and it would not be deemed a suitable alternative on the basis of measures from these subjects.

It is perhaps surprising that no child showed any notable degree of tone decay. The most severe case was exhibited by subject DL. The full extent could not be measured. This child did not score well on other psycho-educational measures and ranks in the lower 25% of the sample for "overall" performance. His speech grade is 4, on the scale from 1 to 5 and his school grade C. His average hearing level is around the mid-range in Group 1. It is possible that rapid tone decay, as a perceptual phenomenon, or as an indicator of underlying central pathology, may effect his performance. However, his score on the Raven's Matrices is also in the lowest percentile, which one would expect to effect his performance in all areas.

The absence of acoustic reflex data highlights the limits of conventional audiometric procedures in the assessment of severe to profoundly hearing-impaired children. With moderate hearing loss this is used commonly as a measure of dynamic range in young children, where loudness judgements are difficult to elicit. A measure of dynamic range is of course essential for good hearing aid fitting, most particularly for naive users, where the reason for rejection cannot easily be ascertained. It was not possible to obtain any dynamic range index with conventional audiometric procedures.

The factor analysis procedure applied to the audiometric data revealed expected common sources of variance in the data. The average threshold measure and the dynamic range cluster, with underlying common variance, accounting for a major percentage of the total variance. The data ultimately reduces to three areas: a threshold related factor; a factor relating to audiometric configuration; and a factor relating to the threshold tone decay phenomenon, this last being comparatively unimportant. The first two areas, then, are the primary audiometric descriptions of the sample.

3.3.2 Psycho-Educational Tests

3.3.2.1 Raven's Progressive Matrices

Controversy surrounds the application of standardised tests yielding IQs, or their equivalent, to hearing-impaired subjects. However, a near normal distribution of data resulted from this study when scores were presented as percentile rank. Only one child scored less than the 5th percentile: four children scored in the 95th and the median result was the 50th percentile. This data differs from Wilson et al. (1975) and James (1984) who both found a bimodal distribution, with the greatest frequencies occurring at either end. Wilson et al. examined subjects in their sample of 34 hearing-impaired children for cause of hearing loss and labelled 8 as having organic brain damage, but removal of this group still lead to an unusual result. They found that 8 of the 26 non-brain damaged subjects scored more than one standard deviation above the 50th percentile. This is twice the expectation stemming from the assumption of a normal distribution. This was not found in the data in the present study, where it was notable that four subjects scored in the 95th percentile and that the distribution was skewed to give the majority score above the 50th percentile. A good degree of intellectual competence in this sample of deaf subjects is indicated. The extreme high scores were not generated by subjects with similarities on other test scores, nor were they related to better hearing acuity, or age. Interestingly, Zwiebel and Merteus (1985) found significant age differences in the structure of their data.

The normal range of scores, with the inclusion of several extreme high scores, suggests that low performance on this measure is not a predictor of poor oral language development, a view supported by other studies (e.g. Trybus, 1980). A contingency table examining the relationship between speech intelligibility and the Raven's Matrices is shown in Table 3.16. Statistical analysis indicates that there is a low association between the two methods of classification (χ^2 at $p<0.05$).

Table 3.16 Comparison of Raven's Matrices and Speeech Intelligibility

	Raven's Matrices		
Speech Intelligibility	Low Score	High Score	Totals
Low Score	6	4	10
High Score	5	6	11
Totals	11	10	21

$\chi^2 = 1.73$
Speech intelligibility : High score is 3 or greater.
Raven's Matrices : High score is in 50th percentile or greater.

3.3.2.2 English Picture Vocabulary Test (EPVT)

The EPVT results did not correlate with the extent of hearing loss for subjects in either group, but there is a strong correlation with the results of the Raven's Progressive Matrices. The notion that factors other than hearing loss underlie acquisition of spoken language is thus supported, as is the empiricle view that the EPVT may be used as a test of intelligence. It is notable that standardised scores could not be used with the test population, as the achievement level was so poor in comparison with the normal hearing children in the standardising population. It is also of interest that the test group do not show a normal receptive vocabulary expansion with increasing age. Both features highlight the poor receptive vocabulary levels of hearing-impaired children. In a normal test situation, it seems preferable to use norms derived from hearing children for comparison, since the ultimate goal must be to have deaf children achieving as their hearing peers on verbal measures. The test is markedly different from the Raven's Matrices, in which one is trying to eliminate the variable of hearing loss. However, the structure of the data for both tests is remarkably similar, considering the different ranges of hearing acuity in the two groups, and the different pre-selection criteria.

It is possible that common factors are involved in the structure of these test results, reflecting a link in the processes of cognition and vocabulary acquisition. The interesting longitudinal study of Gregory and Mogford (1981) indicates that, on average, first words of hearing-impaired children appear at 16 months, compared with 12 months for the normal hearing child, and that the comparative rate of acquisition of words is much slower. The rate of acquisition of new words by the hearing-impaired child after the first 50 words is about 10 words each month, comparing poorly with the normal hearing child who increases from 50 to 100 words in about a month. The implication in their study is that the vocabulary of the hearing-impaired child is taught, rather than acquired by interactive conversation. In a later study (Bishop and Gregory, 1986) they found that the vocabulary increase became dramatic when the child entered school, although analysis of the content showed the home and school environment to provide different linguistic worlds, with a different active vocabulary developing. Gregory and Mogford analysed the content of the 50 and 100-word samples and found that there were significant differences in vocabulary type: in particular, the hearing-impaired children used relatively fewer nominals and relatively more personal-social words. In addition to this perhaps being a feature of the "taught" component in their vocabulary acquisition, they suggest that there may be differences in the developmental cognitive levels, since the hearing-impaired children were chronologically older by the time they had produced 100-word vocabularies. It may be this feature which makes the EPVT appear to reflect IQ, and the common variance found by the factor analysis for the Raven's Matrices and the EPVT may reflect this influence of cognitive development on the EPVT results. It is clearly premature to give weight to this view, particularly in a field which contains many studies with educational and linguistic inferences being made on the basis of insufficient data, but it poses an area where further study is indicated.

The correlation between the receptive vocabulary measure and the Schonell Vocabulary Test is interesting, since it is congruent with the normal data correlation. This could be construed as being compatible with the view that hearing-impaired and normal children have a similar structure in the acquisition of these skills. The two tests are structured similarly in that the words presented decrease in rate of common usage as the test progresses. Their applicability to hearing-impaired children, from the above, would seem to depend, in part, on what the child has been taught. One might expect differences in the vocabularies of the two groups, one group being composed of children in a residential school and the other home based, although this cannot be assessed because of the different degrees of hearing losses. It may be that the similar correlation with normal data is for different reasons for the hearing-impaired group, again reflecting a taught component in the hearing-impaired child's active vocabulary, such that written word recognition and picture labeling develop closely. Caution is required in interpretation of these results until more longitudinal language studies and peripheral assessments are conducted, but it is concluded that the hearing-impaired children reach their scores by different methods to normal hearing children, a topic which is discussed further, in relation to reading skills, below. In this context, the EPVT yields somewhat limited information regarding the overall linguistic status of the child but, for the purpose of the present study, material which could be readily quantified for intersubject comparison was sought.

3.3.2.3 Southgate Reading Test

Results of the Southgate Reading Test are quite interesting, in that it was unexpected to find a ceiling effect. Like intelligence quotient, "reading age" is a psychological construct, limited and constrained by the nature of the measuring instrument. The literature indicates that reading tests generally reveal a severe reading failure with most cases of severe hearing loss (e.g. Wrightstone et al., 1963). In addition to finding that hearing-impaired school leavers in his sample had reading ages at only the 9½ year level, he found that reading age advanced by less than one year on average, between 10 and 16 years of age. Intuitive examination of the data in the present study shows similarities, but the large number of children scoring at the maximum precludes making a comparison with the Wrightstone study. However, there was no correlation between test score and age, which is quite contrary to results from normal hearing children, and which is surprising, even alarming, in a test group with such a wide age range.

Jensema (1975) used the Paragraph Meaning Subtest to evaluate 6871 hearing-impaired children. The test measures a child's ability to understand connected prose. The data indicated a mean reading grade for the 16 year old children of just over 9 years, and showed there to be a marked decline in reading age as degree of hearing impairment increased. This was not found in the present study, but this may be a feature of subject selection. Group 1 subjects have a narrow range of hearing losses. Group 2 is small, and although there are a wide range of hearing losses, the effect of other confounding variables will be proportionally larger. Furth (1966b), reanalysing the data of Wrightstone et al., reported that only 12% of the children tested exhibited a reading age of greater than 11 years, and that the reading age advanced by only one year on average between 10 and 16 years. This reinforces the view that the sample size and the sampling type, as discussed below, of the older children in the present study may have caused the differences from the published data.

The Southgate Reading Test (but Test 2) was used by Redgate (1972) to assess the reading age of 698 hearing-impaired children from 23 different schools. The age range was 9 to 18 years. This is a sentence test, where the testee must choose an appropriate word to complete a sentence from a discrete list. These results showed a gain of approximately one month in reading age for every year of education, culminating in a mean reading age of 7 years 8 months for children in their sixteenth year. The present study did not demonstrate this relationship in the data, although a general trend to improve with age was identified. This difference was possibly a factor of the relative sample sizes in the two studies.

The relationship between score and age is shown in a scatter chart in Figure 3.5 There is a trend for an age related score improvement. The relationship is adversely weighted by the very poor result scored by several of the 11 - 13 year old subjects. These subjects (AS, LL, TH) are not readily distinguished from other subjects in the group by their performance on other tests. It should also be noted that this test was only carried out on Group 1 subjects. These children do not represent a continuous sample for oral skills. Although a mixture of "good" and "poor" students in oral language were selected, children over the age of 11 were only still attending the school if they had failed to be selected for grammar school. The selection criteria for this is biased towards good oral skills. This kind of school bias is not an uncommon factor in the literature on communication and achievement among hearing-impaired children. However, if the data on the children under the age of 11 are examined, the correlation between subject age and reading test result (r=0.31) is not any stronger.

Several authors have discussed the possibility that there is a plateau, or ceiling of reading achievement for hearing-impaired children. The reason for this is not established. Conrad (1979) talks of "a stage of reading in which deaf children may remain trapped", and identifies it as that stage when the child is required not simply to identify a single word, but to read for meaning and draw inferences from strings of words with syntactic structure. Quigley and Kretschmer (1982) concluded from a literature review that reading scores "tend to plateau" at about 13 to 14 years of age in deaf children. Whilst this sort of effect is seen as a trend in the data in the present study, the Southgate Test of Reading (Test 1) is a lower-level type of reading task and may not tap the more complex tasks described by Conrad (1979). The "age plateau" in the current study appears at a later age than that found by Conrad.

A common criticism of the teaching of reading to deaf children lies in the lack of appropriate material, with provision of gradual, systematic and repeated exposure to new language structures and vocabulary. The

Guidelines series was developed as an "in-house" solution to this deficit and, whilst it is not the purpose of this thesis to evaluate the teaching scheme, it is interesting to note in passing that the scheme does not appear to be having a marked effect on the reading ages, in comparison with reported norms for deaf children. However, other factors affect the results, the ceiling reading age probably being affected by the senior school subject sampling bias.

Whether or not it is preferable to use a simpler reading test task is still under debate. Webster (1983) suggests that since the reading tests devised for the hearing child reflect fairly sophisticated mastery of syntactic structure, the deaf child may be exposed to linguistic structures in these tests which he cannot handle. The tests designed for the hearing child may be too insensitive to the more fragile progress of hearing-impaired readers. In this case, the data revealed by the lower level task may be of more value than initial inspection of the data suggests. Vocabulary measurement may represent the least contaminated measure, in that it is not dependent on complex development of expressive language. Reading tests, then, may be chosen to cover a conglomerate of skills; syntax and inferential skills have not been assessed in the present study. Once the deeper aspects of reading skills are tapped, there is, sadly, some evidence to suggest that the standard reading tests actually over-estimate the hearing-impaired childs reading level. These data derive from assessments of specific reading skills among deaf and hearing children, matched on reading ages, using standardised tests (Moores, 1967; O'Neill, 1973).

In the current literature, the majority view expressed is that deaf children obtain their test scores in different ways to hearing children and that reading age estimates of deaf children are not reliable guides to their functional linguistic, or reading, skills (e.g. Webster et al., 1981; Wood et al., 1981). The poor reading skills of hearing-impaired children are not directly analogous to those of younger hearing children. Interesting support for this view is in an error analysis of Wood et al.s'. data. He notes that, in the multiple choice answers in the Southgate Sentence Test, deaf children tend to converge on the same incorrect solution to difficult items, whereas hearing children did not. Again the small data sample in the present study restricts comment on that aspect, but it is noted that this "error clustering" occurred at greater than chance levels in the current study.

It is interesting that hearing loss correlates so poorly to the reading measure, but this is compatible with the limited available literature. From the data available on children with mild to moderate hearing losses (e.g. Conrad, 1979; Cooper and Arnold, 1981), reading ages of such children are generally found to be more advanced than those of deaf children, but they are still significantly low and more like the reading ages of deaf than hearing children of the same chronological age.

The results of the Schonell Vocabulary Test correlated highly with the Southgate Reading Test. This, from the above arguments, is not surprising, and supports a common mechanism, if different to normal hearing children. The test is similarly unrelated to age or extent of hearing loss, and the reasons for this result are as above.

A current discussion of the factors affecting a hearing-impaired childs reading ability would not be complete without reference to "internal speech", the term used by Conrad (1970) to describe a kind of auditory speech imagery, without articulation. In forming his theories, Conrad used an immediate recall task to investigate the error patterns of deaf and hearing children. It is now thought from this and other work that hearing children and successful deaf readers use a phonologically-based memory code, and that other deaf children use a visually based code (Savage et al., 1986). This theory is supported by work by Chan (1976), in which subjects were asked to mark out all "e" letters in a passage as they read. It was argued that silent "e"s would be more likely to be missed by children who used an internal speech code, and this pattern was displayed by hearing and moderately hearing-impaired children, but not by the severely hearing-impaired children. Later work by Conrad (1979) on homophonous and non-homophonous words also support these views. Conrad argues that internal speech is the defining variable for the hearing-impaired childs' success in lipreading, auditory memory, the intelligibility of speech and reading ability, and this view has found further support (e.g. Pattison, 1983). This view of reading difficulty highlights processing problems, rather than language deficiency, and is of particular interest in the context of the present study. Attempts to identify subjects with specific auditory perceptual problems, and relate the data to the results of the reading tests scores have been made in the present study, and this data is reported in Chapter 7 and summaries of some individual case studies are given in Appendix 2. Analysis of the ep data and the reading test scores has led to only speculative conclusions on the examination of auditory perceptual problems. However, the combination of auditory ep techniques in hearing-impaired, and possible learning disabled, children and studies on reading would make a fruitful avenue of future research. Current studies are concentrated on late responses in hearing subjects.

In general the findings of these psycho-educational tests are in keeping with the trends reported in the literature. The data support use of different standards to compare hearing-impaired children with normal hearing peers, and the view that different mechanisms underlie the achievement scores of the two populations. This does not contra-indicate use of the results as intersubject comparators in the context of the present study, where the psychoeducational performances are compared with behavioural and ep auditory measures. For the inter-subject comparisons, data was transformed, if necessary, and standardised scores were not used.

3.3.3 Combined Data Assessment.

The factor analysis procedure demonstrated a clustering of the tests with a language bias, that is, the Schonell Vocabulary test, the Southgate Reading Test and the EPVT. Although testing slightly different areas of reading and language, there is a strong source of common variance. A strong relationship is established in the data between receptive vocabulary, word recognition and word reading. The fact that the teacher's grade clusters with these variables is not surprising since, consciously or otherwise, the teachers base their grades on tests of this kind. It is perhaps more surprising that Raven's Matrices load on to the same factor. This may mean either that there *is* a language element in this test, or that the other tests have some underlying feature common to the measurement of "intelligence".

Many studies have been designed to examine the relationship between language, and how this affects the performance of hearing-impaired individuals on cognitive tasks. A weakness in some work has been in the assumption that all non-verbal tasks are in fact equally non-verbal, and that a poor performance recorded by hearing-impaired individuals was caused by language deficiencies (e.g.. Evans, 1966). Others have related deficits to communication problems in understanding the test task (e.g. Graham and

Shapiro, 1953). The extent to which impoverished oral language skills effect cognition is still unresolved, partly because of the above problems.

A measure of cognitive function was included in the present study, not primarily in order to contribute to the literature on the relationship between language and cognition, but in order to provide a comparative, non-linguistic measure of intellectual function within the test group. It is therefore encouraging that the test results are not strongly related to extent of hearing loss.

Measurement of speech intelligibility stands alone from these measures, and clearly has a different underlying source of variance. The speech intelligibility was not subject to a factor analysis with the audiometric data. Such analysis may have cast light on to the basis of the variance in this measure and warrants further investigation.

A scatter plot of hearing loss (better ear average) against speech intelligibility score (Fig. 3.6), illustrates the lack of correlation with hearing loss ($r = 0.13$). The slope indices give similarly poor correlations ($r=0.06$). A contingency table was plotted of the hearing loss (as above or below the group mean) and against speech intelligibility grades of equal to and above 3 or below 3. (Table 3.17). Whilst the results are not significant ($\chi 2 = 0.92$), it is interesting to note that only 3 subjects that have hearing levels of worse than the group average have speech intelligibility grades of better than average.

Table 3.17

Hearing loss and speech intelligibility - Group 1

	Speech intelligibility		
Hearing Loss	Above or equal to 3	Below 3	Totals
Above group mean	7	8	15
Below group mean	3	5	8
Totals	10	13	23

The measurement of speech intelligibility predominantly reflects productive language. Since the samples of speech were preselected, expressive language is not being examined, although of course features necessary to successful productive language, such as proprioception and auditory monitoring, are examined, implicitly. The other tests in this group, apart from the Raven's Matrices, are concerned with measuring features of receptive and expressive language. From the inter-test correlations, and current theoretical knowledge, speech intelligibility is more likely to be related to speech perception, than any of the other variables measured here, and so factors underlying perception of speech sounds may also underlie speech production.

The precise inter-relation between speech production and perception is still a topic of debate in the literature, particularly in relation to language acquisition and in relation to speech production in deaf subjects. Theories of speech perception are broadly divided into the active and passive theories. The active theories of speech postulate that there is an interaction between speech production and perception, such that the listener only perceives sound combinations which a vocal tract could make. Their perception is conditioned by their expectations, based upon knowledge of speech production possibilities. Active theories of speech emphasise the role of linguistic knowledge, articulatory knowledge, knowledge of various vocal tract outputs, and knowledge of contextual influences in the decoding of speech. The view of auditory perceptual disorders proposed by Rees (1973, 1974) and other authors, and discussed in Chapter 1, is based on an active speech perception model.

It is still of interest that there is apparently little relationship between the speech intelligibility measure used in this study and the other language related measures. One might also expect to see a relationship between auditory measures and both speech production and the language related tests. Examination of the factor matrices (Tables 3.15a and 3.15b) demonstrate the likely underlying common variance in the EPVT and the average audiometric measure. There are few rigorous studies from which to draw data to assist in the interpretation of these findings. Gregory and Mogford (1981) showed that the age at which the child reached 10, 50 and 100 words in their vocabulary correlated highly with the degree of hearing loss. Whilst the different data presentation makes direct comparison of the studies inappropriate, the Gregory and Mogford findings are not incompatible with the findings here.

As an observation incidental to the study, the data would not appear to provide support for Rees' theory of auditory dysfunction. Nevertheless, it cannot be ignored that the motor theory of speech perception has exerted a powerful influence on the work on speech perception, in that there has been a tendency to look at speech and language in terms of phonetic, grammatical, and semantic variables, with little regard to the acoustic aspects.

The passive theories of speech perception emphasise the sensory filtering mechanisms of the listener (e.g.. Fant, 1967). It is based on a speech feature detection mechanism, and the perceptual deficit theory of auditory perceptual problems (e.g. Keith, 1980), described in Chapter 1 is based on this view of speech perception processes. One might expect peripheral auditory damage to have a severe effect on this mechanism. The results of the present study cannot strictly be explained on the basis of either theory, alone, and are more in keeping with the view, discussed earlier (e.g. Wiig & Semel, 1976), that there is a combination of these mechanisms fundamental to the speech perception process, and involved in its breakdown.

Evidence for a direct relation between speech production and hearing loss is scarce (e.g. Markides, 1985), whilst there is more indicating a relationship between hearing loss and receptive language ability. If one assumes a link between speech perception and production, it is perhaps fruitful to examine the studies of the effect of hearing loss on speech perception. A number of studies have been addressed to the relationship between peripheral processes and speech perception, without debate on the underlying speech processing mechanism. Pure-tone sensitivity has been shown to account for "sensitivity loss" for speech quite well (Studdert-Kennedy, 1976). It does not account for more than 25% of the variability of speech discrimination scores. However, studies have not unequivocally demonstrated a relationship between peripheral processes and speech discrimination.

Dreschler and Plomp (1980) studied 10 hearing-impaired children aged between 8 and 13 years, eight of whom had sensorineural (or mixed) hearing losses of a moderate degree, and two of whom had mild conductive hearing losses. Their measures included frequency selectivity (critical bandwidth and critical ratio) and a measure of speech intelligibility for sentences in different levels of speech-spectrum background noise. The speech scores gave a correlation of 0.90 and 0.79 with critical ratio and critical bandwidth respectively; however, correlation between pure-tone hearing loss and speech intelligibility in noise was 0.90 for mean loss and 0.87 for the slope of the loss. It is therefore difficult to ascribe deterioration in speech discrimination either to sensitivity loss or to the separate effect of reduced frequency selectivity. The data of Tyler and Summerfield (1980) is similarly inconclusive: measures of the sharpness of psychoacoustic tuning curves and gap-detection performance correlated well with speech discrimination as measured on the Four Alternative Auditory Feature (FAAF) test of Foster and Haggard, (1979), but "these analyses do not allow for the effects of other variables (e.g. age, pure-tone threshold), which may mediate the correlations" (Tyler and Summerfield 1980).

In a more detailed study, Tyler, et al. (1982) examined the relationships between thresholds in the quiet, thresholds in noise, pure-tone masking, psychoacoustic tuning curves, temporal integration, the Fry Word Lists in noise, and FAAF in noise, for groups of normal subjects and subjects with cochlear hearing loss. For the latter group, pure-tone thresholds correlated significantly with speech discrimination, indicating that sensitivity loss can act as a gross indicator of severity of disability, but can account for little over a quarter of the variability in speech scores. Tyler et al. assessed psychoacoustic performance at both 0.5 and 4 kHz, and several of the frequency-resolution measures, particularly those measured at 4 kHz, correlated significantly with speech intelligibility. Again, much of the variability remains unaccounted for, and again it is not possible to separate the effects of poor frequency resolution from the effects of pure-tone sensitivity loss.

Tyler et al. did, however, find a significant correlation between temporal integration and pure-tone threshold at 4 kHz, with no similar correlation between speech scores on FAAF and temporal integration. In further analysis of their data, they examined the correlations between all their psychoacoustic and speech perception measures. Since it is established that higher absolute thresholds are correlated with poor PTC tuning, poor temporal processing and poor discrimination of speech in noise, they partialled out the effect of hearing loss in their analysis. This left gap-detection and temporal difference thresholds, giving low but significant correlations with speech discrimination.

Festen and Plomp (1983) carried out principal component analysis on a correlation matrix of twenty auditory measures taken from twenty-two adults with moderate to sensorineural hearing loss. Their analysis revealed principal factors, where frequency resolution loaded on one and aspects of sensitivity loss loaded on to the other. The authors did not attempt to predict speech discrimination from the two principal components, but they found that they only accounted for 65% of the total test variability (48% for the sensitivity loss component and 17% for the frequency resolution component), leaving an unaccounted 35%.

These studies have not been successful in revealing a successful predictive measure of the affect of sensorineural hearing loss on speech discrimination. Spoken intelligibility, being a step further removed from the psychoacoustic measures, is even less easily predicted. In the latter case, severity of loss serves as a broad guide only, whereas it can be related to speech discrimination to some extent. It has been shown in the present study that the successful development of oral language in hearing-impaired children can vary dramatically, independent of the extent and slope (as measured by the Bamford, 1980, index) of hearing loss. The analysis of this aspect of the data in the present study has perhaps been restricted by the severe extent and small range of hearing losses.

Previous studies on speech perception may have failed because there have been few attempts to assess affects of perceptual tasks independent of hearing loss. In a future study, it would be interesting to examine a wide range of psycho-acoustic tasks in relation to speech production, since there are clearly factors underlying it which are not accounted for by either extent of hearing loss, various measured aspects of oral language competence, or intelligence.

An additional aspect not referred to in the previous studies is the additional mediating role of central processes. As described in the introduction, there are considerable difficulties in assessing this aspect in children with known acuity deficits. An investigation into this aspect, using electrophysiologic measures, was therefore carried out with the test population, in the present study, and is described in Chapter 6.

3.3.4 Summary

In summary, a range of pyscho-educational measures, a measure of speech intelligibility, and a range of audiometric tests were carried out with two groups of hearing-impaired children. The tests were successful in providing an across-the-range-profile on each child. Test findings were generally compatible with reported data on hearing-impaired subjects. Some insight into the structure of the data and the relationships between the tests has been provided.

In reviewing these data, it is noted that the two groups tested represent different, but overlapping, test populations, the one representing severely to profoundly hearing-impaired children, perhaps commonly described as "deaf",, the other, let us say, "partially hearing". The latter group have been the subject of comparatively few studies in the literature, as regards their speech, language and educational characteristics (Davis et al., 1986). This is perhaps because their educational/communicative success is more assured, and yet this data shows that a complacent view of this groups' language should not be taken. The available data tend to be limited to case studies (Oller and Kelly, 1974; West and Weber, 1973), experimental studies on small groups of children (Brannon, 1968; Davis and Blasdell, 1975), or information about large groups gathered for school records (Davis et al., 1981; Kodman, 1963; Shepard et al., 1981). More work has been done on the severely to profoundly deaf group, although ths two cannot be totally separated. Definitions of profoundly and partially hearing differ from study to study, and it is inappropriate to completely categorise the two, and deal with the arising issues separately.

Factor analysis procedures were successful in demonstrating a simpler underlying order in the data. Although in the principal component analysis more than 20% of the variance was left unaccounted for, certain trends emerged. A strong relation was found between oral measures of language and reading. Cognitive function showed a weaker relation to these tests and had a larger percentage of unique variance. Ratings of speech intelligibility showed little common variance with the receptive language measures. This is an interesting finding given the vocational and social importance of good speech intelligibility, when receptive language measures are commonly administered as the educational yardstick. However, it is noted that the language measures used here are vocabulary biased, whereas speech intelligibility, particularly as perceived by the naive listener, is influenced by grammatical complexity and abnormality, prosodic and contrastive features. McDermott and Jones (1984) found speech intelligibility to be most related to an articulation measure (the Templin Darley Articulation Test). The intelligibilty ratings were derived from read passages, and fluency and prosody may be reduced by the use of structures alien to the childs' normal usage, and by the increased complexity of the task.

Hearing threshold related measures have been shown to have common sources of variance with the EPVT and, by extrapolation, with other language measures. Other audiometric measures do not relate to the language measures, speech intelligibility, or cognitive function. This supports the view that other processes must contribute to speech intelligibility. There has been an attempt in this study to to reduce non-auditory sources of variance, such as home language environment. Thus it seem that perceptual phenomena (other than the extent of the hearing loss), physiological, proprioceptive, cognitive and linguistic phenomena, underlie a childs' ability to produce clear speech. The site of auditory dysfunction, and its' related perceptual phenomena, may be one source of variance.

The results of the tests on these children have produced a number of features which suggest that further exploration into underlying factors of variance would be fruitful. The structure of language in the deaf child has been widely, though far from conclusively, investigated, and current thinking is reviewed in Bamford and Saunders (1985). These tests of psycho-educational ability tap both intellectual and language performance, but the relationship between language and cognition is still a debated area. One view is that the depleted auditory input of the child with the hearing impairment results in qualitatively different cognitive processes, which not only give poor verbal language performance, but also impose theoretical limitations on the further development of normal spoken language skills (e.g., Myklebust, 1964). The second view is that prelingually hearing-impaired children possess normal cognitive processes but suffer from general restrictions in experience, interactions and opportunities to learn (Furth, 1964, 1966). Thus, if adequate linguistic experience can be provided, language development will be essentially normal, although very likely delayed. Currently, the relationship is seen as interdependent and interactive, with development in one area having implications for development in the other, but it is apparent in the literature that we need to extend our knowledge about the nature of language disabilities of hearing-impaired children, and about the underlying processes and causes of these deficits. This may come partially from a physiological and partly from a cognitive understanding for individuals and for the deaf population as a whole. To examine this area more thoroughly, it would be interesting to obtain detailed language assessments, which tap the language structure, in conjunction with auditory and cognitive function tasks.

Amongst the literature in the field addressing the relationship of hearing and cognition to language development, there is very little pertaining to the effect that reduced central nervous system efficiency may have. The debate has largely been a combination of the abstract and cognitive/ language studies on groups of hearing-impaired subjects. Conrad (1980) quotes animal auditory deprivation studies to indicate that there may be evidence for a relationship between disturbances of central neurological function and poor oral language skills. Reviews of auditory deprivation (Kyle, 1978; Ruben, 1980 and Webster, 1982) demonstrate evidence for physiological neuronal degeneration in the auditory pathways, consequent upon auditory deprivation. The extent to which this may affect language may perhaps only be shown by studies which can demonstrate the central auditory system dysfunction, since behavioural studies are necessarily confounded by the accompanying language deprivation which occurs. To this extent extrapolations cannot be usefully made from animal studies.

The sensory versus linguistic deprivation debate was fuelled by the case of Genie (Fromkin et al., 1974) who was a severely environmentally deprived child, who only began hearing language in early adolescence, and who showed considerable advances in receptive and productive language in less than two years after discovery. Her language function was still restricted (Curtiss, 1977), but the case supports the "critical period" theory of language development (Lenneberg, 1967). The fact that she did make such rapid progress either reflects very sadly on current habilitation procedures with the hearing-impaired child, or suggests that some may have central auditory problems which complicate their language acquisition skills. Possibly many children are affected in this way, though perhaps in too subtle a manner for current detection methods. The animal studies cited earlier do indicate structural changes occuring as a result of the period of deprivation, and this occurs in the presence of even partial losses.

CHAPTER 4

HIGH FREQUENCY HEARING AND SPEECH INTELLIGIBILITY

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4.1 INTRODUCTION

The work of Berlin et al. (1978) and of Chasser and Ross (1979) strongly suggests that where a child has hearing in the frequencies above 4 kHz, which is better than his hearing at lower frequencies, then this may have a positive effect on his speech perception and his speech intelligibility. For this reason, it was decided to assess the hearing of the children in the present study at 12 and 16 kHz, in addition to the conventional test frequencies, to ascertain whether the presence of residual high frequency hearing was a factor distinguishing the children with good oral language skills. This chapter is devoted to the study of high frequency hearing and speech intelligibility in the test population. Due to the technical and calibration requirements of assessment above 8 kHz, the early part of this chapter is concerned with instrumentation. International standards have not been established for frequencies above 8 kHz and, since the choice of instrumentation and calibration procedures have varied widely in previous studies, it was necessary to complete a small normative study of high frequency audiometry, prior to assessment of the test population.

4.2 ASPECTS OF CALIBRATION AND INSTRUMENTATION

4.2.1 Historical Perspective

It has long been recognised that measurements of frequencies above 8 kHz may be useful. As early as 1830, William Hyde Wollaston had described the audible range as 0.03 to 18 kHz. In 1830, the French physicist, Felix Savart, used, firstly, rods with a relatively brief decrement and, secondly, a sawtooth siren invented in 1681 by Robert Hoobin, to measure human response to high frequency tones. Attempts to duplicate these results were made by Seebeck, using a perforated disc siren; by Pauchon, using a steam siren, and by Melde, using a vibrating plate method, but widely different results were obtained. Probably the best known instrument was developed by Sir Francis Galton. The Galton whistle was introduced into clinical use in 1878 and was controlled by a micrometer screw. About the same time measurements were made using Konig's rods, which were thick, steel, cylindrical rods, suspended by threads, and activated by striking with a mallet. This produced very high frequencies as the rod vibrated longitudinally. Similarly, varying lengths of string, under strong tension, were rubbed longitudinally to generate longitudinal vibrations. These early attempts to measure the upper frequency limit were designed to refine the quantitative methods of differentiating between air and bone conducted sound, and hence represented attempts to localise the underlying lesion.

Bezold Edelmann attempted to quantitatively assess auditory acuity over a range of frequencies using a "continuous frequency series". The test set consisted of ten tuning forks, two organ type pipes and a Galton whistle. As a result of the various studies, further attempts were made to develop acoustic generators, leading eventually to the invention of electric instruments. An early audiometer, testing up to 16 kHz, was devised by Wien, but the first well-designed electric audiometer was the Western Electric 1A audiometer (1923). Fowler, Wegel and Fletcher completed pioneering psychoacoustic studies using this instrument which provided high frequencies nominally of 8.192, 10.321, 13.004 and 16.384 kHz at the earphones. The first commercial audiometers, however, were limited to fewer discrete frequencies, and high frequency work was little used from then on due to problems of calibration. The American Medical Association Council on Physical Therapy specified conditions up to 8.192 kHz in 1937, and this upper limit is in use today. This limit was considered adequate, since for some time it was thought that the audiometric information below 8 kHz was the most important, particularly with reference to hearing for speech.

4.2.2 Instrumentation and Calibration Development

The use of high frequency tones in the assessment of hearing has been limited by difficulties in accurate assessment, due to the acoustic characteristics of high frequency pure tones. The short wavelength causes difficulties in transducer-meatal coupling. It is assumed that standing waves are created when using the conventional earphone coupler. This would detrimentally affect calibration accuracy, and cause a large inter-subject threshold variation. Attempts to establish normative standards have concentrated on developing a satisfactory transducer-meatal coupling system, but there are considerable differences in the results of different studies (summarised in Table 4.1). Techniques fall into three categories : free field, hand-held earphone, and headband earphone.

Table 4.1

STUDY	TRANSDUCER	CALIBRATION METHOD	PSYCHOPHYSICAL METHOD	SUBJECT AGE	TEST EAR	THRESHOLDS (dB SPL) TEST FREQUENCY (Hz) 12 Mean	12 s.d.	14 Mean	14 s.d.	16 Mean	16 s.d
Rosen et al 1964	Loudspeaker fixed at 10λ from meatus	$\frac{1}{4}$" microphone at ear canal and ear drum of Schilling Artificial Head	Manual descending threshold	10-19	L + R	20.1		24.9		40.4	
				20-29		28.5		31.9		52.1	
				10-19		17.9		23.9		40.0	
				20-29		23.8		35.5		56.1	
Zislis and Fletcher (1966)	Hand held condenser microphone, built into a probe tip	Average voltage of threshold of students measured with a $\frac{1}{2}$" microphone	Self recording Right ear tested first (left ear only reported here)	11-13	L	10.75		13.18		25.40	
				14-16	L	15.28		15.30		31.28	
				16-18	L	9.40		12.43		44.63	
Harris and Ward (1967)	PDR-10 earphone + MX41-AR cushion Hand Held	1" condensor microphone at eardrum in artificial head	Manual descending threshold	16-18	L + R (Left first)		6.05	6.1	12.02	19.3	21.7
				10-12		13.1	10.73				
Myers and Harris (1970)	Head fixed 6' from speaker at 90° azimuth	Microphone at (1) virtual centre of head (2) Eardrum of Schilling head	Self recording	19-23	L	17.0	3.6	6.0	4.4	30.0	5.2
Northern et al (1971)	Hand held condenser microphone built into probe tip	" Condenser microphone at eardrum and with coupler	Self recording	20-29	L or F	13.3	18.1	24.4	18.6	41.9	20.7
Osterhammel et al (1977)	Loudspeaker and PVC horn coupled ear	Coupler and " condenser microphone	Manual method of Limits	10-19	L or R	34.0	10.4	32.7	12.4	45.3	16.4
				20-29		35.6	1.0	36.1	14.7	59.9	18.0
Beiter and Talley (1976)	PDR-8 Pure Tone (headband) system	$6cm^3$ coupler and S.L.M.	Manual modified Hughson-Westlake procedure	19-22	L + R	41.6	7.35	39.7	55.7	58.3	4.3[illegible]
Fausti et al (1979)	Dynamic coupler with ceramic earphone	Modified $6cm^3$ coupler $\frac{1}{2}$" condensoer microphone	?	18-27	?	16	6	24	14	32	10
Gauz et al. (1981 a,b)	Headband mounted condenser microphone, built into a probe tip	Microphone at 90° to transducer, to give output SPL	Self recording	23-28	Better or R	9.5	24.5	23.1	28.0	41.2	19.6
Henry and Fast (1984)	Osterhammel quasi-free field system (modified)	as above	Modified form of method of adjustments	18-24	Either	24.5		21.8		47.3	

Sivian and White (1933), of Bell Telephone Laboratories, sought to overcome the standing wave problem in the free field by using warble tones. However, Shaw and Teranichi (1968) demonstrated that the contribution to the acoustic characteristics of the tone by the concha and ear canal cannot be ignored. The concha and cymba concha produce important resonances in the 6-10 kHz region that change with the angle of incidence of sound. If a free field method is used, it must clearly be devised so as to minimise the inter-subject variability caused by these various mechanisms.

It was already realised that angle of incidence was an important parameter in free field tests at high frequencies. Rosen et al. (1966), in an early large study of high frequency hearing, mounted a loud speaker in a rigid cage-like construction, such that the speaker was always 10 wavelengths from the ear, at exactly 90° azimuth. A sighting device and a "bubble level" ensured exact horizontal radiation.

A different approach was made by Osterhammel et al. (1977) who, working in collaboration with Shaw, designed a quasi free field system in which the modified audiometer output was fed to a 0.025 m Dome Tweeter, which yielded a nearly uniform polar plot and had an almost flat frequency response from 2-20 kHz. A conical P.V.C. horn was attached to the face of the speaker, acting as an adaptor to a 25 mm long, lined metal tube which was fitted into the base of an L-shaped wire-mesh screen. The long process of the screen was fitted around the ear (Fig. 4.1). Test-retest trials compared favourably with conventional pure tone audiometry. The method has been used more recently, with slight adjustment to the sound delivery system, by Henry et al. (1985). The technique requires instrumentation which may be considered complex, by clinical standards, and testing must clearly be conducted in an environment suitable for free field acuity testing.

Design of a suitable transducer-meatal coupling system is only part of the problem of assessment above the conventional frequencies. It is also necessary to devise satisfactory calibration techniques for both free field and earphone methods. In some cases, for example Rosen et al. (1964), a Schilling artificial head was used in connection with a precision miniature capacitor microphone to establish the equivalent eardrum SPL. An alternative is to use a 1/8" microphone close to the eardrum (Figure 4.2b). Although this, at first sight, seems the most accurate way in which to

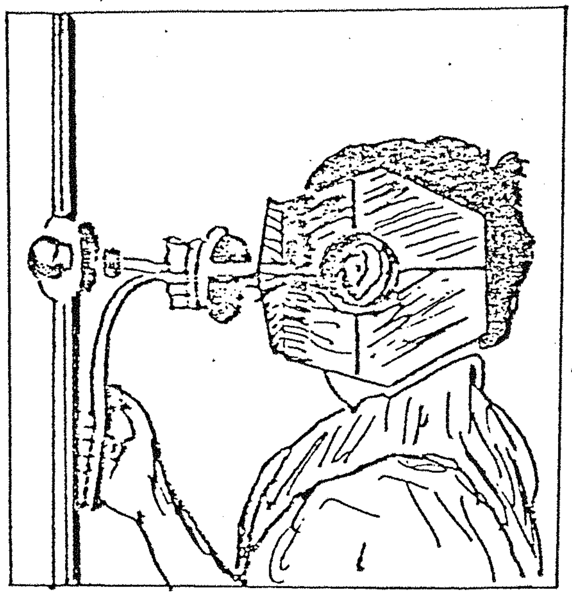


Fig. 4.1 A quasi free field system of high frequency audiometry (after Osterhammel et al 1977)

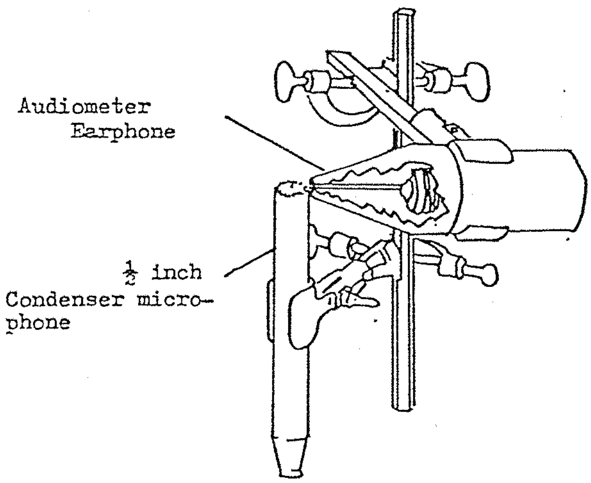


Fig 4.2a The High Frequency reference coupler used to calibrate high frequency audiometers as described by Northern et al (1972).

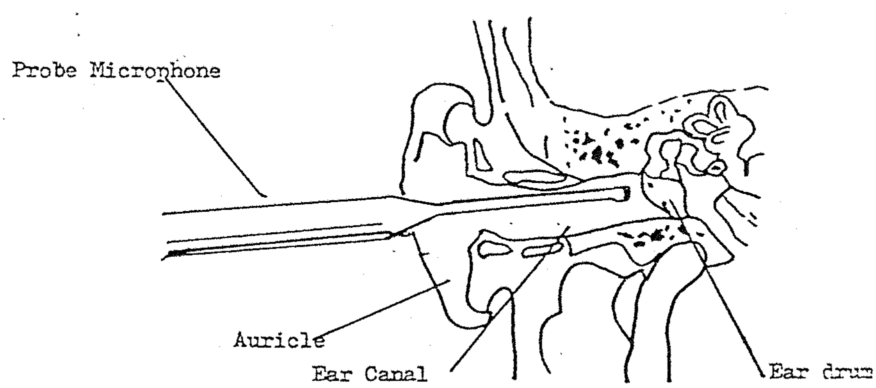


Fig 4.2b Cross section diagram of the ⅛" microphone as it was placed in the ear canal to measure the sound pressure level at the eardrum.

determine SPL at the eardrum, Shaw and Teranichi (1968) showed that ear canal resonances adversely affect these measures. The Osterhammel system was calibrated via a specially designed coupler, which matched the diameter of the hole in the screen, and a 1/6" condenser microphone.

Earphone transducers have been used in many studies. Recent rapid advances in commercial Hi-Fi technology have widened the choice of available earphones, and there is now a selection available with good responses up to 20 kHz. A high frequency system, with an incorporated high-output, low noise filter/amplifier reduces the low frequency noise, which may occur with a commercial dynamic earphone and ceramic diaphragm as the transducer (Fausti et al., 1979).

The absence of a standard calibration technique presents difficulty, even when an earphone method is used. The various standard organisations have specified an upper audiometric limit of 8 kHz for calibration data. A coupler technique is commonly used in the reported studies, but standardised couplers are designed to reflect input impedances of up to only 8 kHz, and also considerable differences exist between earphone measurements for different couplers and between different earphones.

Stelmachowicz et al. (1982), testing with a Koss HV/X earphone, used a Koss Corporation flat plate coupler, but corrected their recorded threshold values with data from real ear measures. In the study by Fausti et al. (1979), a specially designed 6 cm^3 coupler was used to calibrate the output at the earphone. In contrast, Beiter and Talley (1976), using a PDR-8 earphone in measures of high frequency hearing, simply measured the sound pressure at the earphone via a 6 cm^3 standard earphone coupler. These authors describe their results as being in reasonably close agreement with other studies. Laukli and Mair (1985), used a commercial system with a headband mounted earphone and found figures in approximate agreement with the oft-reported early study of Harris and Ward (1967). The transducer which these authors used was a Permoflux PDR-10 earphone mounted on an MX/41-AR cushion, hand-held in the position of maximum loudness. The threshold phone voltages were converted into SPL using a Schilling artificial head, with a condenser microphone at the position of the eardrum.

The first commercially available system for high frequency audiometry was the Tracor-Rudmose self-recording audiometer, which has a frequency range of 4-18 kHz. This was used by Zislis and Fletcher (1966), in an investigation of high frequency auditory acuity of school children, and it has an in-the-ear probe transducer. This consisted of a Brüel and Kjær capacitor microphone, polarised at 200V and modulated by the audio signal as the transducer. The microphone was housed in a small diameter metal tube, which was lightly packed with steel wool, ending at a plastic conical tip, which could be sealed at the entrance of the ear canal. The authors used the Rudmose calibration, in which the thresholds of 12 audiometrically naive high school subjects were measured.

The AC modulating voltage was measured for each subject at each frequency, and an average voltage over subjects was calculated for each frequency. The average voltage was applied to the earphone, and the SPL measured using a 1/2" Brüel & Kjær microphone, placed so that the metal tube of the earpiece was parallel to the diaphragm of the microphone, and 1/32" away. The transducer was hand-held by the subject during testing. Zislis & Fletcher found that their results differed considerably from the original Rudmose calibration at frequencies above 11 kHz. They suggested that the limited number of subjects used by Rudmose were hyperacoustic. Tracor later supported a further "real ear" calibration (Northern et al., 1972) in which a loudspeaker was used to measure "eardrum SPL". The subject was seated in an anechoic chamber with his head clamped firmly. His ear canal was "straightened" and the pinna taped in place. Output from the ARJ-4HF Tracor-Rudmose audiometer was transduced by an Altec high frequency loudspeaker, at 0.45mm and 90° azimuth from the subject's ear. The microphone was positioned within 1/8" of the eardrum, and the threshold eardrum SPL measured for the loudspeaker-presented signal. The loudspeaker presentation was compared with the audiometric threshold and an appropriate coupler-ear conversion was made. However, the impedance of the transducer system influences the transfer function which converts "calibration SPL" to "eardrum SPL" values, so the calibration technique remains questionable.

Several other commercial high frequency audiometers are now available. An example is the Demlar 20K, which is based on work by Fausti et al. (1979), and uses an earphone technique. The transducers are high fidelity earphones (Koss HV/1A) equipped with soft rubber foam supra aural cushions, back venting to smooth the high frequency response. Calibration is effected using a 6cm^3 cavity, in rubber, with a hole for the half inch condenser microphone. The instrument has been favourably evaluated by Laukli and

Mair (1985) and in clinical studies by Cunningham et al. (1983) and Ahonen and McDermott (1984). Earphones are the most convenient of the transducer systems to market in a clinical package, even though they are perhaps not the most reliable of the transducer systems.

A comprehensive study of transducer systems suitable for high frequency audiometry was carried out by Myers and Harris (1970) in which seven different systems were compared. These authors obtained threshold data from a small group of subjects, using three MAF systems, two headband MAP systems and two hand-held MAP systems. Two of the MAF systems were similar, in that the transducer was a loudspeaker, set at a fixed distance and 90° azimuth for the head, with the subject's head being held in place by a chin rest. The absolute sound pressure levels and frequency responses of the system were evaluated over the whole frequency range of interest, both at the virtual centre of the subject's head, using a free field microphone calibration, and at the eardrum, using a Schilling artificial head. In one method, noise bands (50 ms rise fall 1/3 ms on/off) were used as the stimulus, to overcome the standing wave pattern problem, and were transduced via a Sphericon loudspeaker. In the second method, pure tone pips (50 ms rise fall, 1/3 ms on/off) were transduced via an Altec 288C loudspeaker with a cylindrical horn 0.18 m long, and 0.025 m internal diameter.

In the third MAF system, the driver was more precisely coupled to the eardrum, in the manner described by Rosen et al. (1966). A pair of phonic tweeters were mounted at one end of a 0.15 m open-sided cage, the other end of which surrounded the pinna. The Schilling artificial head was used in calibration. A PDR-8 earphone was evaluated, both hand-held and headband mounted. In the first case, calibration was effected by first asking the subject to indicate the placement for maximum loudness and then coupling the earphone (1) to the artificial head, and (2) to the National Bureau of Standards coupler, with 0.2 V to the driver.

The other hand-held systems utilised the Rudmose self-recording audiometer, as used in the study by Zislis and Fletcher (1966) and calibrated as described by those authors. In view of the doubt surrounding this method, it was also calibrated in the free field, using the Schilling artificial head, to measure eardrum SPL. The final system utilised the Rudmose audiometer, but with the probe tip held in the canal by a headband, where it remained throughout the session. Each of these systems gave usable reliability. The MAF system which generated pure tones over a 1.80 m distance gave the greater variance at most frequencies up to 20 kHz. Of the MAP systems, the Rudmose audiometer with fixed headband showed least variability over frequencies, whilst the PDR-8 earphone, headband system showed greatest variability. However, the maximum variability shown is 7 dB at any frequency. When the reference threshold SPL's obtained by the different systems are compared, the noise band MAF and the PDR-8 pure tone hand-held MAP approximate most closely. This is encouraging, in view of the very dissimilar transducers, stimuli and transducer eardrum coupling. Developing from this work, more recent studies have examined the reliability of the less complicated, more clinically suitable systems, and further support has been found for the use of high fidelity phones (Stelmachowicz et al., 1982; Ising et al., 1986).

In comparison with the body of data on which the 1964 and 1975 ISO standards on frequencies up to 8 kHz are based, the attempts to establish normative high frequency standards are diminutive. Further, the studies cannot be easily compared because of the differences in instrumentation and calibration techniques. In the last 20 years several studies have been concerned with providing audiometric standards, for example Rosen et al. (1964), Zislis and Fletcher (1966), Harris and Ward (1967), Northern et al. (1972), Beiter and Talley (1976) and Gauz et al. (1981).

Northern et al. (1972) measured high frequency thresholds on adult subjects covering a large age range, and subsequently made recommendations of standard reference levels 0 dB HTL for 10-18 kHz. These authors used the Tracor-Rudmose ARJ4-HP self-recording audiometer. The biological HTL values were converted to SPL in decibels as measured using the coupler described by Zislis and Fletcher (Fig. 4.2), and with the added correction to eardrum SPL described earlier and tabulated in this study. The data of Zislis and Fletcher and four other authors are converted to eardrum SPL for comparison (Table 4.2).

Berlin et al. (1978) rejected the Rudmose self-recording audiometer, because they found such high signal-to-noise ratio that many normal hearing subjects detected the noise before they were able to detect the tone. This has been a problem for some years with high frequency audiometers. Berlin et al. collected normal data, reported here, using a hand-held microphone assembly. Their main study with children, however, was conducted using a set of MX41-AR earphone cushion mounted transducers. Another area of difference in reported studies lies in the stimulus used, that is warble, pulsed or continuous tones. In a comparative study of these presentation types, Hamill and Haas (1986) found little difference between the latter two types, but warble tones gave better thresholds by an unacceptable margin at some frequencies only.

Table 4.2

Median eardrum SPL in decibels for zero threshold (to nearest decibel

Frequency kHz	Sivian & White	Dadson & King	Rudmose (TRACOR)	Zislis & Fletcher	Harris & Meyers	Northern et al
8	20	17	16	14	13	21
12	35	29	14	18	16	20
14	46	37	17	22	30	27
16			18	38	37	36

4.2.3 Subjects used for Studies of Normal High-Frequency Hearing

There have been a number of attempts to devise reference equivalent thresholds sound pressure levels for frequencies above 8 kHz. Although differing in instrumentation and stimulus presentation, most of the studies used rigorously controlled physical conditions. The choice of subject, age and criterion for selection varied considerably between studies. This is an area of difficulty in audiometry calibration in general. For calibration below 8 kHz, ISO 389 states that subjects must be otologically normal. That is "understood to be a person (within the inclusive age range 18 to 30 years) in a normal state of health who is free from all signs or symptoms of ear disease and from wax in the ear canal, and has no history of undue exposure to noise".

In a critical study of the international standards for air conduction audiometry, Robinson et al. (1981) demonstrate that an apparently representative group of normal subjects may give a collective threshold, corresponding to audiometric zero, at all frequencies. In an earlier publication (Robinson et al., 1979), they suggest that the degree of otologic normality is a critical factor. A rigorous approach to subject selection, as suggested by these authors, is not apparent in any of the published studies. Further complications arise by the choice of the most appropriate age group to test.

Subjects of different ages and markedly different noise histories were studied by Rosen et al. (1964) using subjects from a Sudanese tribe and from three major city populations. Those authors demonstrated that noise appears to reduce high frequency acuity, even in the lowest age group (10-19 years). Their figures also demonstrate a marked decrease in hearing acuity above 12 kHz with increasing age, by the end of the second decade. Northern et al. (1971) also tested subjects over a wide age range, reporting threshold data for the decades, from 20 to 60 years. In this data the decrease in hearing acuity with increasing age is more marked.

Following Rosen's study, Zislis and Fletcher (1966) tested three groups of male and female subjects aged 11-13, 14-16 and 16-18 years. They did not find a significant age effect, but reported a tendency for the younger subjects to perform at a slightly better level than the older subjects. Harris and Ward (1967) also tested school children, but in three groups aged 10, 11 and 12 years. At lower frequencies, the data from these two studies are very similar, but at higher frequencies the Harris and Ward thresholds were more acute by up to 20 dB (at 18 kHz).

Myers and Harris (1970) aimed not only to provide threshold data for comparison with other studies, but also to compare transducer types and psychophysical methods. This presumably influenced their decision to use subjects aged 17-23 years, despite the earlier evidence that high frequency acuity begins to decrease towards the end of the second decade of life. Beiter and Talley (1976) and Fausti et al. (1979) also assessed subjects in the same age range. (Table 4.1)

The authors also differed in their choice of criterion for selection of normal subjects. Zislis and Fletcher (1966) selected all the children who had a normal otological history and who did not have any history of high noise exposure. Harris and Ward (1967) included all children who, on otoscopic examination, showed an unscarred and pearly grey eardrum. Northern et al. (1971) testing people attending the 1968 American Speech and Hearing Association Convention, required their subjects to complete a questionnaire concerning their auditory history. They also underwent an otoscopic examination. Subjects who had been exposed to noise were not excluded from this study. None of these authors required normal auditory thresholds in the range less than 8 kHz. In sharp contrast to this, Fausti et al. (1979) required subjects to have hearing of better than 10 dB HL at frequencies 0.25 to 8 kHz and to have a normal otologic history. From their original 21 subjects a sample of 30 ears were selected to give a preliminary reference based on best rather than average, high-frequency sensitivity in young adults. Myers and Harris (1970) and Beiter and Talley (1976) also had a criterion of audiometric normality at frequencies less than 8 kHz, but their requirements were less stringent.

It is important to draw a distinction between audiometrically normal and otologically normal. In some cases, the subject inclusion is based on the former. Henry and Fast (1984) note from their study, that there is little predictive value in the thresholds at 4 and 8 kHz, regarding frequencies above 8 kHz. Whilst it is a useful extra requirement, it is important that subjects included are otologically normal. For example, Laukli and Mair (1985), testing subjects in the age range 20 to 24 years, required normal middle ear function. They sub-divided their group into those with thresholds of better than 10 or 25 dB HL, between 0.125 and 8 kHZ. Their final published data is based on the former, smaller sub-group (n=12). Gauz et al. (1981b) also required normal auditory acuity, of better than 5 dB HL, and for his subjects to be otologically normal. There is thus a notable range of audiometric requirements presented by the various researchers.

Subject criterion and selection provides a major source of variability between studies. It is probable that an age specific reference threshold may be optimum, coupled with a strict requirement of otologic normality. Currently, where a clinical study is undertaken using high frequency audiometry, an age-matched study using normal hearing subjects is one solution.

4.3 METHODOLOGY AND INSTRUMENTATION

The preceding review of high frequency audiometry indicates the need for careful selection and calibration of the instrumentation, use of appropriate subjects and an understanding of the test validity of the technique chosen. Prior to the assessment of high frequency thresholds on the test population, several steps were taken to ascertain these points:

1. Selection of appropriate transducers
2. Technical and biologic calibration of instrumentation
3. Assessment of earphone placement effects.

Since the children participating in the main study were undergoing a large number of other tests, it was important that the technique chosen for measurement of high frequency auditory acuity would easily fit into the test sequence. An earphone stimulus presentation was preferred since:

i) This would not involve the child's introduction to further test sessions

ii) The free field methods which yielded the most consistent results involved fixing the subject's head with respect to the apparatus. This was not considered desirable in the present study, since some of the children are quite young. The earphone techniques require less equipment, are easier to set up for each subject, and take less test time.

The earphone techniques showing the least variance and lowest thresholds were obtained with a hand-held or ear-probe system. However, in their comparison of seven different systems, Myers and Harris showed the greatest variance to be 7 dB (for the PDR-8 headband mounted system). This is only just outside the accepted clinical limits of conventional audiometry. Further, whereas "lowest", or "best", thresholds are perhaps necessary in establishing a reference threshold, this was not considered essential where the hearing of a sample of normal hearing children were to be used as a reference population, against which the hearing of the test population of hearing-impaired children could be compared. Berlin et al., 1978, similarly used a headphone technique in order to carry out a comparative study on groups of children, and the most recent commercial systems also use standard headphone techniques.

A conventional clinical method, similar to that described and justified by Beiter and Talley (1976) was used in this study. The preceding review on instrumentation and calibration, centred on the determination of eardrum sound pressure level, and the alternative difficulties of earphone calibration, in the absence of earphone coupler data. If only an estimate of sound pressure level in the ear canal is made using a non-standard earphone and artificial ear, then a reference threshold must be obtained by assessing a normal hearing population. These measures would not be repeatable using a different system.

It was not appropriate to utilise the TDH-49 earphone used in conventional audiometry because of its limited frequency response. (Fig. A4.1) The frequency response of several types of commercial high fidelity phones were compared in order to identify a transducer with a fairly flat frequency response in the region 4 to 18 kHz. Technical details appear in Appendix 4.

Since the children in the main study were aged between 6 and 17 years and since the sensitivity to stimuli in the higher frequencies begins to decrease by the end of the second decade, normal reference thresholds were determined on children in the same age group. It was considered particularly important to have a normal comparison group since eardrum SPL measures were not made.

4.4 BIOLOGICAL CALIBRATION ON NORMAL HEARING CHILDREN

4.4.1 Test Method

High frequency hearing in a sample of normal hearing children was tested by finding the auditory threshold at frequencies of 4, 8, 12 and 16 kHz, using the instrumentation and earphone SPL calibration described above.

The normal hearing subjects were between 7 and 16 years old, and were attending a local play scheme. Subject selection was reliant on parental approval. Twenty children who, on simple questioning, demonstrated no obvious history of otological problems, and whose eardrums and ear canals were of normal, healthy appearance, completed a pure tone audiogram at the conventional frequencies. All testing took place in an anechoic room.

For inclusion in the high frequency hearing study, subjects were required to meet the following criteria:

i) Ability to reliably carry out pure tone audiometry

ii) Tympanograms showing normal shape and compliance with middle ear pressure of ± 50 mm H_2O

iii) Pure tone thresholds at frequencies 0.25 to 8 kHz better than or equal to 20 dB HL, with no more than 10 dB difference between thresholds at any two frequencies.

Six boys and seven girls, mean age 9.9 years, were then tested at higher frequencies, using the high frequency audiometric system, described earlier, the signal being transduced by the Beyer DT441 earphones. The children were first allowed to become accustomed to the quiet room.

The earphones were placed over the child's ears, by the tester, in each case. Instructions were as for normal manual audiometry, using the modified Hughson-Westlake ("ten down - five up") procedure. The children were first given practice in listening to the highest test frequencies. Threshold determination was carried out at 4, 8, 12, and 16 kHz, in that order. The first test ear was varied randomly.

4.4.2 Results of Experiment I

Subject threshold values are reported for all subjects in Table A4.1. None of the children reported any difficulty in listening to the high frequency stimuli, following a practice period. A statistical summary of the data is given in Table 4.3.

Comparisons were made of the left and right ear threshold data. Paired t-tests were carried out at each test frequency, and at the 5% level there were no significant differences between left and right ear threshold results at any frequency. (Table A4.2.)

Table 4.3

Mean and medium high frequency threshold values in earphone-coupler dB SPL

FREQUENCY (kHz)

	4			8			12			16		
	L	R	L+R	L	R	L+R	L	R	L+R	L	R	L+R
mean	13,9	14,3	14,1	23,6	22,8	23,2	32,6	28,8	30,7	34,5	40,5	39,6
median	10	13	15	25	22	22	27	28	27	39,5	42	42
s,d,	3,14	5,60	4,37	5,68	6,07	5,66	6,61	7,59	7,14	5,90	8,51	7,33
range	6	20	16	16	20	20	24	20	24	15	20	20

Comparison of threshold results of male and female subjects, by students t-tests, did not reveal any significant difference at the 5% level at any frequency. (Table A4.3.)

The threshold means and medians, across subjects, were calculated for left and right ears (Table 4.4). These results fall within the results of other studies showing comparatively higher thresholds at 12 kHz (Fig. 4.3). The variance in the data appears to be smaller than that of some studies, where the information is given (Table 4.5).

Table 4.4

Threshold means across subjects

FREQUENCY (kHz)

	4			8			12			16		
	L	R	L+R	L	R	L+R	L	R	L+R	L	R	L+R
mean	13,9	14,3	14,1	23,6	22,8	23,2	32,6	28,77	30,69	34,13	40,46	37,31
median	10	13	15	23	22	22	27	28	27	37	42	39,3
s,d,	3,14	5,60	4,37	5,68	6,07	5,66	6,69	7,596	7,282	5,899	8,511	7,863
range	6	20	16	16	20	20	24	20	24	20	20	23

Table 4.5

Standard deviations of the mean thresholds recorded on varoius studies

Study	Test frequencies			n
	8	12	16	
Zislis and Fletcher [1] (1966)	8.9	17.5	46.7	20
Harris and Ward (1967)	8.0	10.73	21.65	240
Northern et al [2] (1971)	14.3	18.1	20.7	117
Osterhammel and Osterhammel [3]	7.7	9.8	16.0	44
This study	5.7	7.1	7.1	26

[1] Boys age 11 - 13 years
[2] Age group 20 - 29 years
[3] Age group 10 - 19 years

A one-way analysis of variance was used to compare the subject threshold variance at 4 and 8 kHz obtained using the two different transducers. At 4 kHz, the variance of threshold measures do not differ significantly at the 5% level. At 8 kHz, there are significant differences (Table A4.4). The absolute threshold differences are predominantly less than 10 dB (Fig.4.4), which is within an "acceptable" error range for clinical pure tone audiometry.

4.4.3 Discussion of Results of Experiment I

The most notable difference between this study and others is the mean threshold at 12 kHz. The other studies reported here show a marked increase in threshold in dB SPL with increasing frequency. This may be due to a problem arising from the calibration technique. Five subjects, with thresholds which are higher at 12 kHz than at 16 kHZ, in at least one ear, dominate the result. Two probable reasons underlie this. Firstly, the age of the subject and inexperience with specific listening tasks, increases the variability of the result at all frequencies. In theory, older subjects and experienced listeners find the higher frequencies more difficult to detect. Secondly, threshold studies more commonly are carried out in 2 dB steps. This study uses 5 dB steps, increasing the effect of averaging over the subjects with extreme thresholds. It should also be noted that the subjects were otologically normal, as determined by questioning only.

Although the left and right ear data were not significantly different in

Fig 4.3 Comparison of several studies of high frequency hearing

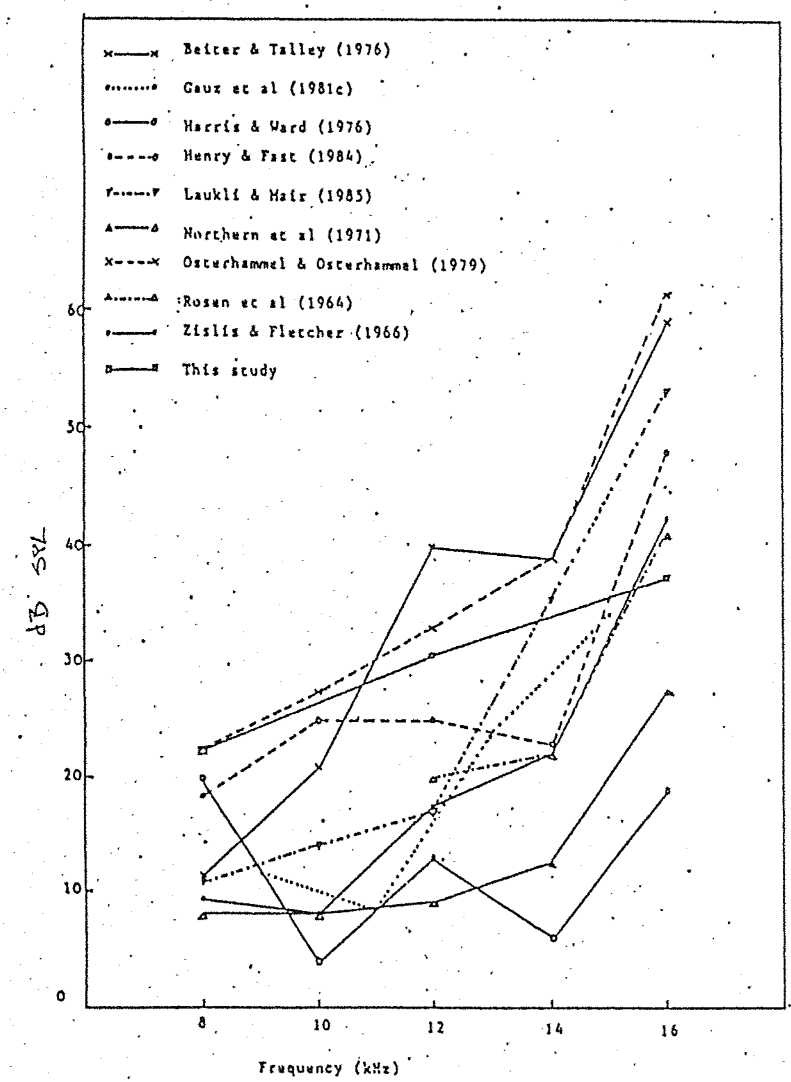
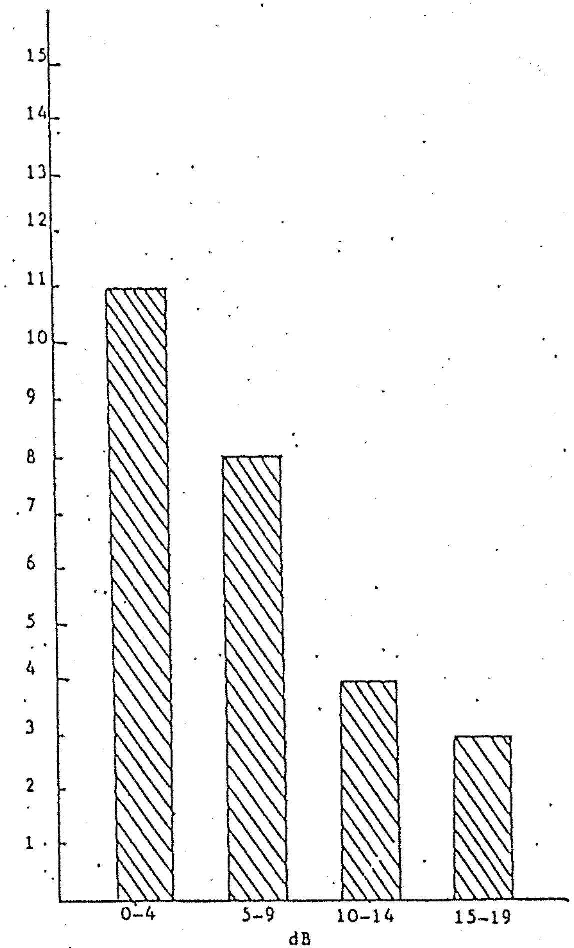


Fig 4. 4



Comparison of Audiometric results at 8kHz

Absolute threshold difference using TDH-49 earphones and Beyer 441 earphones.

this study, Zislis and Fletcher (1966) found the left ear to be more sensitive to high frequency stimuli than the right ear, in their study. However, this result has not been duplicated by other investigators. Further, Zislis and Fletcher presented stimuli to the right ear first in each case. Learning effects may have contaminated their results and it is difficult to make comparisons with their data.

No gender difference in high frequency auditory acuity was found in this experiment. Some authors have reported gender differences, but in older subjects only. It is probable that occupational and lifestyle effects may have caused reduction in auditory sensitivity in the older male subjects, and that this difference will not be shown in children. No significant gender differences were found by Harris and Ward (1967) in their study on children.

4.5 INVESTIGATION OF MEASUREMENT VARIABILITY

4.5.1 Test Method

It has been suggested that one reason for the unreliability of thresholds in the high frequencies is the presence of standing wave patterns in the ear canal and hence, due to varying earphone placement (e.g. Hicking, 1966). Accordingly, the repeatability of threshold determination on the same subject using the TDH-49 and Beyer DT441 earphones were compared.

Eight normal hearing young adult subjects participated in this study (ages 22-25 years). Audiological and otological requirements were as for Experiment 1. Each subject completed a pure tone audiometric assessment at 4 and 8 kHz, using both sets of headphones, and, additionally, at 12 and 16 kHz using the Beyer system. Thresholds above 8 kHz were not compared on the two systems, since the frequency response of the TDH-49 earphone falls away at around 10 kHz. Whilst this is not of consequence at low sound pressure levels, it was considered that it may be in the main study, where high intensities would be used.

Subjects were tested with one transducer and then the other, on each of three consecutive days. The test system used first was varied randomly.

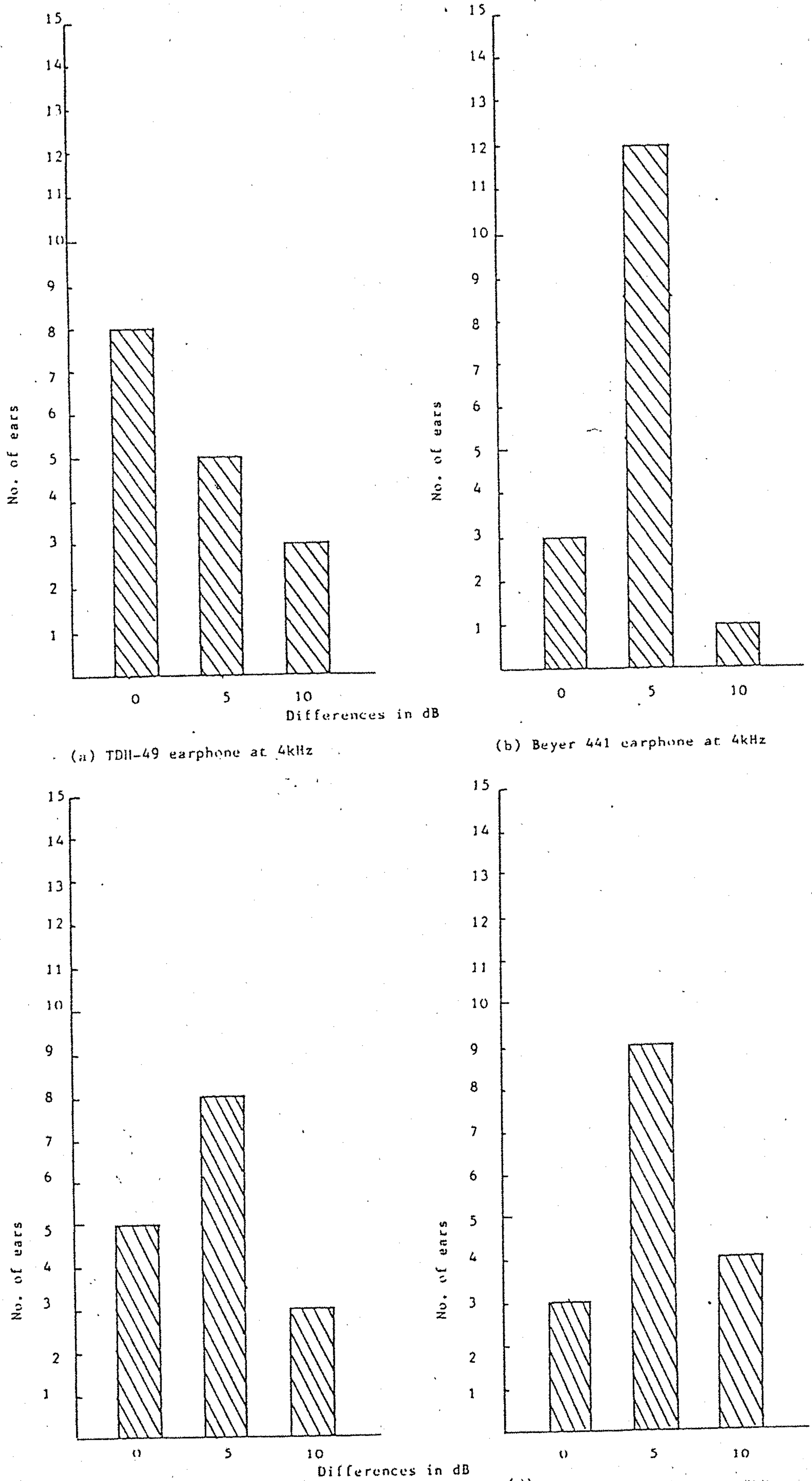
Audiometric procedure was identical for both conditions. Subjects were given a practice session listening to the high frequency sounds.

4.5.2 Results of Experiment 2

A reported feature of high frequency audiometry is that it is unreliable due to psychological difficulties in attending to rarely heard test sounds (Rendell and Miller, 1983). In contrast to experiment 1, four of these subjects complained that the higher frequency stimuli were difficult and unpleasant to listen to. However, a complete data set was obtained.

An analysis of variance procedure was used to compare threshold measures across repeat sessions, subjects and earphones (Tables A4.5 and A4.6). At 4 and 8 kHz, there were no significant differences between the results of thresholds measured on successive days ($p>0.01$). Analysis of the difference between the earphones showed no significant difference at 4 kHz ($10\%>p>5\%$). The difference was more marked at 8 kHz, and inspection of the data suggest that this was due to higher thresholds being obtained with the Beyer earphone. The interaction term in the analysis of variance between headphone type and retesting was not significant at 4 kHz. This suggests that differences between the headphones would remain constant. At 8 kHz there is some indication that the difference between the headphones may vary over days ($10\%>p>5\%$). Significant differences between subjects were found at the 1% level at 8 kHz. An analysis of variance procedure was used to examine the threshold data obtained using the Beyer phones at 4, 8, 12 and 16 kHz on three separate days (Table A4.7). There were significant differences between subjects or between results obtained in the separate test sessions. There were, as expected, significant differences between frequencies, but the insignificant interaction term indicated that this remained constant over days. Results are more favourable than those obtained by Ising et al. (1986). This is probably due to subject selection and test conditions. The comparative absolute differences for each phone at two frequencies are shown in Fig. 4.5. No overall trends were observed and differences are predominantly within clinical acceptability.

Fig 4.5



(a) TDH-49 earphone at 4kHz

(b) Beyer 441 earphone at 4kHz

(c) TDH-49 earphone at 8kHz

(d) Beyer 441 earphone at 8kHz

Comparison of audiometric results using TDH - 49 and DT - 441 earphones. The maximum test/retest differences are given

4.5.3 Discussion of Results of Experiment 2

The repeatability of the threshold measurements obtained on different days suggests that earphone placement may not be a critical factor in the variability of the high frequency thresholds. The results are comparable with session effects recorded by Hamill and Haas (1986). Thresholds are sufficiently repeatable, using this method, to warrant the use of the "high frequency audiometric" system in further studies on hearing-impaired children. Although there were significant differences in the variability at different frequencies using the Beyer phone, these differences were maintained at repeat sessions. This is compatible with the recent findings of Henry and Fast (1985), investigating diurnal variations in high frequency audiometry. Also, by deduction from their study, some of the variation may be due to diurnal variation, rather than headphone placement. This could be investigated further but was not examined in the present series of experiments.

The mean hearing thresholds of the normal hearing children, at 12 and 16 kHz in dB SPL, were equated to an audiometric zero at these frequencies. Thus further audiometric measurements on the test group could then be plotted on an extended audiometry form, to facilitate comparisons with the normal hearing group.

4.6 HIGH FREQUENCY HEARING MEASURES ON THE TEST POPULATIONS: A COMPARISON WITH MEASURES OF SPEECH INTELLIGIBILITY

4.6.1 Experiment 3(a)

4.6.1.1 Subjects

Severe to profoundly hearing-impaired children, attending a residential school (Group 1).

4.6.1.2 Method

Part 1. Evaluation of High Frequency Thresholds.

Hearing thresholds in the conventional audiometric range were obtained from the 20 children in the main study, who were attending the residential oral/aural school for deaf children. Sensitivity to pure tones at 12 and 16 kHz was then evaluated using the high frequency audiometric equipment and method previously described.

Part 2. Assessment of Speech Intelligibility.

Speech samples, consisting of a short familiar reading passage were collected from each child. The material chosen was simple and familiar, being drawn from classroom material forming the basis of their language stimulation programme.

The recorded samples were re-recorded in three different random orders, each sample being cut to 20 seconds duration. A panel of naive listeners was then asked to listen to the speech samples, and to judge them for intelligibility on a five point scale, 1 to 5, where 1 was "completely intelligible speech" and 5 was "completely unintelligible speech". This was based on the equal interval speech intelligibility scale of NTID, and is typical of intelligibility scales used with the hearing-impaired. The panel attended for each of three sessions, the first being counted as a practice session, and the sessions were each one week apart. Thus, each panel judged the speech complex in different random orders on three different occasions. The script of the passage was read by the panel members before the session, to ensure that all the listeners had a standard familiarity with the passage.

Comparisons of the panel data from the sessions using a one-way analysis of variance showed there to be no significant differences in the variance of the two sessions. A mean speech intelligibility grade was then taken over panel members from the two sessions, and assigned to each child.

4.6.1.3 Results

Five children were judged as having speech grades of 2 or better. Six of the twenty children had measurable hearing in the frequencies above 4 kHz. Their audiograms are shown in Figure 4.6. Of these six children, three had been classified as having good speech intelligibility (Figs. 4.6a, b and c). The remaining three children having some measurable hearing in the high frequencies scored very poorly on speech intelligibility (Figs. 4.6d, e and f). The audiogram of the two children classified as having good speech intelligibility, but who did not have measurable hearing at frequencies above 4 kHz are shown in Fig. 4.7. These results are summarised in the contingency table, Table 4.6, where "good speech" is the category applied to a speech intelligibility rating grade of 2, or better. Statistical analysis using the chi-squared test of these results did not show a significant difference between the groups. However, it is interesting to note the presence of the residual high frequency hearing in these children, classified as better speakers.

Table 4.6 Contingency table summarising the occurrence of high frequency hearing in a group of twenty children with severe to profound hearing loss, subcategorised as good and poor speakers.

	Good speakers	Poor Speakers	Totals
High frequency hearing	3	3	6
No high frequency hearing	2	12	14
Totals	5	15	20

$\chi^2 = 2.85$ (not significant, $p < 0.05$)

Fig 4.6 (part one)

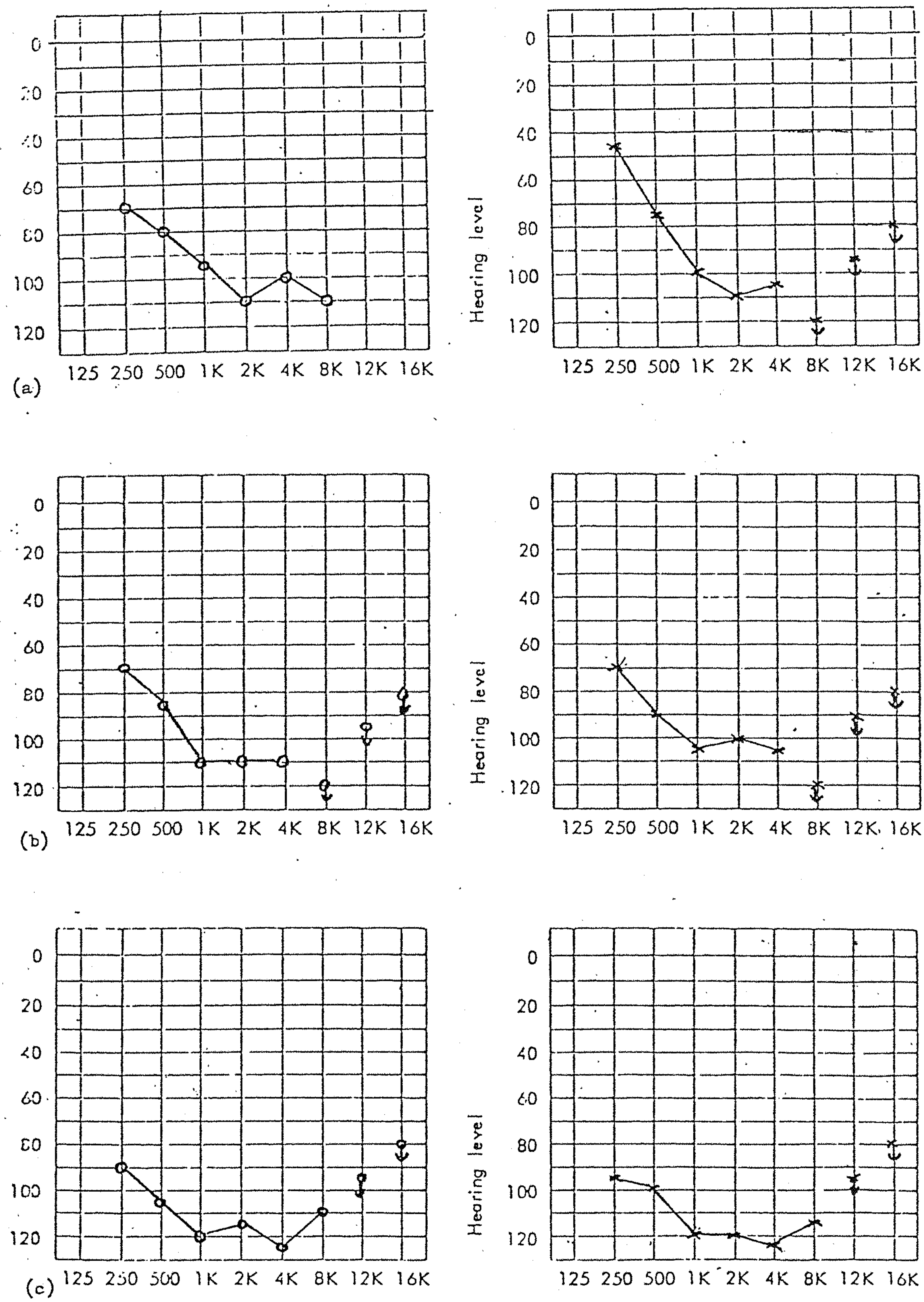
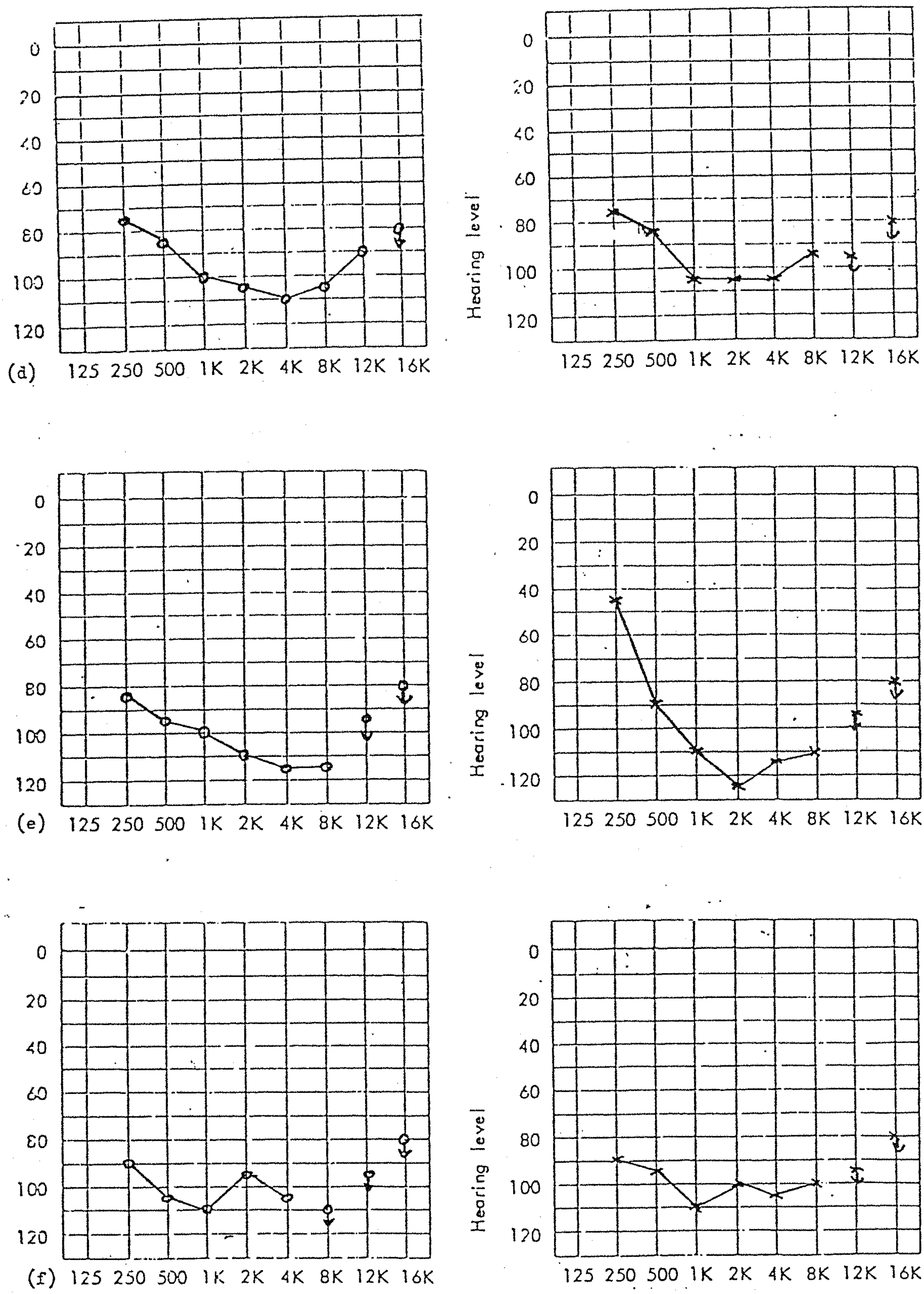


Fig 4..6 (part two)



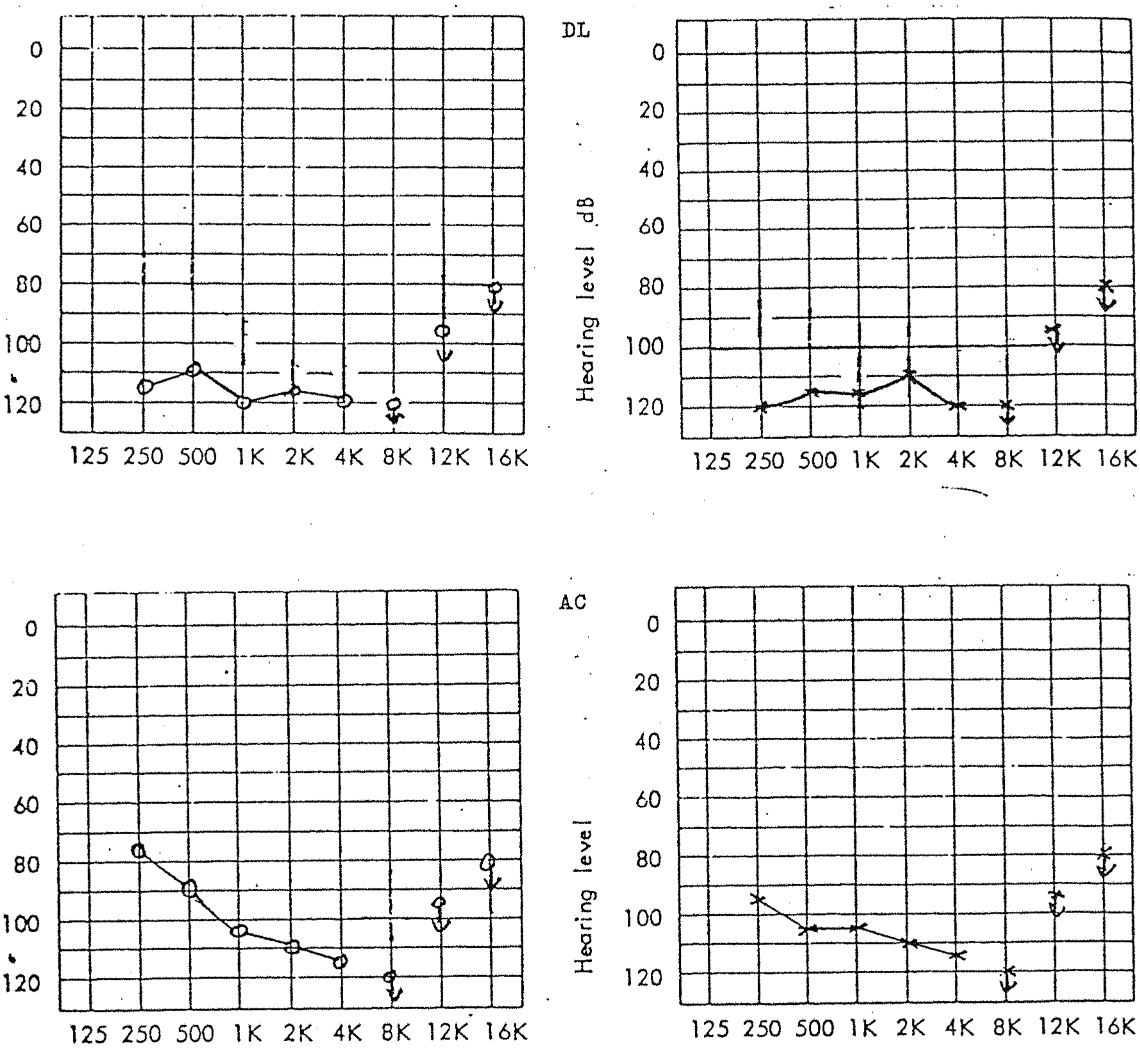


Fig 4.7 Audiograms of two of the children graded as hearing fairly intelligable speech (a score of 2 or higher)

4.6.1.4 Discussion of Results

In the small sample tested on this study, the subjects possessing measurable hearing thresholds at frequencies above 4 kHz were congruent with the children having good speech intelligibility in three out of six cases. The sample is very small, and only a qualitative discussion of these results is possible, as they do not form two clearly defined populations. It may only be speculated that the presence, or not, of hearing in the higher frequencies may have positively affected these children's speech. Clearly, many other factors are involved, in both the actual speech quality and the listeners judgement, some of which have been discussed in earlier chapters. Speech intelligibility is difficult to quantify and the type of continuum involved is complex (Schinvetti et al., 1981), but verbal descriptors used, as the basis of a rating scale supply a method with some validity (Conrad, 1979). Although the technique is subjective the descriptors presumably reduce the inter-listener variability and remind them that the task is a comparative one. It is the comparative aspect which makes it the most suitable for this application. Experienced listeners are considered to give reliable results (Markides, 1983). Inexperienced listeners are used in this study, because of the difficulty of assembling a panel of equally experienced listeners. Subtelny et al. (1980) have shown that inexperienced listeners judging adult speech can achieve similar levels of agreement after training. The listeners here received a short training period, and inter-listener variability was partly offset by the large panel size (Doyle, 1987).

Chasser and Ross (1979) suggest that it is more fruitful to confine a search for children having useful high frequency hearing to those whose audiometric configuration slopes upwards from 2 kHz, and who have, at most, a moderate to severe hearing loss. The children tested in Experiment 3(a) generally had very poor auditory thresholds, and a downward sloping audiogram. The study of high frequency hearing and speech intelligibility was therefore extended to the second group of children who had widely ranging degrees of hearing impairment.

4.7.2 Experiment 3(b)

4.7.2.1 Subjects

Children with hearing impairments from moderate to severe, attending various educational institutions, but all under the auspices of the Hampshire Education Authority.

4.7.2.2 Method

Part 1. Evaluation of High Frequency Thresholds.

Eleven hearing-impaired children took part in this study. Audiometric measurements were exactly as described above.

Part 2. Evaluation of Speech Intelligibility.

These children were not assessed for speech intelligibility in the same way as the first group. In this case the experimenter described each child's speech as either (1) clear and intelligible or (2) difficult to understand. The judgements were made prior to carrying out audiological tests, and were made independently.

4.7.2.3 Results

The audiometric configurations of the children having measurable hearing at frequencies above 4 kHz are shown in Figure 4.8. The audiograms (a), (b), (c) and (d) were obtained from children who were described as intelligible, good speakers. Audiograms (e) and (f) were obtained from children described as having poor speech. Two of the remaining children were each described as good speakers, and their results are shown in Fig. 4.9. The data are summarised in Table 4.7. It was not possible to demonstrate a significant difference between the groups, but as the numbers involved are very small it is more realistic to discuss the results qualitatively. The data from both groups is summarised in Table 4.8 where, again, no significant difference between the groups was demonstrated.

Fig 4.8 (part one)

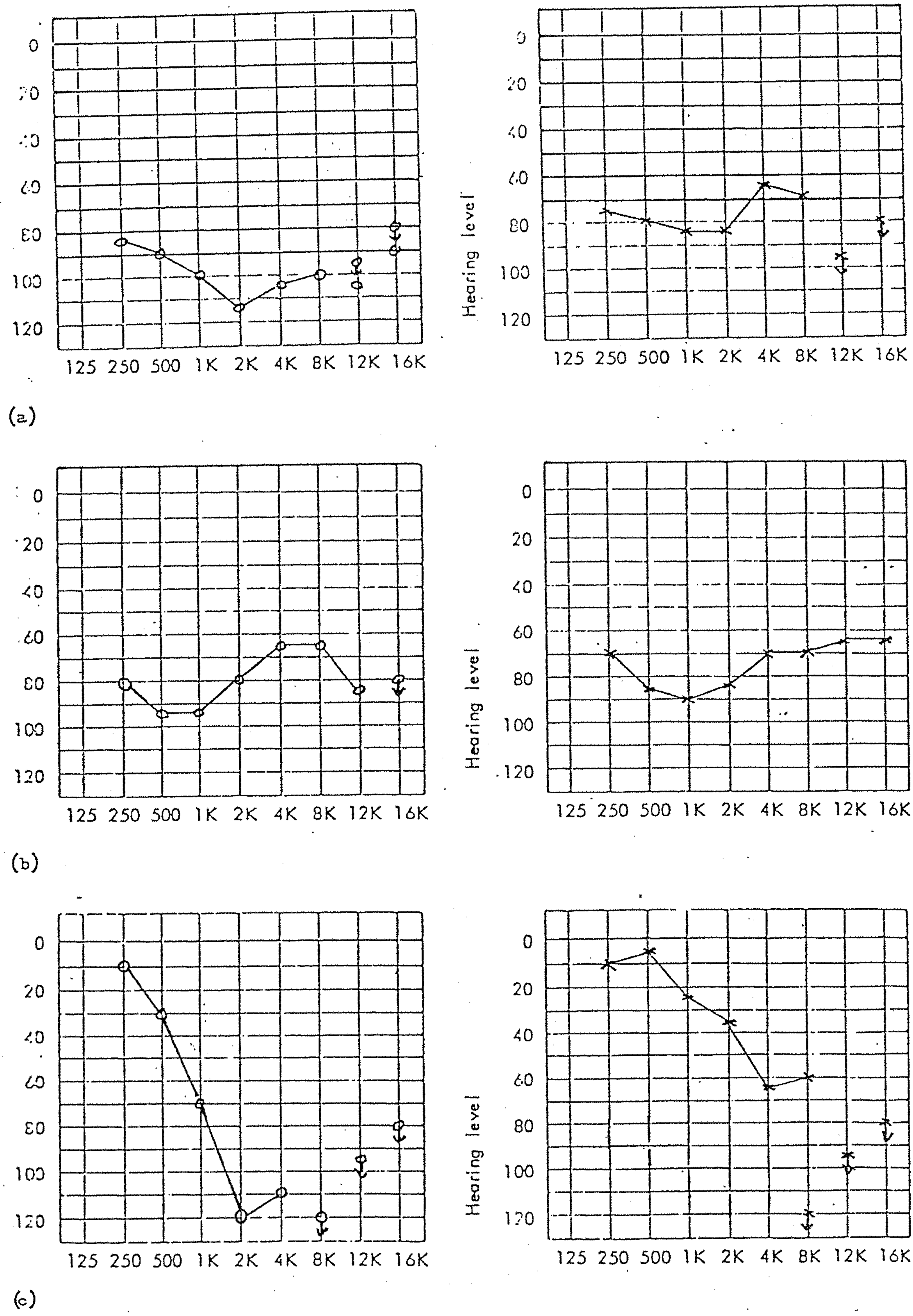
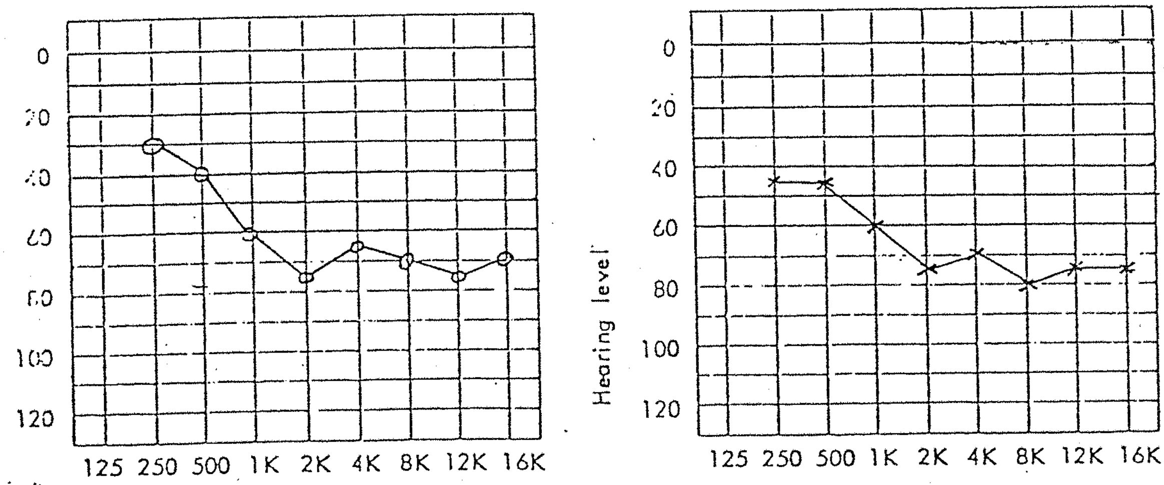
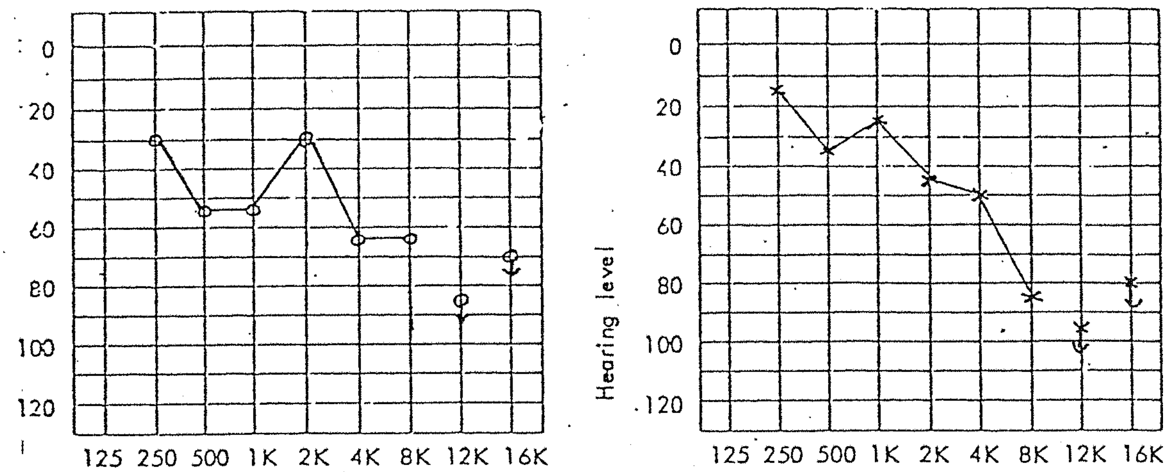


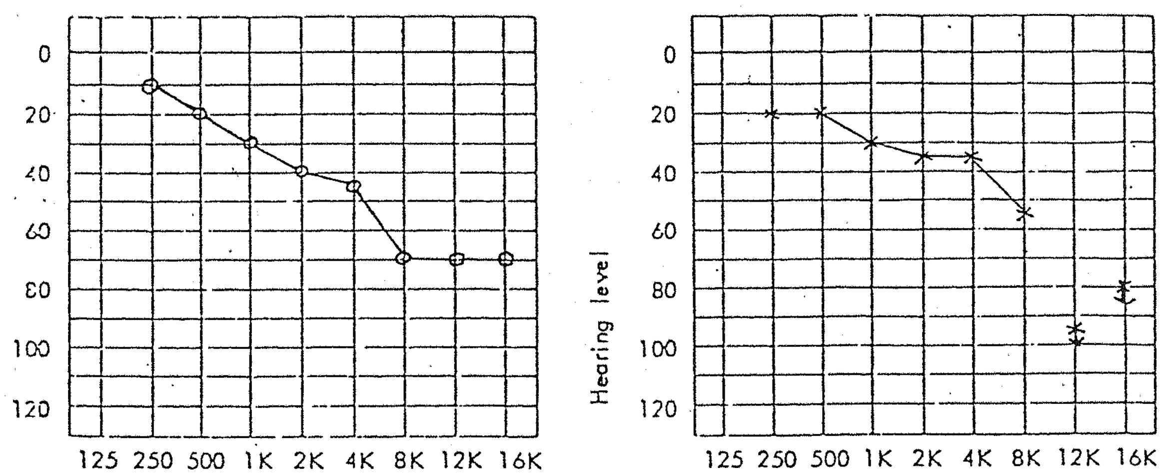
Fig 4. 8 (part two)



(d)

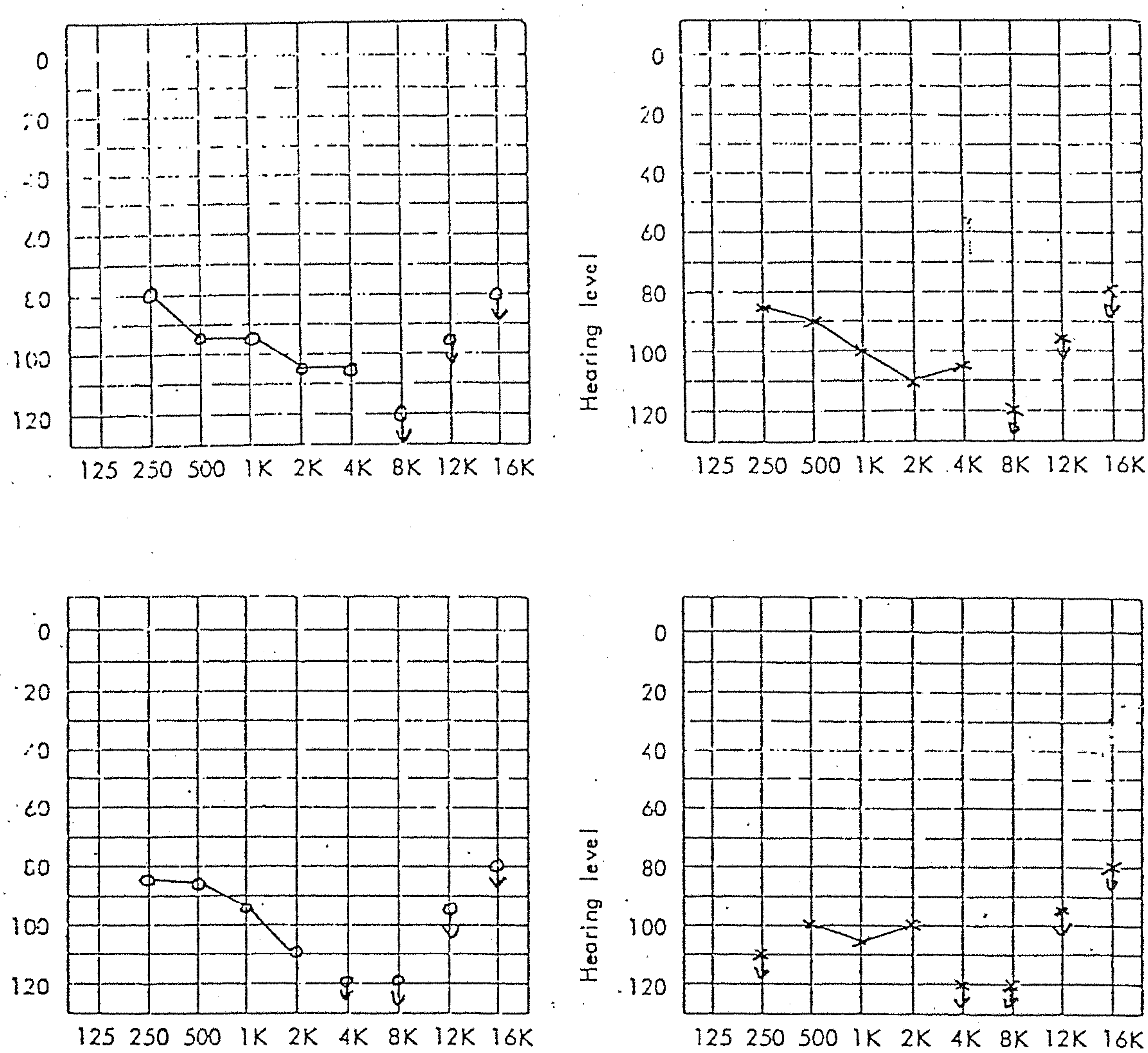


(e)



(f)

Fig 4.9



0
20
40
60
80
100
120
Hearing level
125 250 500 1K 2K 4K 8K 12K 16K

Table 4.7 Contingency table summarising the occurrence of high frequency hearing in a group of eleven children with mild to severe hearing loss, subcategorised as good or poor speakers by the experimenter's judgement.

	Good speakers	Poor Speakers	Totals
High frequency hearing	4	2	6
No high frequency hearing	1	4	5
Totals	5	6	11

χ^2 = 0.24 (not significant, $p < 0.05$)

Table 4.8 Occurrence of high frequency hearing in a group of children with varying degrees of hearing loss, subcategorised as good or poor speakers by two methods.

	Good speakers	Poor Speakers	Totals
High frequency hearing	7	5	12
No high frequency hearing	3	16	19
Totals	10	21	31

χ^2 = 2.52 (not significant, $p < 0.05$)

4.6.2.4 Discussion

Although there are more factors involved in a child's speech intelligibility than audiometric configuration, this study indicates that the presence of useable hearing in the high frequencies may contribute. The detailed study of the signal processing abilities of a hearing-impaired person with residual "ultra-audiometric" hearing, made by Collins et al. (1981), showed that she could usefully process the signals which fell within the band of the best hearing. These authors felt that the hearing in the higher frequencies was useful to her in speech communication. A study by Monsen (1978), where he classified his population by normal procedures, shows the better speakers to have rising configurations to their audiograms. As he only tested in the conventional frequencies, it can only be hypothesised that these speakers may have usable hearing above 8 kHz, which has assisted their production of intelligible speech.

In this study, it is of interest that, of eleven children tested, six had measurable hearing in the high frequencies and, of these, four children were among the total six who had been classified as good speakers. It is also interesting to note that one of the children, classified as a good speaker, had an audiogram with a configuration leading to difficulties in finding optimal amplification. This child was a very poor aid user, disliking both of his aids strongly. An overall important observation from this experiment is that individuals with similar pure tone averages below 2 kHz may differ widely in the higher frequencies, and this may then affect their speech intelligibility.

4.8 SUMMARY AND DISCUSSION OF STUDIES OF HIGH FREQUENCY HEARING

Some studies on high frequency hearing were carried out to ascertain whether there was any contribution to the childrens' spoken language from preserved ultra-audiometric hearing. This may be regarded as just another factor in the comparison with audiometric variables, but the state-of-the-art in high frequency testing, and the special interest it may have, entailed a subset of experiments. Having established an audiometric norm, for the high frequencies of interest, the two test populations making up the subjects of the main study were assessed. There is evidence that the presence of measurable hearing in the frequencies 4-16 kHz assists a child with the production of intelligible speech, but it is not possible from these studies alone to state the extent to which the residual high frequency hearing may be helping these children, especially since, in the cases where conventional amplification is being worn, it would not be effective in these frequencies. It is a confounding factor that this assessment of ultra-audiometric hearing has taken place after years of personal and group hearing aid use by the children. Particularly as the basal section of the cochlea is the most susceptible to insult, noise damage may have affected remaining high frequency function. However, there are features in this data collection which indicate that a positive contribution from residual high frequency hearing cannot be ignored. If preserved high frequency hearing is to be usefully exploited, it must be identified at an early age and the appropriate action taken; for example, the fitting of a high frequency emphasis hearing aid.

There are sufficient positive findings here to support the view that all cases of congenital deafness, or cases where speech intelligibility is better than conventional audiometry would suggest, be assessed for hearing in frequencies above 8 kHz (Bergstrom and Morgan, 1983). Interestingly, this view is supported by histologic findings on patients with Mondidnis' syndrome. Feglal et al., (1985) find young subjects to have exceptionally well preserved basal fibres in the cochlea.

Within the context of the main study, the presence of high frequency hearing alone has not been sufficient to distinguish the children who have achieved good speech intelligibilty from those children who have poor speech intelligibility, but it cannot be excluded as a positive contributory factor to speech intelligibilty in some cases.

CHAPTER 5

DETERMINATION OF RECORDING PARAMETERS AND NORMATIVE DATA FOR THE AUDITORY ELECTROPHYSIOLOGICAL RESPONSES

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5.1 EXPERIMENT 1

DETERMINATION OF THE OPTIMUM RECORDING PARAMETERS OF THE AUDITORY BRAINSTEM RESPONSE

5.1.1 Introduction

An experiment was designed with the aim of defining the optimum filter bandwidth to be used in the recording of brainstem electric responses, with particular reference to the main study. As described earlier, the waveform is most commonly studied for two reasons. Firstly, to investigate the neurological site of the disorder affecting the auditory pathway, by analysis of the whole waveform. Secondly, to obtain an estimate of auditory threshold using Wave V.

In recent years, many publications have described brainstem ep recordings from normal subjects and from patients with audiological and/or neurological disorders. However, waveforms recorded in different laboratories and using different commercial systems, still show markedly different features in response latency, amplitude and morphology. This is due in part to the lack of consensus about the lower frequency of the highpass filter (Urbach and Pratt, 1981). Confirmation of this has been obtained in studies investigating some effects of filter cutoff and slope on the waveform. Table 5.1 presents the recording parameters used in a selection of the important early site-of-lesion studies, in which lower frequency of the bandwidth varies from 0.01 to 0.25 kHz. The lowpass filter cutoff is of less interest, since most of the response energy lies at frequencies below 3 kHz (Elberling, 1979; Doyle and Hyde, 1981). The main purpose of the lowpass filter is to smooth the waveform estimate and to prevent aliasing errors. Examination of the frequency spectrum of the ABR (Boston, 1981; Osterhammel, 1981; Fridman et al., 1982; Suzuki, 1982; Hall, 1986) has led to a greater appreciation of the importance of optimal filter pass bands.

An experiment was designed to investigate the effects of using different filter cutoff frequencies on the waveform. Previous investigations on recording bandwidth have mostly been restricted to study of specific individual peaks (e.g. Boston and Ainslie, 1980; Kevanishvilli and Aphonchenko, 1979).

Table 5.1

Some Bandwidths Used in ABR REcordings

Study	Year	Cutoff Frequencies (kHz)
D. Jewett and J. S. Williston	1971	0.01-2.50
A. C. Coats and J. L. Martin	1977	0.02-3.00
J. W. Bauer et al.	1974	0.03-3.00
W. A. Selters and D. E. Brackman	1977	0.03-3.20
A. Klein and D. C. Teas	1978	0.05-2.50
K. Hecox and R. Galambos	1974	0.08-3.00
K. Robinson and P. Rudge	1977	0.08-2.50
J. A. Wolfe et al.	1978	0.08-3.43
A. Starr and J. Achor	1975	0.10-3.00
S. J. Stockard and V. S. Rossiter	1977	0.10-3.00
K. H. Chiappa	1978	0.10-3.00
O. Yamada et al.	1979	0.10-1.00
H. J. Rosenhamer	1977	0.12-4.50
K. Møller and B. Blegvad	1976	0.15-4.50
K. Terkildson et al.	1975	0.20-4.50
H. Sohmer and M. Feinmesser	1973	0.25-5.00

It was hypothesised that the optimal bandwidth for recording all the peaks would differ from that bandwidth which is optimal for the recording of the Wave V. To avoid the confounding effects of different phase shifts with different cutoff frequencies, introduced with analogue filters, a digital filtering technique was used to determine:

a) The filter bandwidths which would optimise the recording of brainstem electric responses, and

b) The bandwidth required for optimum recordings of the whole waveform.

The hypothesis embedded in the second aim given above, is based on studies of the spectral energy composition of the auditory brainstem responses, which indicate that there are both high and low frequency components in the ABR. The Jewett Waves I-V contain mainly frequencies in the range 0.40 to 1.30 kHz and are superimposed on a low frequency wave with frequencies below 0.50 kHz (Lang et al., 1981; Takagi et al., 1985; van Olphen, 1985). The frequency spectrum of the waveform also varies with the stimulus frequency spectrum (Suzuki and Horiuchi, 1977), lower frequency stimuli increasing the relative importance of the lower frequency components. Elberling (1979) and Doyle and Hyde (1981) have shown the main spectral power of the ABR's at all stimulus intensities to be located below 0.25 kHz. This is shifted to lower frequencies as the stimulus intensity decreases. The spectral composition of the response complex also depends on the time elapsed following onset of the stimulus, the first components containing the higher frequency energy and the later components containing lower spectral energy (Elberling, 1979; Hoke et al., 1984).

Thomas (1984) confirmed this, using a cascaded filtering and optimisation procedure. He broke down the ABR into its constituent components. Based on his analysis, he went on to develop an alternative interpretation of the waveform generating sites. This relationship is beginning to be explored further as evidence on multiple generator sites accumulates.

In the experiment to be described, wideband recordings of click-evoked brainstem responses were made, and then digitally highpass filtered, off-line. Analogue bandpass filters are conventionally used in the recording of ABR's as a means of improving the signal-to-noise ratio, and in the main study analogue filters only are available for use. It has been shown (Boston and Ainslie, 1979; Doyle and Hyde, 1980; Arlinger, 1981; Laukli and Mair, 1981; Møller, 1983) that analogue filters introduce phase distortion which results in latency changes and less wave shape uniformity (van Olphen, 1985). This may be deduced, theoretically, by considering the transfer function.

Any filter may be described as

$$H(jw) = M(w) \exp \big((j)\, O(w)\big)$$

where $M(w)$ is the filter modulus and $O(w)$ is the filter phase at a given angular frequency.

Typically, a reduction in the lowpass filter frequency produces an increase in latency (Møller, 1980), and an increase in the highpass filter introduces phase lead resulting in a decrease in the latency of all the components (Elton et al., 1984; Svensson et al., 1987). The amplitude of the IV/V complex has also been found to decrease between a lowpass filter setting of 0.10 kHZ and a setting of 0.30 kHz (Kavanagh et al., 1984). There are

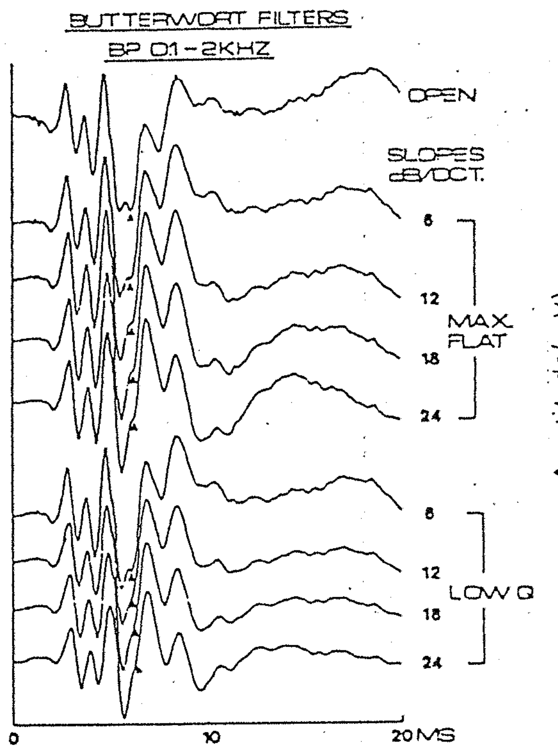
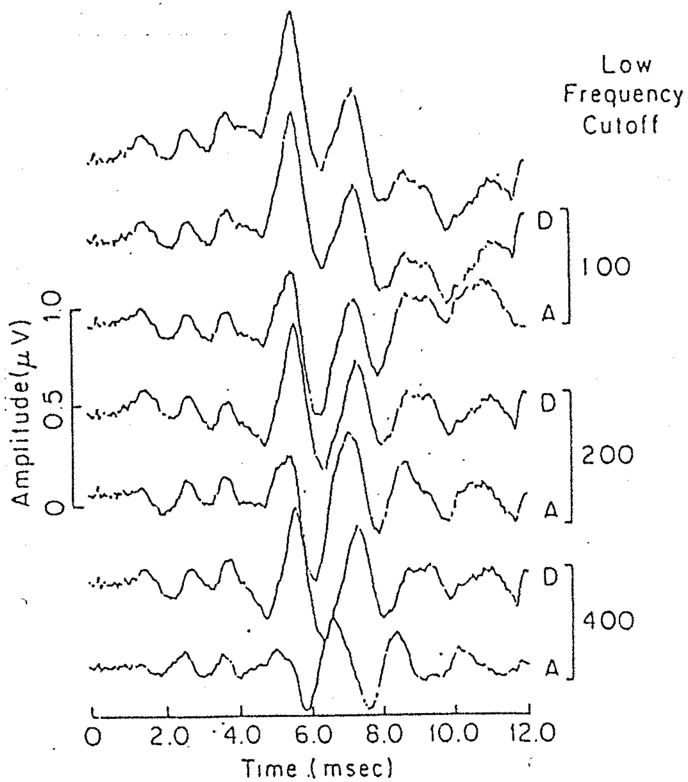
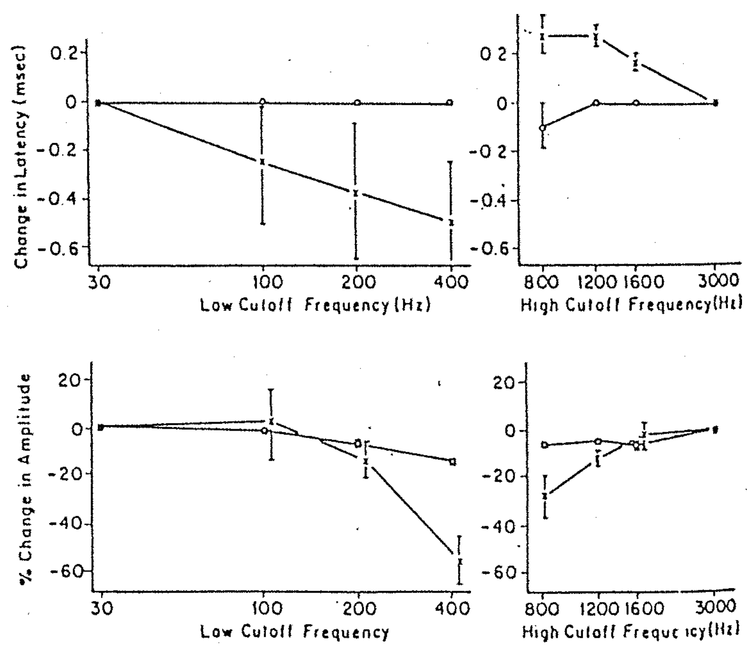


Fig 5.1
Auditory brain stem responses recorded with Vertex negative up through Butterworth filters with different slopes. Click intensity 70 dB SL. 4 000 sweeps. Both "Max Flat" -and "Low Q" settings of the filter are shown. (Osterhammel, 1981).



Effects of anologue and digital high pass filtering on the ABR to 70dB SL clicks. The top trace is unfiltered. D: refers to output of digital filter; A: refers to output of an analogue filter. (Boston & Ainslie, 1980)

Fig 5.2



Absolute change in latency (top) and per cent change in in amplitude (bottom) of wave V as functions of filter cutoff frequencies; average data from two subjects with standard error bars. Reference values are unfiltered responses. O, digital filtering; X, anologue filtering. (Boston and Ainslie, 1980)

Fig 5.3

also reports of the effects of highpass filtering on peak amplitude, polarity and the emergence of non-standard peaks within the waveform (Domico and Kavanagh, 1986). The extent of the resultant phase shift depends partly on the filter type, the most commonly used being Bessel, Butterworth, and Chebyshev. For each filter type, the distortion increases with the filter pole number, and the phase shift characteristics of filters should be carefully considered. Waveform distortion becomes related to both the bandpass frequencies and slope, along with the type of analogue filters used (Fig. 5.1). Increases in slope from 6 dB/octave to a steeper rolloff can result in changes in the IV/V complex (Osterhammel, 1981; Mason, 1984).

This change in phase characteristic does not invalidate the use of analogue filters in auditory brainstem response recordings, their primary role being to increase the ratio of signal-to-noise in the recording, and they involve less expensive hardware and software than digital filters. In the experiment to be described, digital filters have been used so that relative peak amplitude measures can be evaluated, and the effects of phase shift do not complicate the analysis. In Figure 5.2, the comparative effects of digital and analogue filtering are demonstrated (filter slope, 24 dB/octave). It is shown in Figure 5.3 that the response amplitudes obtained with analogue and digital filters, at the same cutoff frequency, differ. However, this is most marked at frequencies above 0.20 kHz, which is probably above the critical area of interest. These results demonstrate the necessity for careful choice and statement of filter bandwidths. In the experiment to be described, digital filters will be used to ascertain the most appropriate filter setting for the main study. Digital filters are void of significant distortion in peak amplitude and latency values following comparative study of the waveform at different cutoff frequencies.

5.1.2 Method

5.1.2.1 Subjects

The ABR was recorded from 3 male and 2 female normally hearing subjects, aged beween 20 and 30 years (mean age 23 years). Their audiometric thresholds between 0.25 kHz and 4 kHz were within 15 dB of audiometric zero and there was no known history of ear disease. Prior to testing, the subject's voluntary threshold to the test stimulus was established, using a modified Hughson-Westlake procedure in 2 dB steps.

Subjects were tested, supine, on a bed inside a double walled, electrically screened, anechoic chamber. The operator and majority of the recording and stimulating equipment were situated outside the room. Subjects were asked to relax and to close their eyes while the stimulus was present.

5.1.2.2 Stimuli

Broad band click stimuli of alternating polarity were presented monaurally through μ metal screened TDH-49 headphones, at a rate of 9.1 s^{-1}. The stimulus was a 0.10 ms alternating rectangular pulse. The electrical signal and the time history of the acoustical waveform are shown in Figure 5.4a. The power spectrum, calculated using the power spectral density function program, is shown in Figure 5.4b. In order to obtain these data, a train of click stimuli were presented, through the headphones, mounted on a Brüel and Kjær coupler, Type 4153. The acoustical waveform was converted to an electrical signal via a ½ inch microphone housed in the coupler, and the resulting signal was recorded on a Nagra IV-SJ recorder, using the built-in anti-aliasing filters. The recorded signal was analysed on a PDP 11/50 computer. The DATS 11 software program was used to perform time series analysis operations on the recorded signal.

The unfiltered click presents energy at a wide range of frequencies to the cochlea, in this case with main spectral peaks at 0.40 kHz and 1.55 kHz. Large areas of the cochlea are stimulated. The results will not be comparable with recordings made of responses to more frequency specific stimuli, due to the dependence of the energy distribution of the ABR on the frequency components of the stimulus.

The ABR was recorded at stimulus intensity levels of 15, 25, 35, 45, 55, 65 and 75 dB SL, presented in random order. 4000 stimuli were presented at the highest intensity at which the whole waveform was to be studied, and 2000 at the lower intensities.

A "no stimulus" run was also recorded for each subject, in order to estimate the signal-to-noise ratio at which only the Wave V was to be of interest.

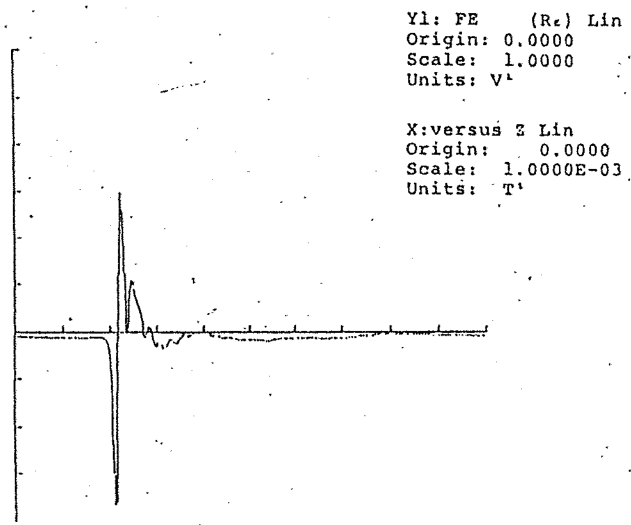


Fig 5. 4(a)

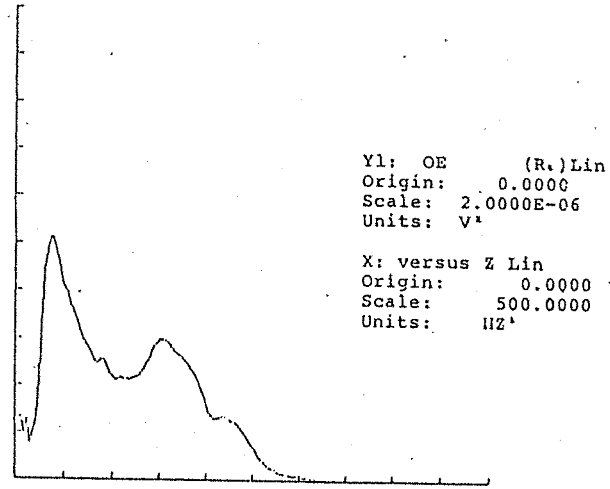


Fig 5. 4(b)

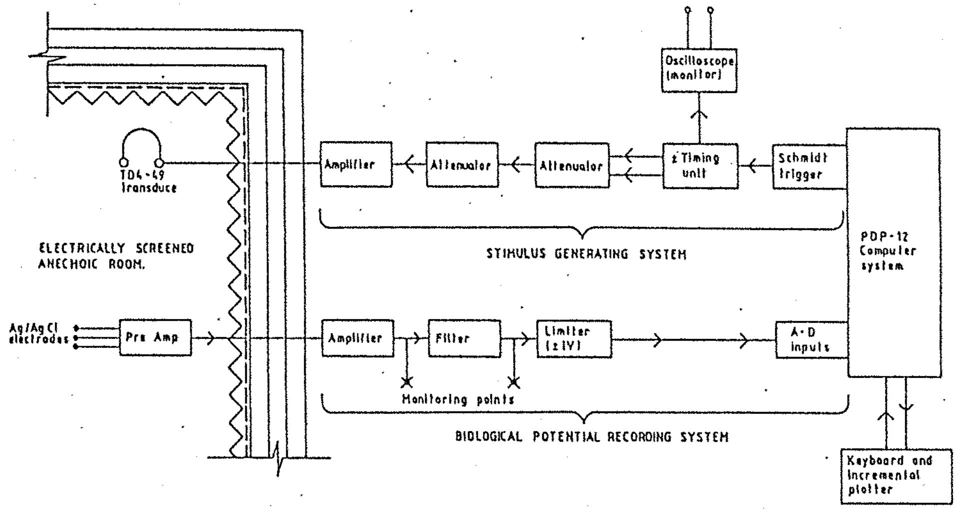


Fig. 5. 5 BLOCK DIAGRAM OF THE STIMULUS GENERATING AND RECORDING SYSTEM

5.1.2.3 Instrumentation

Signals were recorded from Ag/AgCl electrodes using a vertex-ipsilateral mastoid electrode placement, with a forehead electrode serving as ground. Electrode skin contact impedances were less than 2 kΩ at 1 kHz. The recorded signal was fed to preamplifiers inside the anechoic room, and the outputs of these were passed to a main amplifier and bandpass filtered between 0.2 Hz and 3.2 kHz. The data were acquired, averaged and stored on digital magnetic tape, using a PDP-12 computer, for subsequent retrieval and analysis. The data were averaged on two channels, displayed at 500 points per channel. Figure 5.5 shows a block diagram of the recording and stimulus generating system.

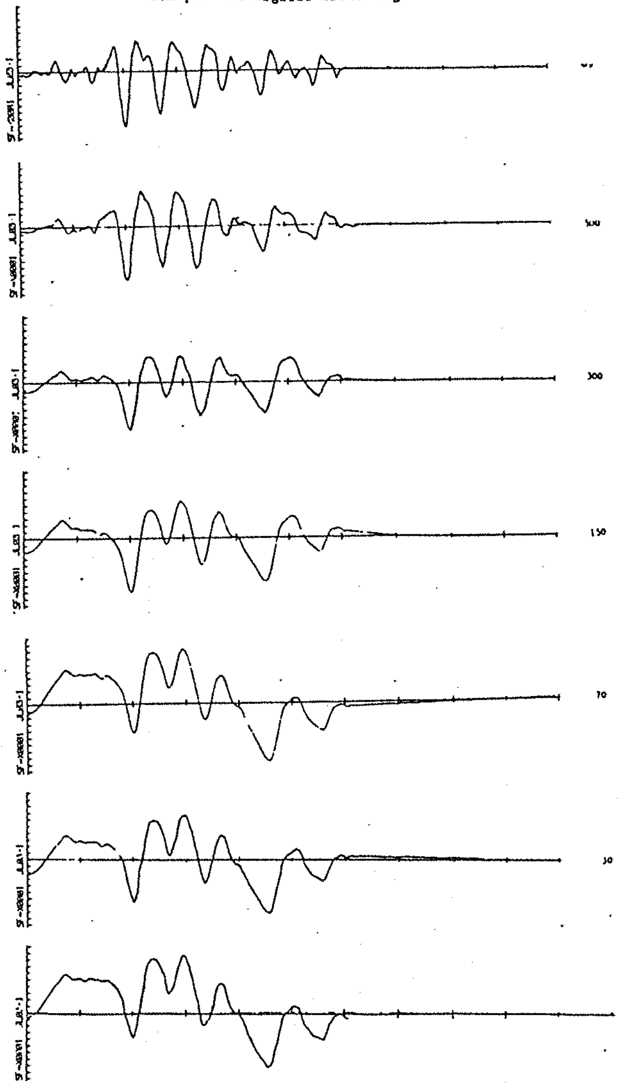
5.1.2.4 Digital filtering

The waveforms were demeaned and cosine tapered over the first and last 40 samples to avoid the effects of transients in the leading and trailing ends of the recordings. As the signal was sampled at a rate of 60 µs between points, cosine tapering over 40 samples is equivalent to tapering of 2.4 ms. This does not affect the area of interest in the trailing edge and is pre-stimulus in the leading edge.

Each waveform was then digitally highpass filtered at 13 highpass cutoff frequencies for each of three filter slopes of 12, 24 and 48 dB/octave. A zero phase shift filter was obtained by repeated application of a second order Butterworth filter formula, which is run backward in time on the forward filtered signal. This results in a symmetrical transfer function. Examples of progressive digital filtering at a filter slope of 24 dB/octave for a selection of the 13 cutoff frequencies are shown (Fig. 5.6) and three identical cutoff frequencies at the three different filter slopes are contrasted (Fig. 5.7)..

The data analysis is concurrently divided into two sections: firstly the effect of digital filtering on threshold estimation, using the Wave V; secondly, the effect of digital filtering on the whole waveform.

Examples of digital filtering.



Filter slope 24 dB/Oct.

Fig 5. 6

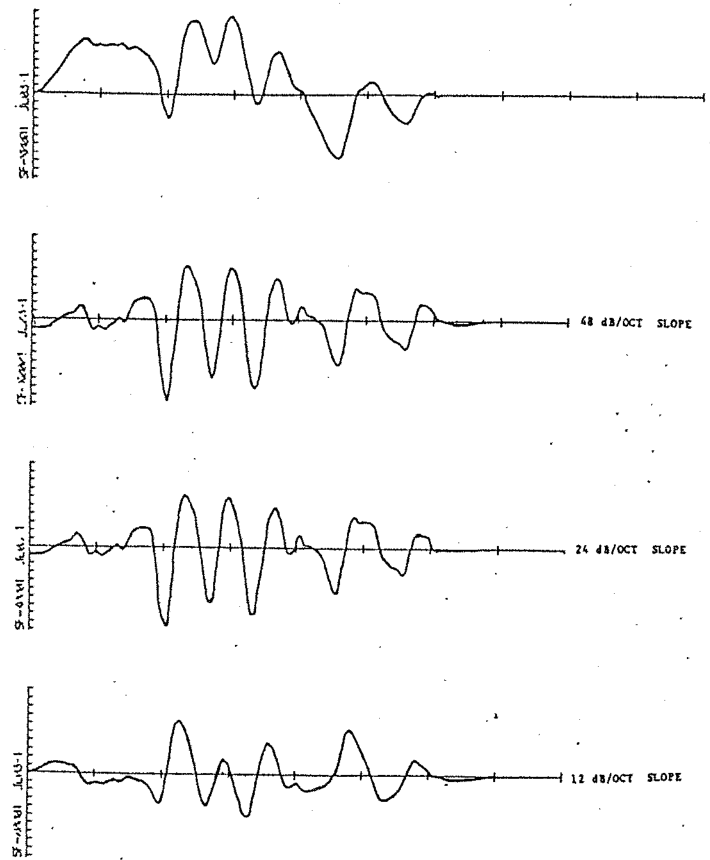


Fig 5. 7

Examples of high pass digital filtering; cutoff at 4 kHz.

5.1.3 Effect of filtering on threshold estimation using Wave V

5.1..3.1 Measurements

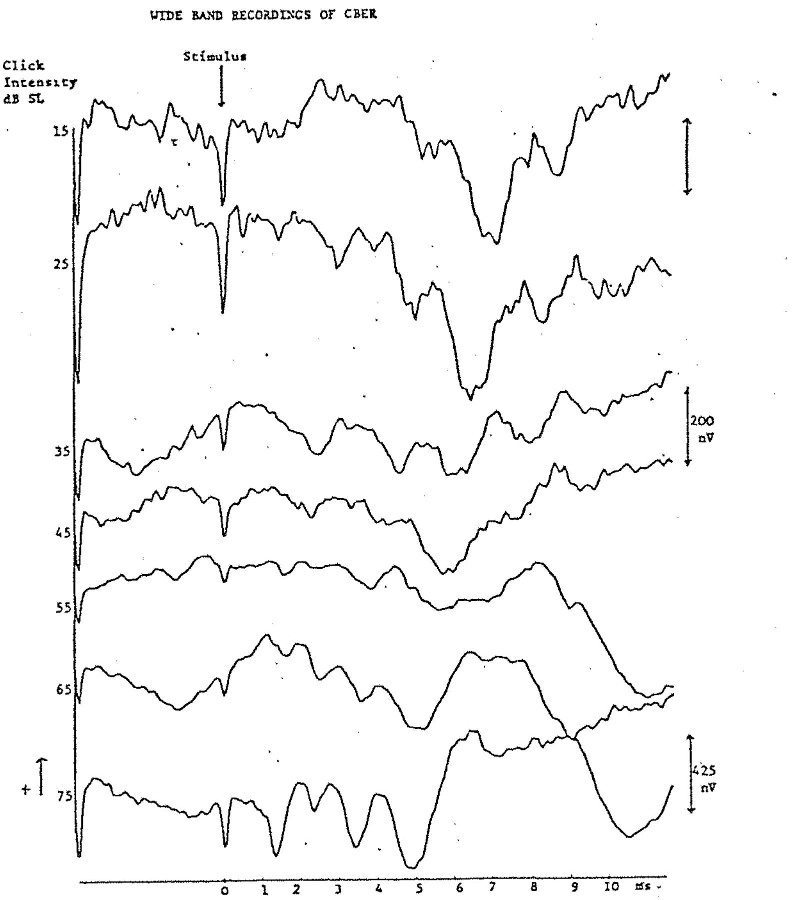
The unfiltered brainstem responses, recorded from each subject at sensation levels of 15 to 75 dB SL were inspected, and examples from one subject are shown in Figure 5.8. Wave V was defined as the most prominent wave near threshold and which decreases in latency as the stimulus intensity increases. The mastoid negative peak to the following mastoid positive peak amplitude of the Wave V was measured in each recording. The seven intensity level recordings were then each digitally filtered at 13 highpass cutoff frequencies and 3 different filter slopes.

As a zero phase shift algorithm was used to digitally filter the recordings, identification of Wave V through the filtered records could be carried out by using a fixed latency technique (Fridman et al., 1986). Thus the peak-to-peak amplitude, at latency values which were kept constant within each intensity level, was measured, using the latency at 0.15 kHz cutoff as a reference. The mean amplitudes across subjects were calculated at each highpass cutoff frequency, for each sensation level.

5.1.3.2 Results

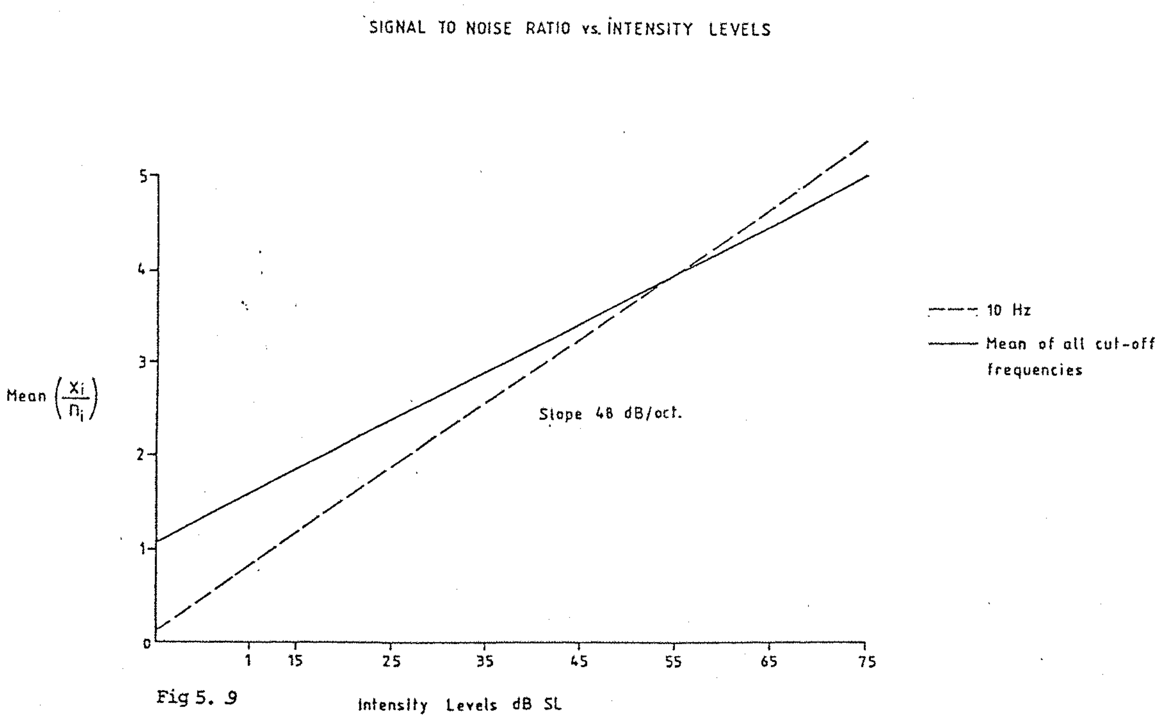
The highpass cutoff values for which the maximum amplitude of Wave V were obtained, at low sensation levels, were determined for each filter slope. These results are summarised in Table 5.2. As anticipated, the maximum values of Wave V are recorded with wide band filter settings, a finding consistent with previous observations and supporting the finding that the spectral content of Wave V is predominantly low frequency (e.g. Osterhammel, 1981). A band pass filter with a low cutoff frequency of greater than 0.02 kHz will cause amplitude reduction of Wave V for a filter slope of 12 dB/octave. For the steeper slopes of 24 and 48 dB/octave, the lower bandwidth limit should not exceed 0.01 kHz.

Using the no-signal run as a reference, the signal-to-noise ratio for each subject was estimated, and the means of the signal-to-noise ratios were calculated across subjects for each intensity and filtered condition. A graph of signal-to-noise ratio (Fig. 5.9) for the 0.01 kHz filter cutoff against stimulus presentation level indicated a 1.04% per dB reduction in



WIDE BAND RECORDINGS OF CBER
Click Intensity dB SL
Stimulus
15
25
35
45
55
65
75
200 nV
425 nV
0 1 2 3 4 5 6 7 8 9 10 ms

Fig 5.. 8



SIGNAL TO NOISE RATIO vs. INTENSITY LEVELS
Mean $\left(\frac{x_i}{n_i}\right)$
10 Hz
Mean of all cut-off frequencies
Slope 48 dB/oct.
0 1 2 3 4 5
1 15 25 35 45 55 65 75
Intensity Levels dB SL

Fig 5. 9

signal-to-noise (best fit line); i.e. there is a total reduction of 78.2% from the highest to the lowest intensity condition. A graph of mean signal-to-noise ratios across frequencies, against stimulus presentation level, indicates a 0.85% per dB increase with intensity; i.e. a total reduction of 62.5% (Fig 5.9). Since the rate of decrease of signal-to-noise ratio is less for the 0.01 kHz highpass cutoff frequencies than for the mean across frequencies, the identification of this value as the optimum highpass filter setting for recording the Wave V to threshold is not affected.

Table 5.2

OPTIMAL CUTOFF FREQUENCIES (Hz)

Combined Peaks	Filter Slopes 12	24	48 dB/octave
I, III, V	150	0.2	10
I, II, III, V	70	100	100
I, II, III, V, VI	30	0.2	0.2

A further advantage of wide band recording is illustrated in Figure 5.10 by the graphs of mean amplitudes of Wave V at different highpass cutoffs and three different sensation levels. The absolute amplitude intensity function was found to be steeper with wide band recording than with narrow band recording. This facilitates visual response identification to threshold.

5.1.4 Effect of Highpass Digital Filtering on the Amplitude of the Principal Peaks in the ABR Waveform

5.1.4.1 Measurements

The mastoid-negative to following mastoid-positive peak amplitudes of Waves I to VII in the ABR waveform, recorded at 75 dB SL, were measured for each subject and at each filtered condition. The mean peak-to-peak amplitude of each of the waves was calculated across subjects, and expressed as a percentage of the maximum value, normalised across highpass cutoff frequencies. As Waves IV and VII were not consistently present in these subjects and other studies indicate that these waves are not consistently present in normal hearing subjects, they were omitted from the analysis. For example, in the 1979 study of Chiappa et al., Wave IV was absent in 14% of their 52 cases. The mean amplitudes of each peak were calculated across subjects, at each highpass cutoff frequency, and for each filter slope.

5.1.4.2 Results

The mean amplitudes across subjects, and standard deviations, are listed for each peak and each filter slope in Tables A5.1, A5.2, and A5.3 (pages 373-375). The mean amplitude of each wave was maximised at different highpass cutoff frequencies, shown graphically in Figures 5.11, 5.12, and 5.13. As expected, the earlier waves have maximum energy at higher frequencies than the energy of Wave V. To optimally record any of these waves without consideration of Wave V, a different low frequency limit would be applied. This lower limit is dependent on filter slope and may be increased with decreasing slope, to a small extent. It is clear from examination of the graphs in which the peak amplitudes have been normalised (Figure 5.14, a to e) that, as the lower cutoff frequency is increased, the amplitude of Wave III is increased slightly and the amplitude of Wave V is decreased slightly. This is compatible with the observation that the main feature of the ABR is a slow wave on which high frequency waves are superimposed, and with the Boston and Ainslie study (1979), in which a growth of Wave III and a similar reduction in Wave V was observed, with increases in the highpass cutoff frequency.

For each filter slope and at each highpass cutoff frequency, the normalised mean amplitudes of each peak were multiplied together to give the cross products of the mean amplitude. These were normalised for each of the filter slopes (Tables A5.4 to A5.6) and plotted at each highpass cutoff frequency (Figs 5.15 to 5.17). Wave IV is not included in the analysis for the reasons discussed. However, it should be noted that it increases in amplitude as the highpass cutoff frequency increases. In fact the IV/V complex changes in morphology, as shown also by Svensson et al. (1987). Wave VI should perhaps be omitted due to difficulties in identifying the mastoid positive peak of this wave, as the waveform varied considerably between subjects. The maximum point of each curve represents the highpass filter cutoff which would optimally record these combinations of waves.

MEAN AMPLITUDE OF JEWETT V vs. HIGH PASS CUT OFF FREQUENCY

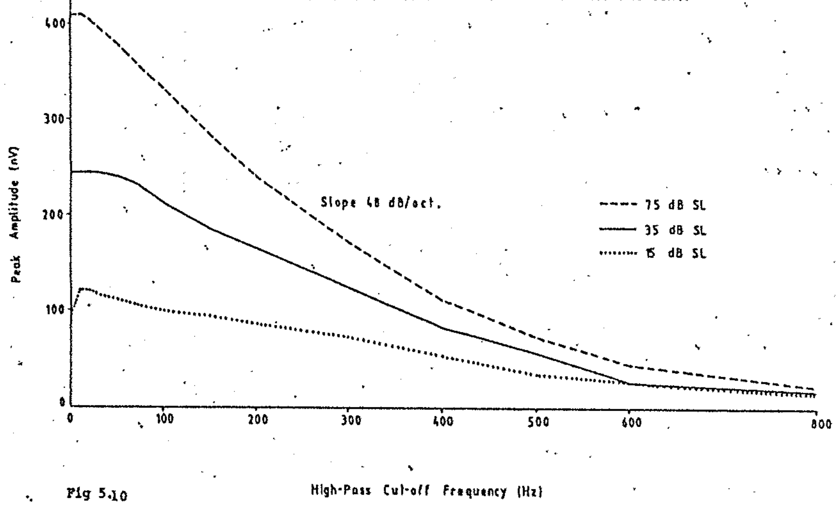


Fig 5.10

AMPLITUDE OF EACH PEAK VS. HIGH-PASS CUT OFF FREQUENCY
FILTER SLOPE 48 dB/OCTAVE

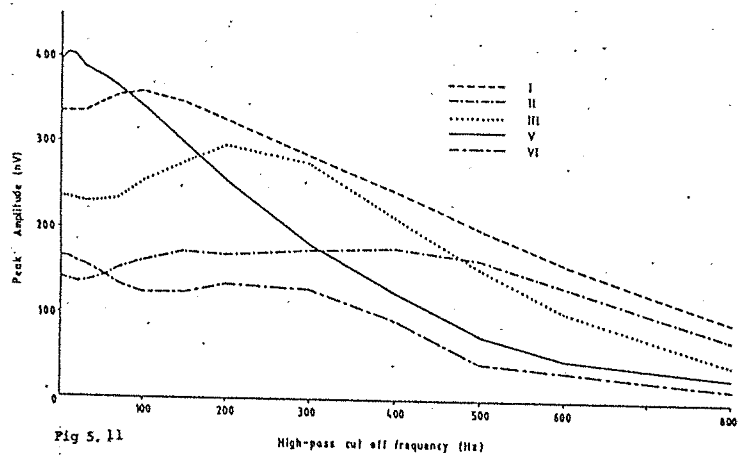


Fig 5. 11

AMPLITUDE OF EACH PEAK VS. HIGH-PASS CUT OFF FREQUENCY
FILTER SLOPE 24 dB/OCTAVE

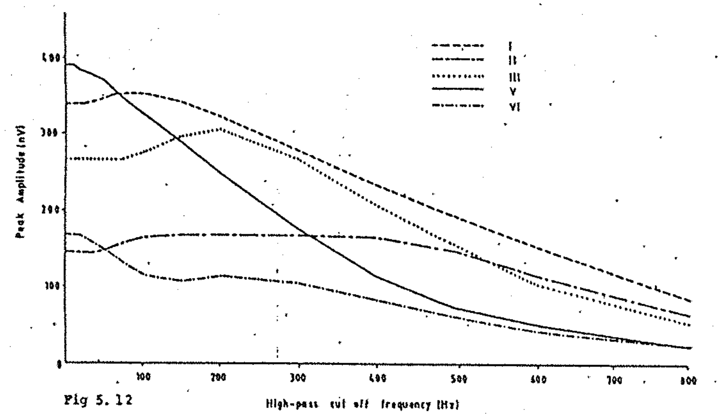


Fig 5. 12

AMPLITUDE OF EACH PEAK VS. HIGH-PASS CUT OFF FREQUENCY
FILTER SLOPE 12 dB/OCTAVE

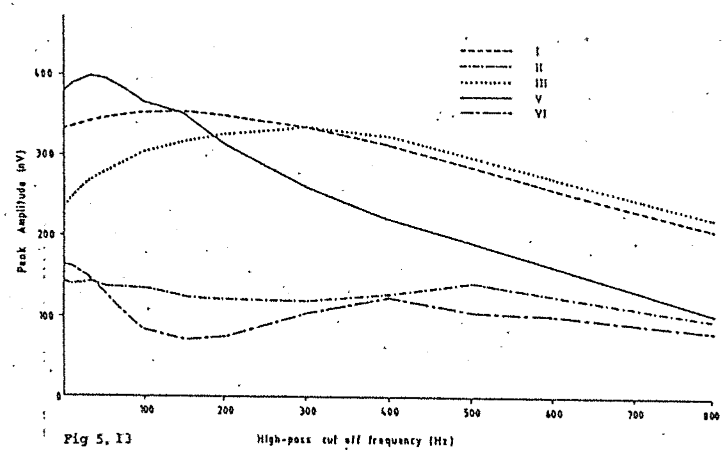


Fig 5. 13

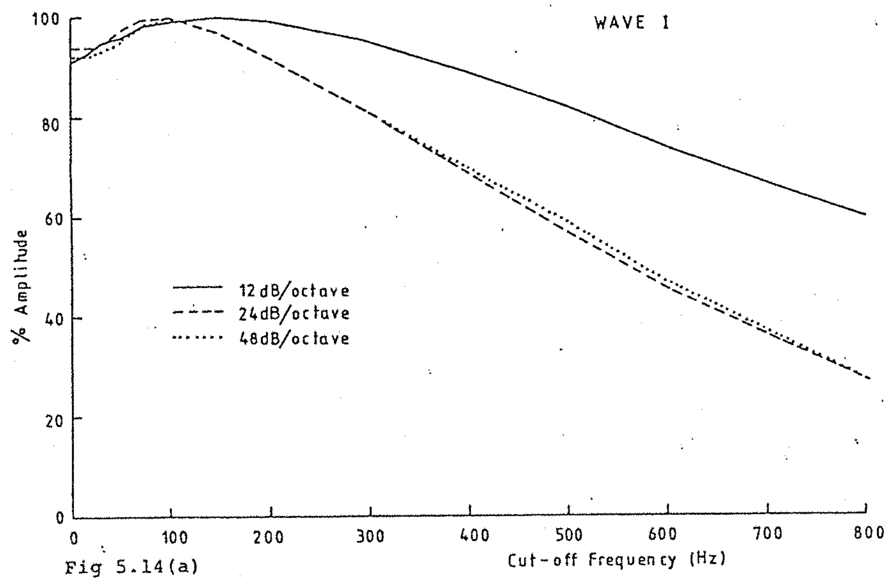


Fig 5.14(a)

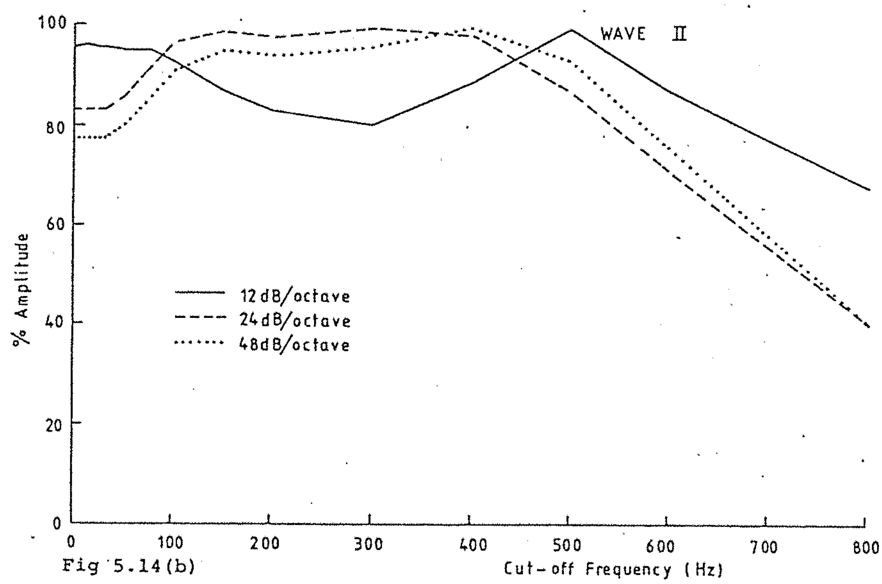


Fig 5.14(b)

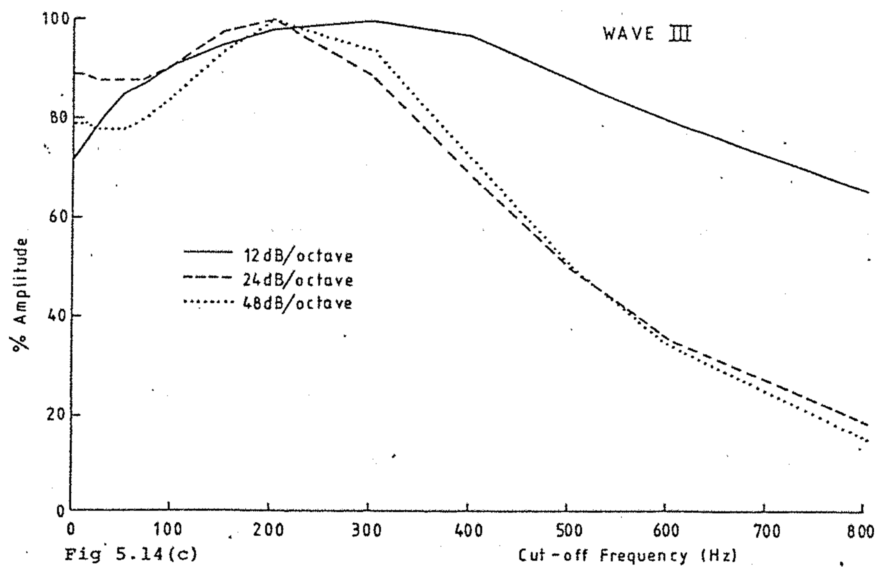


Fig 5.14(c)

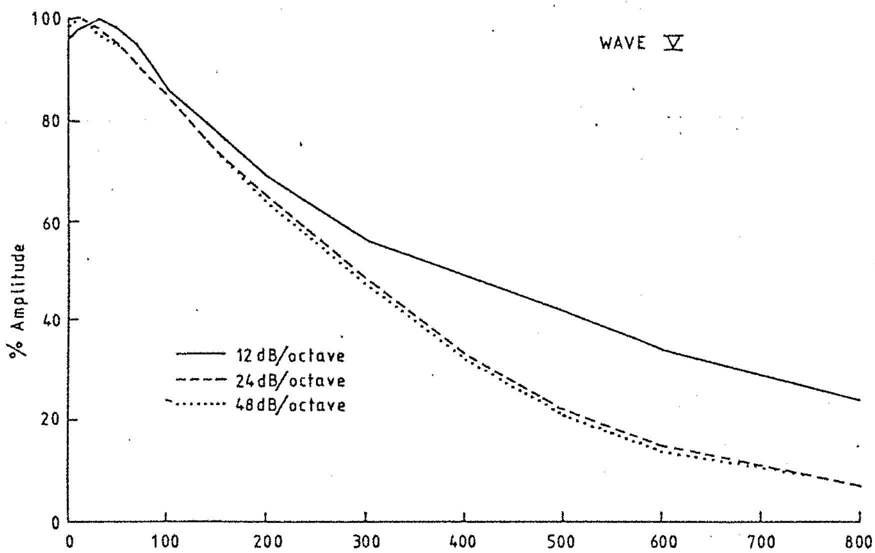


Fig 5.14(d)

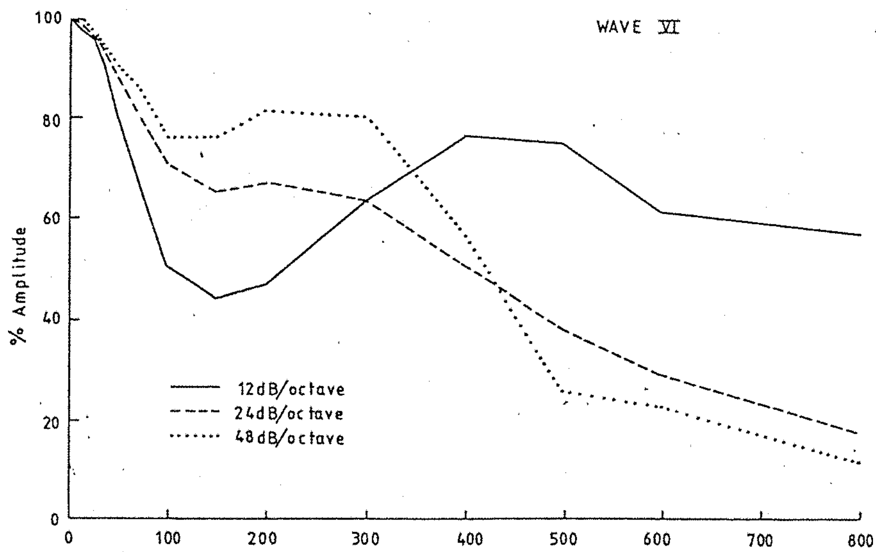


Fig 5.14(e)

Normalised Cross Products

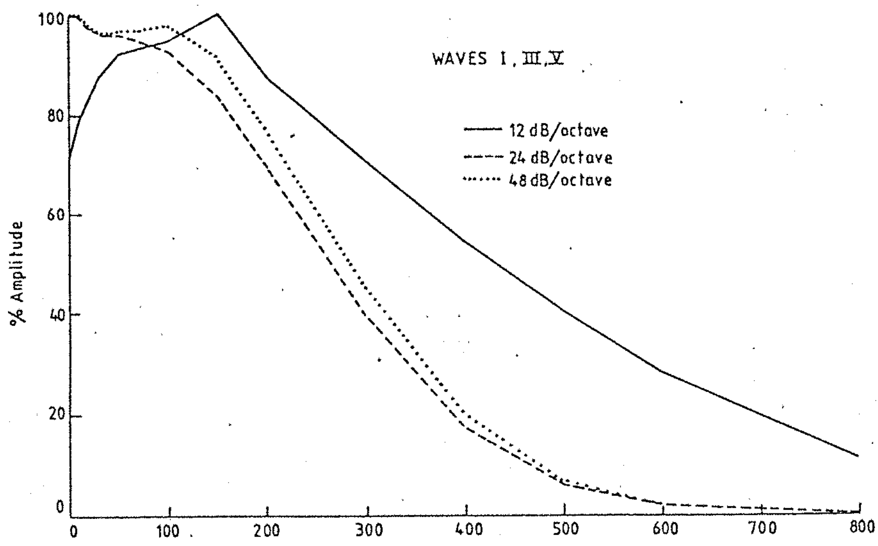


Fig 5.15

Normalised Cross Products

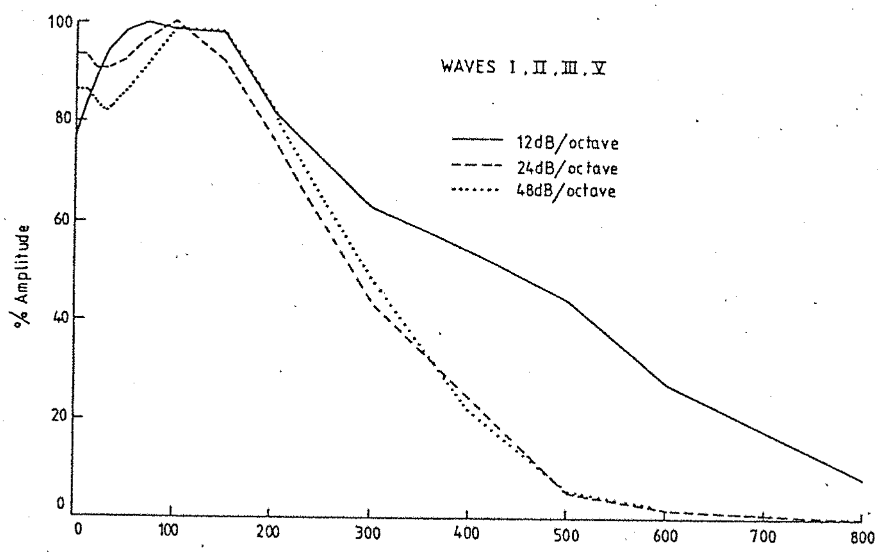


Fig 5.16

Normalised Cross Products

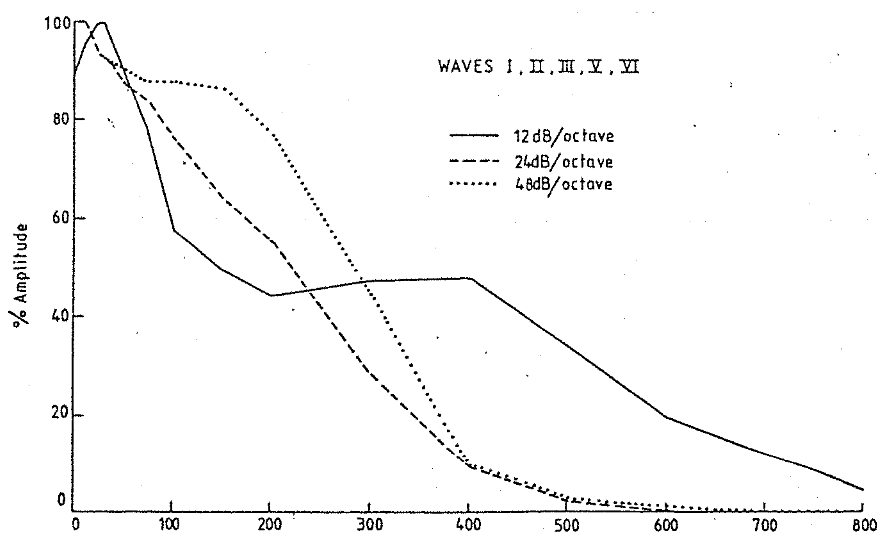


Fig 5.17

Inspection of the graphs of percentage amplitudes by cutoff frequencies of the individual peaks initially shows surprising results. Waves I, III, V and VI are each maximised at a well defined cutoff frequency. The lower filter slope results in a broader plateau on the graph, and moves the maximum to a slightly higher frequency, which would be expected due to the difference in passband at the 3 dB point, and is compatible with the observation of Osterhammel (1981), that a low slope filter setting at a highpass cutoff will permit more of the frequency spectrum to be obtained in the averaged response pattern. The spectrum of Wave II would appear to be broader, in that the effect of varying the highpass cutoff frequency between 0.10 and 0.40 kHz has little effect on the amplitude of Wave II at the higher frequency slopes. This plateau is extended into a higher frequency range by using the less steep filter slope.

Cross correlation analysis has therefore been carried out in the three conditions described. When Waves I, III and V are considered alone, it is clear that a wide band recording is optimal, except at a low filter slope of 12 dB/octave, where a higher cutoff is permissible. The addition of Wave II to the product suggests that a higher cutoff is desirable due to the higher spectral content of Wave II.

5.1.5 Discussion of filtering effects

These results indicate that, to record the ABR optimally, the filter band should be selected according to the purpose of the recording and the slope of the filters. The study also illustrates the importance of stating the recording parameters, since changes in recording parameters modify the relative ascending peak amplitudes of the response waves.

Previous investigations in this area have been concentrated in four directions:

i) Analysis of the spectral composition of the ABR (Elberling, 1979; Kevanishvilli and Aphonchenko, 1979; Osterhammel, 1981; Van Olphen, 1985; Kamath et al., 1987; Takagle et al., 1985; Hall, 1986).

ii) Determination of the effect of digital or analogue filtering on the ABR (Boston and Ainslie, 1979; Elberling, 1979; Kevanishvilli and

Aphonchenko, 1979; Osterhammel, 1981; Møller, 1983; Svensson et al., 1987).

iii) Comparison of analogue and digital filtering effects (Boston and Ainslie, 1981; Elton et al., 1984; Domico and Kavanagh, 1986).

iv) Comparison of types of analogue filter techniques (Doyle and Hyde, 1980).

Results of studies of spectral composition enable predictions of optimal filter characteristics, but there are discrepancies between studies in both areas.

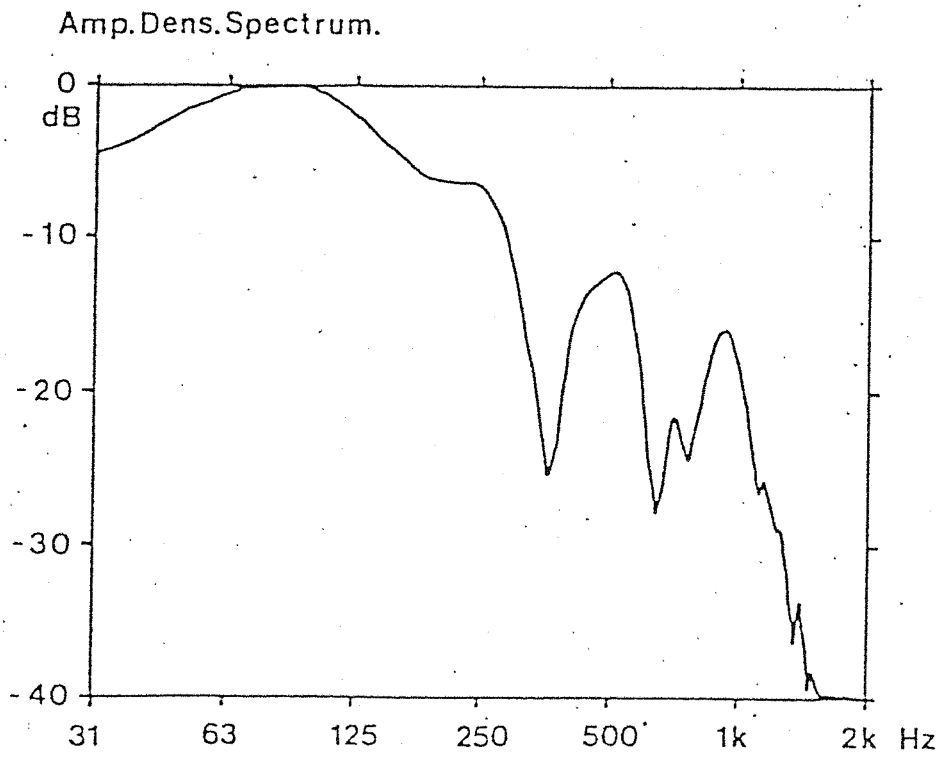
Elberling (1979) found the amplitude density spectra of the ABR, near threshold, to maximise between 0.063 and 0.125 kHz following FFT analysis. He reports the half power frequency for high intensity at 0.11 kHz and at low intensity at 0.09 kHz (Fig. 5.18). The main power of the response is below 0.25 kHz, with a lower emphasis at low intensities (Fig. 5.19). Similar results were obtained by Osterhammel (1981). He related the distinct peak at 0.5 kHz to the activity surrounding Wave V, and the third peak at 1 kHz to the contribution of Waves I-III. The spectral analysis carried out by Kevanishvilli and Aphonchenko (1979) (re-analysed by Elberling, 1979), is compatible with these findings. Kamath et al. (1987) determined three principal peaks in the spectrum at 0.17, 0.52 and 0.95 Hz respectively, with Waves III and V contributing the lowest and dominant energy components. Similar results were obtained by Hall (1987). Both these authors demonstrated the potential for examining the spectral content of the ABR in clinical studies. Thomas (1984), in his optimisation technique, describes the delayed component as having energy above 0.70 kHz and the slow background wave as having frequency components below 0.30 kHz. Wave V is described as being the result of the superimposition of these two. From the digital filtering experiments, Kevanishvilli and Aphonchenko (1979) predict the constituent components to be:

Waves I-III energy between 0.4 and 1.0 kHz
Wave III energy between 0.1 and 0.9 kHz
Waves IV-V energy between 0.1 and 0.5 kHz

Inspection of the spectrum, however, indicates that the main power of the response does lie below 0.25 kHz. The present study yielded results which are compatible with this. Waves I, V and VI are maximally recorded, reflecting maximum energy below 0.2 kHz; Wave III lies between 0.1 and 0.3 kHz and Wave II appears to have a broader spectrum. Urbach and Pratt (1986) also used a digital filtering technique to examine the components of the total waveform. They employed three shaped bandpass filters to determine three frequency peaks, approximately consistent with the findings in the spectral analysis studies. In summary, there is agreement about the spectral composition of the ABR, but the allocation of peak contributions to this is not clear.

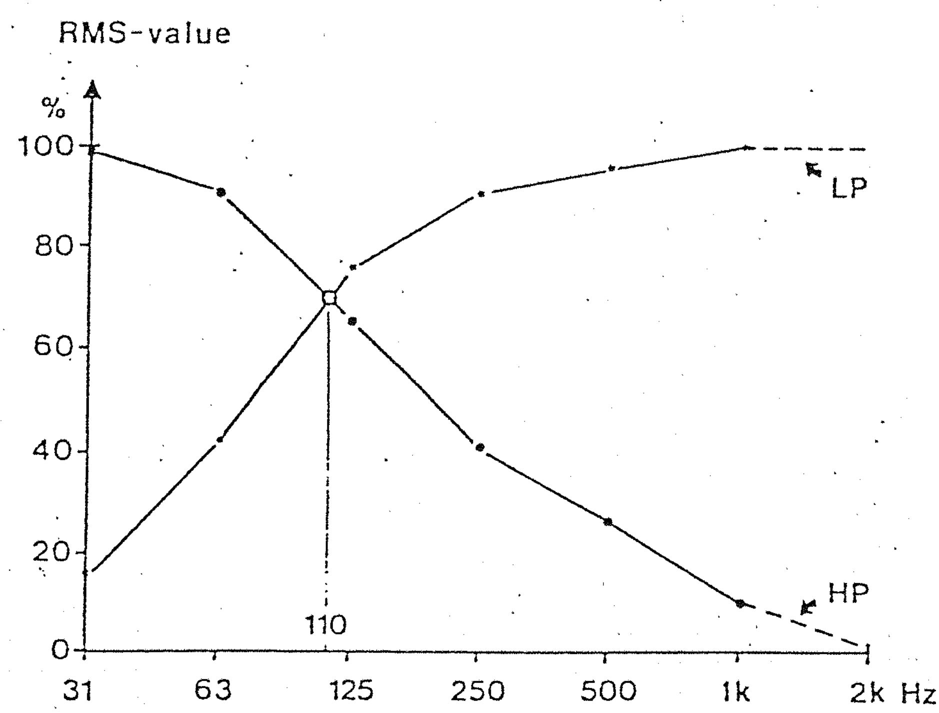
Looking to the practical implications of digital filtering studies, Kevanishvilli and Aphonchenko (1979) propose highpass filtering above 0.08 kHz. They note that filtering up to 0.05 kHz did not affect the amplitude of response. This is contrary to the findings of this study which are more in accord with the results of Terkildson et al. (1975). These authors did not find the amplitudes of Waves I and V to be affected by cutoff frequencies from 0.05 to 0.08 kHz. This study finds Wave V to be reduced by 5-10% between 0.05 kHz and 0.07 kHz highpass cutoff (slope of 48 dB/octave) and Wave I to have no measured energy in this range, so that it is not affected by a cutoff of 0.08 kHz.

Comparison of digital and analogue filtering techniques leaves no doubt that the former is the preferred method, because of the reduced resulting waveform distortion. However, a general purpose digital computer is required, and is expensive, although there is now a tendency for packages to be available with some commercial evoked potential systems. Whichever technique is used, the filter characteristics must be carefully chosen and clearly stated for both cutoff frequency and slope. If digital filters are available, a relatively steep slope may be used, and optimal frequency cutoff chosen as illustrated here. Higher cutoff frequencies may be used, as latency changes are not introduced and, as shown here, the individual waves are not defined at high cutoff frequencies, when the slow wave activity is excluded. If analogue filters are to be used, it is preferable to use a lower slope, say 6 dB/octave, for the highpass filter, to reduce overshoot and enable more of the low frequency spectrum to be retained. The main purpose of the lowpass filter is to prevent aliasing errors and to present a smooth waveform, and often a steeper slope is used for this filter. Below 0.10 kHz, waveform distortion due to the analogue filter is probably insignificant (Urbach and Pratt, 1986; Svensson et al., 1987).



Amplitude density spectrum of the ABR. 0dB corresponds to the highest value of the spectrum. (Elberling, 1979)

Fig 5.18



The RMS value of differently filtered waveforms, calculated as the percentage of the RMS value of the unfiltered waveform, as a function of cut off frequency. (Elberling, 1979)

Fig 5.19

Elton et al. (1984) examined the interaction of slope (from 6 to 24 dB/octave) for both analogue and digital filters. Their digital filtering technique differed from the present study in using a digital simulation of analogue Butterworth type filters. This is achieved by repeated application of a second order recursive filter formula, and results in the digital filter having the same frequency and phase characteristics as the corresponding analogue filters (Sherg, 1982). Elton et al. inspected the whole waveform. Their observations are compatible with the present study. The effects of increasing the steepness of filter slope parallel those produced by increases in frequency.

It is apparent from this work of Elton et al., that a translation of optimal digital filter cutoff frequency values to analogue filters should be made with caution. In Fig. 5.20 the peak-to-peak measures, used by Elton et al., and comparable to this study, demonstrate the different effects of digital and analogue filtering on Waves I, III and V.

The last area described (iv) concerns studies which have examined the differences between filter types. Doyle and Hyde (1981) discuss the use of Bessel filters compared with the more commonly used Butterworth filters. Although recommended by Osterhammel (1981), because of their apparently superior phase characteristics. Doyle and Hyde found them to cause similar distortions in the highpass application. The phase characteristics are linear as a function of frequency (Osterhammel, 1981), but not in the area of interest (Doyle and Hyde, 1981). The discussion on "best" analogue filter is still unresolved and currently Butterworth remain the most commonly used.

In summary, from this study, the highpass cutoff frequencies for analysis of the whole waveform, with particular reference to peaks I, II, III and V were found to be 0.07 kHz, with a slope of 12 dB/octave and 0.10 kHz with slopes of 24 and 48 dB/octave. Where Wave V only is to be of interest, then as low a cutoff slope as possible should be used, with slopes of 24 and 48 dB/octave. With a slope of 12 dB/octave, a slightly higher cutoff frequency may be used (0.5 kHz).

Predictions of the energy in various waveform peaks, based on these results, are comparable with other studies and on spectral analysis of the waveform. From comparative studies of analogue and digital recording, it is apparent

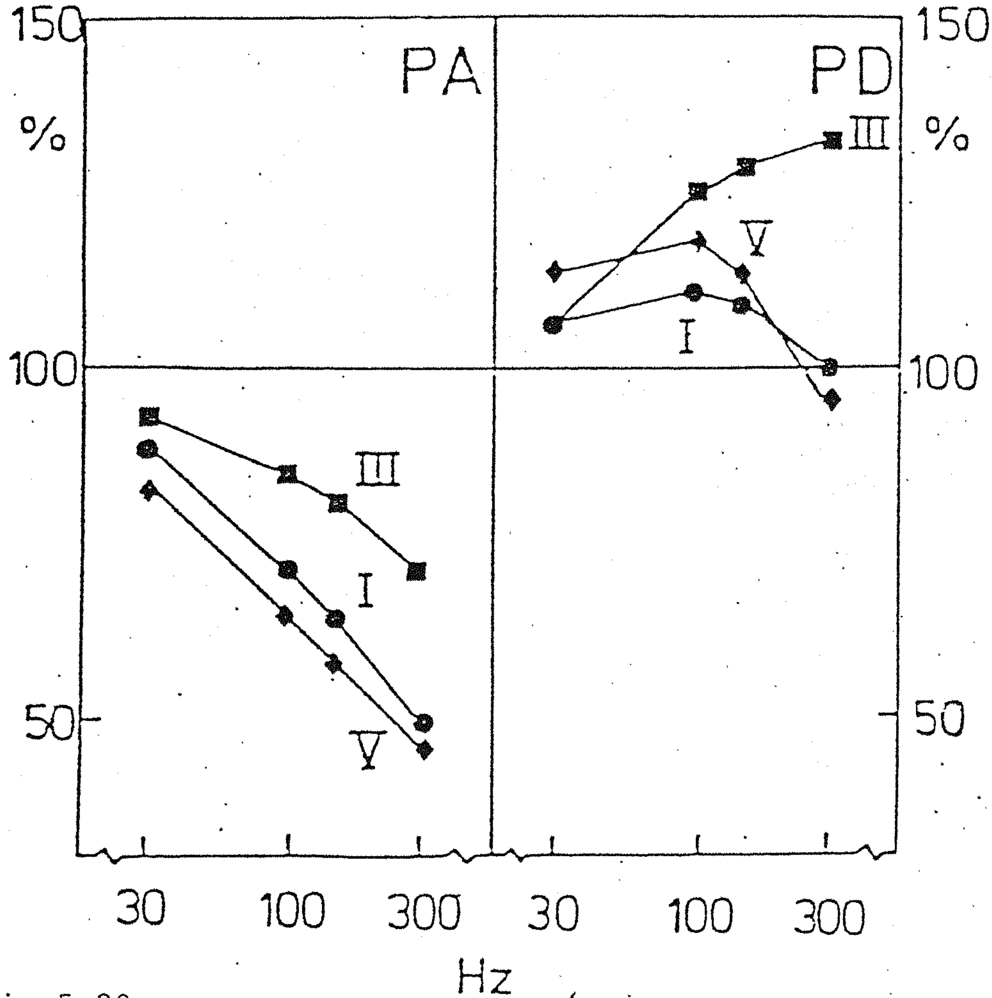


Fig 5.20

Mean ABR measures of waves I, III and V. The peak +. peak amplitudes are shown as properties of the wide band recorded signal (Elton et al, 1984).

that caution must be used in extrapolation of these results to recordings of the ABR through analogue filters, but the results may be applied to studies below 0.10 kHz with clinical acceptability. Further experimentation is needed in these areas to obtain data which directly compare the results with analogue settings. Predictions on relative amplitudes, obtained with various cutoff filters, may be made for application in the main study, in the frequency range of interest.

5.2 EXPERIMENT 2

CHARACTERISTICS OF THE ABR AND MLR IN A NORMAL POPULATION

The instrumentation to be used in the main study was assembled by technical staff at ISVR and had not been used for previous clinical or experimental work. A physical calibration had to be carried out prior to the main study. An extended normative study was then carried out to establish data values in a normal population against which the experimental group could be compared. This was necessary as normative data for other instrumentation with differing stimulating and recording characteristics could not be used as a reference against the clinical population. Specific interest is focused on the derivation of latency and amplitude intensity functions. A quantatitive description of some of the sensitised tests of brainstem function will be provided. Clinical cases of patients with known aetiologies will also be examined in this section.

The aims of the preliminary normative study were to:

a) Establish normative latency and peak-to-peak amplitude recordings for the ABR and MLR at a fixed stimulus intensity

b) Establish normal parameters for the principal peaks in the ABR and MLR waveform, for a range of stimulus intensities to near threshold

c) Correlate the threshold of the ABR and the MLR with behavioural thresholds.

In each case, optimal recording conditions as determined in the earlier experiment on recording parameters were used.

Measures were made with stimuli presented with reference to a normal reference zero (HL) and presented with reference to the subject's own threshold. This was to establish a normal reference ABR at a range of fixed intensities with which the clinical cases could be compared, and to establish a normal latency-intensity and amplitude-intensity function with reference to individual thresholds.

5.2.1 Experimental procedure

5.2.1.1 Instrumentation

Details of the components of the instrumentation are described below. The general structure and layout is as in the block diagram showing the apparatus used in Experiment 1 (Fig 5.5). Details of the instrumentation used in Experiment 2 are given in Appendix 1. The apparatus was located in a quiet room in University Wing of Southampton General Hospital. The subjects were tested supine on a couch in an electrically screened (a mesh cage) and sound-treated booth. The pre-amplifiers were located near the patient's head and all other instrumentation was outside the booth. The subject was viewed via a closed circuit camera as the window was obscured with the electrical shielding.

5.2.1.2 Stimulus and recording parameters

Broad band click stimuli of alternating polarity and 100 μs duration were presented monaurally through μ metal screened TDH-49 headphones, at rates of 9.1 and 16.6 s^{-1} (for easy comparison with other studies, these will be referred to as rates of 10 and 20 s^{-1} in the following text). The stimulus was a 0.10 μs alternating rectangular pulse. The electrical signal and the time history of the acoustical waveform are shown in Figure 5.21a. The power spectrum is shown in Figure 5.21b. The data was collected as for the previous experiment and analysed in the same way.

Stimulus intensity was calibrated by the conventional technique of comparison with a pure tone at 1 kHz. Click stimuli were transduced in the normal way through the headphone and converted to an electrical signal in a Brüel and Kjær coupler, Type 4152. The amplitude of a 2 kHz tone (5/200/5) was established on an oscilloscope (Tektronix type 555). The

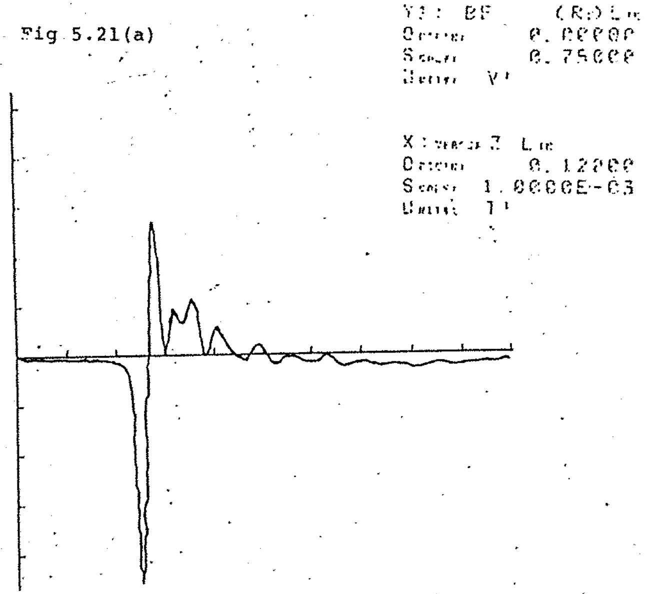


Fig 5.21(a)

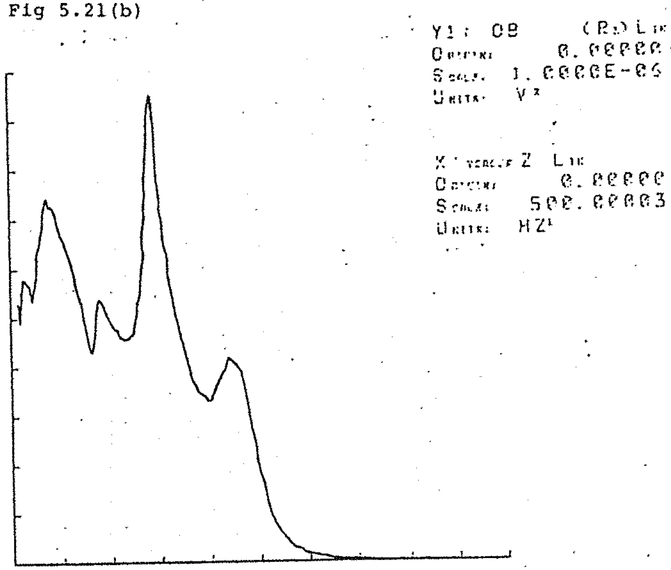


Fig 5.21(b)

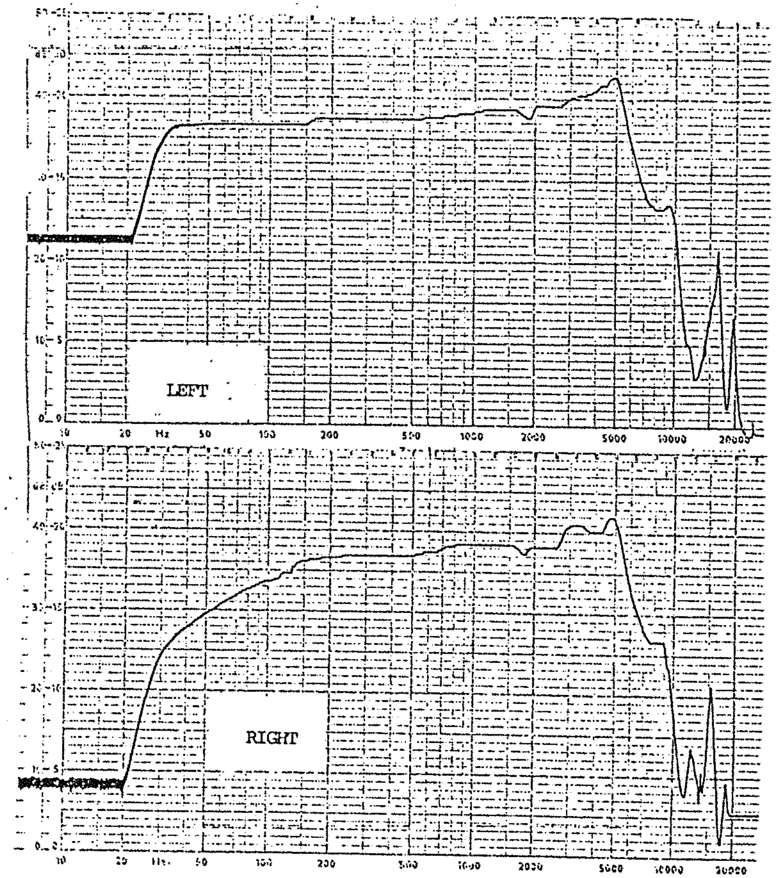


Fig 5.21(c) Frequency response of screened TDH-49 headphones.

amplitude of a chain of click stimuli at constant intensity was matched in amplitude with the 2 kHz tone to establish the equivalent click level. The equivalent sound pressure level of a 60 dB click on the stimulus generator dial was found to be 93 dB SPL, through both headphones. The subjective calibration showed this to be equivalent to 55 dB nHL. The frequency response of the screened phones was checked, as described in chapter 4, and the response is shown in Figure 5.21c.

Recording and stimulating parameters

	ABR	MLR
Recording bandwidth	0.02 and 0.10 kHz to 3.0 kHz	0.015 to 0.200 kHz
Filter slope	48 dB/octave	
Recording window	24.58 ms	60 ms
Auditory stimulus	100 μs click	
Samples	2048	512
Stimulus rate	9.1 and 16.6 s^{-1}	9.1 s^{-1}

Two channel buffered averaging was carried out in each case.

5.2.1.3 Subjects

Five male and five female subjects took part in the experiment. Their ages ranged from 22 to 29 years (mean 24.5). All were considered otologically normal, having no known history, or indication of ear disease, and appeared normal under otoscopic examination. All subjects had a bilateral audiometric configuration which did not exceed 15 dB at any frequency and did not differ by more than 10 dB at any frequency. Middle ear function, as described by tympanometry and acoustic reflex measures, was normal.

5.2.1.4 Method

Each subject was required to attend for two sessions, in order to complete the data collection with the subjects in a relaxed state, this being the optimum condition for ABR and MLR recordings. Following their otological and audiological examination, each subject was prepared for the ep recording. The electrode configuration used was as follows: Vertex (C_z) referred to ipsilateral mastoid (M_1) and contralateral mastoid (M_2). A common forehead ground electrode was used. Electrode impedances were always maintained below 2 k ohms, and this was checked at the beginning, midway, and end of each recording session.

The subject's skin was prepared by rubbing with alcohol and abrading the skin slightly with Bentonite electrode paste. The electrodes were applied with the Bentonite paste and secured with tape at the mastoids and gauze at the vertex. The subjects were instructed to lie on the couch, with their eyes closed, and to be as relaxed as possible. Special attention was given to ensuring minimum neck tension. The lights were dimmed in the test booth.

Subjective thresholds to the click stimulus were determined using a modified Hughson Westlake procedure, the patient responding to the stimulus via a patient response switch.

Two channel ep recordings were made in response to the stimulus intensities listed below, and the resultant traces were printed immediately. Latency measures were made from the screen trace, using the cursors, and marked on the hard copy record. Amplitude measures were later calculated from the hard copy record.

<u>ABR</u>

1) Three runs each of 2048 stimuli at 10 s^{-1} and 80 dB re nHL to the left ear. Recording bandwidth 0.10 - 3 kHz.

2) Three runs each of 2048 stimuli at 10 s^{-1} and 80 dB re nHL to the right ear. Recording bandwidth 0.10 - 3 kHz.

3) Three runs each of 2048 stimuli at 10 s^{-1} and 80 dB re nHL presented binaurally. Recording bandwidth 0.10 - 3 kHz.

4) Two runs of 2048 stimuli at 20 s^{-1} at each of 70, 50, 30,and 20 dB re nHL and then in 5 dB increments to response threshold. These were presented in descending order of stimulus intensity, to one ear only, using a random block design. Recording bandwidth 0.02 - 3 kHz.

5) Two runs of 2048 stimuli at 10 s^{-1} at each of 70, 60, 50, 40, 30 and 20 dB re subjective threshold (i.e. sensation level, SL), presented in a completely randomised factorial design to one ear only. Recording bandwidth 0.1 - 3 kHz.

MLR

6) One run of 512 stimuli at 10 s^{-1} at each of 80, 60, 40 and 20 dB re nHL and then in 5 dB increments to response threshold. These were presented in descending order of intensity. Recording bandwidth 0.025 - 0.175 kHz

Wide band noise masking was presented to the contralateral ear at (Stimulus level- 30) dB in each condition.

Conditions 1, 2, 3 and 4 (ABR) were presented in session 1. Conditions 5 (ABR) and 6 (MLR) were presented in session 2. For the ABR recordings, different filter settings were used for the study of the whole waveform (Conditions 1, 2 and 5) and for the threshold study (Condition 4), as indicated. This followed from the findings of the earlier experiment on recording parameters, in which the optimum recording filter bandwidths were found to differ for optimal recording of Wave V and for a composite of the whole waveform.

Buffered averaging ensured that response averaging ceased in the event of excessive myogenic activity. Two male subjects were rejected, as they were unable to relax sufficiently for clear recordings to be made.

5.2.2 Results of Normal Data Study

The following aspects of the data are examined from the ABR and the MLR records:

5.2.2.1 Measurements made from ABR and MLR data

5.2.2.2 Statistical summaries of data

5.2.2.3 Comparison of monaural recordings - ABR

5.2.2.4 Contralateral versus ipsilateral records - ABR

5.2.2.5 Binaural effects - ABR

5.2.2.6 Gender differences - ABR

5.2.2.7 Intensity effects - ABR

5.2.2.8 Rate effects - ABR

5.2.2.9 Middle latency responses

5.2.2.10 Contralateral versus ipsilateral recordings - MLR

5.2.2.11 Gender effects - MLR

5.2.2.12 Intensity effects - MLR

5.2.2.1 Measurements made from ABR and MLR data

Condition 1) ipsi; latencies and peak-to-peak amplitudes of peaks I - VI
contra; latencies and peak-to-peak amplitudes of peaks II - VI

Condition 2) ipsi; latencies and peak-to-peak amplitudes of peaks I - VI
contra; latencies and peak-to-peak amplitudes of peaks II - VI

Condition 3) left; latencies and peak-to-peak amplitudes of peaks I - VI
right; latencies and peak-to-peak amplitudes of peaks I - VI

Condition 4) Latencies and peak-to-peak amplitudes of each identifiable peak.
It is implicit that peak V is measured to threshold.

Condition 5) Latencies and peak-to-peak amplitudes of each identifiable peak.
It is implicit that peak V is measured to threshold.

Condition 6) ipsi; latencies and peak-to-peak amplitudes of Po-Na-Pa-Nb
contra; latencies and peak-to-peak amplitudes of Po-Na-Pa-Nb

5.2.2.2 Statistical summaries of data

Thornton (1975) did not find there to be significant session effects on repeated measures, so the data collected in the two sessions will be treated as one data pool. This has recently been confirmed from stimuli presented at the rates used in this study by Zasky et al. (1987).

The normal data study is summarised in a series of tables, in Appendix 5. The results do not include data from patients who showed excessive muscle activity, where the neurological response was obliterated. The wave shape was easily identified in each of the subjects reported here. No prominent differences in wave form morphology were observed for left and right recordings, but several differences in contralateral and ipsilateral wave morphologies were seen. Wave IV was absent in records from 2 male and 3 female subjects on ipsilateral recording. It was present in those subjects on the contralateral record. The wave shape was not affected by the rate of stimulation in any case. The waveform morphology did change with stimulation intensity changes.

The ABR latency data on normal subjects recorded in several other laboratories is shown in Table 5.3. The values shown are for ipsilateral, monaural recordings only. It can be seen that the absolute latency values, and the inter-peak latencies recorded in this study, are similar to those found in other laboratories. As discussed earlier, differences in inter laboratory studies exist due to the differences in recording and stimulating conditions, and to differences in population variables. Data in this table have been reported to two significant figures only, and additional calculations have been carried out as indicated. A similar table of amplitude values has not been compiled due to an insufficiency of data. Amplitude ratios were examined and are comparable with the 1.50 value for normals of Musiek et al. (1984).

A composite waveform of the normal, ipsilateral response has been compiled and is shown in Figure 5.22. An example of a normal waveform recorded from one subject is in Figure 5.23. Tables of calculations are recorded in Appendices 5, 6 and 7.

Analyses of variance were carried out to examine treatment and subject effects. To simplify the treatment, only the results of left ear stimulation were used. In summary, these results showed the response to be stable within subjects, between trials, with greater subject variance, $p<0.01$. There were no significant overall subject/trial effects. These results are summarised in Tables A5.49 and A5.50.

5.2.2.3 Comparison of monaural recordings - ABR

To examine for intra-aural recording differences, Student's t-test (henceforth termed 'the t-test') for independent measures was carried out on the left and right, ipsilateral and contralateral, monaural latency and amplitude values. Summary tables are included in Appendix 6.. The latency and amplitude values recorded to left and right monaural stimulation were not found to be different at a significance level of $p<0.05$ (Table A5.51).

Table 5.3

Normal Data from Several Laboratories

Laboratory	Stimulus Intensity (dB SL)	Filter Setting (kHz)	Wave latency (ms) I	II	III	IV	V	I-III	III-V	I-V
Jewett & Williston (1971)	60-75	0.01-10	1.5	2.6	3.5	4.3	5.3	2.0	1.8	3.8*
Lev & Sohmer (1972)	65	0.25-5	1.5	2.5	3.5		5.0	2.0	1.5	3.5*
Picton et al. (1974)	60	0.01-3	1.5	2.6	3.8	5.0	5.8	2.3	2.0	4.3*
Starr & Achor (1975)	65	0.10-3	1.6	2.8	3.8	4.8	5.5	2.2	1.8	3.9*
Stockard & Rossiter (1977)	60	0.10-3	1.9	3.0	4.1	5.2	5.9	2.1	1.9	4.0
Rosenhamer et al. (1978)	60	0.18-4.5	1.7	2.9	3.9	5.2	5.9	2.3	2.0	4.3
Row (1978)	60	0.10-3	1.9	2.9	3.8	5.1	5.8	2.0	2.0	3.9
Gilroy & Lynn (1978)	75	0.15-3	1.6	2.7	3.6	4.7	5.4	2.1	2.1	3.9
Beagley & Sheldrake (1978)	70	0.25-3.2	2.1	3.3	4.3	5.3	6.1	2.2	1.8	4.0
Chiappa et al. (1979)	60	0.10-3	1.7	2.8	3.9	5.1	5.7	2.1	1.9	4.0
Bergholtz (1981)	65	?	1.8	2.9	4.0	5.2	5.9	2.2	1.9	4.1*
Houston & McClelland (1985)	70	0.20-2								3.9
Scharwtz & Berry (1985)	75	0.75-1.5	1.7	2.9	3.8	5.0	5.7	2.1	1.9	4.0
This study	75	0.10-3.5	1.7	2.8	3.8	5.0	5.6	2.1	1.8	4.0

*interpeak latencies not cited in original

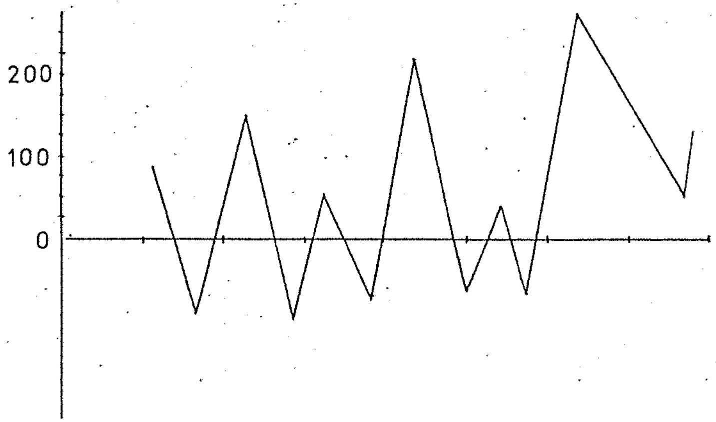


Fig 5.22 Composite ABR based on the mean of 12 normal subjects

Latencies

	I	a	II	b	III	c	IV	d	V	e	VI	f
mean	1.67	2.20	2.54	3.15	3.81	4.25	5.04	5.23	5.39	6.40	7.70	7.81
s.d.	0.14	0.15	0.88	0.16	0.26	0.17	0.18	0.22	0.12	0.18	0.19	0.05

Peak-to-peak amplitudes

	I-a	a-II	II-b	b-III	III-c	c-IV	IV-d	d-V	V-e	e-VI	VI-f
mean	240	247	154	140	302	304	115	121	354	257	84
s.d.	83	81	74	67	104	93	90	102	132	112	52

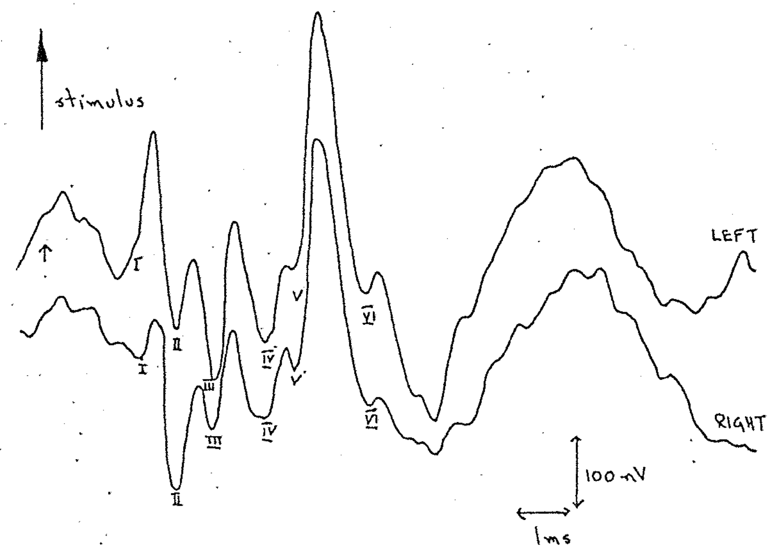


Fig 5.23 Example of a normal ABR to left ear stimulation. Recorded at 80dBnHL 10 s^{-1}, .01-3kHz.

5.2.2.4 Contralateral versus ipsilateral records - ABR

Comparison of the simultaneously measured ipsilateral and contralateral records, using the t-test for related measures, showed significant differences between the peak latencies. The magnitudes of the differences are recorded in Table A5.52. The contralaterally recorded Wave I could only be measured in 33% of cases, and so has been excluded from the analysis. Wave IV was present consistently on contralateral recording, but was not consistently recorded in the ipsilateral data of two male and three female subjects. Wave IV has therefore also been omitted from the statistical analysis. The differences in ipsilateral and contralateral wave latencies were not all in the same direction. Waves II and III, recorded ipsilaterally, lead the contralateral records. Waves V and VI , recorded ipsilaterally, lag the contralateral records. The difference is greater for wave II in female than in male subjects, and is greater for Wave III for male versus female subjects. The ipsilaterally recorded III-V interval is less than the contralaterally recorded value, and the difference is more marked in male subjects. An example of the ipsi/contra effect is shown in Figure A5.1. Mean differences are reported in Table A5.53.

Significant differences in amplitude values were also found on comparison of ipsilateral and contralateral records. The significance levels are reported in Table A5.54 and the differences in the mean amplitude values are reported in Table A5.55. This was most marked for Wave III, which was approximately doubled on the ipsilateral record in comparison with the contralateral record. The contralateral Wave V was increased by approximately 25% in comparison with the ipsilateral recording. A small increase in amplitude was observed for Wave VI. However, Wave II appeared slightly larger on contralateral records than on ipsilateral records.

5.2.2.5 Binaural effects - ABR

The results of the comparison of binaural and monaural stimulation are summarised in Table A5.56, in terms of the significance of the F results. It can be seen that only Wave V is significantly different in amplitude in the binaural condition, and that there are no significant latency effects. The differences in the mean amplitude values are reported in Table A5.57. The summation effect led to increases in amplitude of 22% for male subjects, and 30% for female subjects (monaural : binaural amplitude ratios of 0.78 and 0.70 respectively). These data agree with the published findings that the binaural effect is predominant at Wave V.

Comparison of left and right records to binaural stimulation did not show a significant difference in latency or amplitude, using the t-test for related measures (Data summary in Appendix 7.). An example of the differences in ABR records from one subject to monaural and binaural stimulation is shown in Figure A5.2.

5.5.2.6 Gender differences - ABR

Left and right data were combined and the t-test again applied to examine for gender differences. The latency values were found to be significantly longer in males than in females, at the p<.001 level of confidence. This effect was less marked in the later waves. The results are summarised in Table A5.58, and the t-test summary is given in Appendix 4. There were no significant amplitude effects. The mean ipsilateral latency of Wave I at 80 dB nHL differed in male and female subjects by 0.23 ms, with male subjects demonstrating the longer latencies. The difference in Wave V values was less at 0.21 ms (calculated from all values of Wave V). The mean difference in central transmission time between male and female subjects was 0.06 ms on ipsilateral stimulation, and including all values of Wave V. For the cases where Wave IV was absent, the difference in male/female I-V interval was 0.08 ms and for the cases where Wave IV was present only, the difference was 0.06 ms. There was no significant difference demonstrated between the standard deviations of male and female subjects. Interestingly, the male /female Wave V latency difference was less marked, and not significant for contralateral recordings. The reduced central conduction time was more marked using binaural stimulation; whilst the male/female Wave I-V interval was the same as that found on monaural stimulation, the Wave V latency difference was larger at 0.23 ms. A summary of the mean differences is given in Table A5.59.

5.2.2.7 Intensity Effects - ABR

Records of an individual subject's ABR response to a range of intensities are shown in Figures A5.3. A5.4, A5.5 and A5.6. Ipsilateral and contralateral responses are shown for both recording conditions.

Wave V appears as the most robust of the waves, and is tracked to threshold in condition 4. The mean ABR threshold determined in this way is 5.41 dB (s.d. 2.57), compared with a mean behavioural threshold to clicks of 2.92 dB (s.d. 2.57), a difference of 2.49 dB. The Pearson Product Moment correlation of the two threshold measures is 0.49 (Table 5.4). The threshold of the ABR was also compared to the pure tone thresholds at 1, 2, 4 and 8 kHz and was found to correlate maximally with the threshold at 2 kHz ($r = 0.86$).

In both stimulating and recording conditions, the latency of all the waves increased with decreasing intensity, and the amplitude decreased with increasing intensity. Latency and amplitude functions for both conditions are shown in Figures A5.7 to A5.14. For clarity, only the first five waves have been graphed.

The slopes of the latency-intensity functions are as follows;

At 20 s^{-1}, 0.02 to 3 kHz bandpass, the slope is 0.034 (y intercept, 8.222).
At 10 s^{-1}, 0.10 to 3 kHz bandpass, the slope is 0.030 (y intercept, 7.909).

Comparison of these functions, using the t-test for related measures, showed no significant difference ($p<0.01$) between latency measures at the same intensities ($t = 1.1176$).

The latency-intensity functions of the individual peaks do not follow parallel courses, resulting in inter-peak intervals which are not constant across intensities. In condition 5, the mean I-V interval decreases by 0.58 ms. The change was as large as 0.9 ms for two subjects. The amplitude effects are less meaningful because of the wide variability in the data. The inter-peak latencies (IPL's) are plotted against the stimulus presentation intensities in Figures A5.15 and A5.16. These graphs are derived from the means of the individual IPL's. The graphs of data derived from the means of the absolute peak latency values are presented in Fig. A5.17.

The slopes of the amplitude-intensity functions are as follows;
At 20 s^{-1}, 0.02 to 3 kHz bandpass, the slope is 0.24 (y intercept, -33.79).
At 10 s^{-1}, 0.10 to 3 kHz bandpass, the slope is 0.30 (y intercept, -39.74).

Table 5.4 Threshold Comparisons (Dial Readings)

	Behavioural Threshold (clicks)	ABR Threshold	MLR Threshold
mean	2.92	5.41	9.67
s.d.	2.57	2.57	3.96

Click Threshold Differences

ABR - Behavl.	MLR - Behavl.	MLR - ABR
2.50	3.77	4.17
2.60	6.25	3.59

Correlation of thresholds

(using Pearsons Product-MomentCorrelation Coefficient)

Behavioural thresholds to pure tones and the ABR

1kHz; r = 0.61   2kHz; r = 0.86;   4kHz; r = 0.80;   8kHz; r = 0.55

Behavioural threshold (2 kHz) and ABR threshold(clicks)

r = 0.86

Behavioural threshold (2 kHz) and MLR threshold(clicks)

r = 0.35

ABR threshold and MLR threshold

r = 0.46

5.2.2.8 Rate effects - ABR

Some small effects of stimulus rate change were observed. The mean amplitude of Wave V was significantly ($p<0.01$) larger at the faster stimulus presentation rate, with a difference in the means of 137 nV. The means of the I-V interpeak intervals differed by 0.15 ms.

5.2.2.9 Middle latency responses

The normal data values generated from this study are compared with those of other studies in Table 5.5. It can be seen that there is a wide range of values listed, due to the strong effects described earlier of different recording conditions and stimulating conditions, and due to subject effects. In agreement with Picton et al. (1974) and Ozdamer and Kraus (1983), Na and Pa were found to be the most easily identifiable waves. Na was associated with the least subject variance. The peak, Nb, was large and distorted in two subjects, presumably due to myogenic contamination to the response from the temporalis reflex. Examples of two normal MLR records, recorded sequentially, are shown in Figure 5.24 (page 236).

Table 5.5 Table of normal MLR data (monaural, ipsilateral recordings) from several laboratories

Laboratory	Filter Setting (kHz)	Wave latency (ms)			
		Po	Na	Pa	Nb
Goldstein, 1967	0-0.50 (6 dB/oct)		20.4	31.4	46.6
Madell & Goldstein, 1972	0.05-0.15 (6 dB/oct)	11.3	20.8	32.4	46.5
Goldstein, 1971	0.05-0.15 (6 dB/oct)	13.2	22.7	34.3	49.1
McFarlane et al. 1975	0.025-0.175	10.0	16.0	35.0	46.0
Vivion, 1976	0.025-0.175 (48 dB/oct)	10.0	16.4	26.3	35.5
Robinson and Rudge, 1977	0.08-0.25			24.0	40.0
Kileny and Shea, 1986	0.005-1.5 (12dB/oct)			28.51	

5.2.2.10 Contralateral versus ipsilateral recordings - MLR

Comparison of ipsi- and contralateral recordings showed there to be a small, but significant ($p<0.01$), laterality effect for waves Na and Pa. Na showed a tendency to be later on the contralateral side (mean 0.75 ms), and Pa to be later on the ipsilateral side (0.60 ms). The amplitude, Na-Pa, showed a small but significant increase on the contralateral side. A summary of the comparison is given in Table A5.60. The magnitude of the effects on the means of the ipsilateral and contralateral records is shown in Tables A5 61 and A5.62.

5.2.2.11 Gender effects - MLR

Small but significant gender effects were found in this study for the latencies of peaks Na and Pa and for the amplitude of Po-Na. Latency delays for male subjects in comparison with female subjects were found to be 1.43 and 2.32 ms for waves Na and Pa respectively. The statistical summary appears in Tables A5.63 and A5.64.

5.2.2.12 Intensity effects - MLR

The latency-intensity function shows there to be a reduction in amplitude with decreasing intensity. An example of this effect recorded from one normal subject is shown in Figure A5.18. The magnitude of the mean effect is diminished by the inter-subject variability. The trend is for latency to increase with decreasing intensity. On ipsilateral stimulation, the latency intensity relation was not clear for Pa, but was of the order of 3.5ms for the other waves. On contralateral stimulation, Pa was more easily recognised, and showed a definite latency-intensity relation, decreasing by 7ms over a 70 dB range. Graphs of the latency and intensity functions are shown in Figures A5.19 to A5.22. The slope of the latency-intensity function is 0.08; y-intercept 27.92.

The mean MLR threshold was determined at 9.67 dB HL. This correlates poorly with the behavioural click threshold ($r = 0.35$) and gives a mean difference of 6.75 ms (Table 5.4). It was possible to record Nb to within 10 dB HL of the click threshold for 22 ears. However, the size of this response and the results at the preceding intensity level suggest that this may arise from contamination of the neurogenic response by muscle artefact.

Pa is recorded to threshold in 23 cases, and to within 8 dB in 8 cases. The ABR and MLR thresholds correlate moderately at 0.46.

5.2.3 Discussion of the Results of the Normal Data Study

5.2.3.1 Contralateral versus ipsilateral recordings

The finding of a significant difference in contralateral and ipsilateral records, with early wave latencies leading on contralateral stimulation, and tending to lag for the later waves, is in general agreement with the findings of most other authors. The contralateral record also helped to identify doubtful peaks in the ipsilateral record, particularly the IV/V complex, as has been reported by other authors (e.g. Furune et al., 1985). It is notable that the degree of significance differs considerably between male and female subjects, although the size of the effect does not.

The findings of the present study were similar to those of Stockard et al. (1979), Hixson and Mosko (1979), Mair and Laukli (1980) and Prasher and Gibson (1980). These latter authors found the latency of Wave V, rather than Wave III, to be reduced in the contralateral record. Hughes et al. found shorter Wave II latencies and smaller Wave III and V amplitudes on the contralateral records. Stockard et al. (1979) and Hixson and Mosko (1979) reported a shorter wave III and a longer Wave V on contralateral recording. In contrast, Kevanishvilli (1980) found amplitudes to be larger and Wave V latency to be shorter in the ipsilateral record. Hashimoto et al. (1979) and Zerlin and Naunton (1976) also found similar latencies for Waves IV and V between ipsilateral and contralateral recordings.

Amplitude differences between ipsilateral and contralateral recordings were also in general agreement with the literature, although the range of results is wider than in some studies. The wide variability in results is supported by Lasky et al. (1987), who discarded amplitude measures as being of little current clinical use. No significant differences were found by Van Olphen et al (1979). Others found the contralateral Wave I to be absent (Thornton, 1975), or reduced in amplitude (e.g. Hashimoto, 1979; Barajaas, 1982) as was the case in the present study.

In summary, the discovery of a leading Wave III and a lagging Wave V, of diminished amplitude on contralateral recording of the ABR, is in agreement with several other studies. Comparison of ipsilateral and contralateral effects of clinical populations with normal difference, have not so far yielded promising information (e.g. Barajas, 1982). The physiological basis for the latency difference observed between ipsilateral and contralateral records is still not determined. It has been ascribed to differences in conduction velocity in the pathways (Prasher and Gibson, 1980a), but it is more probable that the response is generated by differently orientated segmental dipoles, giving rise to latency and amplitude differences to recording electrodes in different recording locations (Erwin, 1981). A possibility is that both mechanisms occur, the former accounting for the longer III-V separation.

5.2.3.2 ABR : Binaural effects

Binaural stimulation usually leads to a summation of the responses (Huang and Buchwald, 1978; Stockard et al., 1978b; Van Olphen, 1978). Wave V has been shown to increase in amplitude when binaural stimulation is used, by between 28 and 200%, across studies. This has also been reported as corresponding to the response equivalent of a 20 dB increase in stimulus intensity (Bergholz, 1981). The mean increase across subjects in the present study was at the lower end of this range, but there was also a wide inter-subject range. A two way analysis of variance, with repeated measures on one factor, was used to examine binaural effects in this study, in comparison with monaural and binaural response repeatability. Results were in agreement with published data (Thornton, 1975; Stockard et al., 1978; Chiappa et al., 1979; Ainslie and Boston, 1980); a significant subject effect on the latency and amplitude values of the ABR was found, reducing the strength of monaural/binaural comparison based on pooled data.

5.2.3.3 ABR : Gender Effects

The finding of a gender difference for absolute latencies of the ABR is in agreement with other published studies (e.g. Jerger and Hall, 1980; Seitz et al., 1980) but the finding of an IPL slightly greater in female than in male subjects is not (e.g. Houston and McClelland, 1985; Jerger and Hall, 1980; Thornton, 1987; Thivierge and Côté, 1987). These studies do not report a significant difference in the standard deviations of the male and female subjects. Thornton (1987), comparing the findings on gender effects from ten laboratories, indicates that the inter-gender difference is smaller (2.8 times) than the inter-lab range, and concludes that gender-dependent norms do not greatly improve the clinical detection rate of the ABR. He shows that the mean gender differences in those studies range from 0.06 to 0.27 ms for the I-V interval. He reports an inter-lab range of 0.39 ms and an inter-lab mean of 0.14 ms.

The recording, stimulation, and subject parameters in the present study most closely resemble the parameters used in Thornton's laboratory (Thornton and Colman, 1975; Thornton, 1976; Hyde et al., 1976; Lobaugh, 1980). His study reports a I-V interval difference between genders of 0.09 ms, compared with 0.06 ms from the present study. McClelland and McCrea (1979) report a value of 0.27 ms, which least resembles the results of this study, although the only major difference is a slightly wider subject age range.

The negative result for gender difference of the IPL in this study probably results from the small subject sample size and from the long Wave I latency reported in the present study from the male subjects, discussed earlier. It would appear that the Wave V absolute latency is a better comparator. It is also known that the IPL varies with stimulus sensation level. The high frequency pure tone threshold average of the male and female normal subjects differed by 7.3 dB (2, 4 and 8 kHZ) although all subjects fell within the normally defined range. This factor will contribute to the longer absolute latencies in the male subjects, with Wave I being more greatly affected thatn Wave V, and may have contaminated the study of gender differences.

The data on absolute latency differences are in closer agreement with other studies. Beagley and Sheldrake (1978), testing subjects ranging in age from 14 to 79 years, found significant male/female latency differences, favouring females. Kjær's study, on subjects from 13 to 48 years, showed significant differences for waves III to VI. Jerger and Hall (1980) tested 98 normal-hearing and 221 hearing-impaired subjects, and found consistently shorter Wave V latencies across ages. The reason for this difference is not entirely determined. Previous researches have suggested that physical size and concomitant neuroanatomical distance between various brainstem sites is the most likely reason. As females are physically smaller, even from birth, they are thought to have shorter neurological pathways, thus reducing the travelling, or conduction time, between neurological transmitter sites. If this is so females, should have faster late components. The alternative theory, discussed earlier, is that the difference relates to differing rates of neural maturity and degeneration.

Seitz et al. (1980) found that infant subjects show this gender difference, and they draw a possible association of this with the significant auditory processing advantage observed in female subjects by some laboratories. This, they suggest, has a genetic basis. They note that female subjects acquire language earlier than males, have better sound discrimination abilities and lower touch and pain thresholds than males. Morphologic asymmetry between left and right temporal lobes occurs earlier and is more evident in females than males. These suggestions are an interesting extension of ep measures, but more evidence is required.

5.2.3.4 ABR: Intensity effects

Intensity-latency effects were found, in agreement with other authors (e.g. Rowe, 1977; Stockard et al. 1979; Musiek et al., 1984) and reflect the variable contributions of more apical regions of the cochlea at moderate to high intensities to Waves I and V. The latency-intensity effects observed for Wave I were greater than for the later waves, such that the I-V interval decreased with increasing intensity. A gradual decrease of the I-V interval with intensity is in agreement with Coats (1978).

The transition, which normally occurs at 40 dB SL, and which reflects the morphologic change which occurs in the the AP with increasing intensity, was not seen in the plot of the means of the individual I-V intervals. It was more apparent when the IPL's of the mean peak latencies were examined, reducing the effect of the inter-subject variation (Fig. A5.17). Stockard et al. (1979) examined intensity effects in a group of 64 normal adult subjects. They found changes as great as 0.73 ms, compared with a greatest change of 0.94 ms (mean of 0.53ms) in this study. The trend to a reduction in amplitude with intensity reduction is in agreement with the studies listed above, although there is a less orderly relationship of amplitude-intensity than latency-intensity. This reflects the wider subject variability in amplitude measures, and the small sample size.

5.2.3.5 ABR stimulus rate and recording bandwidth effects

The stimulus rate effects observed are small and are confounded by the differing recording paraameters, and hence probably not important. Although amplitude changes were observed for Wave V, this is not of an order likely to affect response detection. Wave I did not reduce markedly in amplitude as stimulus rate was increased. A change of 0.13 ms was found in the I-V interval for a 10 s^{-1} change, which compares with the observation of Stockard et al. (1979) of a change of 0.1 ms for a 20 s^{-1} increase in stimulus rate. This increase results from an increase in the latency of Wave V with increasing click rate (Thornton and Colman, 1975; Don et al., 1977) It results from incomplete recovery of the response mechanism, in terms of the refractory period of the neural elements, changes in synaptic transmission, and the receptor adaptation or fatigue. Wave V was more clearly defined in the more wide band condition, but this was accompanied by some loss of definition of the earlier waves, and is in accordance with the, previously discussed, spectral composition of the waves.

5.2.3.6 Threshold correlations

The ABR threshold correlated optimally with a pure tone threshold of 2 kHz in normal subjects, in agreement with previous studies (e.g. Gorga et al., 1984). Since it is established that the dominant cochlear effects in the ABR response are predominantly basal, the finding of a relatively high frequency pure tone correlation is to be expected.

5.2.3.7 MLR data

The results of the present study fall within the wide range of normative values reported in the literature. Despite careful precautions, differing myogenic contributions will have contributed to the wide response variability. The variance of the latency and amplitude data was greater in males than in female subjects, and it was the author's subjective impression that the male subjects found it harder to become comfortable on the couch and to relax. As reported earlier, only male subjects had to be eliminated from the normal data sample because of exceessive myogenic activity. Myogenic contamination arises from the post auricular muscle (large negative peak at 11 to 13 ms, followed by a large positive peak at 16 - 18 ms); the temporalis muscle (large negative peak at 17 to 18 ms and a positive peak at 22 to 25 ms); the neck muscles and the frontalis muscle (with peaks in the 30 to 35ms range).

5.2.3.8 MLR - Contralateral versus ipsilateral records

Small, but significant, laterality effects were found on analysis of the MLR records. The generator sites of the MLR have not been definitively determined, as discussed earlier. Ozdamer and Kraus (1982) describe a symmetrical amplitude distribution over the vertex of Pa in normal subjects, and consider that Pa is bilaterally generated in humans (Kraus et al., 1982). Data from their study and others indicate that small changes in electrode position may affect the response amplitudes and latencies, due to multiple generating sites. This could account for the differences seen in this study.

5.2.3.9 MLR - Gender differences

The latency effects seen in this study are probably a continuation of effects observed in the ABR. The size of the effect in relation to Na and Pa is such that the use of male and female norms could be used for the childrens' study.

5.2.3.10 MLR - Stimulus intensity effects

Intensity-latency and intensity-amplitude interactions were observed, which were not the near-linear relationships seen in the ABR records. This agrees with previous studies which have shown a frequency interaction for the latency function. The result is in agreement with the early studies in this area, that the response can be recorded to threshold, with the Na-Pa-Nb complex as the most identifiable (e.g. Wolf, 1977; Mendel et al., 1977; Thornton et al., 1977; McFarland et al., 1977). The proportional amplitude-latency interaction reported there was not found in the present study, but is in agreemnet with later studies (e.g. Kraus et al., 1987a) documenting the effects of filter and rate changes.

5.2.3.11 MLR - Threshold correlation

Table 5.6

SUMMARY TABLE OF ABR RESULTS FROM NORMAL SUBJECTS

Variable	mean	s.d.	
Wave V threshold (0.02 - 3 kHz)	8.12	0.46	ms
Correlation with P.T threshold at 2 kHz	0.86		
I/O/slope; latency (0.1 - 3 kHz b.p.)	0.03		
I/O/slope; amplitude (0.1 - 3 kHz b.p.)	0.30		
I/O/slope; latency (0.02 - 3 kHz b.p.)	0.03		
I/O/slope; amplitude (0.02 - 3 kHz b.p.)	0.24		
Mon. Wave V latency (80 dBnHL)	5.61	0.27	ms
Mon. Wave V amplitude (80 dB nHL)	354.00	122.00	nV
Bin. Wave V latency (80 dBnHL)	5.77	0.21	ms
Bin. Wave V amplitude (80 dB nHL)	466.00	150.00	nV
Monaural/Binaural amplitude ratio	0.79		
I-V interpeak latency (0.1 - 3kHz)	3.95	0.25	ms
I-V interpeak latency (0.02 - 3 kHz	4.07	0.24	ms

Table 5.7

SUMMARY TABLE OF MLR RESULTS FROM NORMAL SUBJECTS

Variable	mean	s.d.	
Correlation with P.T threshold at 2 kHz	0.23		
I/O slope; latency	0.08		
Pa ipsi; latency	27.86	1.56	ms
Pa contra; latency	22.91	1.54	ms
Na-Pa ipsi; amplitude	280.00	232.00	nV
Na-Pa contra; amplitude	285.00	136.00	nV

MLR response may be recorded to within 10 DB of the admitted response, which is adequate for the main study. Threshold correlation is compatible with other findings on children (e.g. Kileny and Shea, 1986; Suzuki et al., 1987) although a greater response detectability was found than in these studies Suzuki et al. (1983a) and Kraus et al. (1985). A summary of the ABR results is given in Table 5.6, and of the MLR results in Table 5.7.

5.3 CLINICAL EXAMPLES

Recordings from cases of known pathology were made in order to have a more complete description of the ABR response behaviour, using the previously described equipment. The latency-intensity function tends to shift upwards towards longer latencies as the 4 to 8 kHz hearing loss increases, with the greatest effect at low click intensities. Thus, the curve tends to shift towards the normal at high intensities. Additionally, the Wave I-V interval tends to decrease with decreasing intensity, and to show an orderly decrease with increasing cochlear high frequency hearing loss (e.g. Coats, 1978; Keith and Greville, 1986).

Coats demonstrated the less steep latency-intensity curves recorded from retrocochlear ears, in comparison with recordings from ears with high frequency cochlear losses of similar degree. Hence, inappropriate action potential preservation may be better demonstrated at lower click intensities. Coats found a tendency towards separation of retrocochlear from cochlear or normal intensity-latency functions for both Wave V and for the I-V interval, using the entire length of the latency-intensity curve.

Whilst the clinical interpretation of this work remains useful, it is now known that the change in the I-V interval with intensity predominantly reflects cochlear processes. This was first demonstrated by Yamada et al. (1979), who investigated several types of sensory loss and found the latencies were only delayed, with respect to normal, for high frequency losses deteriorating from 2 to 3 kHz. Localised cochlear pathology has most effect at low intensities when the spread of excitation is lessened. Some effects of audiometric configuration on Wave V latency have previously been described (Coats and Martin, 1976; Gorga et al., 1985; Jerger and Mauldin, 1978; Møller and Blegvad, 1976; Rosenhamer, 1981), but there has been less attention given to the effect of cochlear processes on the inter-peak intervals (Gorga et al., 1986; Klein, 1986; Keith and Greville, 1987). The differences observed support the assumption that Wave V reflects contributions from a wide area of the basilar membrane and Wave I, more localised activity in the basal region.

The following cases are examples to illustrate the effect of cochlear and retrocochlear pathology in the ABR.

5.3.1 Experimental Procedure

Using the recording and stimulating apparatus previously described, the auditory brainstem responses were recorded from four volunteer, clinical, subjects, and the intensity-latency functions derived. Stimuli were presented at 10 or 20 s^{-1} , with recording bands of 0.1 to 3.0 kHz or 0.02 to 3.0 kHz respectively, and at intensities of 0 to 90 dB nHL.

Subjects tested were;

1) A young normal hearing subject, tested with and without his ear occluded with an ear plug to simulate a conductive loss.
2) a) A 51 year old woman with a flat unilateral hearing loss, with predominantly proven cochlear damage, thought to be the result of a head injury.
   b) A 55 year old woman with bilateral, sloping high frequency hearing loss.
3) Two patients with known brainstem lesions.

5.3.2 Results

The intensity-latency function of recordings from the normal subject are shown (Fig. 5.25) with, and without, his ear occluded. The change in audiometric threshold is indicated. The latencies recorded with ear occlusion are markedly delayed with respect to normal, but the function does not appear to mirror exactly the normal hearing curve as has been suggested by some authors. It is, however, in agreement with the results of Kavanagh and Beardsley (1979), who found that, at high intensity levels,

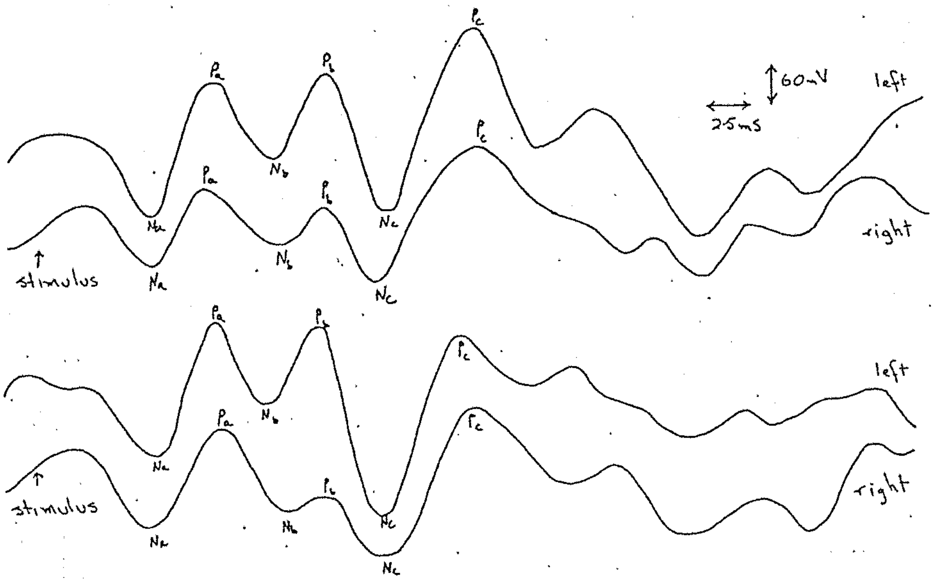


Fig 5.24 Example of 2 normal MLR records. Recorded at $10s^{-1}$ 0.025 - .175 kHz. Subject MB. (Right monaural stimulation at 75dBnHL).

Latency - intensity function recorded from a normal subject and from a subject with a simulated conductive hearing loss.

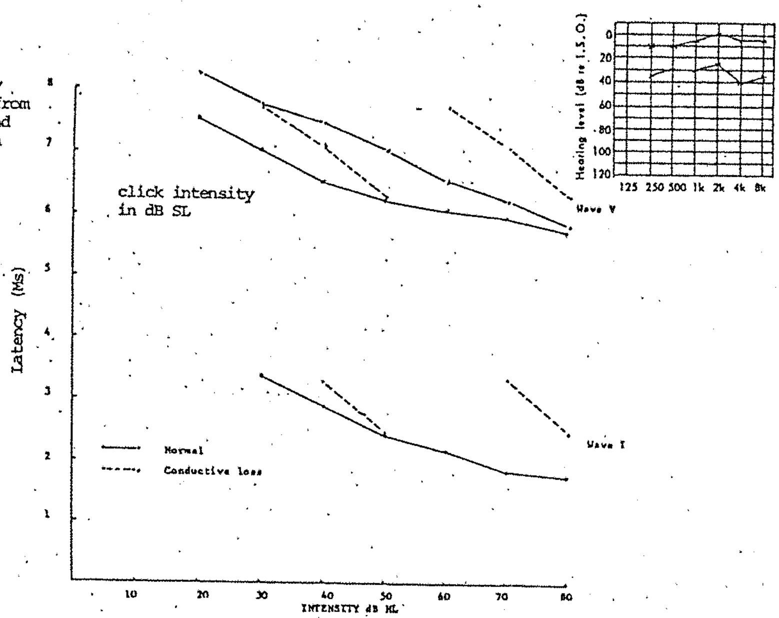


Fig 5.25

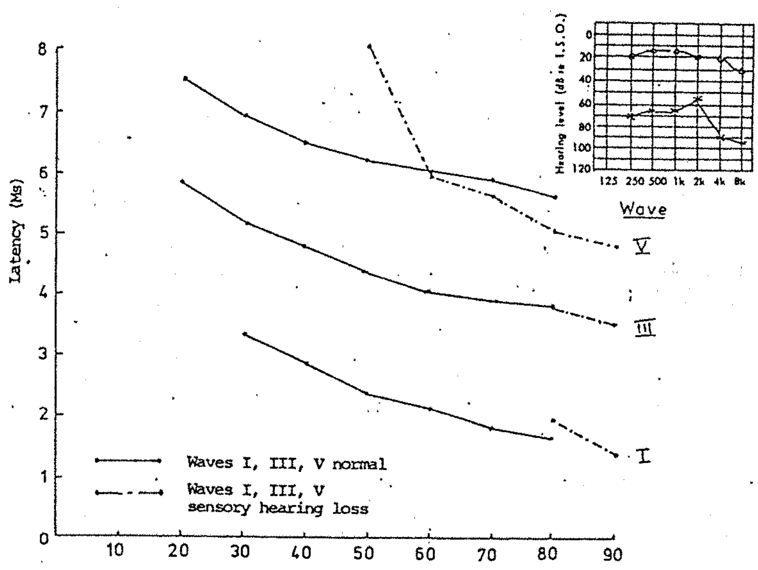


Fig 5.26 Latency - intensity function comparing the normal response and a unilateral sensory loss.

the latency approaches the normal, and that abnormalities are most marked at lower intensity levels.

Results recorded from the ear with the flat unilateral sensory hearing loss are shown in Figure 5.26. ABR results from the good ear are normal. The results from the impaired ear are similar to the recruitment type phenomenon recorded by Coats (1978). Wave V approaches the normal range at moderate intensities, the deviation at the higher frequencies probably due to the slightly greater high frequency involvement. It was not possible to record Wave I to lower levels than indicated in the figure, but it is clearly a steeply sloping function. The I-V interval is reduced at high intensities, as has been found in other studies where a high frequency hearing loss is present (Keith and Greville, 1987). The results from the patient with a steeply sloping high frequency loss show a markedly reduced I-V interval. Wave I is delayed at the highest two frequencies tested, and was not recorded below that. Wave V showed a steeply sloping latency intensity function, with shorter than normal latencies at high intensities (80 dB nHL). These cases support the finding that high frequency hearing losses tend to shorten the I-V interval.

The first patient with a brainstem lesion (Fig. 5.27) had a mild, bilateral sensory-neural loss at high frequencies, and was diagnosed as having multiple sclerosis and possible multiple neurofibromatosis. Wave I was recorded at normal latencies at high intensities, but Wave V was markedly delayed at all intensities with respect to the normal function, and is parallel to the normal function. This confirms the importance of determining the presence of any conductive component.

The second patient with a confirmed brainstem involvement gave slightly elevated thresholds to pure tones, and was originally diagnosed as having left temporal lobe symptoms. Her ABR threshold was normal. The latencies of Waves III, IV and V were all delayed with respect to normal. The intensity-latency function of Wave I was normal, but the Wave V function was clearly shifted and runs parallel to the normal function (Fig. 5.28). The patient has since been found to have a mid-brainstem glioma.

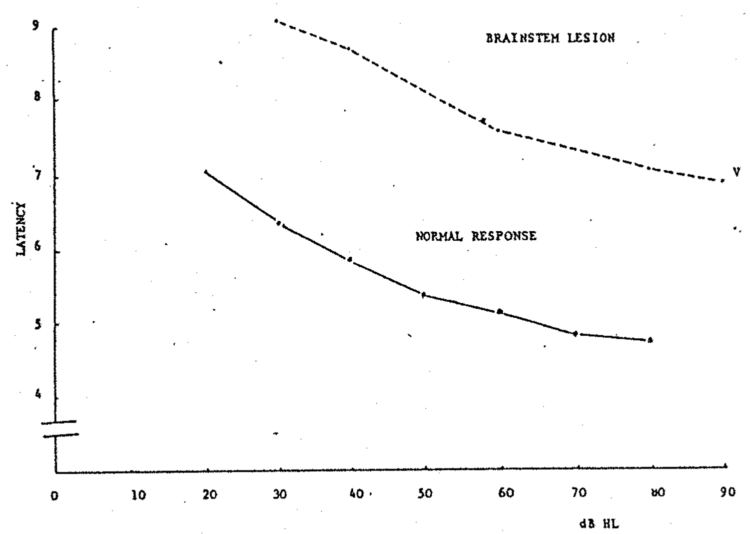


Fig 5.27   Latency - intensity functions comparing the responses from a normal subject and a patient with multiple neurofibromatosis.

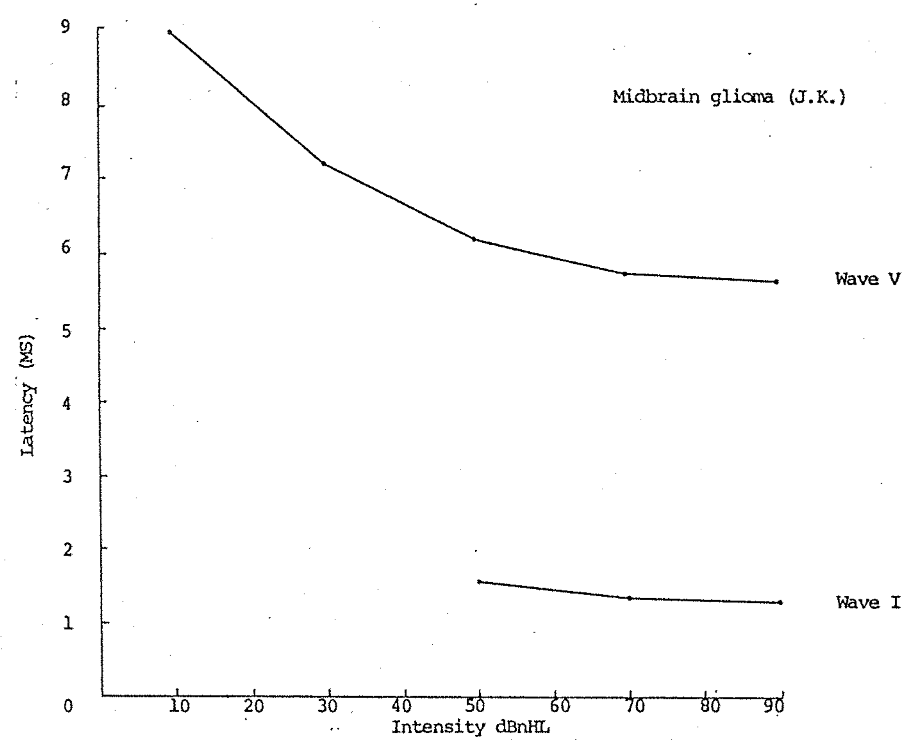


Fig 5.28   Example of the latensy - intensity function in a central lesion.

5.3.3 Discussion

These illustrations demonstrate use of the I-V interval and the latency-intensity funtion in diagnosis. Deviations from the normal function, for the later waves have been, shown to demonstrate a central auditory involvement.

5.4 SUMMARY

In this chapter,two experiments were described, which were necessary preparatory work for the investigation on children in the main study. In the first, the parameters most suitable for recording the ABR in the main childrens' study were determined. In the second, normative ABR and MLR data were collected, and the properties of the responses as revealed in this study, were discussed in relation to current knowledge. Particular attention was paid to possible sensitised measures of brainstem integrity. Clinical case studies were then reviewed.

CHAPTER 6

MEASUREMENT OF AUDITORY ELECTROPHYSIOLOGICAL RESPONSES IN THE TEST POPULATION OF HEARING-IMPAIRED CHILDREN

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6.1 INTRODUCTION

Auditory evoked potentials were used in the current study to assess the integrity of the auditory nerve pathways in order to attempt to identify sites of dysfunction in the pathway. A combination of evoked potential techniques was used, based on the relative applicability of each. Since the children tested in the main study all had substantial hearing losses and were available for only limited repeat assessments, it was decided to test each child by recording ABRs and MLRs to wide band click stimuli, initially. Frequency specific stimuli would be used only to elicit the more rostrally generated SVR, if the initial test session indicated that this might be a useful and informative measure.

As described earlier, the ABR is robust and repeatable as a gross threshold measure, but does not provide frequency specific information. However, it is not threshold information, per se, which is of interest here, but investigation of the site of dysfunction. If the gross ABR elicited in response to a click differs markedly from the threshold predicted on the basis of audiometric information, then the assumption will be made that there is a component contributing to the admitted threshold at a neurological level higher than that reflected by the ABR threshold. For these purposes, there is negligible advantage in using frequency specific stimuli.

It was therefore decided to make the following measures:

To record the response threshold of the ABR;

To record the waveform above threshold where possible;

To examine the interwave latencies, amplitude-ratios, waveform morphology and the latency-intensity function;

To examine the MLR, if the ABR is successfully recorded;

To record the SVR if the previous responses are not compatible with thresholds as predicted from the pure tone audiogram.

Comparisons will be made with the normative threshold and sensitised data obtained and reported in the previous chapter. In this way it is hoped to examine the individual responses for abnormalities and to obtain thresholds at various neurological levels, as indicated by the different response generating sites, described earlier, in some detail.

Ep data from the test population would be predicted to be abnormal, even due to cochlear effects, because of the severity of the hearing losses in the subjects. It was hoped that the study of the response characteristics and waveform morphology, in comparison with normal responses, would contribute to the analysis of the condition of the auditory pathway.

The aim of the ep response recording was:

1. To identify the auditory threshold up to the neurological level appropriate to that response;

2. To try to identify the site-of-dysfunction in the auditory pathway.

6.2 EXPERIMENTAL PROCEDURE

6.2.1 Subjects

The test population comprised two groups of children, designated as Group 1 and Group 2. The classification was as described earlier, in Chapter 2.

Group 1: 25 children, aged between 6 and 17 years, and each being a residential pupil at an oral/aural school for deaf children. The better ear audiometric threshold average ranged from 95 to 118 dB HL (Fig. 3.1, page 112).

Group 2: 11 children, aged between 7 and 15 years, who were selected from hearing-impaired children resident in Hampshire. They were receiving different kinds of educational management. The better ear audiometric threshold average ranged from 33 to 123 dB HL (Fig. 3.1, page 112).

Each child attended for at least one session in which auditory ep response measures were made; some of the children attended for two sessions, depending on the findings at the first session.

6.2.2 Instrumentation

The equipment used for this experiment was as described for experiment 2, Chapter 5.

6.2.3 Method

Children were tested with the same procedure that was used with the adult normal subjects. The child was instructed in how to relax and lie still and co-operate throughout the recordings. For the younger children, an adult familiar to the child (parent or school assistant) was present in the test room with the child throughout, and encouraged the child to co-operate and relax. For ethical reasons, it was not possible to use sedation. It was also of dubious desirability, because of the documented effects of sedation on the MLR. No child slept during testing, but the test had to be abandoned due to lack of co-operation in one case.

Four electrodes were applied, in order that bilateral recordings of responses could be collected. The configuration described earlier was used, and electrodes were applied using the same procedure, with Bentonite paste. No major difficulties were encountered in application of the electrodes with any of the children.

The auditory electric response protocol used was as follows:

6.2.3.1 Session 1

The auditory brainstem response were recorded under three different conditions. Stimulus and recording conditions 1, 2, and 3, as described below, were presented sequentially. Presentation was sequential in the order given, and condition 2 was only carried out if a response was recorded in condition 1. As a buffered averaging technique was used as described earlier, the total number of presentations, and hence the total test time, depended on the recording conditions which prevailed.

Condition 1; Binaural presentation of 100 µs click stimuli, at a rate of 9.1 s^{-1} (referred to as 10 s^{-1}), recording bandwidth of 0.10 to 3 kHz. Three sets of 2048 stimuli were recorded. Stimuli were presented at 80 dB nHL.

Condition 2; Monaural presentation, left and right, of 100 µs click stimuli, at a rate of 9.1 s^{-1} (referred to as 10 s^{-1}), recording bandwidth of 0.10 to 3 kHz. Three sets of 2048 stimuli were recorded. Stimuli were presented at 80 dB nHL.

Condition 3; Click stimuli were presented at levels up to 105 dB nHL until a response was recorded, in 10 dB steps, or down to threshold, in 10 dB steps, according to the results of the previous two stages, for both ears. Stimuli were presented at 16.5 s^{-1}, and a wide band recording paradigm was used, 0.02 to 3 kHz. Sufficient data were collected to establish the Wave V threshold, and to obtain a latency-intensity function, where possible. Responses to 2048 stimuli were averaged.

Wide band noise masking was presented to the contralateral ear at (stimulus level-30) dB HL in each condition. If, in cases of asymmetric loss, the results indicated a suspicion of cross-over hearing effects, the masking level was increased, in 10 dB increments, to an appropriate maximum, and the resultant effect on the response observed.

Data from experiments 1 and 2 indicated that the wide band record was the most effective in revealing Wave V at threshold levels, and that there was no significant loss of information in presenting the stimuli at the faster rate.

6.2.3.2 Session 2

Children returned for a second test session if there was poor agreement between the ABR and behavioural response thresholds, in either direction. If the ABR threshold was poorer than the behavioural threshold, a second session was arranged to try to see if a lower threshold could be recorded. This was done to ensure that the poor results were not caused by the poor signal-to-noise ratios due to less than optimal recording conditions. If the ABR threshold was better than would be predicted on the basis of the pure tone thresholds, then a second session of further ep tests was also organised.

The tests in session 2 consisted of recordings to threshold of the middle latency response, using a 100 μs click, at a stimulus rate of 9.1 s^{-1}, and a recording bandwidth of 0.015 to 0.175 kHz. A 60 ms recording window was used.

Where successful MLR recordings were obtained, it was intended to attempt recordings of the slow vertex response (SVR), at 0.5, 1, and 2 kHz. For the SVR, the stimuli to be presented were phase locked tone bursts of duration 200 ms and rise/fall time of 10 ms, recording bandwidth 1 to 12 Hz. Presentation was to be three sets of twenty stimuli, from which a grand sum would be made, and compared, for response identification. The recording window was set at 1 s. Calibration was effected through the headphones using conventional audiometric standards and techniques, as described earlier.

6.3 EXPERIMENTAL RESULTS

6.3.1 Results of Electrophysiological Assessment

The ep measures are summarised in Tables 6.1a, 6.1b and 6.2, and the information contained in these tables is summarised below.

The absolute peak amplitudes and latencies were recorded at the lowest level obtainable for Group 1 subjects (Table 6.1a) and at both threshold and at 80 dB nHL for subjects in Group 2 (Table 6.1b).

Table 6.1(a)

SUMMARY TABLE OF AUDITORY BRAINSTEM RESPONSE DATA - GROUP 1

Subject	Ear	Wave V thresh dB	I/O slope latency	I/O slope amplitude	Wave V latency ms	Wave V amplitude nV	Binaural V latency ms	Binaural V amplitude nV	Mon/ Bin ratio	I-V IPL ms	Behav.T. at 2kHZ dB HL
DL	L	110	-	-	-	-	-	-	-	-	110
	R	110	-	-	-	-	-	-	-	-	130
EIM	L	105	1.2	1.2	9.5	-	9.8	168	-	-	115
	R	105	-	-	-	-	-	-	-	-	115
AD	L)	failed to complete test									
	R)						-	-	-	-	
GP	L	100	-	-	-	-	7.5	156	-	-	105
	R	100	-	-	-	-	7.8	180	-	-	105
MCa	L	100	-	-	7.6	87	-	-	-	-	110
	R	110	-	-	-	-	-	-	-	-	110
KN*	L	90	0.05	4.5	7.2	124	7.3	524	0.24(100)	4.8	115
	R	90	0.06	0.85	6.8	212	6.8	660	0.32(100)	4.1	120
HD*	L	110	-	-	-	-	-	-	-	-	125
	R	110	-	-	-	-	-	-	-	-	130
SH	L	105	-	-	-	-	-	-	-	-	120
	R	105	-	-	-	-	6.0	224	-	-	120
AC	L	110	-	-	-	-	-	-	-	-	110
	R	110	-	-	-	-	-	-	-	-	110
BW*	L	110	-	-	-	-	5.2	340	-	-	120
	R	105	0.01	4.7	9.2	95	5.1	120	0.6(105)	-	110
DL*	L	110	-	-	-	-	6.0	140	-	-	110
	R	110	-	-	-	-	-	-	-	-	115
MC*	L	90	4.5	5.3	4.8	264	4.6	606	0.4(100)	-	105
	R	100	4.5	5.3	4.8	104	4.7	520	0.2(100)	-	105
CN*	L	100	-	-	7.0	720	-	-	-	-	120
	R	105	-	-	7.7	176	-	-	-	-	125
MP	L	110	-	-	-	-	-	-	-	-	125
	R	110	-	-	-	-	-	-	-	-	120
AS	L	110	-	-	-	-	-	-	-	-	120
	R	110	-	-	-	-	-	-	-	-	130
LL*	L	110	-	-	-	-	-	-	-	-	100
	R	110	-	-	-	-	-	-	-	-	100
JW	L	110	-	-	-	-	-	-	-	-	110
	R	110	-	-	-	-	-	-	-	-	115
ZX	L	100	0.04	4.0	6.7	482	7.3	530	0.9(105)	4.0	115
	R	100	0.06	4.3	6.7	162	7.3	324	0.5(105)	4.4	115
TH	L	110	-	-	-	-	-	-	-	-	115
	R	110	-	-	-	-	-	-	-	-	115
PB*	L	100	-	-	-	-	-	-	-	-	120
	R	100	0.23	0.25	7.2	56	-	-	-	-	120
EM	L	110	-	-	-	-	-	-	-	-	100
	R	110	-	-	-	-	-	-	-	-	95
CT	L	100			9.0	60	-	-	-	-	105
	R	110	-	-	-	-	-	-	-	-	115
DG	L	110	-	-	-	-	-	-	-	-	130
	R	110	-	-	-	-	-	-	-	-	120
BG	L	110	-	-	-	-	-	-	-	-	120
	R	110	-	-	-	-	-	-	-	-	125
TG	L	110	-	-	-	-	-	-	-	-	105
	R	110	-	-	-	-	-	-	-	-	110

TABLE 6.1b

SUMMARY TABLE OF AUDITORY ELECTROPHYSIOLOGICAL DATA - GROUP 2

Sub -ject	Ear	Wave V thresh. dB	I/O slope latency	I/O slope amplitude	Wave V(80) latency ms	Wave V(80) amplitude nV	Binaural V latency ms	Binaural V amplitude nV	Mon/ Bin ratio	I-V IPL ms	Wave V(T) latency ms	Behav.T. at 2kHZ dB HL
MM	L	>110	-	-	-	-	-	-	-	-	8.0	100
	R	>110	-	-	-	-	-	-	-	-	7.8	110
MW	L	35	0.03	1.35	6.0	146	5.9	312	0.5	4.0	7.5	45
	R	35	0.03	2.57	5.5	304	5.9	322	0.9	3.3	6.8	30
SP	L	50	0.02	4.70	5.3	414	5.4	648	0.6	3.6	6.0	75
	R	50	0.02	0.50	5.7	314	5.6	650	0.5	3.4	6.0	75
JC	L	95	0.19	5.54	-	-	-	-	1.3(105)	4.6	8.1	100
	R	90	0.10	9.60	-	-	-	-	1.1(105)	4.3	9.8	105
AD	L	50	0.04	4.39	7.7	212	6.0	292	0.7	3.7	7.3	35
	R	95	0.09	6.90	-	-	-	-	-	-	8.7	120
LT	L	5	0.04	4.39	5.6	422	5.2	652	0.6	3.9	8.1	10
	R	15	0.09	6.90	5.8	338	5.3	546	0.6	4.0	8.1	20
NH	L	70	1.03	0.70	5.7	314	nt	nt	nt	3.5	6.0	75
	R	80	1.03	0.80	9.1	393	nt	nt	nt	-	9.1	80
CS	L	90	0.09	1.60	-	-	-	-	0.7(105)	3.3	6.7	85
	R	105	-	-	-	-	-	-	0.4(105)	4.5	6.5	115
DS	L	45	0.02	0.70	6.0	196	6.1	332	0.6	4.2	6.7	35
	R	45	0.02	1.75	6.0	242	6.1	400	0.6	4.1	6.3	40
PS	L	60	0.07	5.50	5.0	313	-	-	-	-	10.5	65
	R	90	0.16	8.25	-	-	-	-	-	-	8.9	65
MO	L	>110	-	-	-	-	-	-	-	-	-	>130
	R	>110	-	-	-	-	-	-	-	-	-	>130

Table 6.2 SUMMARY TABLE OF MIDDLE LATENCY RESPONSE DATA

Group 2

Subject	Ear	Resp. Thres. dB HL	I/O slope latency ms	I/O slope amplitude nV	<-Peak values at 80 dB nHL->				Behav.T at 2 kHz dB HL
					Pa-ip lat. ms	Pa-ip amp. nV	Pa-ip lat. ms	Pa-ip amp nV	
MM	L	>100	-	-	-	-	-	-	100
	R	>100	-	-	-	-	-	-	110
MW	L	60	0.45	0.35	22.1	260	21.5	376	45
	R	45	0.37	0.48	22.0	320	21.1	390	30
SP	L	70	-	-	22.5	628	22.4	678	75
	R	70	-	-	22.4	650	22.8	660	75
JC	L	>100	-	-	-	-	-	-	100
	R	95	-	-	35.3	301	35.3	492	105
AO	L	80	-	-	24.2	347	24.5	391	35
	R	100	-	-	-	-	-	-	120
LT	L	30	0.43-	0.48-	25.0	314	24.0	404	10
	R	30	0.37	0.59	25.2	307	24.4	395	20
NH	L	70	-	-	22.0	204	24.0	188	75
	R	>100	-	-	-	-	-	-	80
CS	L	}.....not tested							
	R	}							
DS	L	55	0.40	0.40	21.5	348	21.0	394	35
	R	55	0.37	0.37	21.8	236	22.3	281	40
PS	L	70	0.28	0.95	23.0	318	22.8	361	65
	R	70	0.35	0.80	23.2	302	22.9	320	65
MO	L	>100	-	-	-	-	-	-	>130
	R	>100	-	-	-	-	-	-	>130

No subject in Group 1 showed an ABR response at 80 dB HL. This category only appears in Table 6.1b. In Table 6.1b, the threshold value of Wave V is given for Group 2, indicated as "Wave V (T) latency".

As a convenient means of characterising the latency and amplitude intensity functions, the slope of the latency- and amplitude-intensity functions have been calculated and reported, where three or more data points were available. The graphs of amplitude or latency against intensity were plotted, summarised as means of the slopes between subsequent data points.

The monaural/binaural amplitude ratio has been calculated, where possible. This was done at 80 dB nHL, unless otherwise indicated by figures in parentheses. As Wave I was recorded from so few subjects, and as the peak identification proved difficult, the I/V amplitude ratio has not been included in the data summary.

It was not possible to record clear MLR responses from any subject in Group 1. Data which could not be calculated due to missing values is marked " - " in the Tables. Eleven subjects from Group 1 attended for a second test session (marked *), but the MLR response was not elicited from any of these subjects. The SVR was attempted, but was also absent in all but one of these subjects. All subjects in Group 2 attended for two sessions and, of these, the MLR was recorded in six subjects. The SVR was attempted on each of theGroup 2 children, but elicited in only the six cases with more moderate losses (MW, SP, AD, LT, NH, PS). In 5 cases, thresholds were within 20 dB nHL of their pure tone audiogram, and the seventh case, LT, will be discussed in more detail later.

Of the 25 children in Group 1, the ABR was not present in 12 subjects. When the subjects were divided into two groups, on the basis of present or absent Wave V responses, comparison of their pure tone threshold at 2 kHz showed no significant difference, using an independent t-test ($p<0.001$).

Qualitative study of the audiogram shapes of the two groups did not reveal any striking differences. Qualitative analysis of the notes made of recording conditions did not show any differences between groups. However, measures such as the inter-peak intervals and the amplitude ratios will be affected by the low signal-to-noise ratio, since they were obtained at levels closer to threshold than in the normal subjects.

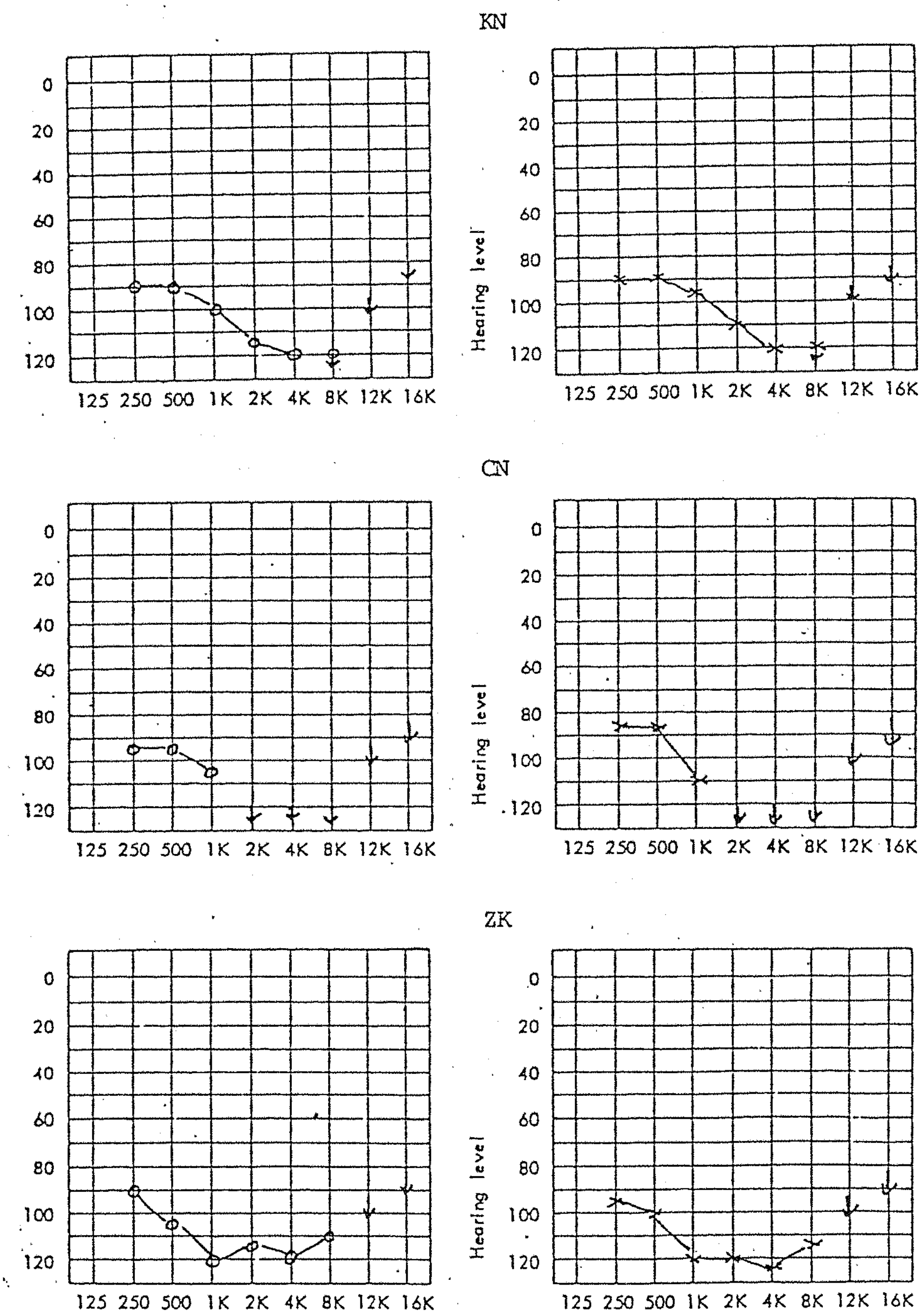


Fig 6.1 Group 1

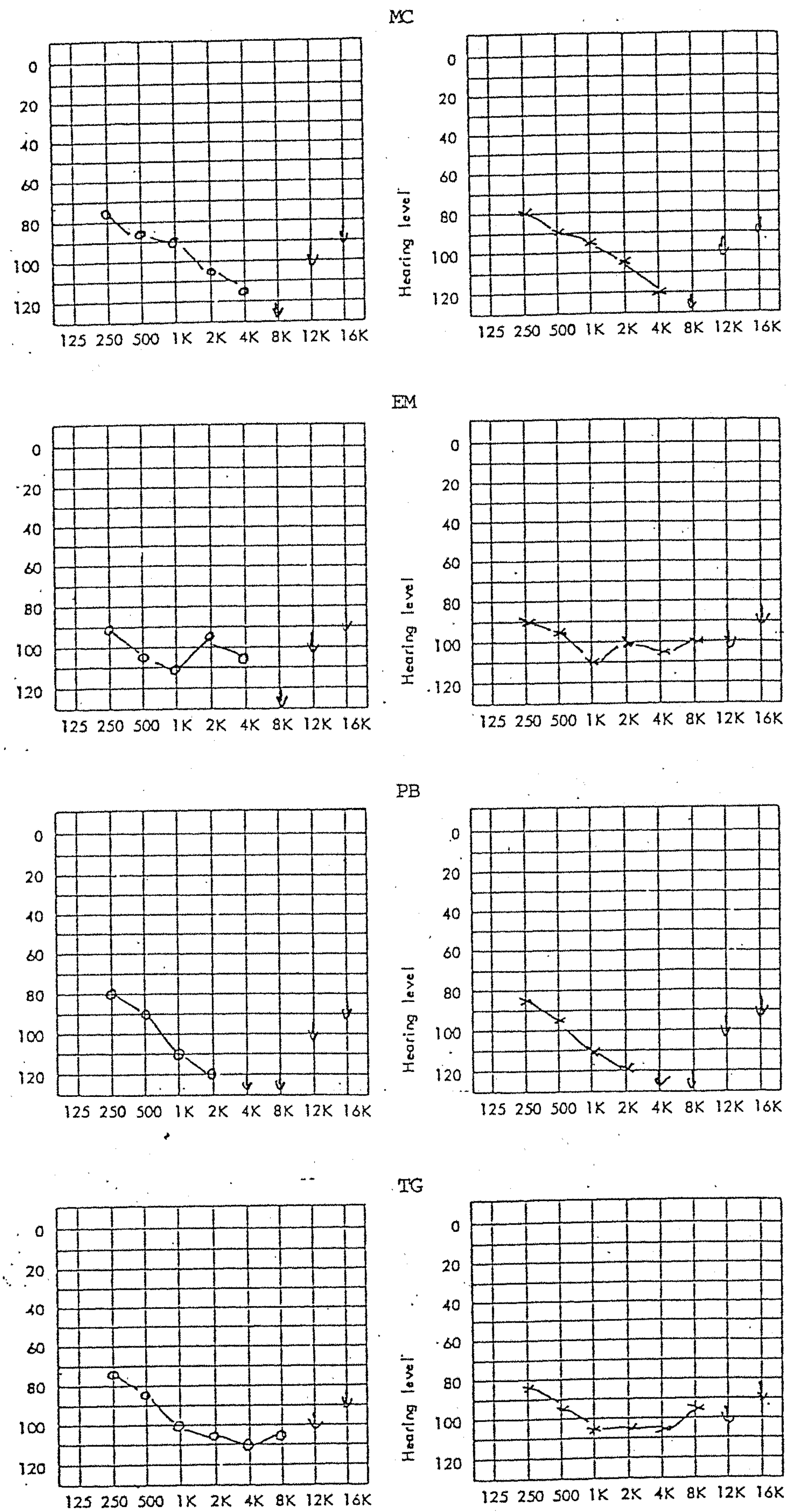


Fig 6.1 Group 1 (continued)

6.3.1.1 Threshold Data

In no case in Group 1 was an ABR threshold recorded at a level more than 20 dB below that of the behavioural threshold averaged over six frequencies. However, in all but one of the cases where the ABR was elicited, the threshold was 5-15 dB better than the behavioural response at 2 kHz. This reflects the predominance of high frequency loss in the subject group. The better-than-expected threshold reflects acuity in more apical, regions of the cochlea than that which is most sensitive at 2 kHz. In the one case where the ABR response threshold was worse than the behavioural response at 2 kHz, the hearing loss configuration was flat. Audiometric information is given in Fig 6.1.

Regression analysis of the pure tone thresholds and the ABR click evoked thresholds, where measurable, showed correlations of 0.44 and 0.91, for Groups 1 and 2 respectively. The large difference between groups reflects the extent and configuration differences between them. The correlation for normal subjects at this frequency was found to be 0.86.

The threshold data and peak latency data from Groups 1 and 2 were examined more closely and results of a series of correlations are reported in Table 6.3, with comparisons from other studies in Table 6.5.. This shows a moderate correlation of 0.69 between Wave V latency and the audiometric average over 0.5, 1, and 2 kHz (better ear). A measurable ABR threshold was recorded from 9 subjects in Group 2, reflecting the better average acuity for the Group. Analysis of the combined data from Groups 1 and 2 showed a significant correlation of 0.97 for the better ear and 0.93 for the worse ear, between the pure tone average audiometric threshold (at 0.5, 1, and 2 kHz) and the ABR threshold.

There is a wide range of latency values at threshold. These are summarised for each group in Table 6.4. The normal value was found to be 8.12 (s.d. 0.46). Threshold data for these cases will be affected by recording conditions; the shorter than normal latencies recorded at threshold from these subjects may partially reflect the ABR threshold having been raised by poor recording conditions, created by myogenic activity.

Table 6.3

CORRELATION MATRIX OF SUBSETS OF AUDIOMETRIC AND ABR RESULTS

This data was derived using the SPSS procedure and the correlation matrix output as a subprogram of FACTOR

Better ear average	/worst ear average	0.94
Better ear ULL	/better ear average	-0.53
Wave V better ear	/better ear average	0.69
Wave V better ear	/worse ear average	0.71
Wave V worse ear	/worse ear average	0.67
Wave V worse ear	/worse ear average	0.93
I/O latency better ear	/ULL better ear	-0.29
I/O amplitude better ear	/ULL better ear	0.20
I/O latency worse ear	/ULL worse ear	-0.36
I/O amplitude worse ear	/ULL worse ear	0.39

Table 6.4 WAVE V LATENCY AT THRESHOLD

	mean	s.d.	range (ms)
Group 1	7.25	1.45	4.0- 9.5
Group 2	7.65	1.37	6.0-10.5
Groups 1 & 2	7.46	1.39	4.0-10.5

TABLE 6.5

REGRESSION ANALYSES OF THE RELATION BETWEEN THE AUDITORY BRAINSTEM RESPONSE THRESHOLD, ABR-T, AND THE PURE-TONE THRESHOLD, PTT, IN FOUR STUDIES

Regression analysis data	Jerger and Mauldin (1978)	Coats and Martin (1977)	Bellman et al. (1984)	van der Drift et al. (1987)
Maximum correlation coeff. of PTT with ABRT	0.48 (at 1-2-4 kHz)	0.65 (at 4-8 kHz)	0.85 (at 2-4 kHz)	0.93 (at 2-4 kHz)
Most favorable slope of the regression line	0.63 (at 4 kHz)	ca.0.9 (at 1-2 kHz)	0.90 (at 4 kHz)	1.10 (at 2-4 kHz)
Minimum standard error of the estimate, dB	15.8 (at 1-2-4 kHz)		19.0 (at 1-2-4 kHz)	11.1 (at 2-4 kHz)

6.3.1.2 Monaural/Binaural Amplitude Comparison

Monaural/binaural amplitude comparisons could only be made for four subjects in Group 1. A wide range of values was recorded, from 0.20 to 0.90, compared to a mean value of 0.79 for normal subjects. This comparison was made at threshold levels for Group 1. For Group 2, the ratio, made at 80 dB nHL, ranged from 0.6 to 0.9 (mean 0.59), for the five subjects who had hearing acuity sufficient to give measurable responses at this level. No relationship was observed between audiogram slope and monaural/binaural ratio.

6.3.1.3 Interpeak Interval Analysis

Wave I could not be identified from the majority of recordings. The I-V latency interval was recorded from only two subjects in Group 1, and ranged from 4.0 to 4.8 ms (normal 4.07, s.d. 0.24). It was recorded from 14 ears in Group 2, and ranged from 3.3 to 4.6 ms. There was no apparent correlation between audiogram slope and I-V latency interval. The steepest slope of audiometric configuration yielded one of the shortest interpeak intervals, and two U-shaped audiograms resulted in long I-V intervals, reflecting, qualitatively, the influence of shape on the I-V interval.

6.3.1.4 Intensity Effects

The slopes of the latency and amplitude function from Groups 1 and 2 show that, at high intensities, above the normal test range of up to 80 dB nHL, a very rapid increase in waveform amplitude and decrease in peak latencies occurs with increasing stimulus intensity. This was most marked in recordings from 5 subjects in Group 1 (Figs 6.2 - 6.6). These waveform morphologies are quite different from the normal waveform, and peak labelling has been attempted in a few cases only. Where possible, the input-output functions for latency and amplitude have been compared to the normal. For example, case KN (Fig 6.2a to 6.2d) shows an unusual response morphology. The waveform shows a large peak complex, resembling the normal IV/V complex. This appears as the most robust wave in the response and is the most clear threshold determinant, but it is of short latency in comparison with the normal Wave V. The amplitude growth of this peak is steeper than normal by about 80%. The peak labelled VI' has a latency more typically associated with Wave V, but not the other features.

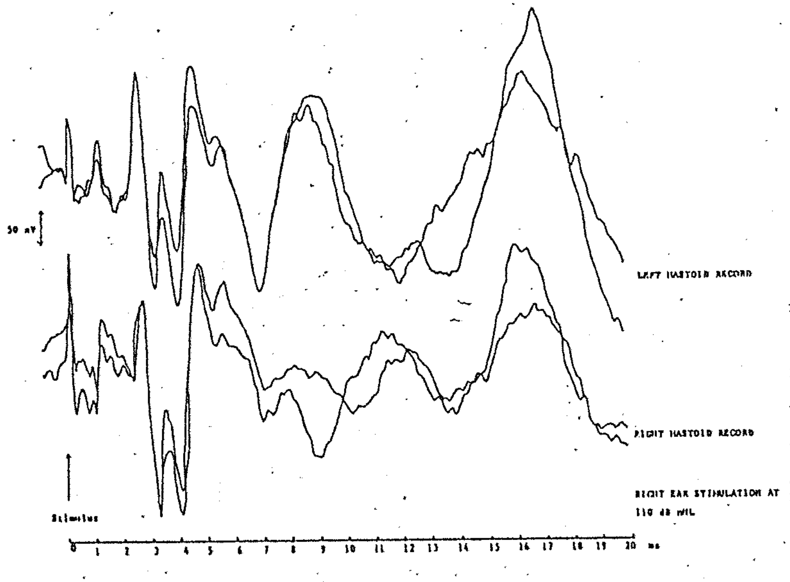


Fig 6.2(a) KN Age 9

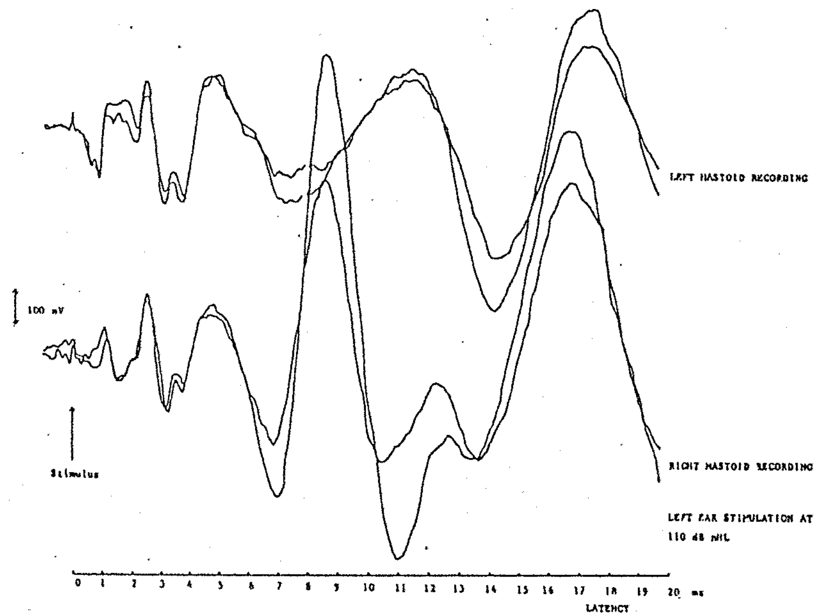


Fig 6.2(b) KN Age 9

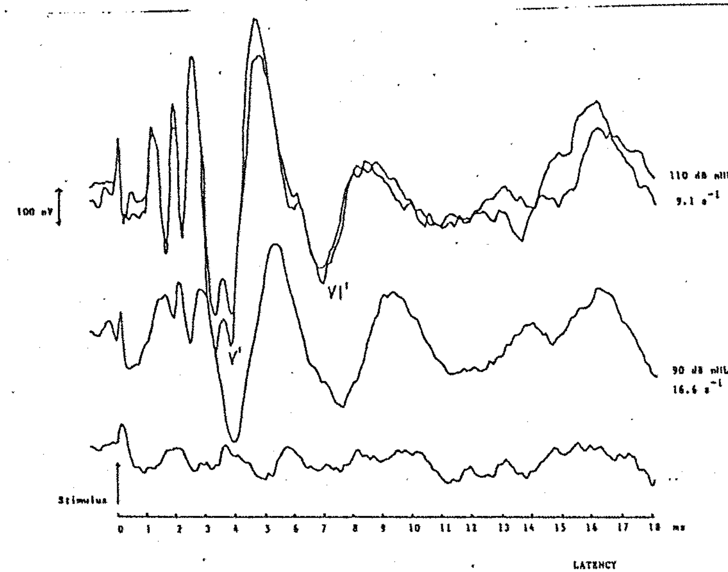


Fig 6.2(c) KN Age 9

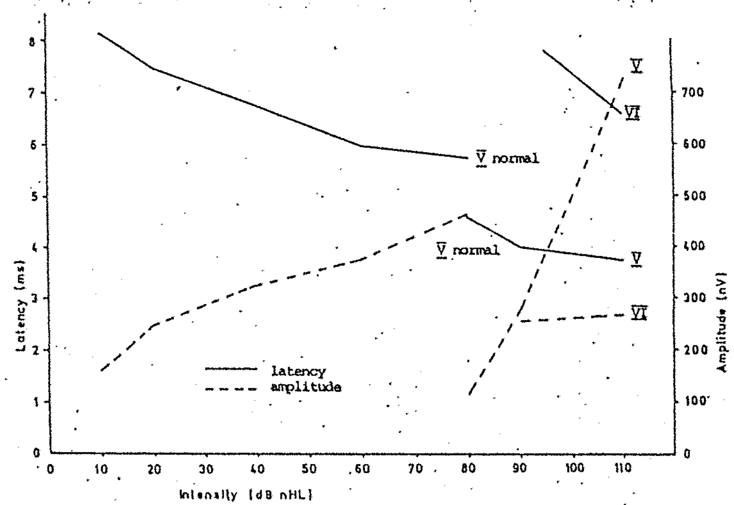


Fig 6.2d I/O functions : subject KN (Group 1)

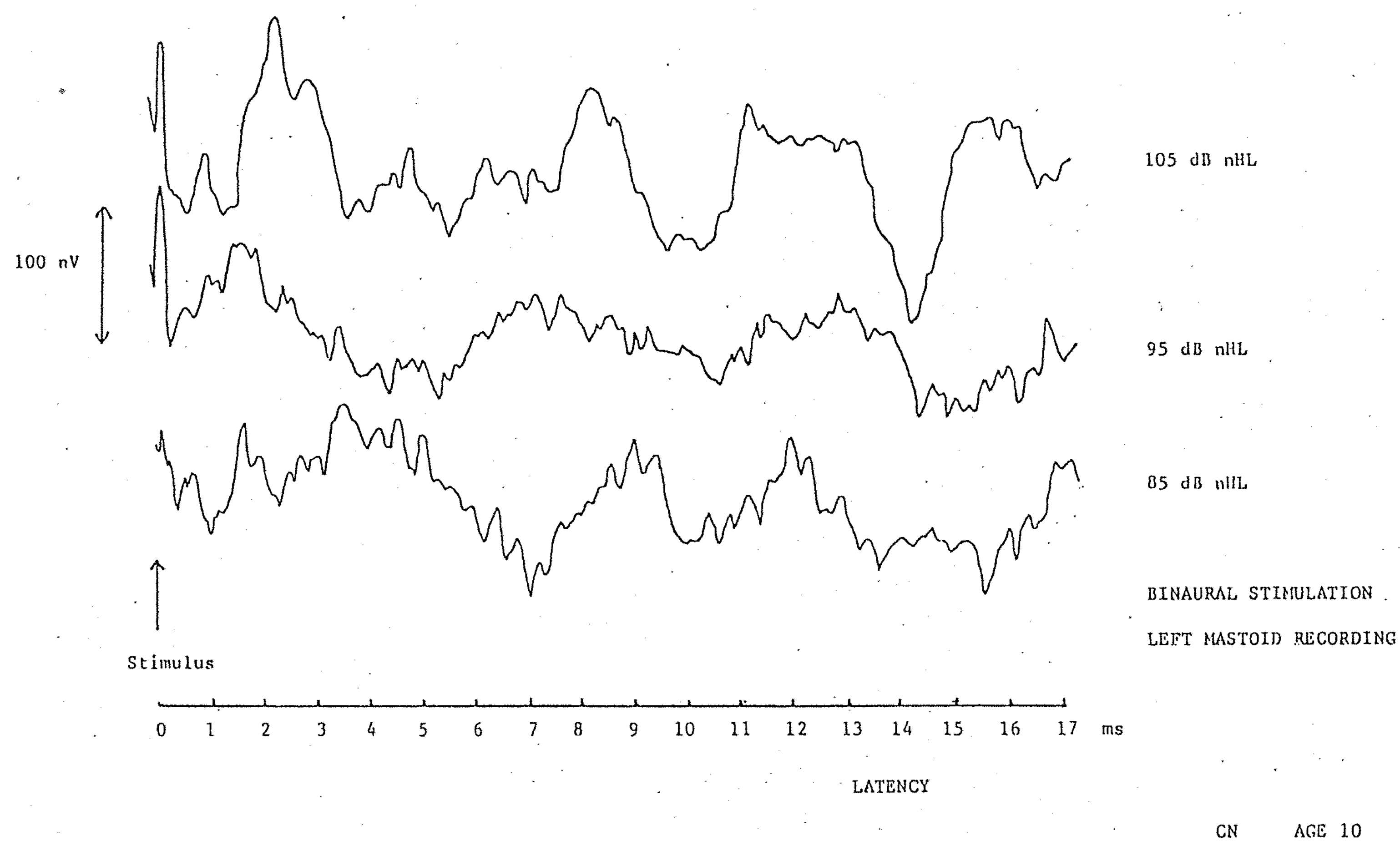

105 dB nHL
95 dB nHL
85 dB nHL
BINAURAL STIMULATION
LEFT MASTOID RECORDING
100 nV
Stimulus
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ms
LATENCY
CN AGE 10

Fig 6.3

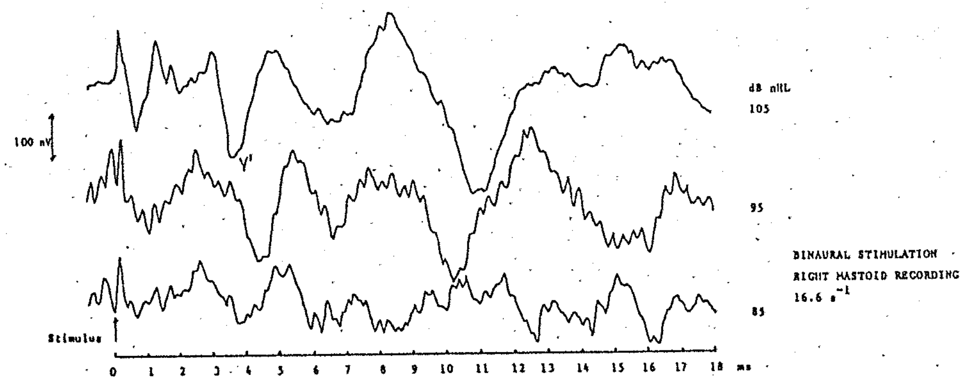


Fig 6.4(a)

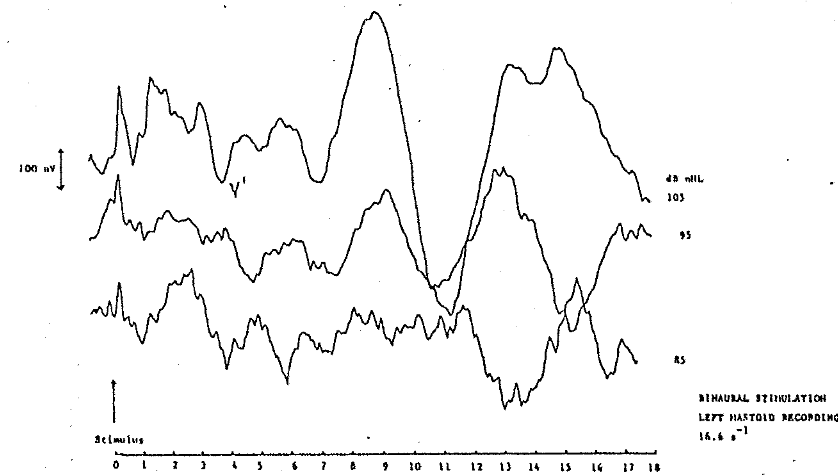


Fig 6.4(b)

ZK AGE 12

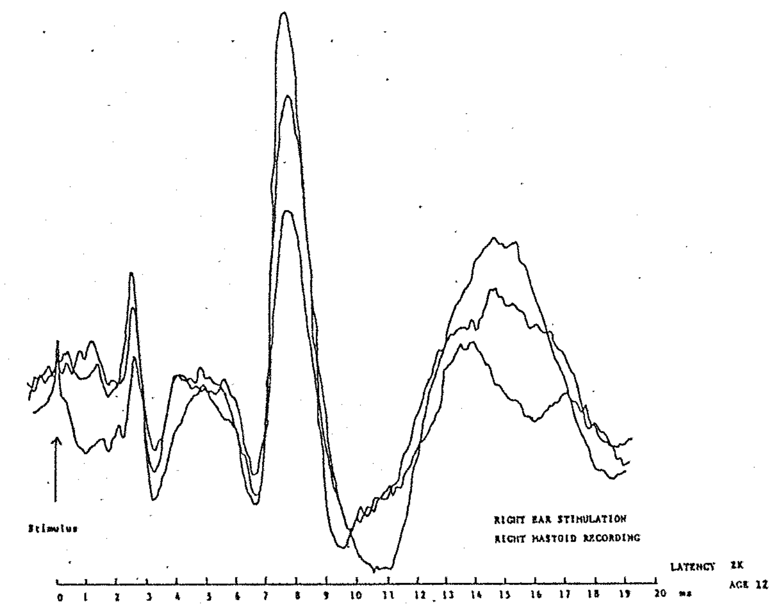


Fig 6.4(c)

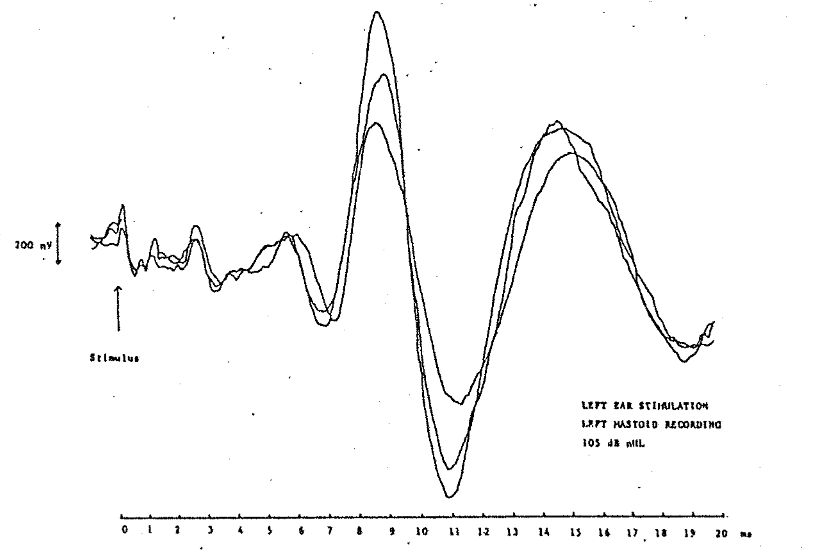


Fig 6.4(d)

ZK AGE 12

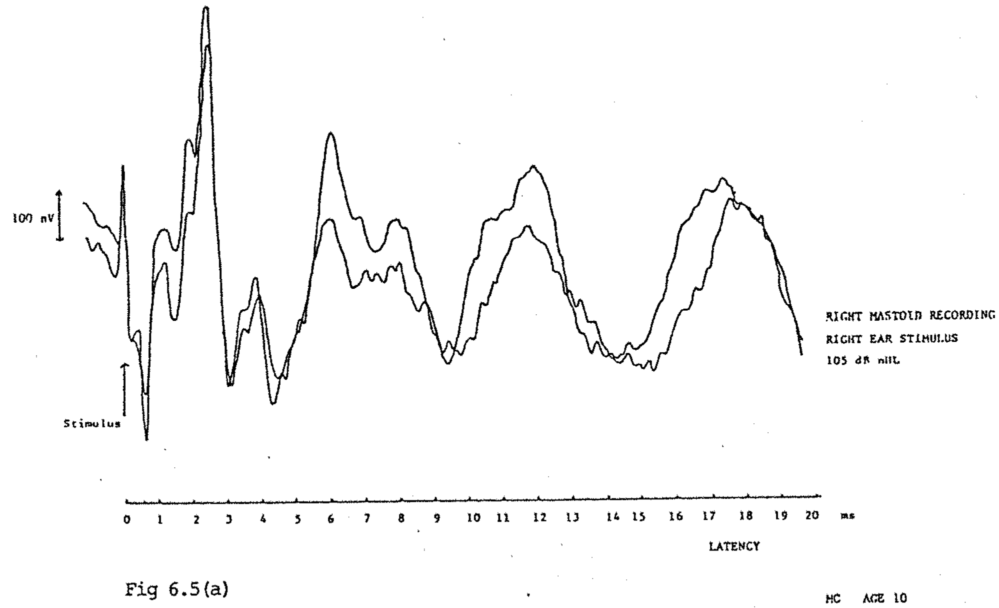


Fig 6.5(a)

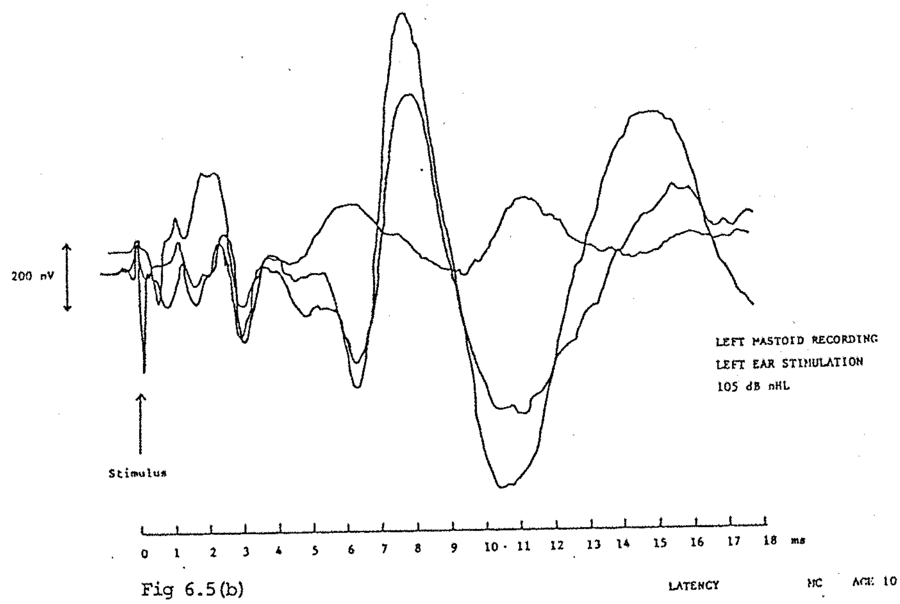


Fig 6.5(b)

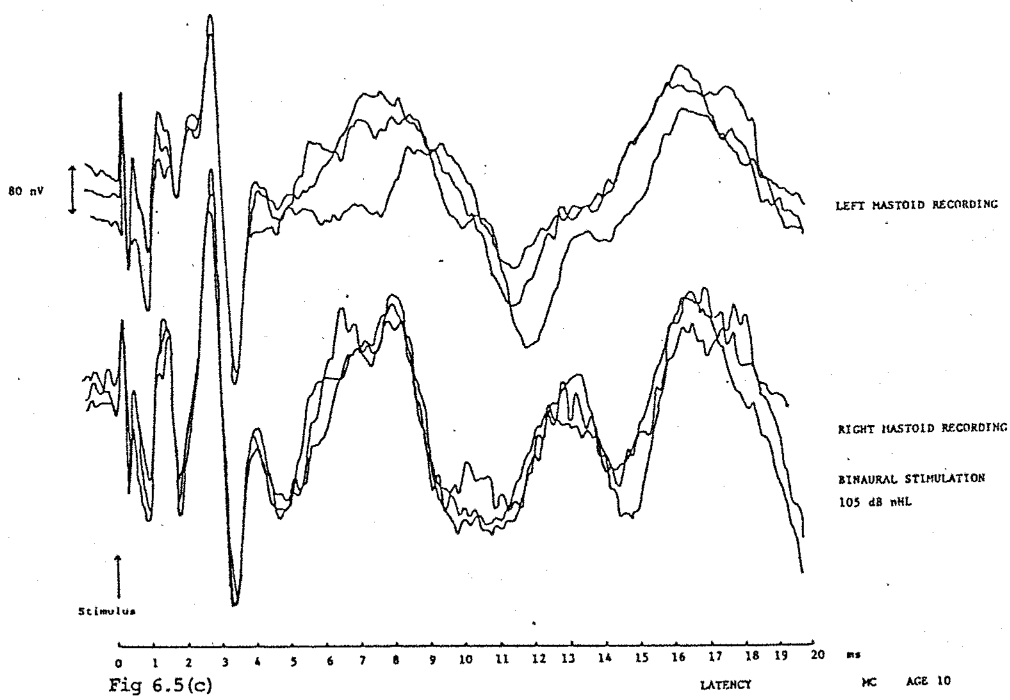


Fig 6.5(c)

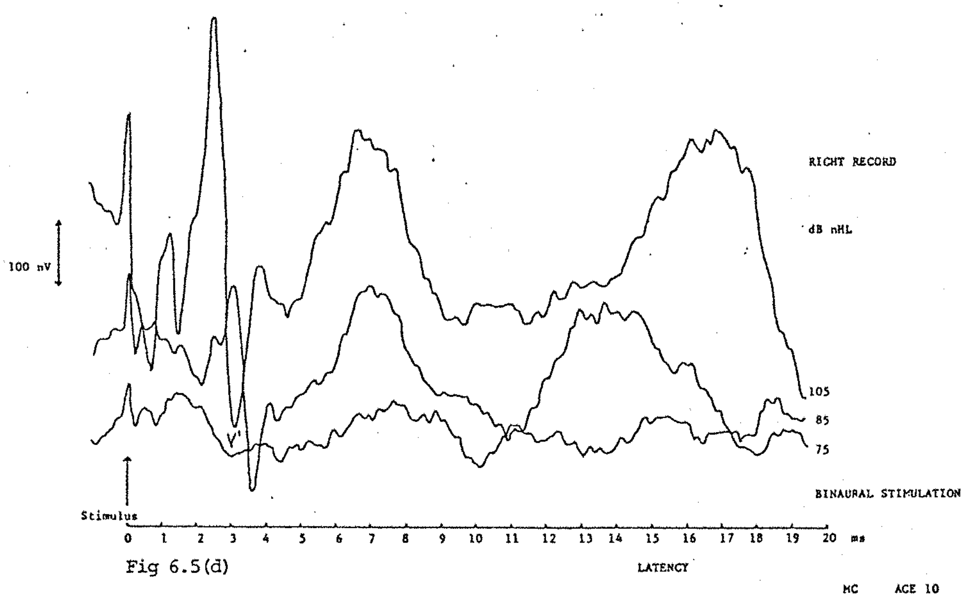


Fig 6.5(d)

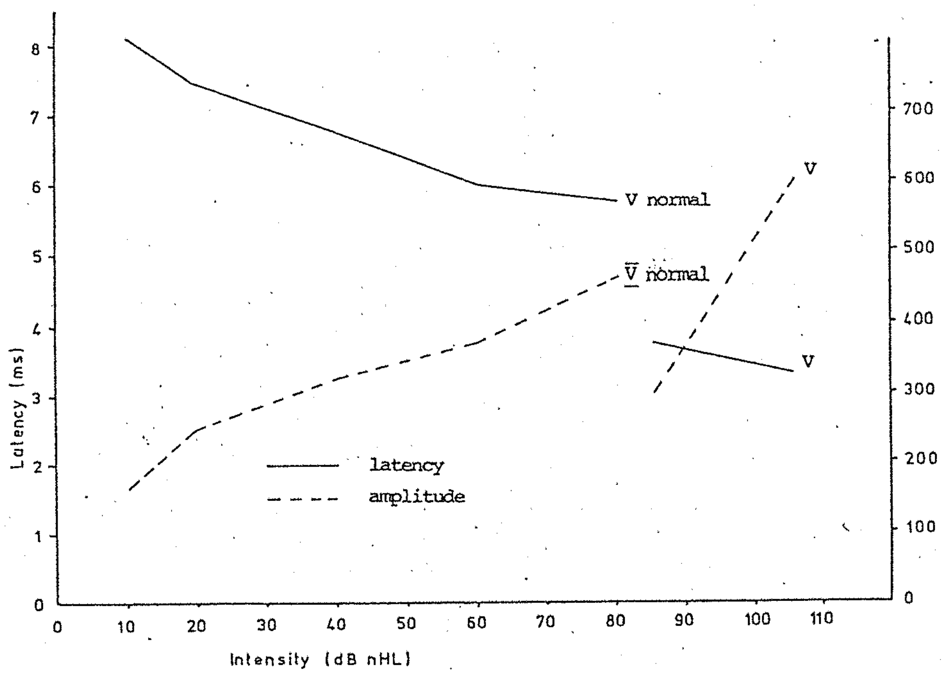


Fig 6.5e

I/O function : subject MC (Group 1)

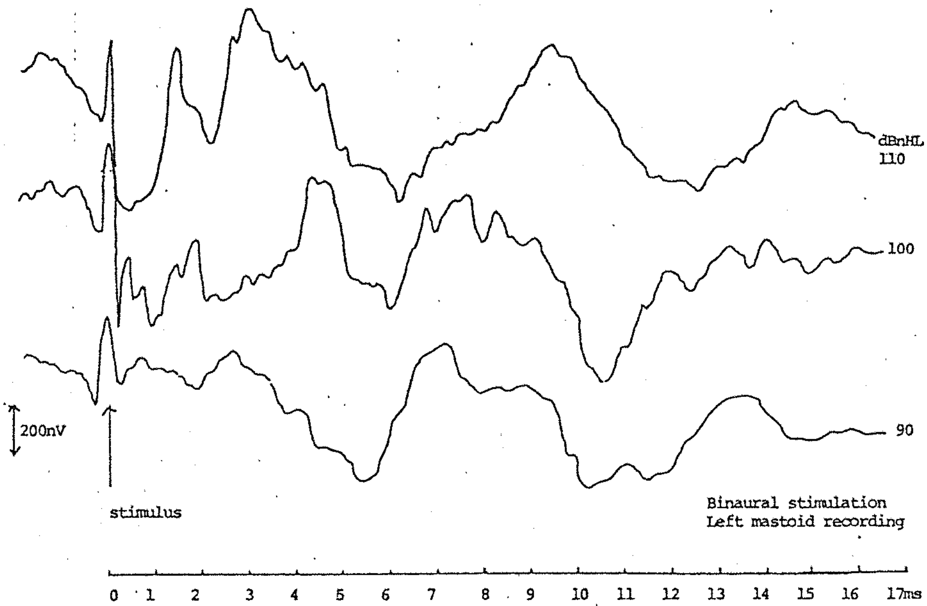


Fig 6.6 EM age 7

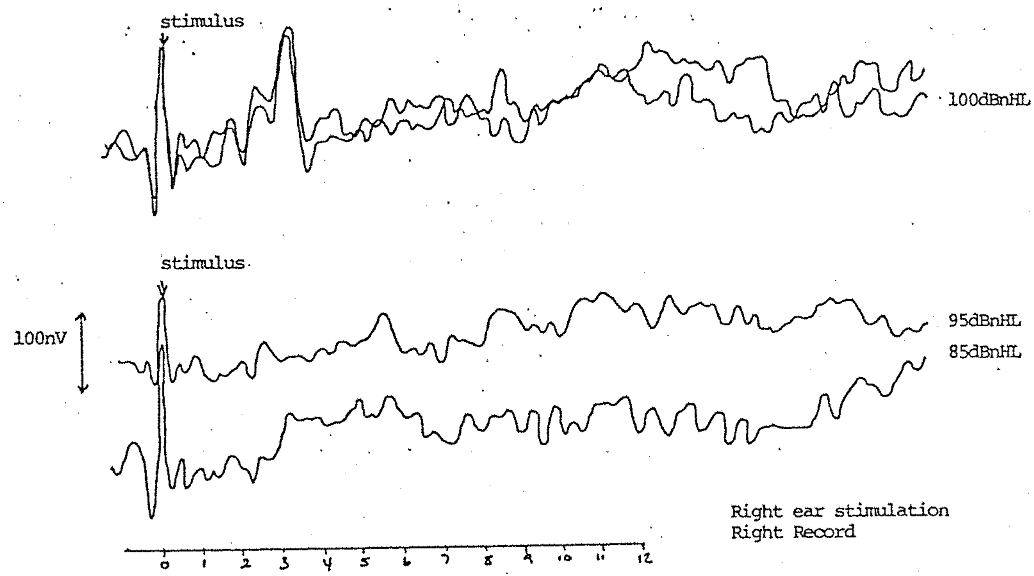


Fig 6.7 Subject PB

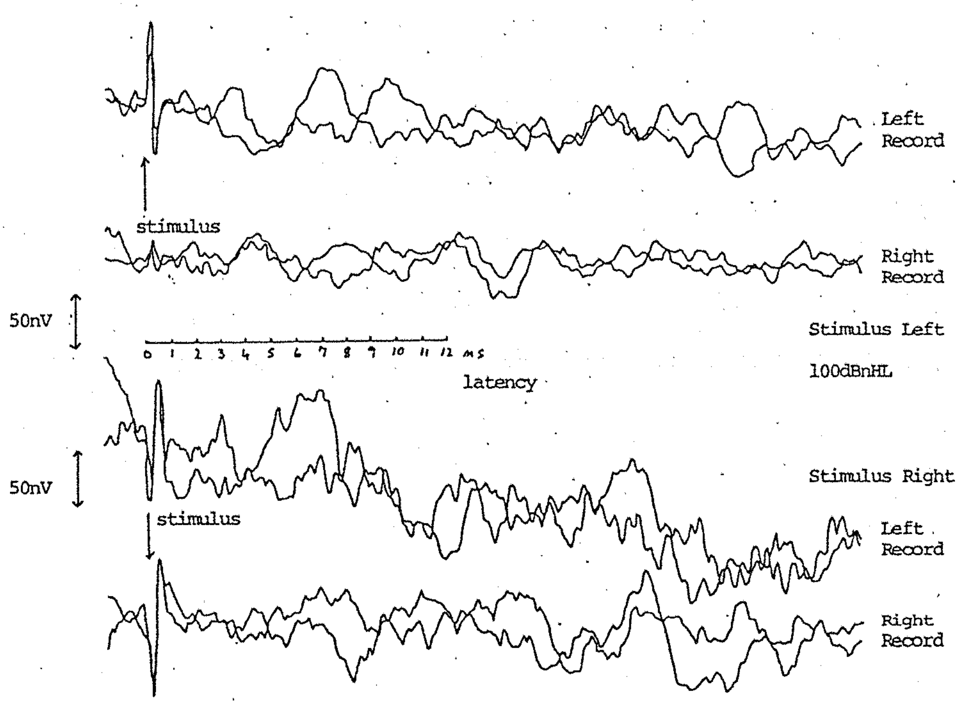


Fig 6.8 Subject TG

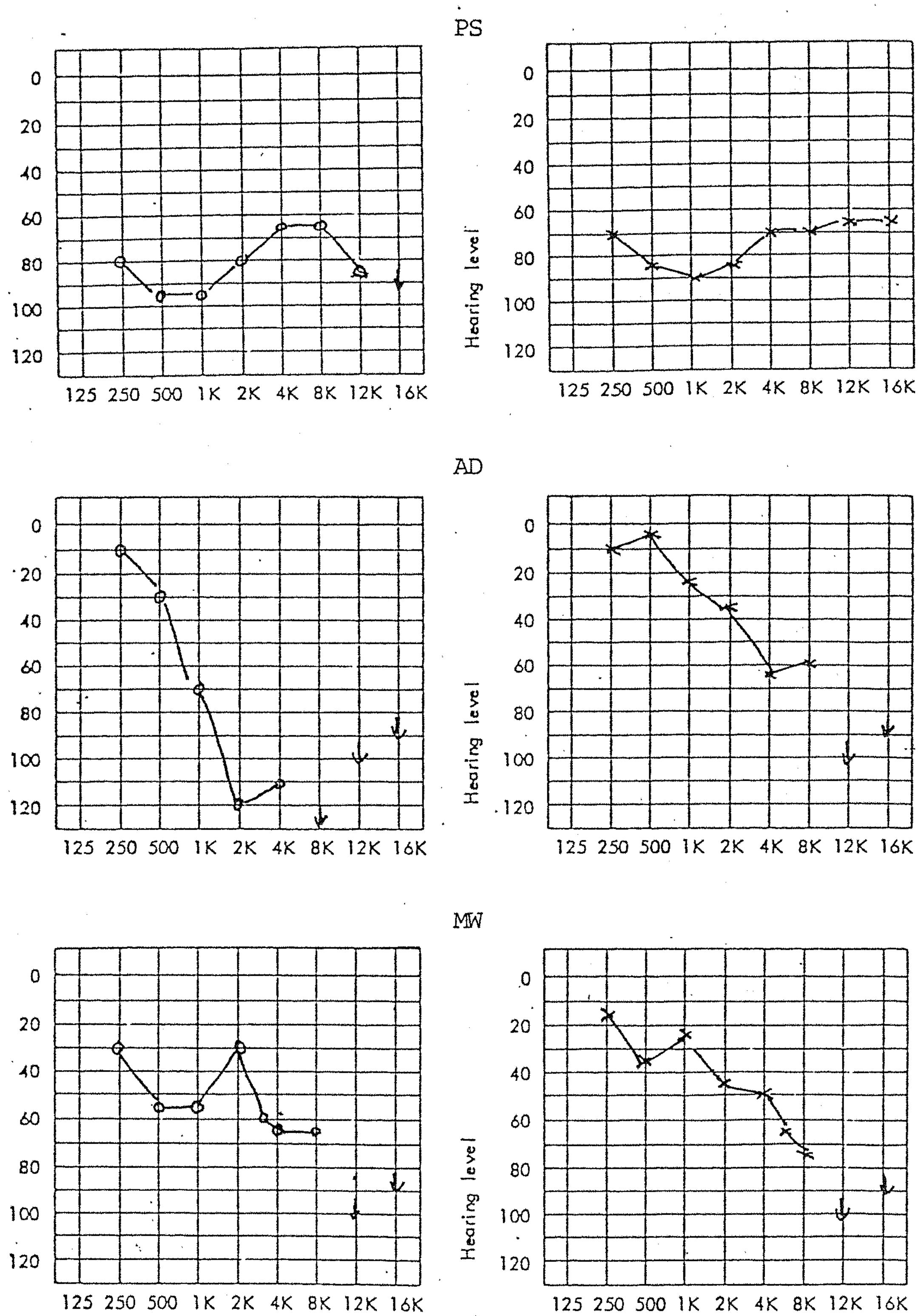


Fig 6.9 Group 2

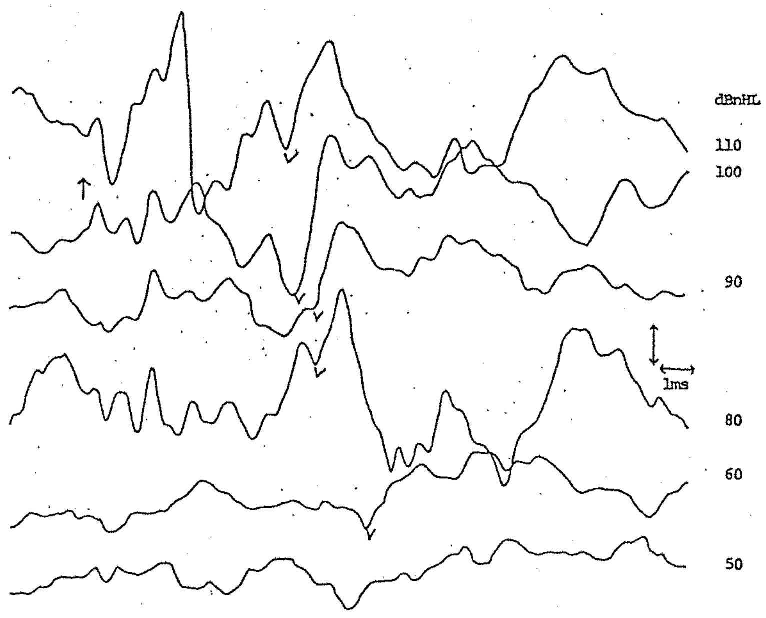


Fig 6.10(a) Left ear stimulation; left record. Subject AD.

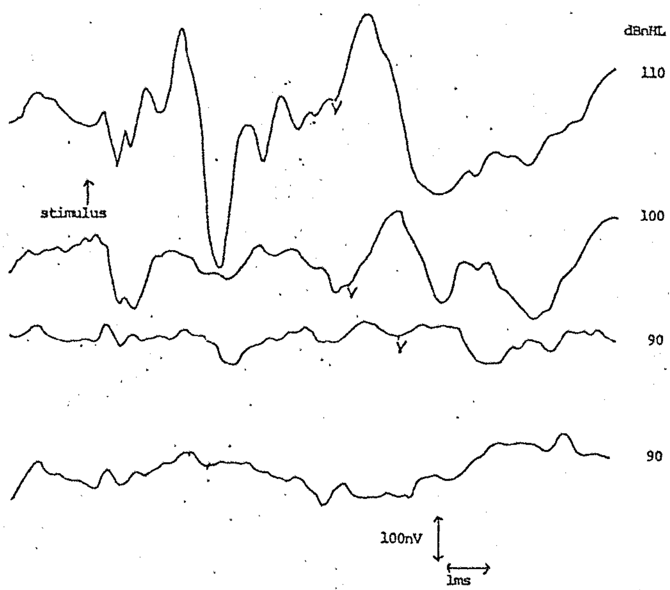


Fig 6.10(b) Right ear stimulation; right record. Subject AD.

I/O functions : subject AD (Group 2)

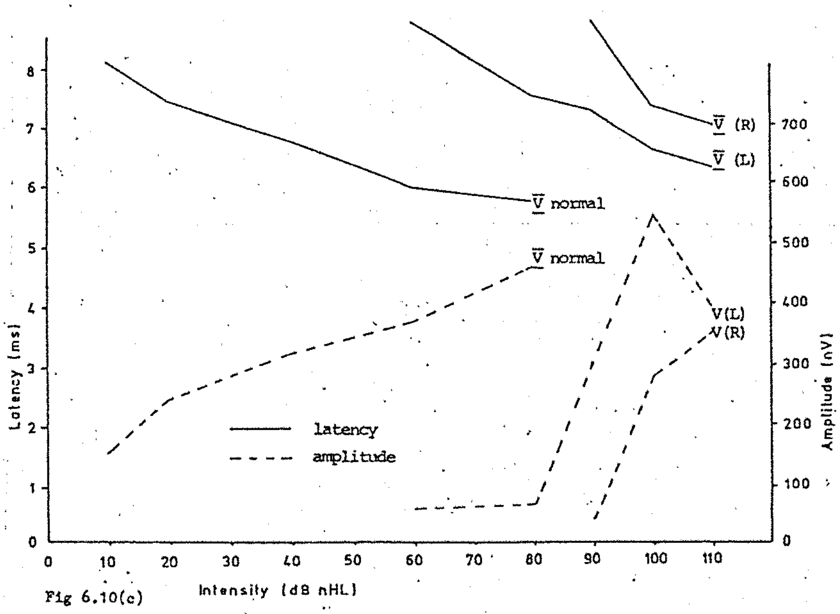


Fig 6.10(c)

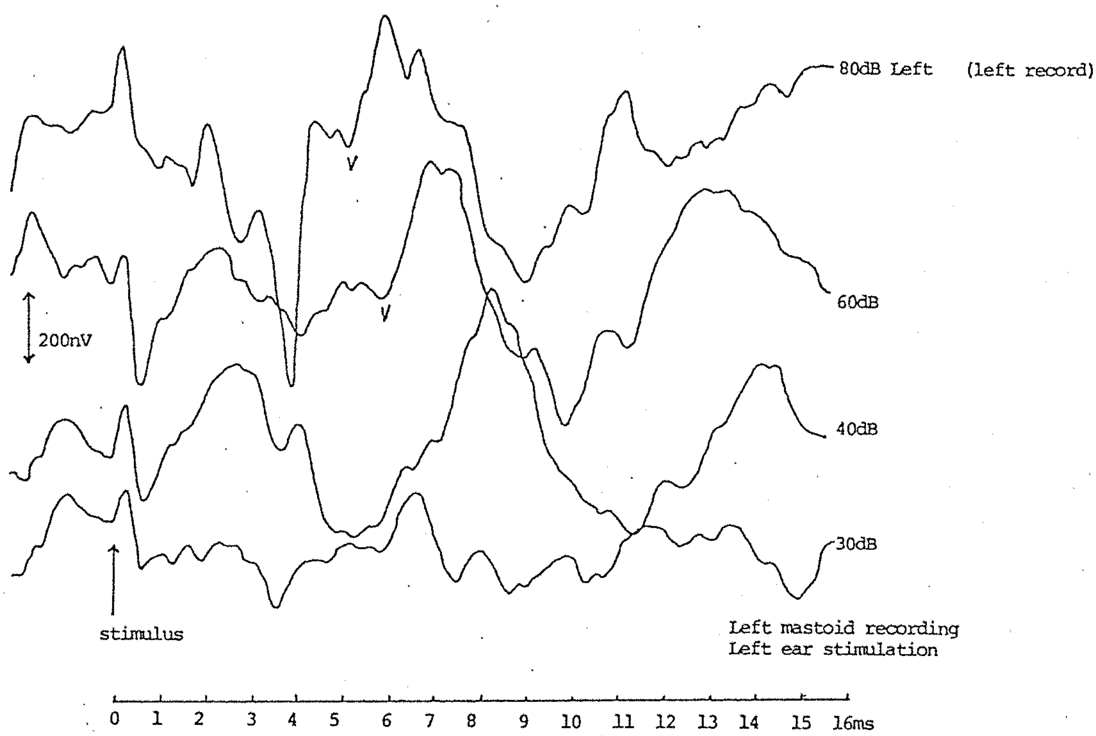


Fig 6.11(a)

MW age 8

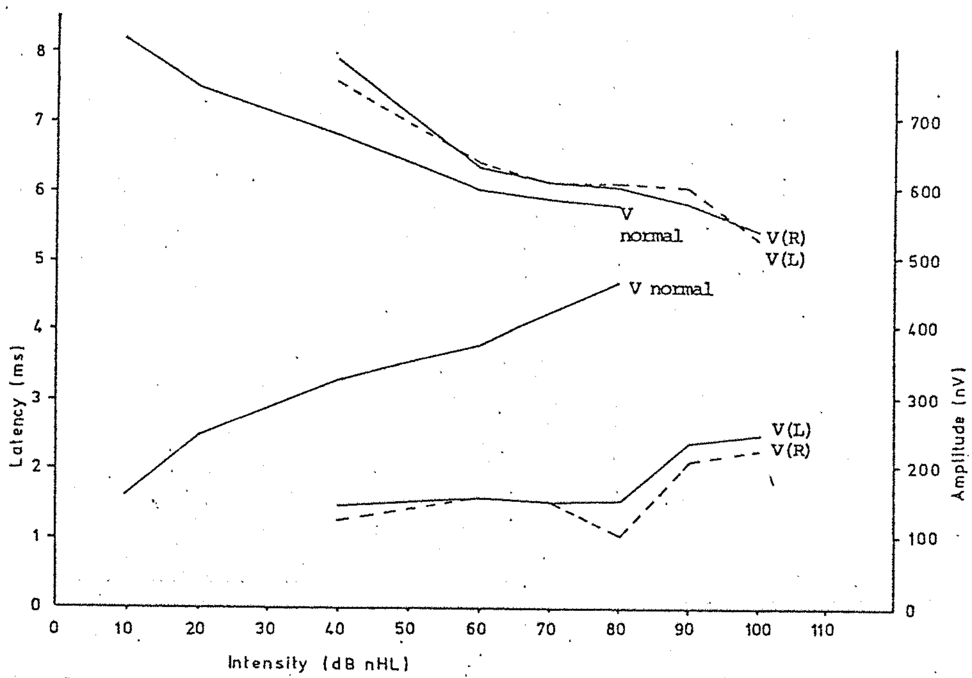


Fig 6.11(b)

I/O function: subject MW (Group 2)

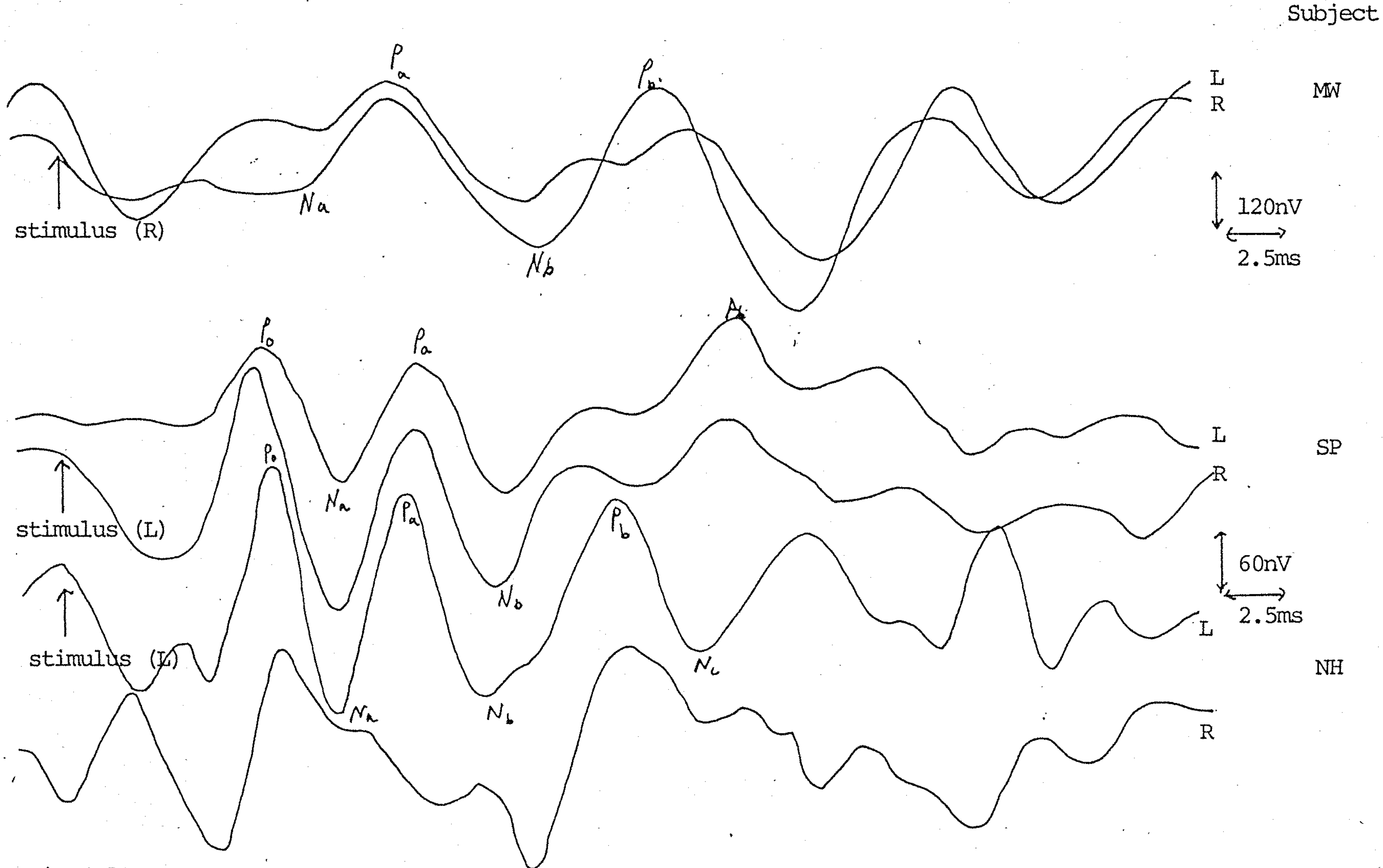


Fig 6.12 Three examples of MLR records from subjects with differing hearing losses

Cases CN, ZK and EM had very clear responses, just 10 dB above the "no response" level. There was insufficient data to plot an intensity-latency function. Again, the most prominent peak complex occurs at 3-4 ms. In the case of subject ZK, myogenic activity was very high, and the large response in the 7 - 11 ms region is probably myogenic in origin. In contrast, subject CN was extremely relaxed and this later complex was not observed.

These results are contrasted with a recording from a subject where this rapid growth in amplitude was not observed (PB in Fig 6.7), and with a subject where no response was recorded (TG in Fig 6.8.). Audiometric information is given in Fig 6.1 for each of these subjects from Group 1. Subject PB is notable because he has a steeply sloping audiogram, in comparison with the subjects described earlier. Although these functions suggest a recruitment type phenomenon, there were not strong correlations between the behaviourally measured uncomfortable loudness level and the slopes of the latency or amplitude functions, as shown in the contingency table (Table 6.3). For subjects from Group 1, individual comparisons could not be made of ABR amplitude growth versus uncomfortable loudness levels, as the latter were too high to be recorded in each case.

The ABR waveforms recorded from subjects in Group 2 were generally of the more normal morphology and character. The ULL's were recorded from subjects in Group 2, and small dynamic ranges were observed in each case. The abnormally steep input-output function was observed in one subject in Group 2 (PS), which was of further interest in that the phenomenon occurred at lower stimulus levels. PS has an unusual hearing loss configuration, with a dip in the mid frequencies. Subject PS also had one of the larger dynamic ranges, at 30dB (in each case the smallest range for that particular subject was compared). Fig 6.9 summarises the audiometric information on these subjects from Group 2.

The Spearman Rho non-parametric statistic was used to examine the relationship between the dynamic range and the steepness of the latency- and amplitude-intensity functions. These were small at 0.18 and 0.55 respectively.

In Figures 6.10a and 6.10b, the recordings for a subject with an asymmetric hearing loss, from Group 2 (AD), show a comparison between the gradual intensity effects recorded from his better ear and the steeper slope from his profoundly impaired ear. This is shown more clearly in the latency- and amplitude-intensity functions (Fig 6.10c). AD has a very steeply sloping loss on his poorer side. The results were not thought to be influenced by hearing cross-over, as shown by masking increases on the good side.

Another example of results from a subject with a moderate loss is shown in Figure 6.11a and 6.11b. This subject (MW) has a bilateral loss, similar in degree on both sides, but with an asymmetric configuration. Similar waveforms and input-output functions were recorded from both sides, and the slope is similar to that found in normal subjects. The slope of the audiometric configuration is only moderate. His MLR responses are shown in Figure 6.12.

6.3.1.5 Middle Latency Responses

Middle latency responses were successfully recorded from 6 subjects in Group 2. However, in each case the contralaterally recorded waveform latencies were markedly similar to values recorded from the normal hearing group. The ipsilateral data differed significantly. The mean ipsilateral latency value for the hearing-impaired group is 22.9 ms (s.d. 1.25 ms), compared to the normative value of 27.86 ms. The difference between ipsilateral and contralateral records was not seen in the hearing-impaired group. Examples of the waveforms are shown in Figure 6.12. This features subjects with moderate (MW) and severe losses (SH and NH) respectively.

Thresholds were recorded to within 10 dB HL of the ABR responses in all but one case.

6.3.2 Comparison of Electrophsiological and Behavioural Data

The data suggested that a major contribution to the hearing loss was located centrally in only one subject, LT, on the basis of comparisons between the audiometric data and ep data. The minor discrepancies encountered in other subjects are probably due, at least in part, to the effects of transmission of the acoustic stimuli through a damaged cochlea, and this will be discussed further later.

Subject LT was attending a small, private school for normal hearing children, and was receiving remedial help from a peripatetic teacher of the deaf for three hours a week. The initial audiometric tests showed a moderate to severe, slightly asymmetrical, hearing loss, with a mild conductive component on the right. Since this agreed with her most recent audiological report, there was no reason to doubt this. Middle ear and acoustic reflex function were within the normal range, although compliance was on the low side of normal on the right. Speech audiometry (AB word lists) was carried out on this child, as her listening behaviour gave resason for suspicion, and speech thresholds were compatible with a pure tone average of 30 dB HL.

LT had been referred to the experimental study as a child who was thought to be managing badly at school, even making allowance for her hearing loss. The extent of the hearing loss was considered to be in some doubt, despite a series of repeatable audiograms. Her speech was normal, and in the psycho-educational component of this experiment she scored above the average. In addition to her auditory symptoms, she complained of dizziness when climbing, and objective rotatory vertigo after swimming. There was nothing in her case history to suggest the reason for her hearing loss, which was detected at six years of age, with uncertain date of onset.

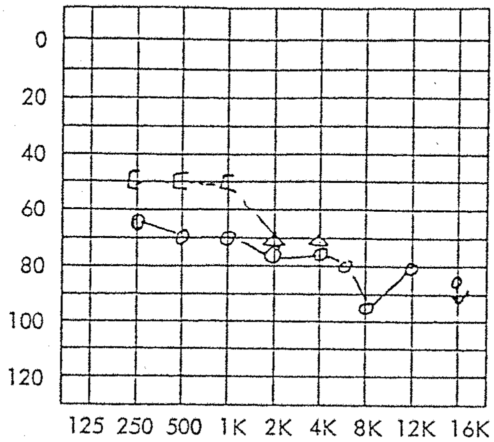
LT's ABR thresholds were recorded near normal levels (left ear, 5 dB; right ear, 15 dB) , raising the suspicion of central auditory involvement, or a non-organic element in her loss. MLR thresholds were recorded to 30 dB, bilaterally, which, given the poorer recording conditions with the children than the adult normals, shows only a minor deviation from the normal. It is noted, however, that the discrepancy is larger than for any other subject. SVR thresholds at 0.5, 1, and 2 kHz were carried out, but normal thresholds could not be determined. This was possibly due to high levels of physiologic noise which also appeared on repeat testing. Clear responses were recorded only as low as 45 dB nHL at 1 kHZ. LT was referred to the Wessex Regional Audiology Unit at I.S.V.R., Southampton University, for a further, independent assessment. Behavioural testing was in agreement with the findings of this study, and the SVR recordings showed similar results.

This case presents something of a puzzle, since the mild discrepancy in ABR and MLR thresholds, and the absence of SVR thresholds, suggest that a central component cannot be eliminated as a cause of this child's auditory difficulties. However, an alternative explanation is that the discrepancies

RIGHT EAR

a-c threshold 0 (● = possible or def. shadow)

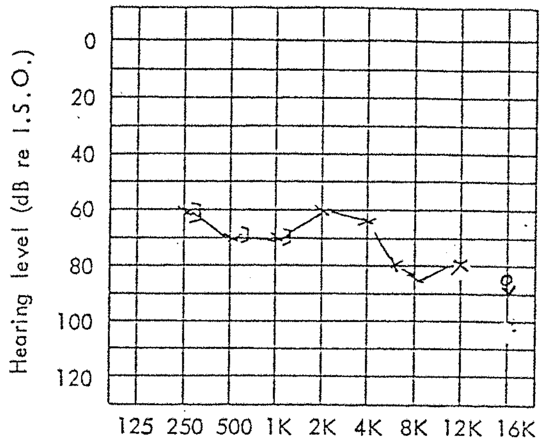
b-c threshold = [(Δ = not masked)



LEFT EAR

a-c threshold X (X̂ = possible or def. shadow)

b-c threshold =] (Δ = not masked)



Comments :

THRESHOLD ADAPTATION

(Carhart Procedure)

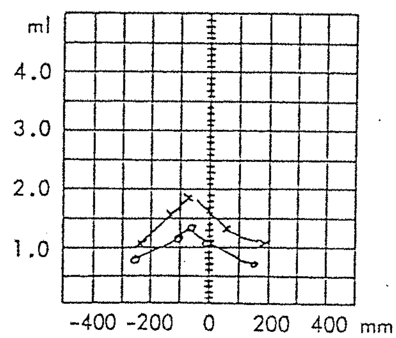
RIGHT	HERTZ	LEFT
– dB	4000	– dB
– dB	2000	– dB
– dB	1000	– dB

Comments :

TYMPANOMETRY (refers to probe ear)

	Probe in (R)	Probe in (L)	
Middle-ear pressure (normal -100 to +50)	-50	-25	(mm H_2O re atm.)
Middle-ear compliance (normal 0.3 to 1.5)	0.5	0.7	(ml equiv. air vol.)

Comments :



ACOUSTIC REFLEX (refers to stim. ear)

	Signal in (R) Contralateral	Signal in (R) Ipsilateral	Hz	Signal in (L) Ipsilateral	Signal in (L) Contralateral
Threshold (tones) dB (HL)	105	105	500	105	90
	105	105	1000	110	90
	115	115	2000	110	80
	115	115	4000	110	95
Reflex growth	normal	normal		normal	normal
White noise (dB SPL)					

Fig 6.13(a) Subject LT. Audiological Summary.

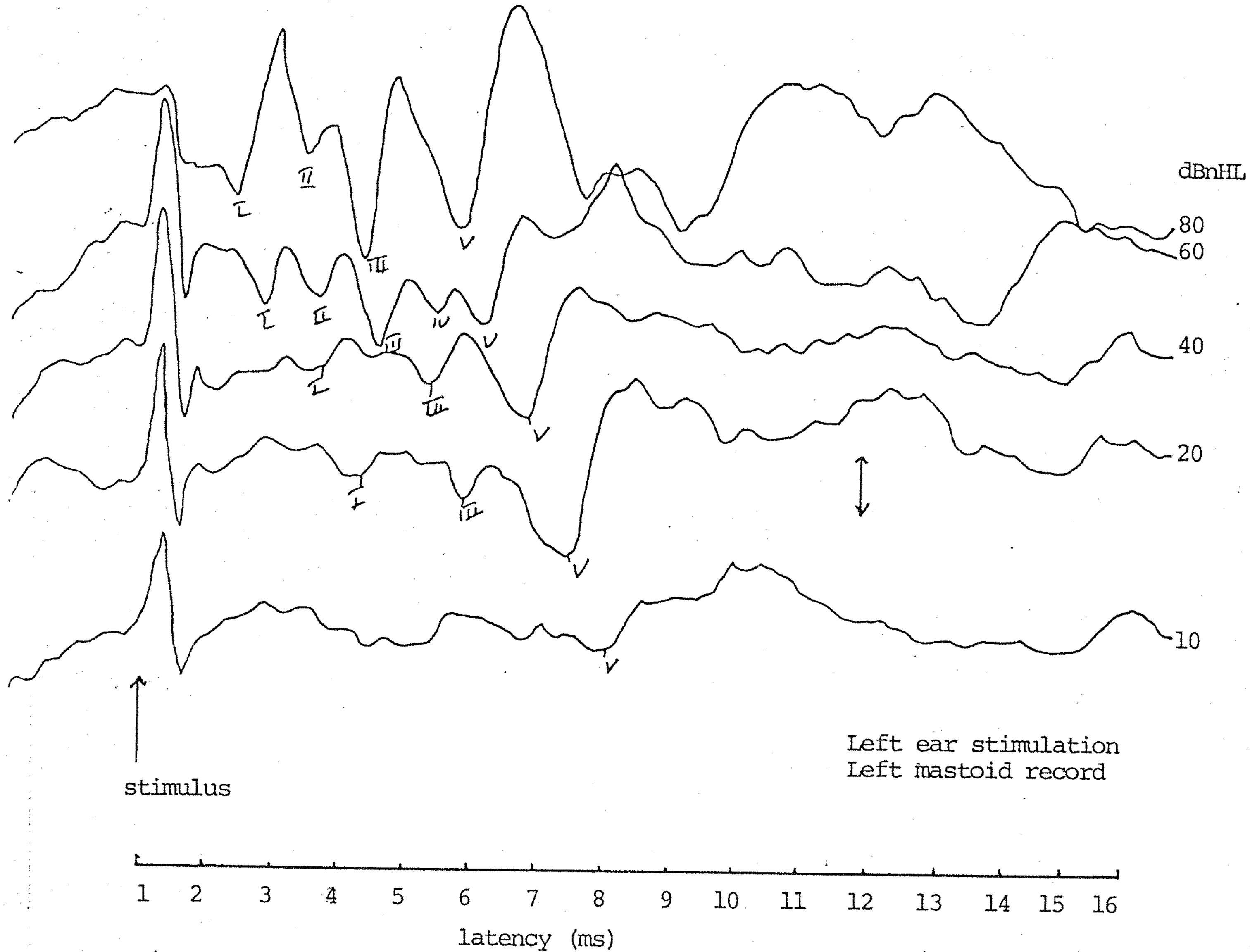


Fig 6.13 (b)

Subject LT

were due, at least in part, to a non-organic element in her hearing loss. The ep tests have confirmed normal peripheral acuity, and there is a mild suspicion of some central problems on the basis of these tests. But examination of the entire audiological picture suggests that at least part of the problem may be non-organic. Her high performance on psycho-educational tests and her good speech intelligibility support the suspicion of a non-organic element. However, her associated symptoms may also be taken at this stage as mildly neurological or as typical of non-organic behaviour. Her manner was, however, sufficiently "deaf" that she had participated in a number of charity and publicity occasions for the hearing-impaired. The referral source was advised accordingly. Further study on this case was also arranged. A synopsis of LT's results appears in Figures 6.13a and 6.13b.

A rank value was given to each child in Group 1, as described earlier, and the ABR results were examined against this background. Of the subjects thought to be displaying the recruitment type phenomenon, the ranks were as indicated by the first figure in parentheses below, and do not relate in an orderly fashion to the ABR results; KN(16, 4), CN(2, 3), MC(5, 5), ZK(20, 4), and EM(3, 2). The second figure is the speech intelligibility score, where 1 is a high score, as described in Chapter 4. Individual cases are summarised in Appendix 2.

6.3.3 Factoring of Electrophysiological Data.

A factor analysis procedure was used to summarise the inter-relationships between the variables in a concise manner. The basic factor model assumes that the variables are additive components of weighted factor, or hypothetical constructs. The data from both groups were pooled for this analysis, and a correlation matrix prepared. Principal component analysis was carried out, where the data were transformed prior to factoring, if necessary, to yield a set of composite variables that are orthogonal (See Appendix 3).

Based on the input matrix, a summary table of the statistical data obtained from the ep measures is given in Table 6.6. A summary of the more notable correlations (greater than 0.6) yielded by the first stage of the factor programme is shown in Table 6.7. The ABR threshold and the best behavioural

Table 6.6

SUMMARY DATA OF ELECTROPHYSIOLOGICAL RESULTS

Variable	Mean	S.D	Cases
Wave V threshold (WE)	107.00	30.64	35
Wave V threshold (BE)	101.43	32.71	35
Latency/intensity f^n (WE)	0.50(0.03)	2.02	35
Latency/intensity f^n (BE)	0.15(0.)	0.76	35
Amplitude/intensity f^n (WE)	1.24(0.30)	2.42	35
Amplitude/intensity f^n (BE)	1.36(0.30)	2.36	35
Wave V latency * (WE)	8.71(8.12)	1.58(0.46)	35
Wave latency * (BE)	8.58(8.12)	1.58(0.46)	35
Monaural/binaural diff. ratio	0.54	1.06	35
MLR threshold	117.06	27.22	34
Best PTT (anyf) (WE)	79.43	24.64	35
Best PTT (anyf) (BE)	71.14	24.65	35
PTT at 2kHz (BE)	97.35	29.63	34

* Wave V latency at threshold
(normal values in parenthesis, where appropriate)

Table 6.7 SUMMARY OF NOTABLE CORRELATION COEFFICIENTS (0.60)

	JVW	JVLAW	IOAMW	BTAFW	JVB	MLRB	JVLAB	IOAMB	BTAFB
JVW	1.00	0.68	0.59	0.67	0.93	0.77	-	-	0.66
JVLAW	0.68	1.00	-	-	0.61	-	0.76	-	-
IDAMW	-	-	1.00	-	0.61	0.70	-	0.71	-
BTAFW	0.67	-	-	1.00	0.72	0.69	-	-	0.94
IJB	-	-	0.72	0.73	1.00	0.64	-	-	0.74
IOLAB	-	-	-	-	-	0.80	-	-	-
MLRB	0.77	-	-	0.64	-	1.00	-	-	0.57
JVLAB	-	0.76	-	-	0.80	-	1.00	-	-
IOAMB	-	-	0.71	-	-	-	-	1.00	-
BTAFB	0.66	-	-	0.94	0.74	0.57	-	-	1.00

pure tone threshold value, independent of frequency, gave a correlation of 0.67 (better ear). The relationship between the 2 kHz pure tone threshold and the ABR threahold is shown in a scatter plot in Fig.5.14. There is a moderate strength correlation (0.8) between the response latency at threshold and the ABR threshold intensity level. There is also a moderate correlation between the ABR and MLR threshold techniques.

The method of principal factoring, without iteration, was used. In the principal component matrix, Table 6.8, the eigenvalues associated with each component represent the amount of total variance accounted for by the factor. The adjacent column gives the percentage of total variance accounted for by this factor (See Appendix 3 for details).

Table 6.8

PERCENTAGE OF TOTAL VARIANCE ASCRIBED TO EACH FACTOR

Factor	Eigenvalue	% of Variance
1	5.899	49.2
2	1.807	15.1
3	1.289	10.7
4	0.979	8.2
5	0.615	5.1
6	0.583	4.9
7	0.283	2.4
8	0.240	2.0
9	0.140	1.2
10	0.097	0.8
11	0.033	0.3
12	0.028	0.2

The initial factor matrix represents the regression weights of the common factors (Table 6.9a). Factor 1 can be seen to be the most important determinant of the Wave V thresholds, the Wave V latencies at threshold, the MLR threshold, and the audiometric data. There is an obvious loading on threshold-related phenomena. In contrast, the latency-intensity functions for both ears are loaded on Factor 2, and the amplitude-intensity functions

Table 6.9a

FACTOR MATRIX, USING PRINCIPAL DEFINED FACTORS,(NO ITERATIONS)

	Factor 1	Factor 2	Factor 3	Communality
Wave v threshold (WE)	0,894	0,122	0,075	0,819
Wave v threshold (BE)	0,943	0,136	-0,033	0,841
MLR threshold	0,785	0,327	-0,289	0,806
Wave v latency (WE)	0,745	-0,395	0,323	0,814
Wave v latency (BE)	0,636	-0,383	0,538	0,908
Best PTT (any f.) (WE)	0,796	0,347	0,158	0,779
Best PTT (any f.) (BE)	0,777	0,377	0,292	0,831
Latency/intensity f^n (WE)	-0,039	0,530	0,065	0,287
Latency/intensity f^n (BE)	-0,236	0,839	-0,033	0,761
Amplitude/intensity f^n (WE)	-0,755	0,106	0,560	0,895
Amplitude/intensity f^n (BE)	-0,54	0,314	0,614	0,776
Monaural/binaural ratio	-0,0687	0,079	0,014	0,478

Table 6.9b

VARIMAX ROTATED FACTOR MATRIX

	Factor 1	Factor 2	Factor 3
Wave v threshold (WE)	0.826	-0.367	-0.048
Wave v threshold (BE)	0.820	-0.485	-0.025
MLR threshold	0.609	-0.618	0.230
Wave v latency (WE)	0.696	-0.108	-0.563
Wave latency (BE)	0.707	0.132	-0.568
Best PTT (any f.) (WE)	0.833	-0.234	0.175
Best PTT (any f.) (BE)	0.886	-0.107	0.186
Latency/intensity f^n (WE)	0.118	0.106	0.511
Latency/intensity f^n (BE)	-0.025	0.135	0.862
Amplitude/intensity f^n (WE)	-0.358	0.864	0.144
Amplitude/intensity f^n (BE)	-0.109	0.821	0.301
Monaural/binaural ratio	-0.575	0.330	0.198

on Factor 3. The monaural/binaural amplitude ratio is loaded on Factor 1, with the threshold-related phenomena.

A simplified analysis was obtained by Varimax rotation (see Appendix 3) and is reported in Table 6.9b. This technique simplifies the regression weights (columns in the matrix). Comparison of the results with oblique rotation did not alter the main findings. The common variance in the threshold-related variables, including the latency of Wave V at threshold, is more clearly seen. There is little variance in common with the amplitude-intensity function (loaded on Factor 2) and the latency-intensity function (loaded on Factor 3), except that there is a common underlying relation between the latency-intensity function and the latency of Wave V at threshold. This is expected, on the basis that the slope of the latency-intensity function in normals varies according to the absolute latency of Wave V.

Figure 6.15 shows a graphical presentation of rotated orthogonal factors. Three figures are shown, such that each factor pair may be presented, using two-dimensional space. From this diagram, it can be seen that the Wave V threshold values, the latency values at threshold, the middle latency, and audiometric threshold all load highly on Factor 1. The three ep also have a fairly high negative loading on Factor 2. The amplitude-latency function data, for both ears, are the only variables to have a high positive loading on Factor 2. The monaural/binaural amplitude ratio shows a high negative loading on Factor 1. The latency-intensity function has a small loading on both Factors 1 and 2, but can be seen to have a strong positive loading on Factor 3. The latency values at threshold have a strong negative loading on Factor 3, but the other threshold data have a small loading on this factor.

In summary, these data, yielded from the factor analysis procedure demonstrate a common source of variance in the threshold data, common unrelated factors underlying the latency-intensity data, and a third source of variance underlying the amplitude-intensity data.

When the data are considered by ear (better or worse), a two factor pattern emerges. For the better ear, the threshold data (Wave V, MLR and best pure tone threshold) load heavily, but only on Factor 1. The latency-intensity loads heavily, only on Factor 2. The latency value of Wave V at threshold has a high negative loading on Factor 2 and a small loading on Factor 1. The amplitude variables do not load heavily on either factor (Fig. 6.16a). Similar results are revealed by a factor analysis on the worse ear data (Fig 6.16b).

6.3.4 Factor Analysis of the Audiometric and Electrophysiological Data.

Having identified variance common to the principal parameters of the ep data base, a similar study with a subset of the audiometric data was carried out. Again, data were pooled from both groups. Table 6.10 gives a summary of the variables examined, together with their statistical summary. The most

Scatter diagram of the PTT at 2kHz vs a function of Wave V threshold

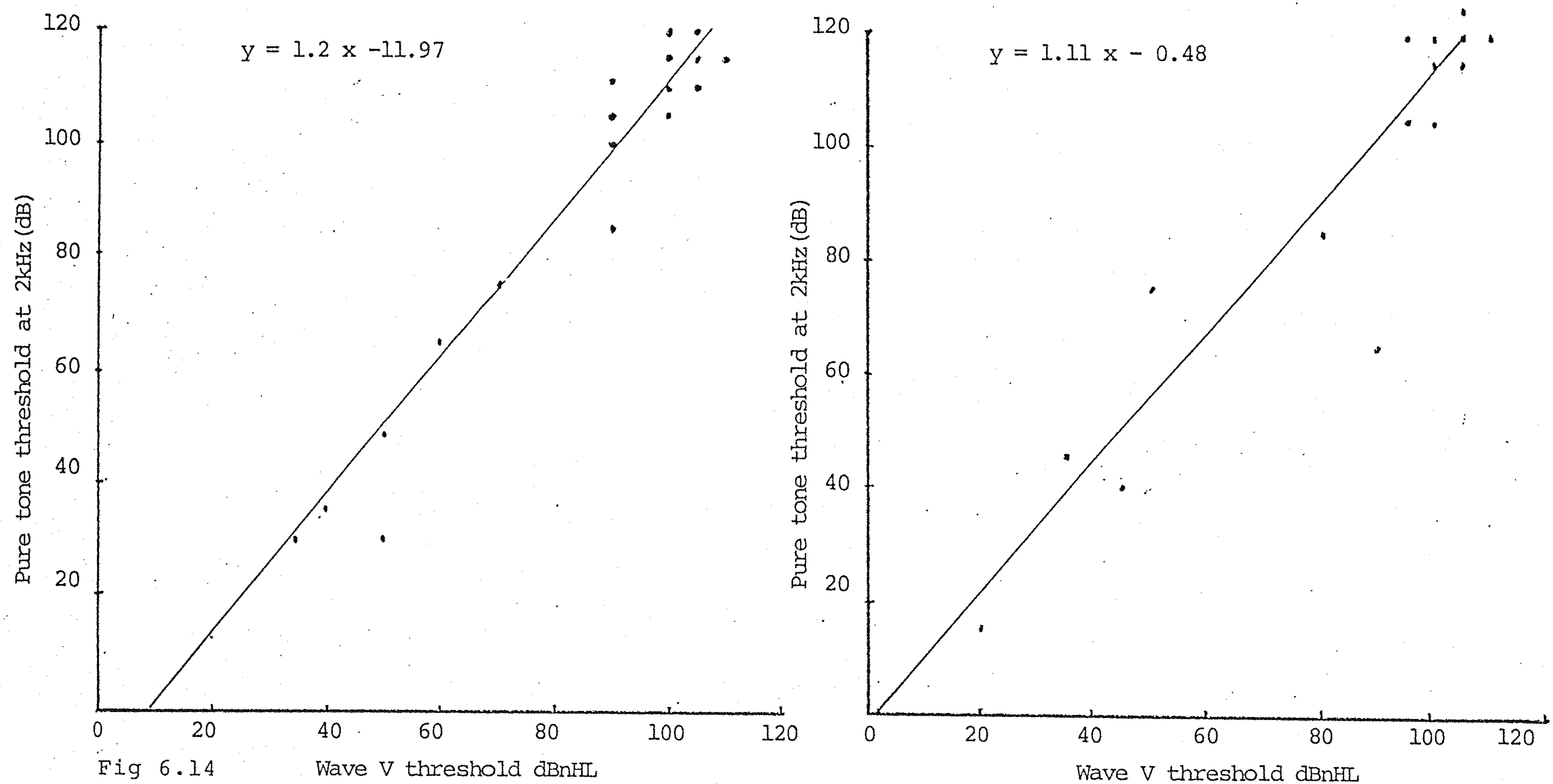
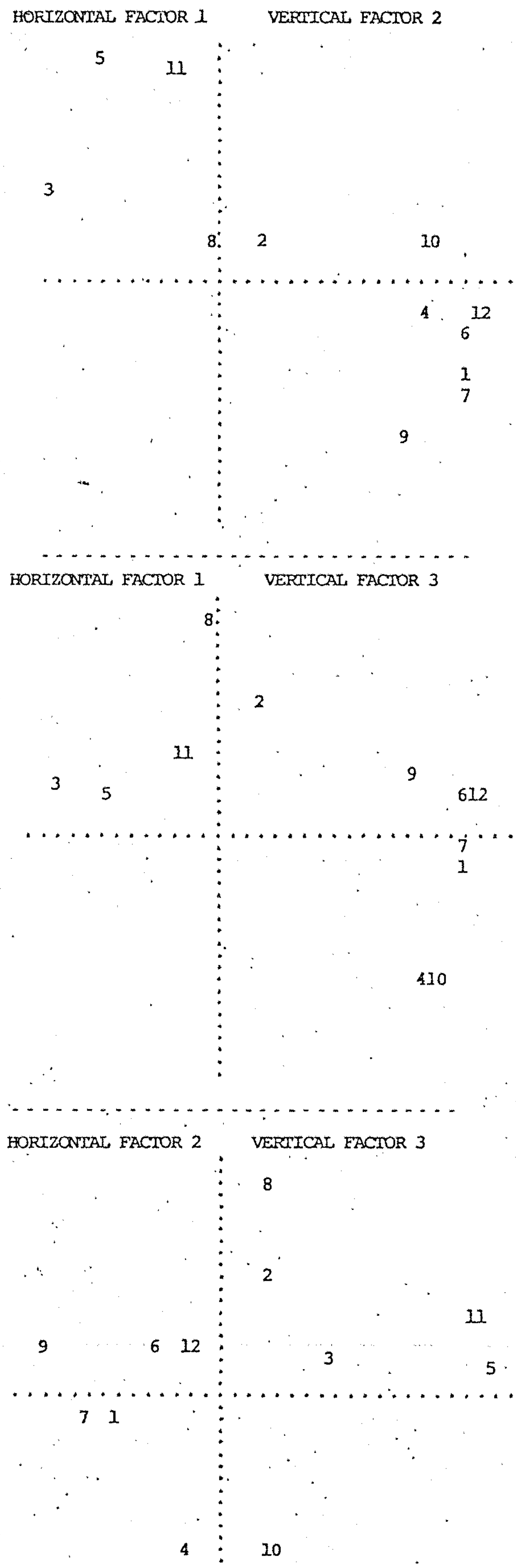
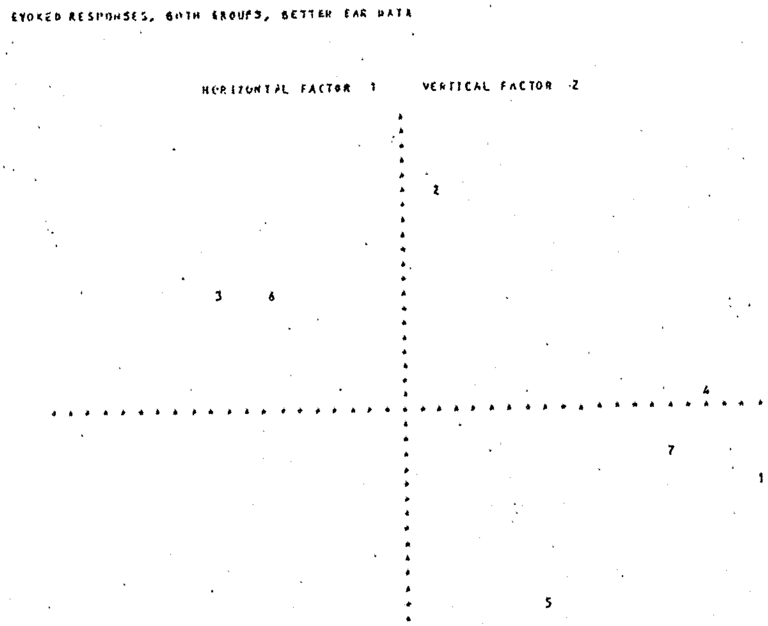


Fig 6.14



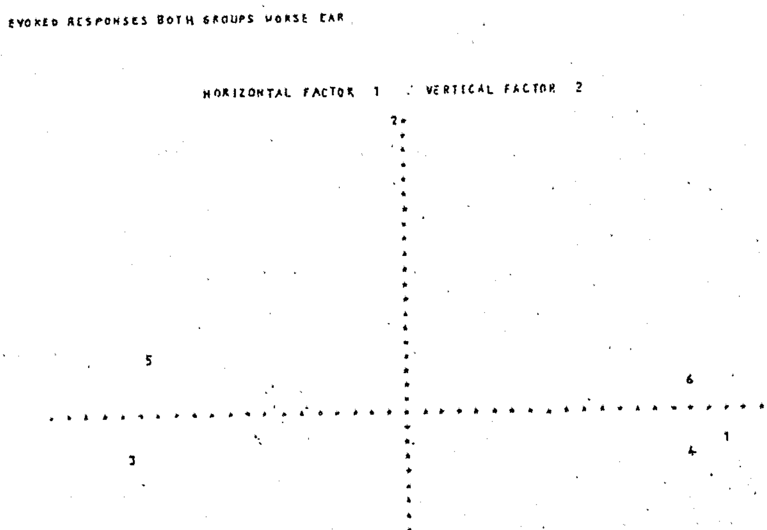
1 = Wave V threshold (WE)
2 = Latency/intensity function (WE)
3 = Binaural/monaural ratio
4 = Wave V latency at threshold (WE)
5 = Amplitude/intensity function (WE)
6 = Best pure tone threshold (WE)
7 = Wave V threshold (BE)
8 = Latency/intensity function (BE)
9 = MLR threshold (BE)
10 = Wave V latency at threshold (BE)
11 = Amplitude/intensity function (BE)
12 = Best pure tone threshold (BE)

Fig 6.15 Graphical presentation of rotated (varimax) orthogonal factors (for evoked response data, both ears)



1 = Wave V threshold
2 = Latency/intensity function
3 = Monaural/bineural amplitude ratio
4 = MLR threshold
5 = Wave V latency at threshold
6 = Amplitude/intensity function
7 = Best pure time threshold

Fig 6.16(a) Graphical presentation of rotated (varimax) orthogonal factors



1 = Wave V threshold
2 = Latency/intensity function
3 = Monaural/binaural amplitude ratio
4 = Wave V latency at threshold
5 = Amplitude/intensity function
6 = Best pure tone threshold

Fig 6.16 (b) Graphical presentation of rotated (varimax) orthogonal factors notable correlations yielded for the initial matrix of correlation coefficients are listed in Table 6.11. Correlations between ears, and correlations less than 0.60, have not been reported; those remaining are threshold-related.

Table 6.11

SUMMARY OF MOST NOTABLE CORRELATIONS

PTA average (6 freq) (BE) and Wave V threshold (BE)	= 0.69
PTA average (6 freq) (WE) and Wave V threshold (WE)	= 0.67
Dynamic range (BE) and Wave V threshold (BE)	= 0.69
Dynamic range (BE) and Wave V threshold (WE)	= 0.71
Dynamic range (WE) and Wave V threshold (WE)	= 0.66

Table 6.12

PERCENTAGE OF TOTAL VARIANCE ASCRIBED TO EACH FACTOR

Factor	Eigenvalue	% Of Variance
1	4.827	28.4
2	2.783	16.4
3	2.343	13.8
4	1.989	11.7
5	1.578	9.3
6	1.206	7.1
7	0.730	4.3
8	0.550	3.2
9	0.487	2.9
10	0.388	2.3
11	0.264	1.6
12	0.203	1.2
13	0.074	0.4
14	0.037	0.2

The method of principal factoring, without iteration, was used to reduce the correlation matrix. The percentage of the total variation ascribed to each of the new factors generated is shown in Table 6.12. Six factors were extracted from this array by principal component analysis, accounting for 86% of the total variance. The resultant factor matrix was rotated, by the Varimax technique, in an attempt to simplify the factor structure. The dominant features of the factor matrix are shown in Table 6.13.

Table 6.13 EXTRACTS FROM THE ROTATED FACTOR MATRIX

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Average PTA (6 freq.) (BE)	0.86	-	-	-	-	-
Average PTA (6 freq.) (WE)	0.91	-	-	-	-	-
Weighted PTA (BE)	-	-	-	0.94	-	-
Weighted PTA (WE)	-	-	-	0.82	-	-
High Frequency Data	(0.57)					
Dynamic Range (BE)	-0.74	-	-	-	-	-
Dynamic Range (WE)	-0.72	-	-	-	-	-
Wave V Threshold (BE)	0.92	-	-	-	-	-
Wave V Threshold (WE)	0.90	-	-	-	-	-
Latency/Intensity f^n (BE)	-	-	-	-	-	0.78
Latency/Intensity f^n (WE)	-	-	-	-	-	0.79
Amplitude/Intensity f^n (BE)	-	-	0.89	-	-	-
Amplitude/Intensity f^n (WE)	-	-	0.94	-	-	-
Wave V Latency at T. (BE)	-	0.86	-	-	-	-
Wave V Latency at T. (WE)	-	0.93	-	-	-	-
Tone Decay (BE)	-	-	-	-	0.87	-
Tone Decay (WE)	-	-	-	-	0.88	-

Only factors loading ±0.60 are reported, for simplicity. From the factor matrix, the factor diagrams were produced graphically, each of the six being paired with every other factor (not illustrated). From these data, the following observations were drawn: The threshold related data load heavily on Factor 1. This is the only dominant clustering of variables. 28% of the variance in the data is accounted for by Factor 1, and predominantly underlies the variables of pure tone average, the Wave V thresholds, the dynamic range and the high frequency data. The remaining variables have only been simplified to cluster by test ear, since the variables each load, paired, on to a single factor.

In summary, the factor analysis has not shown a significant data reduction, or revealed underlying correlations other than among the threshold data. It is interesting that the weighted threshold data do not relate to the other data more strongly.

6.4 DISCUSSION

6.4.1 Threshold Studies

The ep data yielded by this study do not suggest that central auditory impairment is a major factor in the poor speech, or psychoeducational progress, of the participating subjects. The presence of central auditory factors have not been totally excluded, and the possibility of central involvement has been discussed for individual cases.

6.4.1.1 Group 1 Data

In Group 1, most subjects showed hearing losses too severe for complete analysis of threshold data comparisons. The experimental data confirmed the presence of a severe peripheral deficit in each child, whilst not fully enabling investigation of site of dysfunction at a higher level. The technique has the advantage over behavioural methods that severe peripheral deficit can be confirmed, avoiding risk of causing peripheral damage by over amplification, should the site of dysfunction lie more centrally.

Where ABR responses were recorded, the ep data appear predominantly to reflect the output of a damaged cochlea, and the unusual response patterns probably reflect abnormal peripheral activity. It does not appear that there is a relationship between the subjects thought to be showing some kind of recruitment phenomenon from the ABR data and the behavioural data. The comparison with subject rank and speech intelligibility of the subject data, where ABR results could be analysed, are somewhat inconclusive, although KN (rank 16, speech intelligibility score 4), MC (rank 5. speech score 5) and ZK (rank 20 speech score 4) all have poor speech intelligibility and show a rapid amplitude growth in the ABR I/O function. This effect was not seen for subjects CN (rank 2, speech intelligibility score 3) and EM (rank 3, speech intelligibility score 2), who both have relatively better speech. Additionally, KN and ZK were notable as very poor and reluctant hearing aid users. This would be compatible with poor loudness tolerance and very small dynamic range - a property which is not easy to measure in young children. Analysis of the school audiological records showed that these two children were said "not to be showing recruitment problems", which, it transpired, meant that no attempt had been made to investigate loudness growth due to the extent of hearing loss. This is a misconception which may have severe practical limitations.

Loudness recruitment is defined as the observation of abnormally rapid increase in loudness in ears, at elevated sound thresholds. In children, it's presence may be observed by measurement of Uncomfortable Loudness Level (ULL) or by measurement of acoustic reflex thresholds. Due to audiometric limitations, neither of the latter was measurable, for any of the subjects in Group 1, although both were attempted in all cases. There are some practical difficulties in the assessment. Where a severe or profound loss limits the test of the upper limit of the dynamic range exceeds the audiometer maximum output, then a child may be mistakenly labelled as "not recruiting". Loudness discomfort levels need to be carefully and individually calculated in hearing-impaired subjects, as there is poor correlation between LDL's and hearing levels (e.g. Kawell et al., 1988). There has been little work on the accuracy of LDL measures with hearing-impaired children, and guidelines for hearing aid fittings have been generally based on coupler measures (e.g. Matkin, 1986). There is a possibility then, that hearing aids could be fitted with over-amplification as far as loudness comfort is concerned, and that these ABR measures are the first indication that this is happening. Case 6 (ZK), described in Appendix 2, may be an example of this.

The recruitment phenomenon is comparatively recently understood. Studies on the whole nerve action potential and on single fibre responses have been used to examine the physiological basis more specifically. It was thought that the inner and outer populations of hair cells had different thresholds. On this basis, loudness would be coded in terms of which nerve fibres were active, and abnormal loudness growth accounted for in terms of the differential loss of the different types of hair cell. Since the range of thresholds of different nerve fibres is of the order of only 20 dB it is more likely that the changed form of the physiological tuning curves, as a result of cochlear pathology, can account for abnormal loudness growth, on the assumption that loudness is related to the total number of active nerve fibres and to the amount of activity in each. Evans (1975) has been a strong proponent of this neural explanation.

In the normal ear, the physiological tuning curves, as indicated by single-cell recordings from the auditory nerves of animals, have a characteristic shape and frequency. As the stimulus intensity of a signal is raised from some level below threshold, at first only the tips of the curves are activated, and the number of fibres involved will be small. With increased stimulus intensity, there comes a point when the tails of other tuning curves are encountered, and the number of fibres activated thus rises abruptly. In the pathological ear, the effect seems to be to destroy the fine tuning of the curves, leaving only the broad shallow tails. Stimulus intensity has now to be increased considerably before any fibres at all are activated (i.e. before the threshold is elevated) but, as soon as threshold is exceeded, the fibres are recruited rapidly, since the stimulus has already reached the area of the broad tails where the fibre tuning-curves overlap. Apart from the recruitment or activation of new fibres, any one fibre has a dynamic range of activity (of about 40 dB) from threshold to saturated firing, and the functions relating cochlear-fibre discharge rate with stimulus level are steeper in pathological fibres than normal.

Interpretation of the ABR response, against this theory, suggests that as they rapidly increase in amplitude above threshold, they reflect innervation of the broadly tuned curves. Eggermont (1978) defined a population of recruiting ears, which have shorter than normal ABR latencies, and have broad tuning curves, without a sharply tuned part, and a decreased steepness of the high frequency slope. He contrasted this group, whom he found to have a W-shaped narrow band action potential, with normal subjects showing a biphasic action potential. Possibly subjects ZK, KN, and MC, having the very early latency Wave V and the steeply rising amplitude function belong to the first group, and EM and CN to the second. Poor speech perception would result from both the reduced dynamic range available and the resultant broad tuning curves.

The second feature of importance, relating to the threshold studies, is the absence of an MLR response, despite clear ABR responses. The normal subject data indicated differences of less than 10 dB between ABR and MLR thresholds. This may be explained if the MLR threshold is less robust in conditions of poor signal-to-noise than the ABR. The normal data obtained, preparatory to the children's study, were obtained from co-operative young adult subjects. Although this was appropriate for normal data collection, in terms of maturation effects, the recording conditions were better than for the experimental group. A study, specifically directed at comparing threshold specificity of the MLR and ABR in worsening conditions of signal-to-noise would be of interest.

There may be an alternative explanation. Three of the subjects in Group 1 (KN, MC, ZK) and one in Group 2 (PS) had clear ABR thresholds 15 dB or more below the pure tone threshold at 2 kHz, and steep latency-intensity functions. None of these subjects showed an MLR response, though it might have been expected to be present. It is suggested that there may be a connection between these phenomena, and that the elevated MLR threshold does indeed reflect a component of central auditory dysfunction, located in the upper brainstem/mid brain, in the child's hearing loss. The steep latency- and amplitude-intensity functions may then be a result of abnormal inhibitory function, with stimulus growth.

It should be noted that KN and ZK were placed in the lower 50% of the group, as defined by the assigned composite rank score, and that each child had very poor speech intelligibility.

6.4.1.2 Groups 1 and 2. Threshold Prediction

The threshold correlation from regression analysis for Groups 1 and 2, omitting cases where no ABR threshold was recorded, was high when the better and poorer ears were considered separately for both 2 kHz and a mid recorded. The scattergram of the comparison at 2 kHz is shown in Fig 6.14, page 276.

The main studies, prior to this, which examine the relation between the ABR responses and pure tone threshold are summarised in Table 6.5, page 254. There are several studies using ECoG. Of these, Parving et al. (1981) sedated their subjects, and found a strong correlation in the high frequencies between the ep threshold and the pure tone thresholds. They only carried out the regression analysis using the 35% of their cases that had a measurable action potential. Similar data were recorded by other workers using this technique, with correlation coefficients varying from 0.55 to 0.92, depending on the comparison frequencies (e.g. Eggermont et al., 1974; Yoshie, 1973; Bergholtz et al., 1977). Each author reported a trend to false positives by ECoG for low threshold values and a certain under estimation for high threshold values. Although those studies used a stimulus similar to that used in the present study, the measurement is a near field record of the action potential, and a better threshold correlation would be expected due to more favourable signal-to-noise conditions. In moderate hearing losses, where pure tone thresholds up to 4 kHz can be considered as the behavioural acuity average, correlation coefficients may be found with ABR which are comparative with the ECoG threshold estimates (e.g. Spoor and Eggermont, 1976).

The correlation coefficients found in the present study, based on the lower pure tone average of 0.5, 1, and 2 kHz, give a more favourable estimate for this sample, and the result of 0.69 (better ear) falls midway in the range of previously reported studies (0.48 to 0.93). Other studies have tended towards a choice of higher frequencies to average (Van der Drift et al., 1987). Previous studies have used subjects with less severe degrees of hearing loss above 2 kHz, however, and the degree of missing data would make this a considerable difference from the present study. This is probably partly because the sample used in this study is narrow and over selective. The data reported in the literature indicate that, in general, the ABR gives an incomplete representation of hearing sensitivity across the frequency range. The estimation error, varying from 11 to 20 dB in previous studies, is partly due to measurement errors and would seem to be partly due to other factors involved in the relationship between the thresholds.

Accounts in the literature suggest that the latency of the Wave V tends to be shorter in cases of flat audiometric configuration than in a sloping high frequency loss. (Møller and Blegvad, 1976; Jerger and Mauldin, 1978; Gorga et al., 1985). It would appear, from the literature (e.g.Keith and Greville, 1987), that audiometric contour is more important than absolute level in determining the ABR latency. Qualitative examination of the data from subjects in Group 2 support this trend. Qualitative examination of response latencies of Group 1 subjects did not show such a marked trend. This is probably a result of the severity of the losses and more extensive cochlear damage, giving excessive missing data at these levels. Absence of a contribution from a particular region of the cochlea can affect the composition and latency of the ABR waves. The moderate correlation shown here is comparable with some of the other studies in which pure tone thresholds are compared with the ABR Wave V thresholds, but are on the low side. The results are influenced by the few subjects where there was an apparent threshold discrepancy and which are discussed later. The other studies cited here are on adults, with moderate, presumed cochlear deficits. A future avenue of investigation would be to examine the audiometric configuration in comparison with the ABR threshold, and the latency-intensity function.

6.4.2 Interpeak Interval

Studies have shown that the waveform is made up of contributions from stimulation at successive sites along the basilar membrane, with Wave I being highly dependent on basal cochlear fibres and Wave V being influenced by contributions initiated from basal to apical regions of the cochlear (Kramer and Teas, 1979; Klein et al., 1981). The shortening of the I-V interval was reported by Coats (1978) and Gorga et al. (1986) as a feature of high frequency cochlear damage. Although Wave V is delayed, it is less delayed than Wave I, this effect being more pronounced at high intensities, where the energy spread along the basilar membrane is greater. This finding was consistently observed in Group 2; only subjects with limited hearing or flat to U-shaped audiograms did not feature this reduction. This is a departure from the long held view, proposed by Coats (1978), that the change was due to a shortening of the Wave V latency. Møller and Blegvad (1976) had found Wave V to be delayed with respect to normals, where the hearing loss was severe in the high frequencies. This discrepancy is most probably due to differences in the test stimulus intensities, and the degree of high frequency loss and slope. Low frequency hearing losses tend to shorten the I-V interval also, due to earlier than normal Wave V latencies, as the Wave V is more dominated by basal activity. Flat and risinig contour audiograms do not yield such abnormal ABRs (Yamada et al., 1979; Keith and Greville, 1986). This is supported here in that the weighted slope average gave a higher threshold correlation than the threshold at 2 kHz. On a qualitative basis, subjects with rising configurations, in Group 2, tended to have a more normal wave morphology. Keith and Greville find U-shaped audiograms to give a prolonged Wave I-V interval, due to the delayed Wave V latency. Their interpretation is that the usual early contributions to Wave V are absent, and its latency is dominated by later occurring activity from further along the basilar membrane. The reverse is true for Wave I. The longer latency components from the 3 to 4 kHz region are missing, producing an earlier than normal Wave I. The failure to record Wave I in patients with severe hearing loss is in agreement with earlier studies (Hyde, 1985).

One of the stronger correlation coefficients found (0.69) was between the weighted average audiogram (i.e. with slope indication) and the Wave V latency. This may be viewed as support for the view that more abnormal delays in Wave V latency occur with higher frequency losses (Bauch and Olsen, 1986). The correlation of the pure tone threshold at 2 kHz with the latency of Wave V may at first seem surprising. Gorga et al. (1985) and others have found thresholds between 2 and 4 kHz to give the best correlation with Wave V latency. Work by Coats (1978), measuring responses to filtered clicks, and Klein (1986), using a masking paradigm, indicate that the phenomenon is due to the systems' altered frequency response. Ultimately, as discussed, the audiogram configuration seems to be the dominant factor. The delayed wave V in the high frequency losses are due to delays in the travelling time in the cochlear partition, and the accumulated evidence now seems to support this view (Terkildson et al., 1975; Don and Eggermont, 1978; Borg et al., 1981; Eggermont et al., 1980).

With this more recent information on the relationship of audiometric configuration to the I-V interval lies the possibility of carefully examining individual records, like those of the present study, to attribute the I-V interval to cochlear and central process differentially. There is not adequate information currently available to do this except in the most qualitative manner. However, in most cases here the delay could be due to cochlear processes and/or to transmission times in the brainstem pathways.

It seems from these measures, and others, that the cochlear influences on latency throughout the ABR waveform restrict analysis in terms of central conduction time, unless the waveform is studied at different intensities, with interpeak slopes available for examination. The differing interpeak intervals measured here are of some interest, although there are too few examples of each type for quantitative treatment of the data.

6.4.3 Monaural versus Binaural Stimulation

In the present study, the enhanced amplitude obtained on binaural stimulation made it possible to follow the responses to lower levels in 5 cases, such that an ABR threshold was obtained where no response was detected with monaural stimulation. As the latencies are not affected, the binaural data was used to derive the latency/intensity functions. The monaural/binaural amplitude ratios recorded from subjects in Group 1 were low in comparison with normal. This may reflect the high signal-to-noise levels at low threshold levels, reducing the sensitivity of the measure. In Group 2, the range encompassed the normal. The highest value was associated with a steeply sloping audiogram. Møller and Blegvad (1976), comparing the amplitude differences in the ABR to monaural and binaural stimulation, in patients with sensoneural hearing loss, found different results. They found a greater ratio, at high intensities, for patients with flat losses. These authors studied the ratio at a range of intensities, and found parallel functions for gently and steeply sloping losses, but a widening of the interval with increasing intensity. There was no indication of central deficit given by comparison of these data to that of normal subjects.

6.4.4 MLR data

The MLR was successfully recorded in only a few cases from Group 2 subjects, and could not be identified from any Group 1 subjects. There are other reports of unstable or absent responses (e.g. Hirabayashi, 1979; Davis et al., 1983; Okitzu, 1984; Suzuki et al., 1983a; Kraus et al., 1987a) in the literature.

Suzuki et al. (1983a) found differences between the adult's and the child's MLR response. Their study showed the main power of the response to be located around 20 Hz in children but higher, at around 30 to 50 Hz, in adults. Although the highpass filter was set, in the present study, in the knowledge of these data, it was decided to favour the recording bandwidth most suitable for the adult subjects.. Kraus et al. (1985), found that the chances of obtaining a response increased with age up to 10 years. From later studies (Kraus et al., 1987a,b) they infer that this is due to factors which influence the identification of components which are themselves affected by maturation, such as filter effects and stimulus presentation rate. Suzuki and Hirabayashi (1987) found a similar trend. They found the latency of Pa approached the adult value between 8 and 11 years, but that the later peaks of the response matured around 12 -14 years. These findings suggest some reasons why the response detectability may have been reduced in this subject group.

6.4.5 Factoring of Electrophysiological Data

The aim of carrying out principal component analysis was to identify a smaller set of components, accounting for the variance in the data. The clear trend, that variables based on extent of hearing loss had underlying common variance, was not common to the features summarising response growth with increasing stimulus input which appeared in the ep data. It would appear that the two areas reflect two different aspects of auditory function: one of gross stimulus detection, by behavioural means or ep measurement, and one of stimulus processing of the varying input. It is interesting to note, in the light of the earlier discussion, that the behavioural measure supposedly indicating the presence of recruitment (ULL and dynamic range) is clustered with threshold data, and not with the input/output functions for the stimulus response system. This may reflect the grossness of the behavioural measure in the bias in the extent of missing data for the measure, but sheds doubt on the supposition that the input/output function may be used as a guide to the presence of recruitment.

6.5 SUMMARY

In summary, the ep study on severely and profoundly hearing impaired children did not conclusively identify the presence of central disorder in any child. It was strongly suspected in one, but the possibility of a non-organic element has yet to be finally determined. However, the study was successful in confirming that a major proportion, or all, of each child's hearing loss was peripheral in origin. Additionally, some of the properties of the ep responses from the severely damaged cochlea, in comparison with normal findings, were discussed..

Whilst the presence of central auditory dysfunction could not be confirmed, the comparison of various threshold measures led to the suspicion that at least four children in the study had central auditory contributions to their hearing acuity deficit. The site of dysfunction is suggested as upper brainstem or mid-brain. The threshold discrepancies are small, but this is not surprising, as subtle higher auditory deficits would not be expected to result in large sensitivity changes to gross stimuli. This indicates that clinical application of the techniques, used in conjunction as in the present study, could perhaps be improved with the superior recording conditions that may be obtained with the use of sedation. The trade-off between MLR threshold, and identification difficulties due to sedation and due to poor signal-to-noise conditions would require examination. Study of the response characteristics also leads to the conclusion that abnormal loudness growth functions, perhaps greater than thought on the basis of behavioural measures, were adversely affecting the auditory functioning and hearing aid use of some of the children.

CHAPTER 7

SUMMARY AND DISCUSSION

CONTENTS

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7.1 REVIEW OF EXPERIMENTAL DATA

The hypotheses have been put forward that:

1. Central auditory dysfunction may be a contributory factor in the comparatively poor development of oral/aural language skills in some hearing-impaired children, and

2. It may be possible to identify central auditory function as a component of the acuity deficit in hearing-impaired children, using auditory evoked potentials.

The purpose of the investigations described here was to examine the evidence of these hypotheses and to examine the issues arising from a broad ranging assessment on hearing-impaired children.

The investigation comprised two main parts. The principal aim was to obtain psycho-educational data, which would reflect comparative oral/aural language competence and associated skills, from a homogeneous group of severely deaf children. Evoked potential techniques were then used to investigate the site of auditory dysfunction in this same group. A smaller group of children with a wide range of hearing losses, pre-selected as being at high risk for central auditory involvement, were assessed in a similar manner, with an identical goal. This was a less homogeneous group of subjects. The secondary feature of the study was to carry out the necessary preparatory work for an audiometric investigation using high frequency stimuli, and for the electrophysiological studies.

In the present study, a number of audiometric, electrophysiological, and psycho-educational measures were obtained from two groups of hearing-impaired children. The 25 children in the first group were selected as an equally mixed, approximately age matched, group of "good oral achievers" and "poor oral achievers" from a residential school for the deaf, with a firm oral/aural tradition. The children were also selected to have as much in common in their non-educational background as possible. They all had severe to profound hearing losses. The second group of 11 children were pre-selected as having difficulties in oral communication in excess of the expectations of their educators, based on peer group comparisons for children with similar hearing losses. They came from a variety of educational backgrounds, though all were undergoing an oral/aural schooling.

The children all carried out:

(1) An audiometric assessment, including a measure of high frequency acuity

(2) Psycho-educational tests, to include a measure of cognitive function, receptive vocabulary, reading and speech intelligibility

(3) Auditory electrophysiological measures, to include the ABR and MLR to click stimuli.

Qualitative and quantitative analysis was carried out on the data. Factor analysis over the various aspects of the data array revealed that:

(1) Measures relating to extent of hearing loss clustered on one principal factor, whilst other audiometric measures have different underlying sources of variance;

(2) Psycho-educational variables clustered on two principal factors, with variables relating to language skills loading on one and the measure of speech intelligibility on the other. The measure of cognitive function partially loaded with the oral language tests on the first factor;

(3) Three principal factors were extracted during the analysis of audiometric and psycho-educational data. Measures relating to threshold of hearing clustered on Factor 1 with language related measures. The other two factors accounted for the variance in other audiometric measures. The measures of cognitive function loaded to a lesser degree than the oral language related measures on Factor 1. The relative loadings suggest that some of the unaccounted variance in the data derived from that variable;

(4) When a subset of the data from each area was combined and subjected to factor analysis, this did not reveal any

information additional to that reported in the individual areas. The ABR threshold related variables loaded with the audiometric related variables to demonstrate a measure of common underlying variance with oral language variables. The indirect electrophysiologic measures did not share significant common variance in this domain.

The proposed hypotheses have not been rejected or accepted on the basis of this study. The data array has revealed a number of auditory and non-auditory contributory factors to the different rates of progress made by the children in speech and language skills. The ep tests confirmed the extent of hearing loss, as a peripheral phenomenon, in all but one case, where there was probably a non-organic element, and raised a suspicion of central problems in some. Thus, the technique still stands as important in the identification of site of dysfunction, but it would appear that no child in these samples had a significant central component causing their auditory acuity deficit. It is possible, however, that, in addition to the peripheral losses confirmed in each case, some children may have additional, subtle central problems. The large extent of the peripheral loss, confirmed by evoked potential measures, served to obscure this and hinder quantification. This does not invalidate the technique, but clearly positive results have not been obtained from this subject sample. It has been suggested that the minor discrepancies between the objective threshold determination at successive neurological levels, and between the behavioural assessment, may have identified a central component and its site, but with only a mild resultant hearing loss. In three cases in Group 1 this was coincident with poor speech intelligibility. It was also coincident with abnormal ABR response characteristics. It is proposed that these subjects may have central auditory processing problems causing some acuity loss. If the site of dysfunction is central, then, from the discussion in Chapter 1, it is possible that this would result in other perceptual difficulties. There was one exceptional case where the evoked potential thresholds were not compatible with the other measures. In this case, however, a degree of non-organic hearing loss is suspected.

7.2 AUDITORY ELECTROPHYSIOLOGICAL ASSESSMENTS

In addition to this overall examination of the data, results in the individual assessments were carefully examined. Of particular interest was the comparison between the normal and the abnormal electrophysiologic measures. The morphology of responses recorded from the severe to profoundly deaf subjects was not normal, reflecting severe cochlear damage, and the peak latencies showed a qualitative relationship to audiogram shape in some cases. Further, extremely steep input-output functions were obtained, suggestive of a recruitment type phenomenon. The ABR response was more robust to the adverse recording situation, in that it was recorded in several cases where the MLR response could not be elicited.

In Group 1, several subjects had measurable ABR thresholds, but from no subject could an MLR be recorded. The presence of an ABR response does cluster with an expected above average score on the EPVT, but does not otherwise cluster with either "good" or "bad" achievers. In 7 cases, the ABR threshold was 15 dB or more better than the pure tone threshold at 2 kHz. In these cases, where no MLR was recorded, it may be speculated that there is a central component.

The scores of the psycho-educational measures were combined to give a single figure, dimensionless score. The subjects in Group 1 were each assigned a Rank Order Number, based on these scores. The 7 cases described above rank overall at 3, 5, 11, 12. 16, and 22, and give a spread across the range. If the speech rankings alone are considered for these 7 subjects, there is seen to be a preponderance of poor speech intelligibility scores (2, 5, 4, 3, 4, and 5). The contingency table, relating the incidence of "good" or "poor" speech scores to whether or not the ABR thresholds and the pure tone thresholds are coincident, is shown in Table 7.6. The value of χ^2 is not significant, so the null hypothesis that the speech ratings and the ABR/PTA agreement are independent must be accepted, Thus the ABR thresholds that are better than the pure tone thresholds do not predict poor speech discrimination.

Although the data does not relate to the speech intelligibility data, the possibility of a central component is not excluded. The absent response may be due to a central dysfunction of sufficient severity to cause a true auditory deficit. It is perhaps more likely that a disorder disrupting the time coding and neural synchrony may abolish the response. This phenomenon has been proposed as an explanation for cases of absent ABR, with quantifiable hearing (Hyde, 1986). A difficulty in the data interpretation, however, is that no subject in Group 1 (or either of the severe to profound deafness cases in Group 2) have an MLR response. The alternative explanation for this phenomenon, therefore, is that the MLR is less robust in a situation of poor signal-to-noise ratio.

The normal data was analysed in terms of laterality, intensity, gender, and binaural interactive effects. This was to provide a detailed data base against which the data recorded from the hearing-impaired children could be compared. However, due to the paucity of suprathreshold information only qualitative comparisons were carried out. This was a direct result of the extent of peripheral auditory damage in the subjects in the sample. However it was noted that the monaural and binaural ratios fell within the normal range and were not indicative of central problems. The intensity effects differed markedly from the normal in some cases, and have been discussed in depth. The latency values at threshold, or suprathreshold, have been discussed, and possible implications of the abnormal findings noted. Of most interest was the unusual response morphology found in some cases, where the most robust wave was markedly early in comparison with a normal Wave V. Separation of possible cochlear effects from central effects have been discussed speculatively, but the measures of central functions have been dominated by peripheral effects.

The ep results have revealed some interesting phenomena, which it would be of interest to explore in greater depth. In retrospect, assessment of all the children using the SVR may have yielded useful information. Although the response assesses a higher neurological level, it is mediated by a different mechanism to the more peripheral on-off responses. It was perhaps precipitous to assume its absence on the basis of absent ABR or MLR responses, if there is a possibility that a disruption of the timing is the cause of the absent response. The presence or absence of the SVR may have elucidated the above speculations. Interestingly, Cone-Wesson et al. (1987) found a low, but positive, incidence of normal SVR responses in the presence of abnormal peripheral function and/or brainstem response abnormalities in their study of the auditory pathway in high risk infants. The significance of this finding is not yet clear.

7.3 BEHAVIOURAL ASSESSMENTS

An in-depth study of speech intelligibility measures and high frequency hearing has provided some support for the concept that preservation of auditory acuity in the frequencies above 4 kHz may contribute to speech production. Normative data obtained from a group of similarly aged children was in approximate agreement with data from previous studies.

In order to summarise some of the different measures that have been made on the hearing-impaired children, a series of contingency tables are now presented. In Table 7.1, data from Group 1 subjects indicates the relationship between the presence or absence of a measurable ABR threshold, and the listener rated speech intelligibility scores. More subjects were reported with below average scores and absent ABR thresholds than any other condition.

The null hypotheses states that the two distributions are independent, and this is accepted at the 0.05 level of significance. Thus, the predictive value of the Wave V threshold as a determinant of speech intelligibility is not significant. Examination of other contingency tables formulated with combined ep and psycho-educational data shows mixed results. Using data from both Groups 1 and 2, the Wave V threshold classification is independent of the above and below mean classification of the Raven's Matrices, but the agreement between the presence of an above mean score on the EPVT and a measurable Wave V threshold is better than chance. No significant relationship was found, for Group 2 subjects, between an identifiable Wave V threshold and the scores of the Schonell and Southgate tests (Tables 7.2 and 7.3). The EPVT, the Schonell and the Southgate scores have been shown to have some common source of variance. The finding of a significant relationship for the EPVT (Table 7.4), but not for the other two verbal tests, was attributed to group differences. Group 1 has a small range of severe hearing losses, and Wave V was identified in a smaller proportion of subjects than in Group 2. This theory is examined in Table 7.5, but χ^2 is not significant and the null hypothesis that the proportion of correct predictions (Wave V measurable and the EPVT above mean) is the same in both groups is accepted. That is there is not a significant difference between the subject groups on this analysis.

CONTINGENCY TABLES - DATA FROM GROUP 1

Table 7.1 — Speech score

Wave V	Above Average	Below Average	Total
Present	4	3	7
Absent	6	9	15
Total	10	12	22

(Above average speech intelligibility judged as a score of 3-or-better, on the 5 point scale. A score of 1 is "very intelligible").

$\chi^2 = 0.57$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.2 — Schonell Vocabulary Test

Wave V	Above Mean	Below Mean	Total
Present	2	2	4
Absent	9	9	18
Total	11	11	22

$\chi^2 = 0.31$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.3 — Southgate Reading Test

Wave V	Above Mean	Below Mean	Total
Present	3	1	4
Absent	8	11	19
Total	11	12	23

$\chi^2 = 0.46$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.4 E.P.V.T.

Wave V	Above Mean	Below Mean	Total
Present	10	4	14
Absent	6	16	22
Total	16	20	36

$\chi^2 = 5.09$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.5 DATA FROM E.P.V.T. AND WAVE V THRESHOLDS REARRANGED BY GROUP AND CLASSIFICATION CONGRUENCE

	Agree	Conflict	Total
Group 1	18	7	25
Group 2	10	1	11
Total	28	8	36

$\chi^2 = 0.67$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.6 CONTINGENCY TABLE - DATA FROM GROUPS 1 AND 2

Wave V	Raven's Progressive Matrices Above 50%ile	Below 50%ile	Total
Present	13	3	16
Absent	10	10	20
Total	23	13	36

$\chi^2 = 0.57$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

Table 7.7 CONTINGENCY TABLE OF SPEECH SCORES AND THE AGREEMENT BETWEEN THE ABR AND PURE TONE - THRESHOLD AT 2KHZ

ABR/PTA	Speech Score Above mean	Below mean	Total
Agree	6	10	16
Disagree	2	4	6
Total	8	14	22

$\chi^2 = 0.11$ (not significant, $p < 0.05$)
(using Yate's correction for small samples)

The contributions to speech perception, speech production and psycho-educational competence, which have been discussed earlier in Chapter 1 but not investigated in this study, have not been overlooked in the examination of the data array. For example, Wiig and Semel (1976) discuss the effects of attention and selective listening on these areas at length. Attention and selective listening are perhaps of particular interest, since they are dependent upon a combination of peripheral and central integrity. Further examination of these areas in conjunction with a range of evoked response measures would be of interest. One of the most promising of the central auditory assesments discussed in Chapter 1 was the work of Tallal (1976), examining the correlation between processing of rapid speech streams and reading difficulties. If time coding difficulties underlie some absent auditory electric response measures, a comparative examination of children showing this phenomenon and abnormalities on her assessment would be of interest. Future study in this area is suggested.

The presence of severe peripheral hearing loss may, in itself, provide a major obstacle in this work for some time. In a review of the application of ABR assessments in the investigation of learning disabled children, Orbzut et al. (1987) highlight the variability between studies in this area, and call for more rigorous experimental control and analysis techniques. If abnormalities of this kind are so subtle, it may prove difficult to detect them using conventional techniques, in the presence of severe cochlear disorder.

The audiological and psycho-educational assessments revealed some interesting findings. Examination of the initial correlation matrix of audiological findings revealed only a strong correlation between better and worse ear threshold data. There were no significant correlations between any other variables. In particular, it is noted that there was no significant correlation between the slope index and extent of loss; nor between the rate or extent of decay and extent of loss; nor between the presence of high frequency thresholds and either extent or slope of loss. The dynamic range of the subjects is significantly related to the extent of hearing loss. A factor analysis of the audiological data array revealed that none of the factors correlated with each other to a significant extent. When the factor pattern matrix was further simplified, it loaded the audiometric average on Factor 1 and audiometric slope index on Factor 2. The measure of receptive vocabulary, unlike the measure of intelligence, was significantly correlated with hearing loss, in line with other studies. The Raven's Matrices, (a test of IQ) and the EPVT, reported to be related to measures of intelligence, correlate highly at 0.94. The normal range of scores, with the inclusion of several extreme high scores, suggests that low performance on the Raven's Matrices is not a predictor of poor oral language development. Results of the Southgate test appear to suffer a ceiling effect, indicating that the reading age of some of the children in the sample was in excess of the test maximum of 7½ years. When the test results are compared with the results of the Schonell Test, a significant correlation of 0.78 emerges. There was no significant correlation between extent of hearing loss and reading test results. Principal component factor analysis, without iteration, showed the EPVT, the school grade and the Southgate Reading Test to load heavily on Factor 1. Less weight, but still notable loading came from the Raven's Matrices and Schonell Vocabulary test.

Speech intelligibility loaded onto Factor 2, with a less, but notable, negative loading from the Schonell Test. The rotated matrix clearly demonstrated the clustering of the EPVT, the Schonell Vocabulary Test, the school grade and the Southgate Reading Test. The variance from Factor 2 was mostly accounted for by speech intelligibility. It is possible that common factors are involved in the structure of these test results, reflecting a link in the processes of cognition and vocabulary acquisition. No clear relationship was demonstrated between speech intelligibility and any of the psycho-educational variables. It would be interesting to include other measures thought, in the literature, to relate to speech intelligibility, in particular, an articulation measure. It is interesting to note that there was a poor correlation between the teachers' grades for speech and the judgement of speech intelligibility by a panel of listeners not familiar with the individual children, nor familiar with the contrasts of deaf speech. It would not be predicted that a different ranking could be obtained. In two cases, teachers and the panels grades were at opposite ends of the scales. A strong relationship was found between receptive vocabulary, word recognition and word reading. The teachers' grade clusters with these variables and this is not surprising since, consciously or otherwise, the teachers base their grades on tests of this kind. It is perhaps more surprising that the Raven's Matrices loads on the same factor. This may mean either that there *is* a language element in this test, or that the other tests have some underlying feature common to the measurement of "intelligence".

A number of the individual cases are of special interest. Summary data from this study and a report on the childs' speech and language, based on the most recent yearly and half yearly reports of the teaching staff, are given in Appendix 2.

7.4 SUMMARY

The complexity of analysing the cause of a hearing-impaired child's failure to acquire adequate oral language skills is apparent. An attempt has been made in this thesis to examine the contribution of some aspects of auditory dysfunction to this area. The principal aim of the investigation was to examine the effect of site of auditory dysfunction, as determined by auditory ep measures, on the acquisition of oral language. Auditory investigations into the relative effects of extent and congifiguration of auditory acutiy deficit, abnormal adaptation, dynamic range, and high frequency acuity were carried out. In an attempt to quantify the child's prowess with oral language related skills, a range of psycho-eduactional measures and an evalution of speech intelligibilty were carried out, and these studies have raised interesting issues for discussion and further study.

Both the extent and configuration of hearing loss are important measures. It is concluded that there is value in adding further assessments to the evaluations normally carried out to quantify hearing loss. These additions are:

a) Measurement of thresholds above 8 kHz, particularly if the audiometric configuration rises in the frequencies above 1 kHZ

b) Measurement of the ABR, the MLR, and possibly the SVR thresholds, and examination of their latency- and amplitude-functions.

As a result of findings in this study, it is suggested that detailed electrophysiological studies are carried out on young children, identified as hearing-impaired, as an adjunct to normal procedures. Whilst the results described in this study are not conclusive, the data indicate that some information relevant to the management of the child may be yielded; primarily the neurological level of contributions to the auditory deficit, and the stimulus intensity related phenomena. As it is a safe, non-invasive procedure, there can be few objections, other than cost, although the issue regarding optimisation of the signal-to-noise conditions, and sedation difficulties are not yet resolved for the later responses.

Some of the results found here could be discussed only speculatively. In particular, the abnormal response morphology and cases where the response was absent. There is scope for further study into the characteristics of the ep sponse, recorded to high intensity stimuli, and transmitted by a damaged cochlea. The difficulties encountered in interpreting the results of ep measurements, with respect to the stated hypotheses, result partly from a paucity of information in this area. Detailed studies on severely hearing-impaired subjects, using ep measures in conjunction with psycho-acoustic measures, to examine predominantly peripheral effects, would be the next logical step.

With current knowledge, the addition of an auditory ep profile to the audiological assessment confirms the extent of peripheral hearing loss, and indicates the presence, and site of, complicating auditory factors. The character and effect of these are not yet known, and their relationship to psychoacoustical phenomena and central auditory function have not been determined.

Whilst auditory factors, which may contribute to oral language development, have been identified, the experimental group did not contain any subjects manifesting a majority central contribution to their auditory deficit. However, it is the opinion of the author that such a deficit would be demonstrated by this technique, on the basis of trends in the data in these experiments.

The evidence from the audiological and psycho-educational studies supports the view that there is considerable scope to further explore the underlying factor structure of speech and language measures in deaf children. The data here revealed interesting areas of common variance, viewed against current knowledge. Rigorous studies in this field are few, and it is true today that the influences affecting the speech of hearing-impaired children are poorly understood.

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APPENDIX 1

AUDITORY ELECTROPHYSIOLOGICAL INSTRUMENTATION

Stimulus generator:

Made at I.S.V.R. by N.S.Rutt, (contract 9634/19/06), type 777, designed to produce a variety of stimuli in electrophysiological measurements. It comprises two channels and a variety of triggering modes. The stimuli available are; positive or negative polarity or alternating clicks, duration 100 μs; pink or white noise bursts; tone bursts, and phase locked tone bursts with a variety of rise fall times and durations. The output may be directed to a loud speaker, to either or both head phones, to a bone vibrator or to an insert receiver. An external input may also be used.

Amplifiers:

Medelec AA6 Mk III with pre-amplifiers, PA62. These have a common mode rejection ratio of greater than 50,000 : 1 at 50 Hz. (Manufacturer's data). The characteristic frequency could be adjusted, and was set at a low pass value of 3.2 kHz, to avoid anti-aliasing errors.

Filters:

Two Butterworths filters, with a choice of slopes of 24 or 48 dB/octave were used.

Computer averager and data processor:

The DLmicro4 signal processing system guide (Datalab) comprises three modules; the DL400 store, DL401 sweep timer, the DL402 averager histogram module, and the DL403 display controller. These modules are contained in a single crate with a universal bus structure. A second unit houses the DL450 microprocessor system and screen.

The memory module, or store, has a random access integrated circuit memory of 1024 x 20 bit words. Data is stored in two's complement binary notation. This module also contains the binary accumulator. Data transfer time is 5 μs for a 20 bit word capacity, 20 bit word length.

The sweep timer has four sweep and five trigger modes. These modes enable various combinations of stimulus presentations and pre and post stimulus analysis times. There is a delayed sweep mode, a dual sweep mode, a pre-trigger mode and an elapsed time mode. The trigger input is continuously variable over a 1V range.

The averager unit enables single- and multi-channel and pre-trigger averaging by algebraic summation. For single-channel averaging, either half or any quarter of the memory is selected. When one memory section is used to collect a result, another section of the memory is utilised to accept new data.

Simultaneous multi-channel averaging, of up to 4 signal channels is effected by the analogue multiplexer.

The pre stimulus waveform may be analysed using the pre-trigger averaging mode.

Buffered averaging with artefact rejection is possible, but utilises half of the available store. The stored sweep is put into the first half of a divided memory, where it is inspected for signal voltages exceeding plus or minus one volt. Provided the input limits have not been exceeded, the sweep is transferred to the second half of the memory for averaging. If an overload is detected, the whole sweep is discarded and a new sweep is stored. Single channel input utilises half of the memory for accumulation. Two channel simultaneous input utilises two memory quarters for accumulation.

The display controller enables display of all the 1024 words as a single trace, or as two or four memory subgroups, one under the other on the screen; it has an output facility to the chart recorder and automatic scaling. The input signal and the stored signals may be displayed simultaneously. The vertical scale is adjusted automatically during analysis, so that the cumulative data acquisition can be viewed. Each trace has an independent manual vertical position control. The display may be expanded horizontally or vertically for detailed inspection of the traces. A switch pre-selects the number of analysis sweeps to be executed in the triggered signal averaging programme mode. This switch is also used in the manual normalisation of data when automatic scaling function is cancelled. The sweep control may be preset in 2^n increments between 1 (2^0) and 16384 (2^{14}).

The microprocessor is organised as an 8 bit processor, and carries out calculations on data stored in the DL4000 and then returns it to display. Both analogue and digital data are displayed. The programs are controlled from push buttons mounted on the front panel, and the microprocessor has a set of programmes which produce the arithmetic and display functions. Arithmetic calculations can be carried out on any one or part of a memory subgroup. Calculation of parameters associated with special display functions can be carried out. Selection of values of the digital parameters is achieved by a scan left/scan right control. The controls generate the digital parameters for the display modes and the numbers used for arithmetic calculations. The scan control moves a cursor, which is an intensified line which can be moved on the waveform. The address value of the cursor is displayed on the screen. Of the functions available, the only other consistently used function was the smooth function. This operation performs a 3 point regression on a trace.

Addition of the Specify Coordinates program converts the display of cursor data and address in terms of real parameters, voltage and time.

APPENDIX 2

BACKGROUND INFORMATION ON SUBJECTS

GROUP 1

Children in Group 1 were selected from the Sir Winston Churchill School for the Deaf, at Woodford Green, London. Audiological assessment of the child, prior to school entry, took place at a number of centres, including the Nuffield Centre (RNTN & E, Gray's Inn Road), the Audiology Unit,at the Royal Berkshire Hospital, Reading, and the University Department in Manchester.

Language assessment is carried out in the school, using a scale devised within the school, based on annual tests and teachers comments.

The school follows its own language development programme, written and developed in the school (Guidelines) and a strict oral/aural method is followed. All the children in the school would be classified as severe or profoundly hard-of-hearing. The school does not take pupils with multiple disabilities. Children who appear to have additional language problems stay at the school, unless their parents decide that an education based on the manual communication method would be more appropriate. There is special provision for "late starters" at the school.

Subject Profiles

DL	Age; 7 years		Detected as hearing-impaired at 2 years old
		Cause;	unknown
	Schools	Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 1 years	OL 575/ OL 675
		Age 3 years	2 x Philips 8126E

ElM	Age; 7 years		Detected as hearing-impaired at 1½ years old
		Cause;	unknown
	Schools	Age 2 years	P.H.U.
		Age 6 years,	Sir Winston Churchill School
	Hearing Aids	Age 4 years	2 x Philips 8126E

AD	Age; 7 years		Detected as hearing-impaired at 1 year old
		Cause;	unknown
	Schools	Age 2 years,	normal school
		Age 3 years,	P.H.U.
		Age 5 years,	Sir Winston Churchill School
	Hearing Aids	Age 4 years	2 x Philips 8126

GP	Age; 8 years		Detected as hearing-impaired at 11 months
		Cause;	encephalitis
	Schools	Age 4 years,	Sir Winston Churchill School
	Hearing Aids	Age 1 year	1 x Philips ?
		Age 4 years	1 x Willco Monarch
		Age 5 years	2 x Willco Monarch
		Age 7 years	2 x Oticon E22P

MC	Age; 10 years		Detected as hearing-impaired at 2 years
		Cause;	unknown
	Schools	Age 2 years	Nursery (normal)
		Age 3 years	Heston School for the Deaf
		Age 6 years	Sir Winston Churchill School
	Hearing Aids	Age 2 years	1 x Madresco?
		Age 3 years	2 x Philips HP 8126E

HD	Age; 8 years		Detected as hearing-impaired at 1 year
		Cause;	meningitis at 2 weeks
		Medical;	recurrent serous otitis media
	Schools	Age 3 years	PHU
		Age 4 years	Sir Winston Churchill School
	Hearing Aids	Age 5 years	Maico E1 Mk.2

SH	Age; 9 years		Detected as hearing-impaired at 1½ years
		Cause;	genetic
	Schools	Age 2 years	Nursery (normal)
		Age 3 years	Heston School for the Deaf
		Age 4 years	Sir Winston Churchill School
	Hearing Aids	Age 1 year	OL56
		Age 3 years	OL63
		Age 4 years	1 x OL63, 1 Maico Windsor AP180
		Age 7 years	1 Maico AP180 (L)

AC	Age; 9 years		Detected as hearing-impaired at 9 months
		Cause;	meningitis
	Schools	Age 2 years	Nursery (normal)
		Age 4 years	PHU
		Age 6 years	Sir Winston Churchill School
	Hearing Aids	Age 10 months	2 x Madresco
		Age 4 years	2 x Philips 8126
		Age 7 years	2 x Philips 8276 (pa)

BW	Age; 8 years		Detected as being hearing-impaired at 2 years
		Cause;	unknown
	Schools	Age 3 years	Nursery (normal)
		Age 4 years	PHU
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 2 years	Madresco 58C
		Age 5 years	2 x Philips 8126E

MCa	Age; 8 years		Detected as being hearing-impaired at 2½ years
		Cause;	unknown
	Schools	Age 4 years	PHU
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 6 years	2 x Philips HP8114

DeL	Age; 9 years		Detected as hearing-impaired at 2 years
		Cause;	unknown
	Schools	Age 3 years	Nursery (normal)
		Age 4 years	PHU
		Age 6 years	Sir Winston Churchill School
	Hearing Aids	Age 7 years	2 x Philips HP8114

CN	Age; 10 years		Detected as hearing-impaired at 10 months
		Cause;	rubella
	Schools	Age 1 year	Peripatetic teacher
		Age 2 years	Nursery (HI)
		Age 4 years	Sir Winston Churchill School
	Hearing Aids	Age 10 months	2 x OL58
		Age 2 years	2 x Philips HP8123
		Age 6 years	2 Maico Windsor 4W180

AS	Age; 10 years		Detected as hearing-impaired at 2 years
		Cause;	unknown
	Schools	Age 3 years	Nursery (normal)
		Age 5 years	Sir Winstin Churchill School
	Hearing Aids	Age 5 years	Y cord Philips 8126E
		Age 8 years	2 x Danavox 727 L receiver.

LL	Age; 10 years		Detected as hearing-impaired at 2½ years
		Cause;	unknown
	Schools;	Age 3 years	Nursery (normal)
		Age 4 years	Sir Winston Churchill School
	Hearing Aids	Age 6 years	2 x Philips HP 8123

JW	Age; 10 years		Detected as hearing-impaired at 2 years
		Cause;	rubella
	Schools	Age 3 years	PHU
		Age 4 years	Residential School for the Deaf
		Age 5 years	PHU
		Age 9 years	Sir Winston Churchill School
	Hearing Aids	Age 5 years	2 x Danavox 727
		Age 10 years	2 x Siemens 24 PP
		Age 11 years	2 x BE12

MP	Age; 10 years		Detected as hearing-impaired at ?
		Cause;	meningitis
	Schools	Age 3 years	Overseas (English School)
		Age 9 years	Sir Winston Churchill School
	Hearing Aids	Age 9 years	Philips HP8112 CR
		Age 10 years	2 x Maico Windsor AP180

ZK	Age; 11 years		Detected as hearing-impaired at 2 years
		Cause;	meningitis at 1 year
	Schools	Age 2 years	PHU
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 4 years	2 x Amplivox Magnavox
		Age 9 years	2 x Philip's 8126E's PH77

TH	Age; 14 years		Detected as hearing-impaired at 7 months
		Cause;	unknown
	Schools	Age 3 years	PHU
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 10 months	OL58
		Age 13 years	2 x Philips HP 8114
		Age 14 years	2 x Philips 8126E PHN receiver

PB	Age; 15 years		Detected as hearing-impaired at 1 year
		Cause;	unknown
	Schools	Age 3 years	Sir Winston Churchill School
	Hearing Aids	Age 2 years	2 x Philips ?
		Age 12 years	2 x Philips 8114
		Age 15 years	1 x Maico Windsor AP180 CR

EM	Age; 15 years		Detected as hearing-impaired at 1 year
		Cause;	Rubella
	Schools	Age 2 years	Nursery (normal)
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 13 years	2 x Philips 8114
		Age 15 years	2 x Danavox 727 (N receiver)

TG	Age; 16 years		Detected as hearing-impaired at 1 year
		Cause;	unknown
	Schools	Age 2 years	Nursery (normal)
		Age 4 years	PHU
		Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 13 years	2 x Philips 8276E

CT	Age; 16 years		Detected as hearing-impaired at 1 year
		Cause;	unknown
	Schools	Age 4 years	Sir Winston Churchill School
	Hearing Aids	Age 13 years	2 x Philips 6540
		Age 16 years	2 x Wilco Monarch

DG	Age; 16 years		Detected as hearing-impaired at 9 months
		Cause;	unknown
	Schools	Age 5 years	Sir Winston Churchill School
	Hearing Aids	Age 16 years	2 x Philips 8126E. PHP Receiver

Group 2, A Sample of Hearing-Impaired Children in Hampshire

Children in the second group were from a variety of different eduactional backgrounds, and were preselected as children who were not making expected progress, regardless of eduactional method.

MM	Age; 7 years		Detected as hearing-impaired at 1½ years old
		Cause;	unknown
		Medical;	middle ear problems
	Schools	Age 2 years,	Pre-nursery (normal) hearing)
		Age 3 years,	Nursery (normal)
		Age 5 years	P.H.U.
	Hearing Aids	Age 2 years	Y chord, OL 57
		Age 3 years	2 x OL57
		Age 3½ years	2 x Philips 802 B
MW	Age; 8 years		Detected as hearing-impaired at ? years old
		Cause;	unknown
	Schools	Age 3 years,	Nursery (normal)
		Age 5 years	P.H.U.
	Hearing Aids	Age 7 years	2 x BE 11
SP	Age; 9 years		Detected as hearing-impaired at 5 years old
		Cause;	unknown
	Schools	Age 7 years,	P.H.U
		Age 8 years,	Normal school (with P.H.U. help)
	Hearing Aids	Age 7 years	2 x BE 11
		Age 8 years	2 x Rexton p/a
JC	Age; 10 years		Detected as hearing-impaired at 2½ years old
		Cause;	rubella
	Schools	Age 2 years,	Peripatetic help
		Age 4 year	Nursery (normal)
		Age 5 years,	P.H.U.
	Hearing Aids	Age 2 years	2 x OL 58C
		Age 4 years	2 x Philips p/a
		Age 10 years	2 x Oticon p/a

AD	Age; 10 years		Detected as hearing-impaired at 7 years old
		Cause;	unknown
Schools;		Age 5 years,	normal school
Hearing Aids		Nil	

LT	Age; 10 years		Detected as hearing-impaired at 8 years old
		Cause;	unknown (NOHL?)
Schools		Age 5 years	Normal school
Hearing Aids		Nil	

NH	Age; 10 years		Detected as hearing-impaired at 2½ years old
		Cause;	rubella
Schools		Age 4 years	Nursery (normal)
		Age 5 years	P.H.U
Hearing Aids		Age 3 years	Y cord OL 57
		Age 6 years	Y cord OL 67
		Age 9 years	2 x Widex p/a

PS	Age; 10 years		Detected as hearing-impaired at 3 years old
		Cause;	unknown
Schools		Age 3 years	Nursery (normal)
		Age 5 years	P.H.U.
Hearing Aids		Age 3 years	2 x OL57
		Age 6 years	2 x Philips 8126E
		Age 9 years	2 x Rexton p/a

CS	Age; 11 years		Detected as hearing-impaired at 3½ years old
		Cause;	unknown
Schools		Age 3 years	Nursery (normal)
		Age 5 years	P.H.U.
		Age 9 years	Normal school+peripatetic help
Hearing Aids		Age 4 years	OL 57
		Age 7 years	2 x Phillips p/a
		Age 10 years	2 x Widex p/a

DS	Age; 14 years		Detected as hearing-impaired at 7 years old
	Cause;		unknown
Schools	Age 5	years	Normal school+peripatetic help
Hearing Aids	Age 8	years	OL 67
	Age 11	years	BE 11 (L)
	Age 12	years	BE 12 (L)

MO	Age; 15 years		Detected as hearing-impaired at 2 years old
	Cause;		meningitis
Schools	Age 5	years	P.H.U.
	Age 11	years,	School for the Deaf, Margate
Hearing Aids	Age 8	years	OL 67
	Currently 2 x Phillips 8123		

A2.1 CASE STUDIES

A2.1.1 Group 1 Subjects

i) DeL, age 8 years; cause of loss is unknown

Teacher's reports:

Receptive language:

She understands familiar phrases and short sentences and can carry on a short conversation with people familiar to her

Spoken Language:

She has poor voice pitch and level control, and uses her voice minimally. Relies on visual and manual information (gesture) where possible.

Audiometric Information:

She has little measurable hearing, having thresholds in the mid frequencies of 120 db HL on the good side only. She has normal middle ear function, absent acoustic reflexes and no tone decay.

ABR and MLR responses could not be elicited.

Psychometric tests:

She scored badly on all measures, except, notably, the Southgate

Reading Test, where she scored the maximum. She was in the lower 10th percentile on the Raven's Matrices and well below the group mean on both vocabulary scales. Her speech grade was rated as 4, almost unintelligible.

ii) HD, aged 9 years; cause of deafness was meningitis at 2 weeks

Teacher's reports:

Receptive language:

Thought to be poor in comparison with class members.

Spoken Language:

Uses very little gesture, although her speech is not very intelligible.

Speech:

Poor intelligibility. Tends to repeat first syllables.

Audiometric Information:

HD has some low frequency residual hearing (90 dB HL) at 0.25 kHz, 115 dB HL at 0.5 and 1 kHz (the better ear). Low middle ear compliances reflect a history of supperitive otitis media.

ABR and MLR responses could not be elicited.

Psychometric Tests:

HD scored badly on all tasks, including the Raven's Matrices. His speech intelligibility was graded as very poor by the independent panel.

iii) DaL, age 10 years; cause of loss is unknown

Teacher's reports:

Receptive language:

He appears to understand very little from speech alone. He smiles and says "yes" to most questions.

Spoken Language:

He has only a few words in his active vocabulary.

Speech Production:

He makes an effort to use "learnt speech", and then has a pleasant, well modulated voice, with good phrasing.

Audiometric Information:

DaL has a symmetrical hearing loss gently sloping from 80 db HL at 0.25 kHz to a plateau of 110 db HL at 2 kHz. This extends to include 8 kHz, and high frequency responses were obtained at 12 and 16 kHz.

ABR thresholds were obtained to binaural stimulation only, and were compatible with severe to profound peripheral damage.

Psychometric Data:

This shows him to be performing at a much lower than average level across the whole range.

iv) CN, age 10 years; cause of loss was probably rubella

Teacher's report:

Receptive language:

Demonstrates good understanding of familiar speakers, especially if contextual clues are available.

Spoken Language:

His spontaneous language is adequate for him to give explanations to most of his ideas, and he supplements with gesture.

Speech Production:

Uses his voice well, although occasionally omits syllables, but his phrasing is good.

Audiometric information:

CN has a near symmetrical hearing loss, with thresholds at 85 dB HL at 0.25 and 0.5 k Hz, sloping to beyond audiometric limits at 2 k Hz. ABR responses were recorded at 100 db HL. It was not possible to examine the latency-intensity function, though only a small latency shift and amplitude increase was noted for a 10 dB increase in stimulus intensity.

Psycho-educational:

CN is above average in all measures. He scored in the 95th percentile on the Raven's Matrices.

v) MC, age 11 years; cause of deafness is unknown

Teacher's report:

Receptive language:

He understands quite well much of what, even unfamiliar, speakers say. His failure to comprehend on occasions is attributed to poor attention.

Spoken Language:

He makes an effort with spoken language, but uses a lot of gesture. He attempts to use full sentences and answers questions well. His active vocabulary is poor.

Speech Production:

He can produce discriminable consonants well, if using speech in a structured situation.

Audiometric Information:

MC has measurable hearing to 4 kHz, with bilateral thresholds of better than 95 db HL up to 1 kHz. He demonstrated marked and rapid tone decay, bilaterally at several frequencies. Middle ear function is normal, but no acoustic reflexes could be elicited. ABR responses were recorded to a threshold of 90 dB HL on the better ear, and the latency-and amplitude-intensity functions were both steep in comparison with the data from normal subjects. No middle latency responses were recorded.

Psycho-educational:

These measures showed MC to be performing above the group mean. He ranked in the 50th percentile on the Raven's Matrices. His speech intelligibility, however, was ranked as being very poor, by the panel of listeners.

vi) ZK, age 11 years, cause of deafness was meningitis at 2 years

Teacher's report:

Receptive language:

ZK understands very little from speech, without gesture and many contextual clues.

Spoken Language:

Although he has much to say, his limited language skill is evident and he relies on extensive accompanying gesture.

Speech Production

He is reluctant to listen, or to attempt to use his hearing, and this is considered to be a partial cause of his limited range of speech sounds. He produces only a few discriminable contrastive speech sounds. He can produce trains of consonants, but cannot use them in connected speech.

Audiometric Information:

ZK has a bilateral symmetrical hearing loss which slopes from 100 db HL at 0.25 kHz to 120 db HL at 1 kHz, where it plateaus. ABR responses were recorded to 100 dB HL bilaterally, with an abnormal morphology. The latency-intensity function was normal, but the amplitude growth function was markedly in excess of normal. The MLR could not be elicited.

Pyscho-educational:

These measures were among the lowest recorded in the sample, across the range. His speech was rated by the listening panel as being near unintelligible.

vi) AC, age 9 years; cause of deafness was meningitis at 7 months

Teacher's Reports:

Receptive language:

AC follows classroom discussions easily and understands speech from unfamiliar speakers.

Spoken Language:

He readily uses spontaneous, flowing language, with good phrasing, a mixture of simple and compound sentences, and a wide vocabulary.

Speech Production:

AC uses his voice, well. He monitors the pitch and volume of his voice to achieve a pleasant result and has a wide range of contrastive consonant sounds in his repertoire.

Audiometric Information:

AC has a bilateral flat, symmetrical loss at approximately 110 db HL in the frequencies of 1 kHz and above. His hearing in the lower frequencies is better on the right where it slopes to this maximum from 80 db HL at 0.25 kHz. He shows some mild tone decay at 4 kHz only. ABR responses could not be elicited.

Pyscho-educational measures:

The test results show AC to be performing at an above average level across the range of assessments. His score on the Raven's Matrices puts him in the 95th percentile.

vii) PS, age 11 years; cause of heaing loss is unknown

Speech is described as moderate.

Audiometric Information:

PS has a moderate, bilateral, symmetric, U-shaped hearing loss, being maximal at 1 kHz, at 90 db HL. ABR responses confirmed the peripheral loss, on the right, but on the left a better-than-expected threshold of 60 db nHL was recorded. This result was, however, confirmed with the MLR responses, where no response could be elicited on the right, but were obtained at 70 db nHL on the left. The amplitude growth function was much steeper on the right than the left, and steeper than in normals.

Psycho-educational:

Tests showed PS to be performing above the group mean. His results on the Raven's Matrices were in the 75th percentile, but his EPVT result, compared with the standard norms, puts him below the first percentile. It is noted that all the children in Group 2 were referred because their oral language and educational progress was slower than their peers with similar hearing losses.

viii) AD. age 10 years; cause of deafness is unknown

Speech is described as good.

Audiometric information:

AD has a near normal hearing up to 1 kHz on the left, with acuity reducing to a threshold of 60 db HL at 8 kHz. On the right, the loss slopes from 30 db HL at 0.50 kHz to in excess of 120 db HL at 8 kHz. Acoustic reflex and uncomfortable loudness level measures indicate a wide dynamic range, where it is measurable. ABR and MLR thresholds were comparable to his pure tone loss at 2 kHz on the left, and somewhat better than the pure tone threshold on the right. ABR measures of monaural/binaural ratio, input-output function, and peak latencies were within the normal range, or as expected for a steeply sloping sensorineural loss.

Psycho-educational measures showed this child to be functioning above the group mean, and well above average compared with standard norms.

ix) SP. age 9 years; cause of deafness is unknown

Speech is described as moderately good.

Audiometric information:

SP has a mild to moderate, bilateral, almost symmetrical hearing loss most severe at 1 kHz and above. ABR results revealed a click threshold at 50 dB HL bilaterally. The MLR thresholds were 70 db HL bilaterally. The ABR results are somewhat better than predicted but may be due to the good apical preservation of hearing. However, again, central involvement cannot be discounted. ABR measurement parameters were in the normal range, with input-output function slopes on the low side of normal.

Psycho-educational measures were well below the group mean. Her reading is reported as poor.

APPENDIX 3

SPSS AND FACTOR ANALYSIS

The Factor Analysis package used in this study forms part of the Statistical Programs for the Social Sciences (SPSS) package. This system uses FORTRAN. It was carried out on the University of Southampton main frame ICL 2970 computer, using a card input method.

The major application of factor analysis is to locate a smaller number of valid dimensions, or clusters, as factors contained in a larger set. The maximum amount of information from the original variables is summarised in as few derived variables, or factors, as possible. This made it a particularly suitable technique to use in the present multi-topic study. The degree to which a given variable, or several variables, are part of a common underlying phenomenon, may be determined, and theoretical deductions about the structure of the variance data made. The underlying theorem is that within any situation some characteristics of the organism will be more closely related to the response than others, and that defined weightings then are used to indicate the relationships. This is summarised by the following formula:

$$z_{ji} = f(S_j, O_i) \qquad (1)$$

where i is individual i's response in situation j
where S_j are the characteristics of the situation, j and O_i are the characteristics of organism i

Thus, equation (1) becomes

$$z_{ji} = a_{1A}A_i + a_{1b}B_i \ldots\ldots + a_{1n}F_i + c \qquad (2)$$

where a_i is the weighting given
A_i is the individual i's score on characteristic A
c is a measure of uniqueness

For more than one dependent variable, each response has its own set of weights, i.e. when several different kind of responses (X's) are predicted. This leads to the multivariate linear model, and the basis of factor analysis:

$$z_{j1} = a_{1A}F_{1A} + a_{1b}F_{1B} \ldots\ldots + a_{1F}F_1$$

$$z_{j1} = a_{VA}F_{1A} + a_{Vb}F_{1B} \ldots\ldots + a_{VF}F_1 \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where Z_{iV} the response of individual i to dependent variable V

a_{VA} is variable V's weight for characteristic A

F_{iA} is individual i's score for the first characteristic

F_{iF} is the individual score for the f'th characteristic

The characters are referred to as factors, and any scores which are given weights and added together are defined as factors of the resulting variable.

The first step in factor analysis is the preparation of a correlation matrix, of a set of relevant variables. These must be normally distributed. In the present study, this necessitated data transformation is some cases (reading tests, IQ test, vocabulary test, tone decay test). The transformation used was $y = \frac{1}{2}\ln(1+x)/(1-x)$. The correlation between variables selected was R-factor analysis.

The factor program then explores the data reduction possibilities by constructing a new set of variables, on the basis of the inter-relations exhibited in the data. The method chosen here was principal component analysis, which uses defined factor, which are orthogonal.

The principal component model was expressed in equation (3), where each of n observed variables is described linearly in terms of n new uncorrelated components $F_1 \ldots\ldots F_n$, each of which is in turn defined as a linear combination of the n original variables.

The factoring method chosen was principal factoring. In the principal component matrix, the eigenvalues associated with each component represent the amount of total variance accounted for by the factor. In most cases only factors with eigenvalues exceeding one were retained. The eigenvalues enable a means of evaluating the importance of a component by examining the proportion of the total, accounted for, variance:

Proportion of total variance accounted for by component i = λ_i/n

where λ_i represents the eigenvalue of the ith component and
n the number of variables in the set

The factors then give the least squares fit to the entire correlation matrix, each succeeding factor accounting for the maximum amount of the total correlation matrix. In the classical factor method, the factors are not defined and the unique factor in the variance is considered.

The eigenvalues are examined to select the principal factors for analysis and rotation. It is common to reject factors with eigenvalues of less than 1. That proportion of the variance which can be accounted for by the common factors (all factors in the principal component method) is referred to as the communality (h^2).

$$h^2 = (\sum a^2_k + \sum\sum a_j a_k r_{jk})/v$$

The value increases as the number of factors increases.

Factor extraction may be carried out with or without iteration. In this procedure, the communality estimates are entered into the diagonal of the correlation matrix. The observed communality is then calculated for the resulting factor solution, by summing the squared loadings for each variable. The iteration procedure continues until the maximum change between the communalities between estimates is below "x".

In the factor analysis procedure the original axes of measurement may be rotated in an attempt to simplify the factor structure. If the appropriate method is chosen the number of factors may be reduced and the factor loadings simplified. In the unrotated solution every variable is accounted for by two significant common factors, while in the rotated solution each variable is accounted for by a single significant common factor.

Rotation may either be oblique or orthogonal. The former method gives a more realistic representation of the data, because the theoretically important underlying dimensions are not assumed to be unrelated to each other. It also provides more information about the amount of actual correlation between the factors. Both oblique and orthogonal (Varimax, - a method which simplifies columns in the factor matrix) have been used here.

In the orthogonal solution, only one factor matrix results, as the factor estimate and factor structure matrices are identical. In the oblique solution, two matrices result: the factor pattern matrix represents the direct contribution of a given factor to the variance of a variable. It gives the regression weightings on the individual factors. The structure matrix consists of correlation coefficients between the factors and variables. Correlations of the factors can also be directly read using this method.

Missing data was dealt with by the paired deletion method, or replacement by the data mean, whichever was more appropriate.

APPENDIX 4

TECHNICAL ASPECTS OF HIGH FREQUENCY AUDIOMETRY

<u>Contents</u>

A4.1	Selection of transducer	364
A4.2	Test equipment for high frequency audiometry	365
A4.3	Calibration of high frequency system	366
A4.4	Statistical tables Chapter 4 experiments	

A4.1 SELECTION OF TRANSDUCER

An electrical signal, giving white noise rising at 10 dB per octave, was fed into four types of earphone. The earphone under test was placed on the flat plate coupler of the Brüel and Kjær artificial ear, and the output at the earphone transduced via a ½" condenser microphone, Type 4134, and Cathode Follower, Type 2615, to a Brüel and Kjær Audio Frequency Spectrum Type 2113. The analysis was described on a Brüel and Kjær level recorder, Type 2305. The procedure was repeated, using an input sine sweep signal, generated by a Brüel and Kjær beat frequency oscillator, Type 1022, which had a mechanical drive link from the level recorder (Figure A4.2). Both earphones on the headband were tested with the sine sweep. During testing the earphones were held at a 0.18 m separation, to give a constant pressure at the earphone coupler interface, this value approximating the mean inter-ear difference.

The responses of each earphone to the rising electrical signal are shown in Figures A4.3 and A4.4. Fig A4.1 shows the response of the TDH-49 for comparison. The Beyer DT441 600 appears to follow the electrical signal most closely, and yields the flattest frequency characteristic to the sine sweep input (Figures A4.5 and A4.6.). The earphones are seen to be a close match.

The Beyer DT441 600 is a supra-aural earphone, with a flat surface, diameter 8 cm, and it was anticipated that this may reduce the inter-subject variability due to earphone placement. The Beyer DT441 600 earphone was therefore chosen for the study.

A4.2 TEST EQUIPMENT FOR HIGH FREQUENCY AUDIOMETRY

The output of a Solartron Oscillator, Type 105462, was input to a Peters AP6 audiometer, which provided an amplifier and silent switching circuit. Frequency tolerances of 3% were allowed, as measured on a Racal Universal Counter Timer, Series SAS35, 12Mc/S. The audiometer output was conducted via an R/S Type 217-567 transformer, gain 16 dB. The frequency response is shown in Figure A4.7 to match the audiometer output with the 600 ohm impedence earphones. The instrumentation used is depicted in Figure A4.8.

A4.3 CALIBRATION OF HIGH FREQUENCY SYSTEMS

The audiometric dial readings were converted to sound pressure levels via the Brüel and Kjær artificial ear Type 4153, and standard calibration equipment. The "high frequency audiometer" was assembled, as described, and calibrated at the earphone output. The earphone was placed on the flat plate adapter DB 0843 of the artificial ear, which contained a ½" Brüel and Kjær condenser microphone, and the output lead, via a pre-amplifier to a Brüel and Kjær audio frequency spectrometer, Type 2113 (Figure A4.9). Sound pressure levels were recorded for dial settings representing maximum output to noise levels in 10 dB steps at frequencies 4, 8, 12 and 16 kHz. Harmonics were required to be 30 dB down from the fundamental. All testing was carried out within the anechoic room. A full calibration check was carried out on the Peters AP6 audiometer, in accordance with B.S.2497. The frequency response at the earphone was also checked through the entire system.

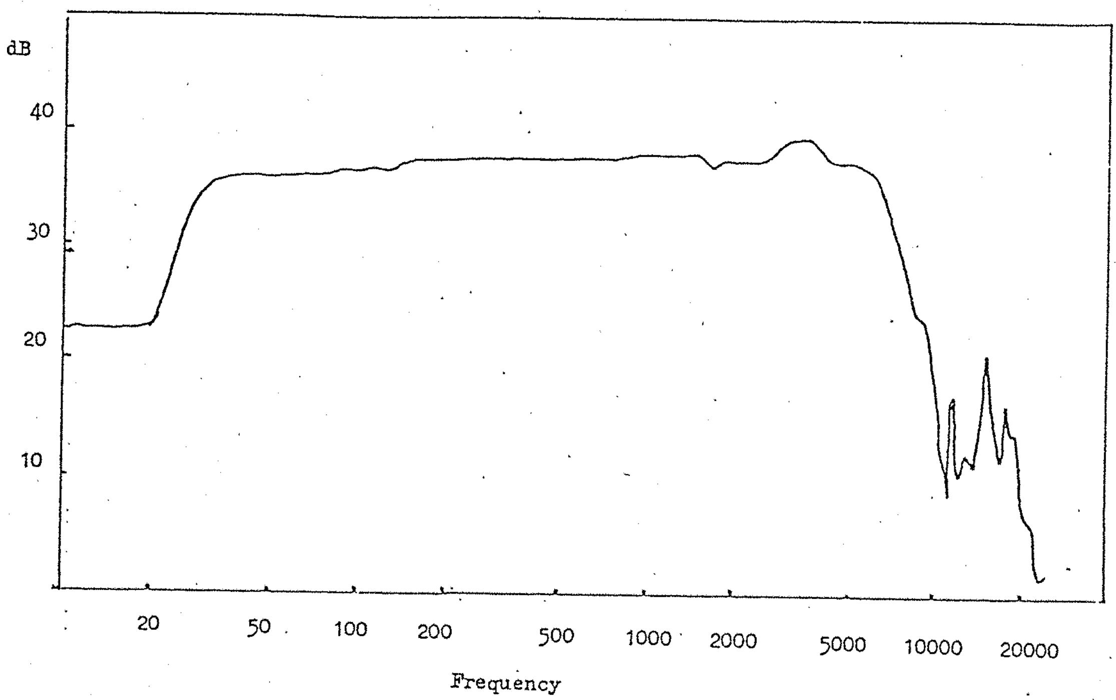
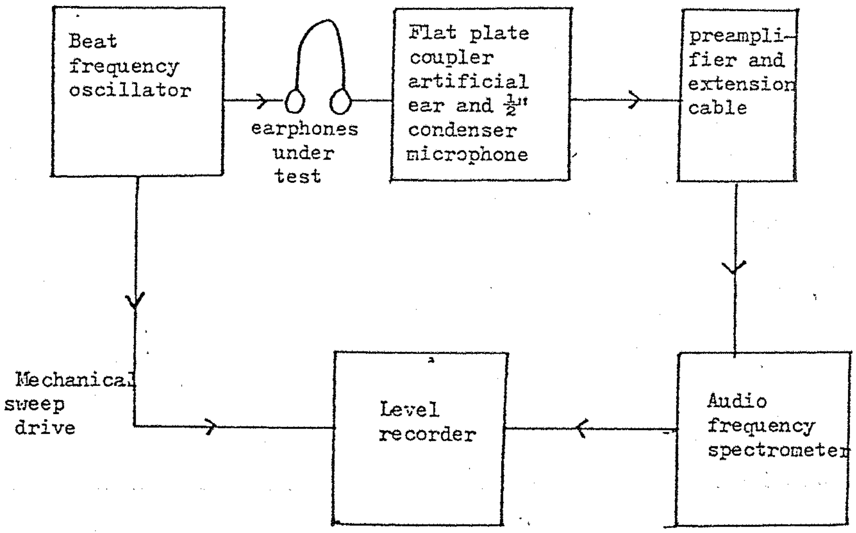


Fig A4.1

Frequency response of a TDH-49 earphone.



Instrumentation required to investigate headphone characteristics

Fig A4.2

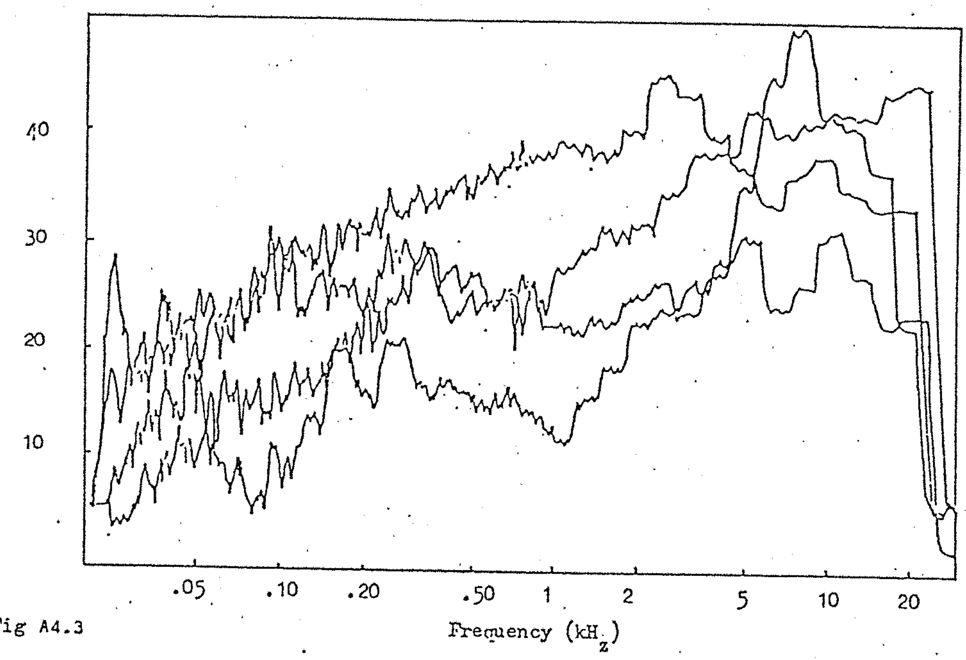
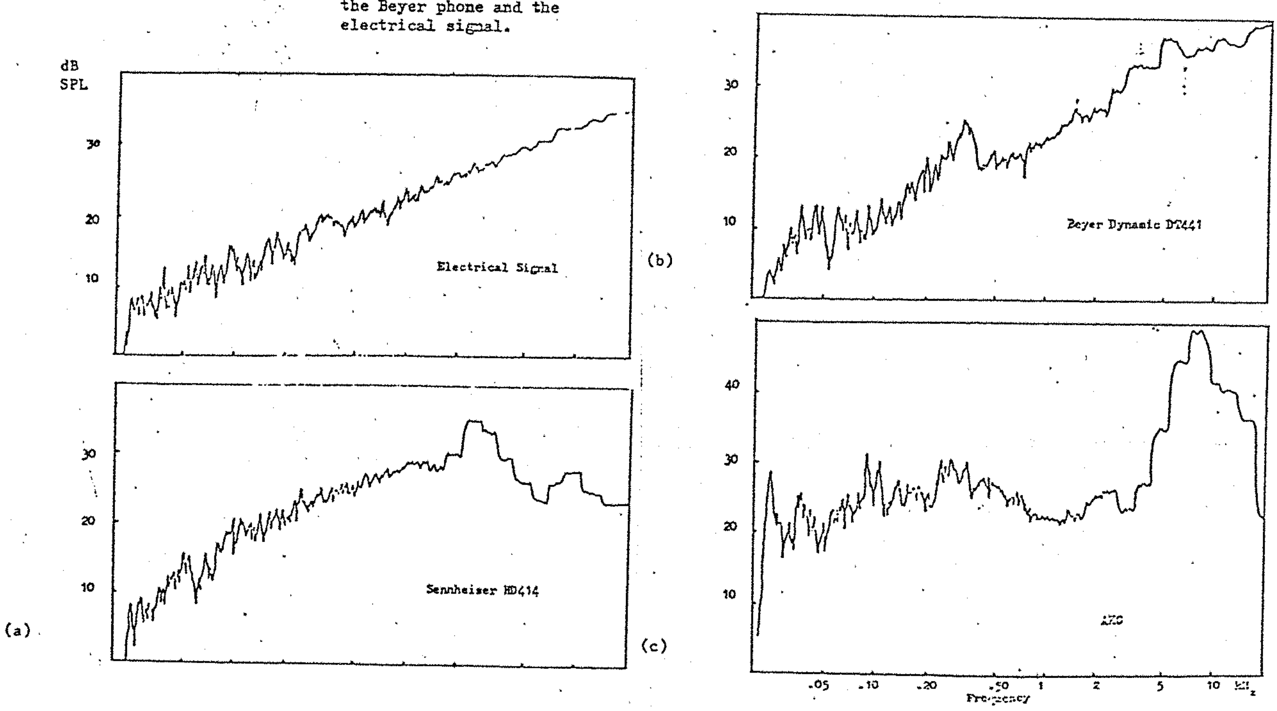


Fig A4.3

Comparison of three earphones with rising electrical signal

Fig A4.4

Comparison of frequency responses of three different headphones Note the similarity between the response of the Beyer phone and the electrical signal.



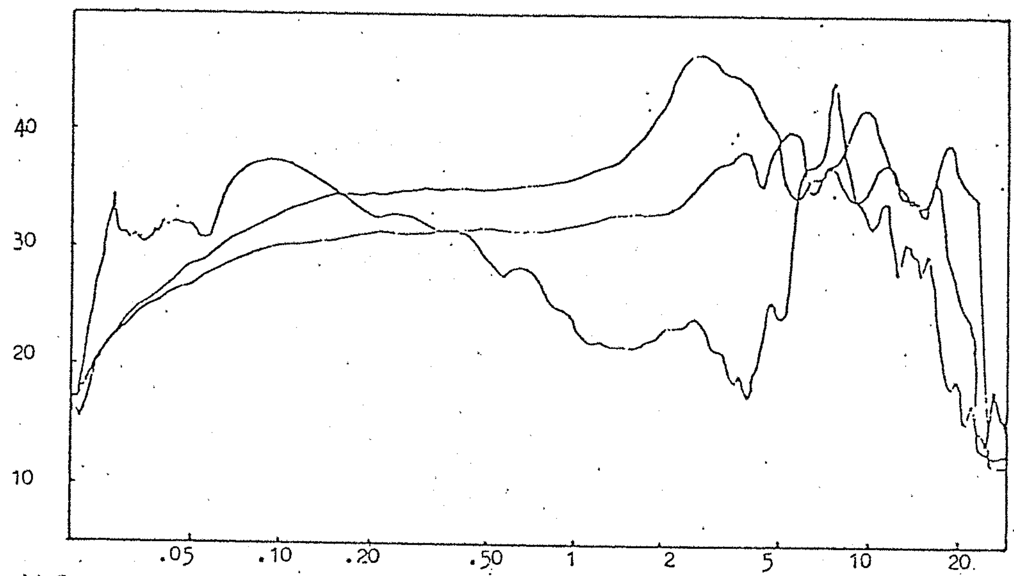


Fig A4.5

Comparison of three earphones using a sine wave sweep stimulus.

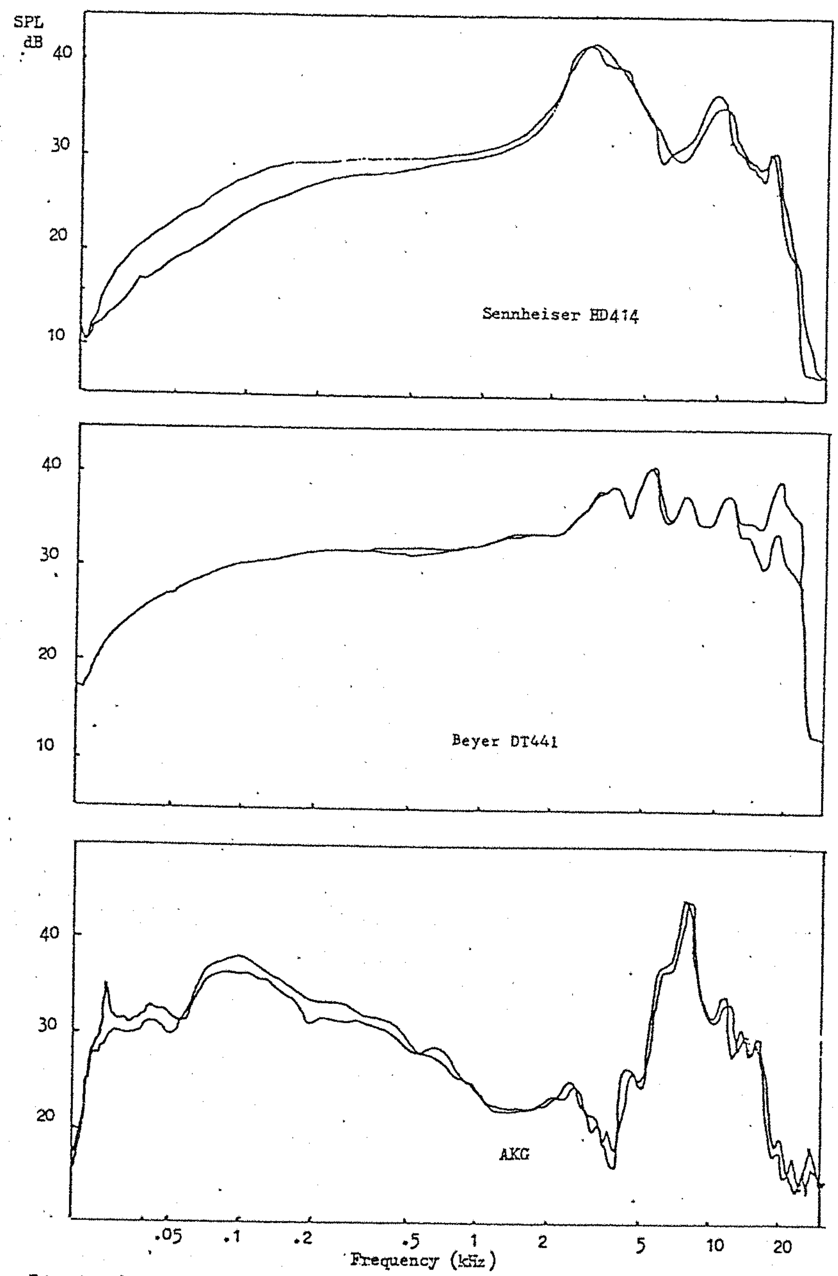
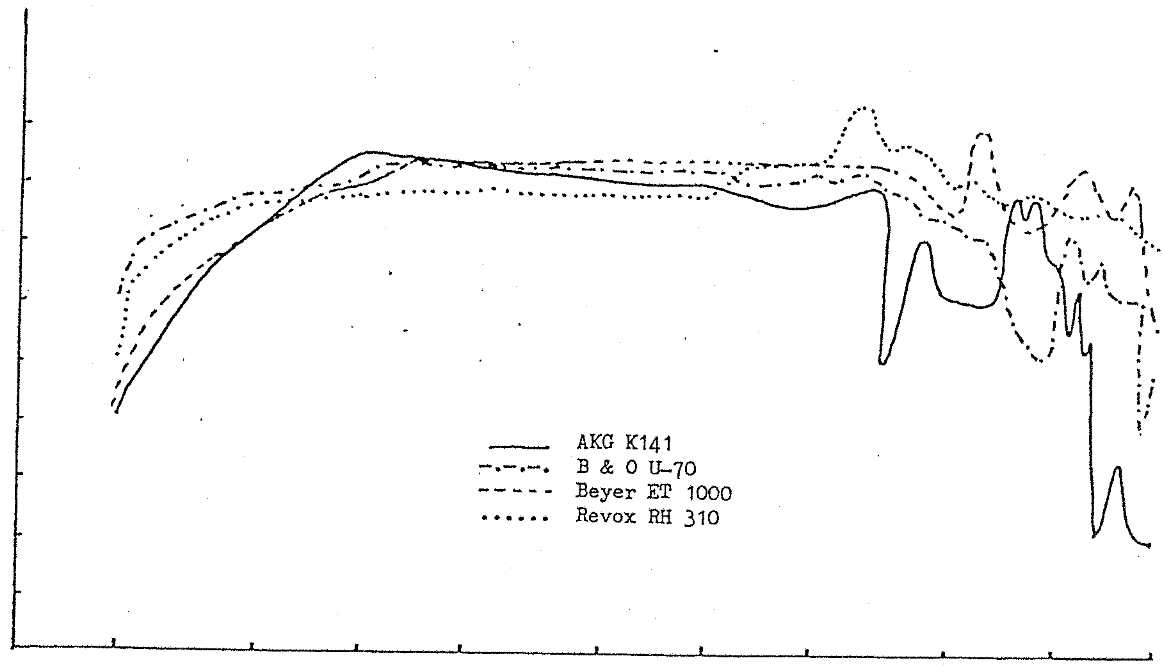


Fig A4.6
Comparison of phones using a B.F.O. sine sweep



Comparison of some hi-fi transducers

from Moir and Stevens (1980)

Fig A4.7

(1)

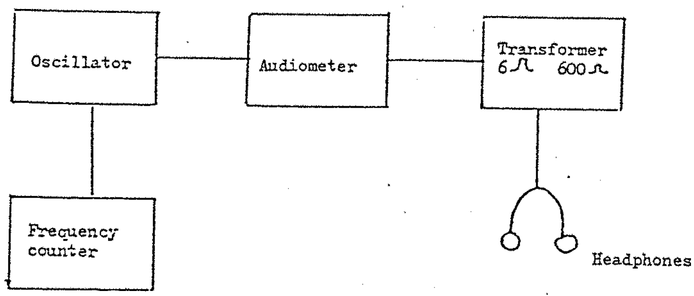


Fig A4.8 Instrumentation for High Frequency Audiometry

(2)

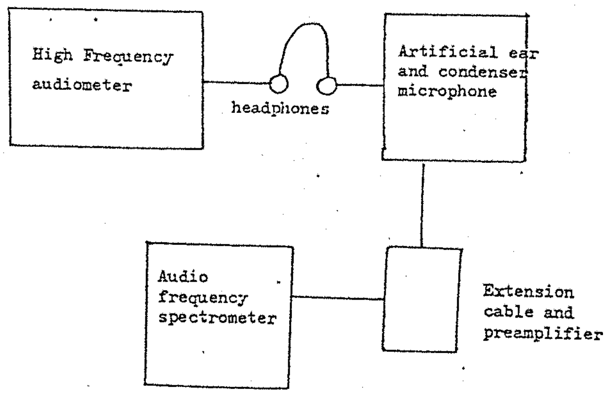


Fig A4.9 Calibration of High Frequency Audiometer

A4. 4 STATISTICAL TABLES FORM CHAPTER 4 EXPERIMENTS

Table A4. 1

High Frequency threshold values in earphone-coupler dB SPL

	Frequency (kHz)							
	4		8		12		16	
Sex	L	R	L	R	L	R	L	R
f	12	13	32	32	35	33	42	32
f	12	3	22	22	34	28	27	32
f	12	8	27	17	34	33	33	37
f	12	18	33	27	39	38	32	32
f	17	23	17	12	24	23	47	52
f	13	13	22	22	15	18	27	42
f	17	18	22	27	34	38	32	32
m	17	18	22	22	34	38	32	32
m	7	8	22	17	29	18	33	32
m	16	20	32	32	34	28	37	52
m	12	18	17	17	39	18	37	47
m	17	13	22	27	34	38	33	37
m	17	13	17	22	34	33	37	52

Table A 4.2

Comparison of Left and Right Ear Threshold

	Frequency (kHz)			
	4	8	12	16
F	3.17	1.17	1.29	2.12
t	-0.30	0.67	1.94	-2.72
df	12	12	12	12

Table A4.3

Comparison fo male and female data

	Frequency (kHz)			
	4	8	12	16
F	1.42	1.34	1.19	1.20
t	0.59	0.63	-0.68	0.71
df	24	24	24	24

$F=[n_1\sigma_1{}^2/(n_1-1)]/[(n_2\sigma_2{}^2)/(n_2-1)]$

H_o rejected if $F>2.69$, at $p<0.05$;

H_o rejected if $-2.064\leq 2.064$

Table A4.5

Comparison of TDH 49 phone and Beyer DT phone

Results of testing 8 subjects, at 4kHz on three separate days.

Source	ss	df	MS	F
Block	97	7	13.8	0.723
Treatments	97	5	19.4	1.015
A	20	2	10.0	0.520
B	70	1	70.0	3.660 *
AB	7	2	3.5	0.18
Residual	668	35	19.1	
TOTAL	939	52	135.8	

Where A represents days, B represents phones.

* indicates significant results

Table A4.6

Comparison of TDH-49 phone and Beyer DT141 phone

Results of testing 8 subjects at 8Khz on three separate days.

Souce	ss	df	MS	F
Block	1530	7	218.6	17.920
Treatments	1715	5	342	28.600
A	7.5	2	318	0.316
B	1644.5	1	1644.5	134.800 *
AB	63.	2	31.5	2.580 *
Residual	426	35	12.2	
TOTAL	3671	52	2567.8	

Where A represents days, B represents phones,

and * represents significant results

Table A4.7

Comparison of Threshold Obtained with the Beyer DT earphone. at 4 frequencies. on 3 days.

	Source	55				
1.	Blocks	2284	7	326	4.46	*
2.	Treatments	23433.5	11	2136	0.03	
3.	A	69.5	2	34.8	0.48	
4.	B	23276	3	7758.6	106.079	*
5.	AB	87.5	6	14.6	0.1996	
6.	Residual	5632.5	77	73.14		
	TOTAL	54783	106	10337.14		

A represents days, B represents frequencies.

APPENDIX 5

AUDITORY ELECTROPHYSIOLOGICAL MEASURES: TABLES AND FIGURES

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Table A5.1

JEWETT WAVES I - VI AMPLITUDES

48 dB/Octave.

High Pass Cutoff Frequencies (Hz)

WAVE		.2	10	20	30	50	70	100	150	200	300	400	500	600	800
I	$\bar{x}$	334.80	333.80	333.00	333.00	343.40	351.60	357.00	346.40	325.40	284.20	242.00	201.20	160.80	91.60
	σ	113.84	113.86	114.81	114.38	113.57	110.98	107.81	101.15	91.94	73.53	58.75	47.85	37.84	20.70
II	$\bar{x}$	140.80	140.00	139.00	139.60	145.60	153.40	164.80	172.00	170.80	174.20	179.80	167.60	138.00	72.20
	σ	67.84	68.56	70.17	70.38	69.09	66.90	65.00	64.68	64.31	68.19	67.80	63.32	54.32	31.70
III	$\bar{x}$	235.20	233.00	230.60	229.60	231.80	238.20	252.80	277.80	295.80	278.80	215.20	153.20	104.80	45.40
	σ	52.70	52.46	52.93	54.15	59.18	61.65	62.03	62.30	66.93	67.71	60.18	48.25	38.26	20.94
V	$\bar{x}$	395.80	403.40	398.20	389.40	378.60	362.40	339.60	297.00	252.40	181.00	122.00	75.80	48.40	25.00
	σ	127.73	122.57	116.05	112.17	107.83	106.88	104.59	91.00	74.94	44.03	24.22	19.92	18.73	12.35
VI	$\bar{x}$	163.20	162.40	159.80	156.80	148.20	136.20	124.80	126.20	134.40	131.20	94.00	44.00	33.20	17.80
	σ	103.55	101.34	94.60	87.88	77.73	65.90	58.11	63.21	69.95	61.39	32.88	26.20	16.51	7.85

Table A5.2

JEWETT WAVES I - VI AMPLITUDES

24 dB/Octave

High Pass Cutoff Frequencies (Hz)

WAVE		.2	10	20	30	50	70	100	150	200	300	400	500	600	800
I	$\bar{x}$	331.40	331.00	331.00	334.00	341.60	349.70	349.20	337.60	217.80	277.20	236.20	191.20	152.00	88.60
	σ	113 60	113.53	114.15	113.67	113.67	110.86	105.86	97.97	88.69	70.20	56.86	45.14	34.11	19.14
II	$\bar{x}$	140.80	141.60	140.60	141.20	146.00	153.60	163.40	167.00	165.80	168.40	166.00	146.80	119.60	67.80
	σ	67.49	67.59	68.36	67.99	68.03	66.81	66.97	67.30	68.65	71.96	68.93	60.35	49.40	24.82
III	$\bar{x}$	264.80	264.20	261.80	261.60	261.20	263.60	274.20	294.40	302.40	268.60	208.40	152.00	108.20	56.21
	σ	25.08	26.58	26.58	26.70	30.74	35.78	43.15	53.40	62.76	66.23	57.21	45.55	36.02	20.91
V	$\bar{x}$	385.60	283.60	379.20	375.00	362.80	348.40	326.00	284.00	245.60	177.60	119.00	76.80	51.20	24.20
	σ	137.25	133.59	126.65	121.69	118.26	116.21	111.68	94.75	73.45	40.68	26.16	20.98	18.39	12.93
VI	$\bar{x}$	166.20	166.00	162.00	158.20	146.80	133.60	118.80	108.80	113.60	106.60	84.60	64.40	48.00	29.20
	σ	103.57	103.25	100.94	97.65	87.09	73.19	60.29	49.44	35.78	30.10	27.70	22.71	19.65	12.21

Table A5.3

JEWETT WAVES 1 - VI AMPLITUDES

12 dB/OCTAVE.

High Pass Cutoff Frequencies (Hz)

WAVE		.2	10	20	30	50	70	100	150	200	300	400	500	600	800
I	$\bar{x}$	331.40	335.20	338.60	342.00	347.20	351.40	355.40	356.20	350.40	335.40	313.20	288.20	261.00	201.80
	σ	113.60	109.05	105.83	103.95	100.60	97.94	93.87	90.49	85.65	75.80	63.90	57.02	51.29	41.64
II	$\bar{x}$	141.20	141.60	140.40	140.40	139.50	138.00	136.00	127.60	122.00	118.40	129.80	145.80	127.40	99.40
	σ	66.91	61.27	58.31	54.40	51.83	52.19	54.72	52.99	63.23	73.12	80.33	85.78	64.00	32.06
III	$\bar{x}$	238.00	248.00	258.20	267.20	280.00	289.20	302.40	318.80	330.20	337.00	327.20	298.40	273.00	225.40
	σ	56.74	59.74	64.18	66.66	71.59	74.70	83.37	91.77	97.37	96.57	96.60	92.57	86.29	73.22
V	$\bar{x}$	380.00	390.60	396.80	401.60	396.60	386.40	369.20	354.20	316.60	260.40	223.40	195.60	167.20	103.40
	σ	144.87	146.87	144.67	141.57	127.27	120.46	131.74	128.23	118.44	97.05	91.94	88.27	83.33	52.18
VI	$\bar{x}$	164.00	161.40	157.60	150.40	132.06	111.06	92.60	72.40	77.80	105.40	127.00	107.80	101.06	83.20
	σ	104.24	107.22	105.06	98.77	79.97	62.16	51.90	47.90	46.17	37.67	39.48	35.44	30.56	30.95

Table A5.4

NORMALISED WAVE AMPLITUDES AND CROSS PRODUCTS

48 dB/Octave

High Pass Cutoff Frequencies (Hz)

	.2	10	20	30	50	70	100	150	200	300	400	500	600	800
WAVES														
I	93.78	93.30	93.28	93.84	96.19	98.49	100.00	97.03	91.15	79.61	67.79	56.36	45.04	25.66
II	78.31	77.87	77.30	77.60	80.98	85.31	91.66	95.66	94.99	96.89	100	93.21	76.95	40.00
III	79.51	78.77	77.96	77.62	78.36	80.53	85.46	93.91	100	94.25	72.75	51.79	35.42	15.35
V	98.12	100.00	98.71	96.53	93.85	89.84	84.18	73.62	62.57	44.87	30.24	14.79	12.00	6.20
VI	100	99.50	97.92	96.00	90.81	83.46	76.47	77.33	82.23	80.39	57.60	26.96	20.34	10.91
CROSS PRODUCTS														
III, V	99.33	100.00	97.47	95.50	96.05	96.75	97.68	91.08	77.43	45.72	20.02	7.44	2.59	0.03
II, III, V	86.88	86.79	84.15	82.74	86.87	92.18	100.00	97.32	82.17	49.47	22.44	6.10	2.22	1.41
-VI	100.00	99.39	94.83	91.55	90.80	88.54	88.00	86.61	77.74	45.77	10.30	1.89	0.52	0.17

Table A5.5

NORMALISED WAVE AMPLITUDES AND CROSS PRODUCTS

24 dB/Octave

High Pass Cutoff Frequencies (Hz)

WAVES	.2	10	20	30	50	70	100	150	200	300	400	500	600	800
I	94.77	94.65	94.65	95.51	97.68	100.00	99.86	96.53	90.88	79.27	66.97	54.68	43.47	25.34
II	83.61	84.09	83.49	83.95	86.70	91.21	97.03	99.17	98.46	100.00	98.57	87.17	71.02	40.26
III	87.57	87.74	86.57	86.51	86.38	87.17	90.67	97.35	100.00	88.82	68.92	50.26	55.78	18.59
V	100.00	99.24	98.34	97.25	94.09	90.35	84.54	73.64	63.69	46.05	30.86	19.92	13.28	6.28
V1	100.00	100.00	97.47	95.19	88.33	80.39	71.48	65.46	68.35	64.14	50.90	38.70	28.89	17.57

CROSS PRODUCTS														
I, III, V	100.00	99.31	97.08	96.81	95.66	94.90	92.21	83.47	69.74	39.06	17.16	6.59	2.49	0
I, II, III, V	93.43	93.30	90.57	90.83	92.68	96.73	100.00	92.41	76.73	43.65	24.46	6.42	1.98	0
I - VI	100.00	100.00	94.49	92.53	87.62	83.21	76.51	64.73	56.13	29.98	10.30	2.67	0	0

Table A5.6

NORMALISED WAVE AMPLITUDES AND CROSS PRODUCTS

12 dB/Octave

High Pass Cutoff Frequencies (Hz)

	.2	10	20	30	50	70	100	150	200	300	400	500	600	800
WAVES														
I	93.03	94.10	95.06	96.01	97.47	98.65	99.78	100.00	98.37	94.16	87.95	80.96	73.27	56.65
II	96.84	97.11	96.30	96.30	95.68	95.68	93.28	87.50	83.68	80.93	89.03	100.00	87.38	68.18
III	70.62	73.59	76.62	79.29	83.09	85.76	89.73	94.60	97.98	100.00	97.09	88.43	81.01	66.77
V	94.62	97.26	98.80	100	98.75	96.22	91.93	91.93	78.83	64.84	55.63	48.71	41.63	25.75
VI	100	98.41	96.10	91.71	80.52	67.68	50.37	44.14	47.44	64.02	77.43	65.73	61.59	50.73
CROSS PRODUCTS														
III, V	71.47	77.44	82.74	87.75	91.96	93.60	94.64	100.00	87.36	70.20	54.01	40.10	28.41	11.20
II, III, V	77.29	83.96	88.97	94.12	98.24	100.00	98.57	97.70	81.63	63.34	54.28	44.71	27.72	8.52
-VI	89.54	95.73	99.06	100.00	91.64	78.40	57.52	49.96	44.88	47.05	48.70	34.09	19.78	5.01

A5.2 Summary of Data Recorded in Experiment 2, Chapter 5

Conditions 1 and 2, Tables A5.7 - A5.22

ABR; monaural stimulation, ipsilateral recordings, latency data for both ears, all values of Wave V included, Table A5.7

ABR; monaural stimulation, ipsilateral recordings, latency data for both ears, values of Wave V included where Wave IV is absent, Table A5.8

ABR; monaural stimulation, ipsilateral recordings, latency data for both ears, values of Wave V included where Wave IV is present, Table A5.9

ABR; monaural stimulation, latency data by ear, ipsilateral recordings, all values of Wave V included, Table A5.10

ABR; monaural stimulation, latency data by ear, ipsilateral recordings, values of Wave V included where Wave V is absent, Table A5.11

ABR; monaural stimulation, latency data by ear, ipsilateral recordings, values of Wave V included where Wave IV is present, Table A5.12

ABR; monaural stimulation, ipsilateral recordings, amplitudes for both ears, all values of Wave V included, Table A5.13

ABR; monaural stimulation, ipsilateral recordings, amplitudes for both ears, values of Wave V included where Wave IV is absent, Table A5.14

ABR; monaural stimulation, ipsilateral recordings, amplitudes for both ears, values of Wave V included where Wave IV is present, Table A5.15

ABR; monaural stimulation, ipsilateral recordings, amplitude data by ear, all values of Wave V included, Table A5.16

ABR; monaural stimulation, ipsilateral recordings, amplitude data by ear, values of Wave V included where Wave IV is absent, Table A5.17

ABR; monaural stimulation, ipsilateral recordings, amplitude data by ear, values of Wave V included where Wave IV is present, Table A5.18

ABR; monaural stimulation, contralateral latency values, both ears, Table A5.19

ABR; monaural stimulation, contralateral latency values, by ear, Table A5.20

ABR; monaural stimulation, contralateral amplitude values, both ears, Table A5.21

ABR; monaural stimulation, contralateral amplitude values, by ear, Table A5.22

Condition 3, Tables A5.23 - A5.34

ABR; binaural stimulation; latency values for both ears, all values of Wave V included, Table A5.23

ABR; binaural stimulation; latency values for both ears, values of Wave V included where Wave IV is absent, Table A5.24

ABR; binaural stimulation; latency values for both ears, values of Wave V included where Wave IV is present, Table A5.25

ABR; binaural stimulation, latency values presented by ear, all values of Wave V included, Table A5.26

ABR; binaural stimulation, latency values presented by ear, values of Wave V included where Wave IV is absent, Table A5.27

ABR; binaural stimulation, latency values presented by ear; values of Wave V included where Wave IV is present, Table A5.28

ABR; binaural stimulation, amplitude values for both ears, all values of Wave V included, Table A5.29

ABR; binaural stimulation, amplitude values for both ears, values of Wave V included where Wave IV is absent, Table A5.30

ABR; binaural stimulation, amplitude values for both ears, values of Wave V included where Wave IV is present, Table A5.31

ABR; binaural stimulation, amplitude values presented by ear, all values of Wave V included, Table A5.32

ABR; binaural stimulation, amplitude values presented by ear; values of Wave V included where Wave IV is absent, Table A5.33

ABR; binaural stimulation, amplitude values presented by ear, values of Wave V included where Wave IV is present, Table A5.34

Condition 4, Tables A5.35 - A5.38

ABR; latency intensity function, ipsilateral, at 10 s^{-1}, 0.1-3 kHz, Table A5.35

ABR; latency intensity function, contralateral, at 10 s^{-1}, 0.1-3 kHz, Table A5.36

ABR; amplitude intensity function, ipsilateral, at 10 s^{-1}, 0.1-3 kHz, Table A5.37

ABR; amplitude intensity function, contralateral,at 10 s^{-1}, 0.1-3 kHz, Table A5.38

Condition 5, Tables A5.39 - A5.42

ABR; latency intensity function, ipsilateral, at 20 s^{-1}, 0.02-3 kHz, Table A5.39

ABR; latency intensity function, contralateral, at 20 s^{-1}, 0.02-3 kHz, Table A5.40

ABR; amplitude intensity function, ipsilateral, at 20 s^{-1}, 0.02-3 kHz, Table A5.41

ABR; amplitude intensity function, contralateral, at 20 s^{-1}, 0.02-3 kHz, Table A5.42

Condition 6, Tables A5.43 - A5.48

MLR; monaural stimulation, ipsilateral recordings, latency data, both ears, Table A5.43

MLR; monaural stimulation, ipsilateral recordings, amplitude data, both ears, Table A5.44

MLR; monaural stimulation, contralateral recordings, latency data, both ears, Table A5.45

MLR; monaural stimulation, contralateral recordings, amplitude data, both ears, Table A5.46

MLR; latency and amplitude functions, ipsilateral recordings, Table A5.47

MLR; latency and amplitude functions, contralateral recordings, Table A5.48

A5.3 Experiment 2, Chapter 5: Data Summaries and Statistical Treatments

Table A5.7
ABR; Monaural Stimulation   Ipsilateral recordings, data for both ears

Sex	No. of Ears	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	12	mean	1,79	2,96	3,98	5,07	5,70	7,72	2,2	1,74	3,92
		s.d.	0,13	0,07	0,16	0,19	0,23	0,17	0,18	0,29	0,26
females	12	mean	1,56	2,70	3,60	4,89	5,51	7,58	2,09	1,89	3,98
		s.d.	0,13	0,19	0,19	0,10	0,28	0,24	0,14	0,19	0,23
males & females	24	mean	1,67	2,83	3,81	4,99	5,61	7,65	2,14	1,81	3,95
		s.d.	0,17	0,19	0,25	0,18	0,27	0,22	0,17	0,24	0,25

* all values of JV included

Table A5.8
ABR; Monaural Stimulation   Ipsilateral recordings, data for both ears

Sex	No. of Ears	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	4	mean					5,52				3,71
		s.d.					0,23				0,21
females	6	mean					5,37				3,78
		s.d.					0,31				0,23
males & females	10	mean					5,42				3,74
		s.d.					0,27				0,22

* only values of JV included where JIV is absent

Table A5.9
ABR; Monaural Stimulation   Ipsilateral recordings, data for both ears

Sex	No. of Ears	Measure	I	II	Wave latencies (ms) III	IV	V*	VI	I-III	III-V	I-V
males	8	mean					5,80				4,02
		s.d.					0,16				0,16
females	6	mean					5,70				4,08
		s.d.					0,19				0,16
males & females	14	mean					5,74				4,05
		s.d.					0,17				0,18

* only values of JV included where JIV is present

Table A5.10

ABR; Monaural stimulation   Presented by ear, ipsilateral recordings

Sex	Ear	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean	1,83	2,97	4,01	5,15	5,76	7,74	2,17	1,76	3,93
		s.d.	0,15	0,07	0,13	0,16	0,21	0,21	0,19	0,26	0,26
females	left	mean	1,55	2,72	3,64	4,90	5,53	7,66	2,09	1,89	3,98
		s.d.	0,12	0,18	0,19	0,10	0,23	0,18	0,11	0,20	0,18
males & females	left	mean	1,65	2,84	3,81	5,04	5,65	7,70	2,13	1,82	3,95
		s.d.	0,14	0,18	0,26	0,18	0,25	0,19	0,16	0,23	0,22
males	right	mean	1,74	2,94	3,96	4,99	5,64	7,70	2,22	1,72	3,91
		s.d.	0,08	0,08	0,18	0,20	0,24	0,13	0,17	0,28	0,26
females	right	mean	1,56	2,68	3,64	4,88	5,49	7,51	2,08	1,90	3,98
		s.d.	0,13	0,21	0,19	0,11	0,33	0,29	0,17	0,18	0,28
males & females	right	mean	1,65	2,81	3,80	4,91	5,59	7,66	2,15	1,81	3,94
		s.d.	0,14	0,20	0,26	0,20	0,26	0,25	0,18	0,25	0,27

* all values of JV included

Table A5.11

ABR; Monaural stimulation   Presented by ear, ipsilateral recordings

Sex	Ear	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean					5,60				3,73
		s,d,					0,20				0,24
females	left	mean					5,37				3,87
		s,d,					0,20				0,10
males & females	left	mean					5,46				3,78
		s,d,					0,25				0,18
males	right	mean					5,43				3,71
		s,d,					0,14				0,25
females	right	mean					5,38				3,73
		s,d,					0,41				0,31
males & females	right	mean					5,68				3,71
		s,d,					0,22				0,25

* only values of JV included where JIV is absent

Table A5.12

ABR; Monaural stimulation   Presented by ear, ipsilateral recordings

Sex	Ear	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean					5,84				4,03
		s,d,					0,09				0,22
females	left	mean					5,72				4,07
		s,d,					0,12				0,16
males & females	left	mean					5,78				4,05
		s,d,					0,12				0,19
males	right	mean					5,75				4,02
		s,d,					0,21				0,21
females	right	mean					5,68				4,11
		s,d,					0,25				0,16
males & females	right	mean					5,43				4,05
		s,d,					0,27				0,20

* only values of JV included where JIV is present

Table A5.13
ABR; Monaural Stimulation — Ipsilateral recordings, amplitude values for both ears

Sex	No. of Ears	Measure	I	II	III	IV	V*	VI	I/V
			Peak-to-peak amplitudes (nV)						
males	12	mean	208	130	246	74	310	66	1,40
		s.d.	74	66	64	40	88	34	0,60
females	12	mean	274	378	358	158	396	102	1,50
		s.d.	90	76	106	106	136	60	0,62
males & females	24	mean	240	154	302	116	354	84	1,46
		s.d.	88	74	104	90	122	52	0,64

* all values of JV included

Table A5.14
ABR; Monaural Stimulation — Ipsilateral recordings, amplitude values for both ears

Sex	No. of Ears	Measure	I	II	III	IV	V*	VI	I/V
			Peak-to-peak amplitudes (nV)						
males	4	mean					280		
		s.d.					38		
females	4	mean					522		
		s.d.					66		
both	8	mean					404		
		s.d.					134		

* only values of JV where JIV is absent included

Table A5.15
ABR; Monaural Stimulation — Ipsilateral recordings, amplitude values for both ears

Sex	No. of Ears	Measure	I	II	III	IV	V*	VI	I/V
			Peak-to-peak amplitudes (nV)						
males	8	mean					126		
		s.d.					100		
females	8	mean					324		
		s.d.					122		
both	16	mean					324		
		s.d.					108		

* only values of JV where JIV is absent included

Table A5.16

ABR; Monaural Stimulation   Ipsilateral recordings,amplitude values by ear

Sex	Ear	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean	200	180	240	66	302	56	1,44
		s,d,	64	64	62	40	82	34	0,76
females	left	mean	292	160	370	188	428	106	1,50
		s,d,	70	64	70	100	128	64	0,66
males	right	mean	216	138	254	84	320	76	1,34
		s,d,	86	66	68	40	94	36	0,40
females	right	mean	254	194	348	126	364	96	1,50
		s,d,	104	80	132	110	142	60	0,64
males & females	left	mean	246	140	304	126	364	82	1,48
		s,d,	82	68	92	96	124	56	0,70
males & females	right	mean	234	166	300	104	340	86	1,42
		s,d,	96	78	114	82	120	48	0,54

* all values of JV included

Table A5.17
ABR; Monaural Stimulation   Ipsilateral recordings, amplitude values by ear

Sex	Ear	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean					280		
		s,d,					34		
females	left	mean					540		
		s,d,					90		
males	right	mean					282		
		s,d,					46		
females	right	mean					508		
		s,d,					36		
males & females	left	mean					410		
		s,d,					150		
males & females	right	mean					404		
		s,d,					124		

* only values of JV included where JIV is absent

Table A5.18
ABR; Monaural Stimulation   Ipsilateral recordings, amplitude values by ear

Sex	Ear	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean					314		
		s,d,					98		
females	left	mean					372		
		s,d,					108		
males	right	mean					338		
		s,d,					106		
females	right	mean					272		
		s,d,					98		
males & females	left	mean					344		
		s,d,					104		
males & females	right	mean					268		
		s,d,					82		

* values of JV included where JIV is present

Table A5.19

ABR; Monaural Stimulation   Contralateral values for both ears

Sex	No. of Ears	Measure	Wave latencies (ms) II	III	IV	V	VI
males	12	mean	3,03	3,93	5,10	5,88	7,76
		s.d.	0,08	0,17	0,18	0,16	0,20
females	12	mean	2,79	3,61	5,10	5,88	7,76
		s.d.	0,18	0,21	0,26	0,38	0,24
males & females	24	mean	2,91	3,77	5,01	5,78	7,71
		s.d.	0,18	0,25	0,24	0,31	0,25

Table A5.20

ABR; Monaural Stimulation   Contralateral latency values, by ear

Sex	Ear	Measure	Wave latencies (ms) II	III	IV	V	VI
males	left	mean	3,03	3,95	5,12	5,90	7,72
		s.d.	0,05	0,15	0,21	0,13	0,23
females	left	mean	2,80	3,60	4,92	5,67	7,74
		s.d.	0,16	0,22	0,28	0,44	0,25
males & females	left	mean	2,92	3,78	5,03	5,79	7,73
		s.d.	0,17	0,23	0,26	0,34	0,24
males	right	mean	3,03	3,90	5,08	5,87	7,79
		s.d.	0,19	0,19	0,14	0,18	0,16
females	right	mean	2,78	3,62	4,92	5,66	7,57
		s.d.	0,20	0,21	0,26	0,30	0,29
males & females	right	mean	2,91	3,76	5,00	5,76	7,68
		s.d.	0,20	0,24	0,22	0,26	0,26

Table A5.21
ABR; Monaural Stimulation   Contralateral amplitude measures for both ears

Sex	No. of Ears	Measure	Amplitudes (nV) II	III	IV	V	VI
males	12	mean	158	142	140	240	50
		s.d.	82	64	56	132	42
females	12	mean	202	202	198	320	80
		s.d.	96	78	88	86	52
males & females	24	mean	180	172	168	282	66
		s.d.	82	78	78	126	50

Table A5.22
ABR; Monaural Stimulation   Contralateral amplitude measures by ear

Sex	Ear	Measure	Amplitudes (nV) II	III	IV	V	VI	I/V
males	left	mean	140	134	128	206	56	
		s.d.	72	76	54	108	52	
females	left	mean	160	206	244	306	98	
		s.d.	74	88	92	52	60	
males & females	left	mean	160	170	182	256	78	
		s.d.	76	88	92	98	60	
male	right	mean	176	152	152	272	46	
		s.d.	90	52	60	150	26	
females	right	mean	224	200	162	342	60	
		s.d.	110	68	58	136	38	
males & females	right	mean	200	176	158	306	52	
		s.d.	102	64	60	144	32	

Table A5.23

ABR; Binaural Presentation   Latency values for both ears

Sex	No, of Ears	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	12	mean	1,93	3,08	4,07	5,20	5,86	7,71	2,13	1,79	3,92
		s,d,	0,11	0,08	0,09	0,13	0,19	0,22	0,11	0,22	0,25
females	12	mean	1,79	2,94	3,86	5,08	5,80	7,69	2,07	1,93	4,01
		s,d,	0,16	0,16	0,23	0,18	0,17	0,32	0,13	0,21	0,22
both	24	mean	1,78	2,95	3,88	5,08	5,77	7,71	2,09	1,89	3,99
		s,d,	0,19	0,15	0,23	0,18	0,21	0,31	0,13	0,23	0,22

* all values of J V included

Table A5.24

ABR; Binaural Presentation   Latency values for both ears

Sex	No, of Ears	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	2	mean						5,50			3,43
		s,d,						0,06			0,14
females	1	mean						5,43			3,73
		s,d,						0,16			0,06
males & females	3	mean						5,48			3,53
		s,d,						0,10			0,19

* only values of JV included where JIV is absent

Table A5.25

ABR; Binaural Presentation   Latency values for both ears

Sex	No, of Ears	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	10	mean					5,93				4,03
		s,d,					0,12				0,12
females	11	mean					5,70				4,09
		s,d,					0,16				0,16
males & females	21	mean					5,81				4,06
		s,d,					0,18				0,14

* only values of JV included where JIV is present

Table A5.26

ABR; Binaural Stimulation   Latency values, presented by ear

Sex	Ear	Measure	Wave latencies (ms) I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean	1,94	3,09	4,09	5,20	5,89	7,76	2,15	1,77	3,92
		s.d.	0,13	0,06	0,08	0,13	0,21	0,14	0,13	0,24	0,28
females	left	mean	1,58	2,83	3,70	4,87	5,62	7,70	2,11	1,92	4,03
		s.d.	0,10	0,07	0,16	0,77	0,18	0,40	0,11	0,25	0,19
males & females	left	mean	1,78	2,95	3,90	5,07	5,74	7,73	2,13	1,84	3,98
		s.d.	0,19	0,15	0,24	0,17	0,23	0,30	0,12	0,25	0,24
males	right	mean	1,92	3,07	4,05	5,20	5,86	7,67	2,12	1,81	3,92
		s.d.	0,11	0,09	0,10	0,13	0,17	0,27	0,10	0,21	0,24
females	right	mean	1,66	2,81	3,67	4,98	5,74	7,69	2,01	2,06	4,08
		s.d.	0,10	0,07	0,14	0,16	0,15	0,37	0,13	0,11	0,17
males & females	right	mean	1,79	2,94	3,86	5,08	5,80	7,69	2,07	1,93	4,01
		s.d.	0,16	0,16	0,23	0,18	0,17	0,32	0,13	0,21	0,22

* all values of JV included

Table A5.27

ABR; Binaural Stimulation   Latency values for both ears

Sex	Ear	Measure	I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean					5,5				3,36
		s,d,					0,06				0,06
females	left	mean					5,43				3,73
		s,d,					0,15				0,06
males & females	left	mean					5,45				3,55
		s,d,					0,10				0,21
males	right	mean					5,53				3,50
		s,d,					0,06				0,17
females	right	mean					-				-
		s,d,									
males & females	right	mean					5,53				3,50
		s,d,					0,06				0,17

Wave latencies (ms)

* only values of JV included where JIV absent

Table A5.28

ABR; Binaural Stimulation   Latency values for both ears

Sex	Ear	Measure	I	II	III	IV	V*	VI	I-III	III-V	I-V
males	left	mean						5,95			4,03
		s,d,						0,19			0,11
females	left	mean						5,65			4,09
		s,d,						0,17			0,15
males & females	left	mean						5,80			4,06
		s,d,						0,21			0,13
males	right	mean						5,92			4,02
		s,d,						0,09			0,13
females	right	mean						5,74			4,08
		s,d,						0,15			0,17
males & females	right	mean						5,82			4,05
		s,d,						0,16			0,15

Wave latencies (ms)

* only values of JV included where JIV is present

Table A5.29
ABR; Binaural Stimulation Amplitude values for both ears

Sex	No, of Ears	Measure	Peak-to-peak amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	12	mean	199	203	256	173	406	112	0,49
		s,d,	72	100	74	27	99	65	0,15
females	12	mean	330	342	472	303	485	147	0,74
		s,d,	110	152	101	112	184	150	0,28
males & females	24	mean	264	273	364	242	446	112	0,62
		s,d,	112	144	138	150	150	60	0,26

* all values of JV included

Table A5.30
ABR; Binaural Stimulation Amplitude values for both ears

Sex	No, of Ears	Measure	Peak-to-peak amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	12	mean					386		
		s,d,					69		
females	12	mean					940		
		s,d,					19		
males & females	24	mean					592		
		s,d,					278		

* only values of JV included where JIV is absent

Table A5.31
ABR; Binaural Stimulation Amplitude values for both ears

Sex	No, of Ears	Measure	Peak-to-peak amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	12	mean					411		
		s,d,					104		
females	12	mean					443		
		s,d,					125		
males & males	24	mean					430		
		s,d,					114		

* only values of JV included where JIV is present

Table A5.32

ABR; Binaural Stimulation   Amplitude values presented by ear

Sex	No, of Ears	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean	202	204	258	161	429	108	2,12
		s,d,	78	102	70	27	103	66	
females	left	mean	343	232	482	302	547	110	1,59
		s,d,	111	142	100	110	235	62	
males & females	left	mean	273	268	373	232	488	107	1,79
		s,d,	118	138	144	106	177	63	
males	right	mean	195	195	254	185	383	117	1,96
		s,d,	67	67	81	22	89	65	
females	right	mean	317	356	457	304	423	184	1,33
		s,d,	110	162	104	118	122	200	
males & females	right	mean	256	264	356	250	403	114	1,57
		s,d,	109	146	138	106	107	58	

* all values of JV included

Table A5.33
ABR; Binaural Stimulation   Amplitude values presented by ear

Sex	No, of Ears	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean					386		
		s, d,					110		
females	left	mean					940		
		s, d,					19		
males & females	left	mean					664		
		s, d,					270		
males	right	mean					386		
		s, d,					33		
females	right	mean					-		
		s, d,					-		
males & females	right	mean					446		
		s, d,					146		

* only values JV included where JIV is absent

Table A5.34
ABR; Binaural Stimulation   Amplitude values presented by ear

Sex	No, of Ears	Measure	Amplitudes (nV) I	II	III	IV	V*	VI	I/V
males	left	mean					438		
		s, d,					106		
females	left	mean					547		
		s, d,					235		
males & females	left	mean					454		
		s, d;					108		
males	right	mean					384		
		s, d,					98		
females	right	mean					468		
		s, d,					128		
males & females	right	mean					408		
		s, d,					108		

* only values of JV included where JIV is present

Table A5.35 ABR: Latency Intensity Function

Ipsilateral, at $10s^{-1}$, 0.1-3 kHz; n is the number of recordings.

Intensity (dB SL)	Measure	I	II	III	IV	V	VI	I-III	III-V	I-V
		Wave latencies (ms)								
80	mean	1,67	2,83	3,81	4,99	5,61	7,65	2,14	1,81	3,92
	s.d.	0,17	0,19	0,25	0,18	0,27	0,22	0,17	0,24	0,25
	n	24	24	24	20	24	24	24	24	24
70	mean	1,79	2,98	3,95	5,19	5,89	7,64	2,18	1,90	4,07
	s.d.	0,09	0,16	0,20	0,19	0,16	0,34	0,14	0,34	0,30
	n	24	24	24	20	24	24	24	24	24
60	mean	2,10	3,12	4,08	5,21	6,00	7,74	1,97	1,87	3,85
	s.d.	0,21	0,15	0,14	0,13	0,24	0,28	0,24	0,21	0,23
	n	24	24	24	18	24	24	24	24	24
50	mean	2,35	3,29	4,34	5,33	6,17	7,86	1,91	1,90	3,93
	s.d.	0,29	0,31	0,25	0,15	0,17	0,28	0,23	0,30	0,61
	n	18	20	24	14	24	24	18	24	18
40	mean	2,83	4,04	4,73	5,98	6,51	8,36	1,95	1,71	3,73
	s.d.	0,18	0,34	0,39	0,21	0,22	0,35	0,25	0,27	0,20
	n	14	8	24	14	24	18	14	24	14
30	mean	3,31	4,73	5,21	5,98	6,97	9,02	1,98	1,46	3,34
	s.d.	0,35	0,07	0,36	0,21	0,38	0,32	0,35	0,38	0,62
	n	6	2	6	11	24	14	6	6	6
20	mean	0	0	5,84	7,35	7,56	0	1,90	0	0
	s.d.	0	0	0,53	0,25	0,40	0	0,38	0	0
	n	0	0	4	2	24	0	4	0	0

Table A5.36 ABR; Latency Intensity Function.

Contralateral, $10s^{-1}$, 0.1-3 kHz; n is the number of recordings.

Intensity (dB HL)	Measure		Wave latencies (ms) II	III	IV	V	VI
80	mean		2,91	3,77	5,01	5,78	7,71
	s,d,		0,18	0,25	0,24	0,31	0,25
	n		24	24	24	24	24
70	mean		3,08	3,95	5,07	5,97	7,69
	s,d,		0,13	0,19	0,36	0,30	0,32
	n		24	24	24	24	22
60	mean		3,13	4,03	5,17	6,04	7,86
	s,d,		0,16	0,16	0,22	0,20	0,31
	n		23	24	22	24	22
50	mean		3,42	4,23	5,43	6,25	8,00
	s,d,		0,31	0,22	0,46	0,38	0,38
	n		13	22	21	24	21
40	mean		3,83	4,68	5,91	6,64	8,48
	s,d,		0,39	0,53	0,37	0,32	0,53
	n		7	24	14	24	19
30	mean		4,52	5,05	6,49	6,89	8,71
	s,d,		0,25	0,38	0,24	0,52	0,46
	n		4	21	12	24	13
20	mean	0	0	5,72	0	7,58	8,81
	s,d,	0	0	0,31	0	0,59	0,28
	n	0	0	12	0	23	2

Table A5.37 ABR; Amplitude Intensity Function

Ipsilateral, at $10 s^{-1}$, 0.1-3 kHz; n is the number of recordings

Intensity (dB SL)	Measure		Wave latencies (ms) I	II	III	IV	V	VI
80	mean		240	153	117	332	328	84
	s.d.		88	72	102	90	106	52
	n		24	24	24	24	24	24
70	mean		162	138	213	85	284	74
	s.d.		32	74	127	70	83	30
	n		24	24	20	20	24	24
60	mean		93	92	148	84	219	73
	s.d.		43	56	83	37	99	32
	n		24	24	24	18	24	24
50	mean		73	53	100	44	182	68
	s.d.		50	27	42	20	67	52
	n		18	20	24	14	24	24
40	mean		67	41	92	40	180	54
	s.d.		23	17	49	20	37	26
	n		14	8	24	14	24	18
30	mean		60	53	15	93	168	56
	s.d.		19	4	46	9	77	46
	n		6	2	6	11	24	14
20	mean	0	0	0	90	26	133	12
	s.d.	0	0	0	60	5	52	0
	n	0	0	0	17	4	24	2

Table A5.38 ABR; Amplitude Intensity Function

Contralateral, at $10s^{-1}$, 0.1-3 kHz; n is the number of recordings

Intensity (dB HL)	Measure		Wave latencies (ms) II	III	IV	V	VI
80	mean		180	172	168	282	66
	s.d.		82	78	78	126	50
	n		24	24	24	24	24
70	mean		128	124	141	226	96
	s.d.		61	62	98	32	23
	n		24	24	24	24	24
60	mean		78	116	100	210	88
	s.d.		32	71	58	60	28
	n		23	24	22	24	22
50	mean		60	83	70	191	60
	s.d.		20	34	39	75	20
	n		13	22	21	24	21
40	mean		38	77	44	184	56
	s.d.		11	33	15	69	40
	n		7	24	14	24	19
30	mean		34	74	42	173	54
	s.d.		7	37	34	36	32
	n		4	21	12	24	13
20	mean	0	0	68	0	152	46
	s.d.	0	0	37	0	66	38
	n	0	0	12	0	23	2

Table A5.39 ABR; Latency Intensity Function

Ipsilateral, at $20s^{-1}$, 0.02-3 kHz; n is the number of recordings.

Intensity (dB SL)	Measure	I	II	III	IV	V	VI	I-III	III-V	I-V
		Wave latencies (ms)								
80	mean	1,67	2,93	3,80	5,05	5,74	7,54	2,13	1,88	4,07
	s,d,	0,23	0,27	0,30	0,22	0,32	0,24	0,30	0,37	0,34
	n	24	24	24	18	24	20	24	24	24
60	mean	2,17	3,19	4,06	5,19	5,98	7,74	2,02	1,89	3,83
	s,d,	0,33	0,36	0,21	0,34	0,34	0,42	0,30	0,21	0,46
	n	24	24	22	20	24	16	22	22	24
40	mean	3,05	3,37	4,64	5,72	6,71	8,25	1,78	1,94	3,86
	s,d,	0,31	0,51	0,42	0,47	0,56	0,61	0,44	0,57	0,30
	n	12	6	18	12	24	10	12	18	12
20	mean	0	0	5,36	6,31	7,44	9,56	0	1,87	0
	s,d,	0	0	0,37	0,69	0,42	0	0	0,59	0
	n	0	0	4	6	24	1	0	2	0
10	mean	0	0	6,14	0	8,12	0	0	0	0
	s,d,	0	0	0	0	0,46	0	0	0	0
	n	0	0	1	0	24	0	0	0	0

Table A5.40 ABR; Latency Intensity Function,

Contralateral, at $20s^{-1}$, 0.02-3 kHz; n is the number of recordings.

Intensity (dB HL)	Measure	II	III	IV	V	VI
		Wave latencies (ms)				
80	mean	2,97	3,83	5,09	5,91	7,65
	s,d,	0,23	0,31	0,24	0,28	0,50
	n	24	24	20	24	18
60	mean	3,16	4,10	5,24	6,08	7,54
	s,d,	0,26	0,34	0,50	0,40	0,64
	n	20	22	22	24	14
40	mean	3,85	4,77	5,97	6,72	8,12
	s,d,	0,0	0,37	0,47	0,46	0,36
	n	1	16	8	24	8
20	mean	0	0	6,86	7,52	0
	s,d,	0	0	0,0	0,52	0
	n	0	0	1	24	0
10	mean	0	0	0	8,07	0
	s,d,	0	0	0	0,34	0
	n	0	0	0	24	0

Table A5.41 ABR; Amplitude Intensity Function

Ipsilateral, at $20s^{-1}$, 0.02-3 kHz; n is the number of recordings

Intensity (dB SL)	Measure	Wave latencies (ms) I	II	III	IV	V	VI
80	mean	259	135	261	90	465	143
	s.d.	113	71	69	54	161	69
	n	24	24	24	18	24	20
60	mean	119	98	152	70	379	167
	s.d.	61	49	44	39	120	83
	n	24	24	24	22	24	16
40	mean	76	51	95	37	326	193
	s.d.	27	24	36	19	136	93
	n	12	6	18	12	24	10
20	mean			15	27	248	56
	s.d.			6	30	77	2
	n	0	0	4	6	22	2
10	mean	0	0	0	0	160	0
	s.d.	0	0	0	0	82	0
	n	0	0	0	0	24	0

Table A5.42 ABR Amplitude Intensity Function

Contralateral, at $20s^{-1}$, 0.02-3 kHz; n is the number of recordings

Intensity (dB HL)	Measure	Wave latencies (ms) II	III	IV	V	VI
80	mean	118	180	91	355	146
	s.d.	63	78	48	138	88
	n	24	24	20	24	18
60	mean	66	107	78	334	121
	s.d.	29	65	29	122	58
	n	20	22	22	24	14
40	mean	12	90	67	303	101
	s.d.	0	40	30	133	52
	n	1	16	8	24	8
20	mean	0	0	17	216	0
	s.d.	0	0	0	70	0
	n	0	0	1	24	0
10	mean	0	0	0	142	0
	s.d.	0	0	0	50	0
	n	0	12	0	24	0

Table A5.43 MLR; Monaural Stimulation

Ipsilateral recordings, latency data for both ears

Sex	No, of Ears	Measure	Wave latencies (ms) Po	Na	Pa	Na
males	5	mean	16,41	19,34	24,56	32,83
		s,d,	1,34	0,75	2,31	2,31
females	6	mean	15,52	17,91	22,24	32,19
		s,d,	0,98	1,33	1,79	2,20
males & females	11	mean	15,96	18,63	23,40	32,50
		s,d,	1,21	1,28	2,34	2,22

Table A5.44 MLR; Monaural Stimulation

Ipsilateral recordings, amplitude data for both ears

Sex	No, of Ears	Measure	Amplitudes (nV) Po-Na	Na-Pa	Pa-Nb
males	5	mean	139	175	334
		s,d,	88	57	100
females	6	mean	72	194	437
		s,d,	38	34	203
males & females	11	mean	103	186	390
		s,d,	72	100	169

Table A5.45 MLR; Monaural Stimulation

Contralateral recordings, latency data for both ears

Sex	No, of Ears	Measure	Wave latencies (ms) Po	Na	Pa	Na
males	6	mean	16,4	19,08	23,23	32,46
		s,d,	1,69	1,32	1,15	1,64
females	6	mean	15,3	17,78	22,53	32,46
		s,d,	0,86	1,28	1,59	3,22
males & females	12	mean	15,94	18,43	22,95	32,46
		s,d,	1,40	1,44	1,41	2,45

Table A5.46 MLR; Monaural Stimulation

Ipsilateral recordings, amplitude data for both ears

Sex	No, of Ears	Measure	Amplitudes (nV) Po-Na	Na-Pa	Pa-Nb
males	6	mean	117	202	329
		s,d,	58	90	87
females	6	mean	104	269	365
		s,d,	42	108	187
males & females	11	mean	110	235	370
		s,d,	48	101	166

Table A5.47 MLR; Latency and Amplitude Intensity Functions

Ipsilateral recording; data for both ears.

Intensity (dB)	Measure	Wave latencies (ms)				Amplitudes(nV)		
		Po	Na	Pa	Nb	Po-Na	Na-Pa	Pa-Nb
80	mean	15,53	18,12	27,86	31,00	146	280	416
	s,d,	1,10	0,97	1,56	1,83	148	232	198
	n	14	17	18	18	14	17	18
70	mean	15,96	18,63	23,40	32,50	103	186	390
	s,d,	1,21	1,28	2,34	2,22	72	100	169
	n	22	22	22	22	22	22	22
50	mean	16,21	19,3	24,0	33,94	174	219	383
	s,d,	1,02	1,25	1,52	1,80	65	119	162
	n	21	21	24	24	21	21	24
30	mean	17,12	20,16	25,26	33,92	112	182	344
	s,d,	1,35	1,46	1,87	2,64	50	60	147
	n	23	23	24	24	23	23	24
20	mean	17,49	20,84	26,36	33,71	97	159	244
	s,d,	1,42	1,55	1,61	2,90	34	28	93
	n	14	14	14	14	14	14	14
10	mean	18,28	21,67	27,86	34,95	123	168	215
	s,d,	1,01	0,76	2,06	1,80	48	74	103
	n	10	11	21	20	10	11	20

Table A5.48 MLR; Latency and Amplitude Intensity Functions

Contralateral recording; data for both ears.

Intensity (dB)	Measure	Wave latencies (ms) Po	Na	Pa	Nb	Amplitudes(nV) Po-Na	Na-Pa	Pa-Nb
80	mean	15,88	18,19	22,91	30,47	115	286	408
	s,d,	1,00	1,06	1,54	1,94	94	136	189
	n	18	18	18	18	14	17	18
70	mean	15,94	18,43	22,95	32,46	110	235	370
	s,d,	1,41	1,48	1,41	2,45	49	101	169
	n	24	24	24	24	24	24	24
50	mean	16,21	19,10	24,29	33,11	136	300	371
	s,d,	0,98	1,01	1,52	1,84	61	80	139
	n	22	22	24	24	22	22	24
30	mean	17,02	19,87	24,92	34,28	110	202	359
	s,d,	1,15	1,25	1,72	2,57	55	94	148
	n	23	23	24	24	23	23	24
20	mean	17,76	20,55	26,74	34,71	90	169	268
	s,d,	1,78	1,74	1,81	3,680	41	78	90
	n	14	14	14	14	14	14	14
10	mean	18,38	22,45	29,09	34,68	129	184	207
	s,d,	1,03	2,64	2,94	1,93	82	84	136
	n	8	8	22	22	8	10	20

Table A5.49 ABR; Subject Effects

(Significance of F values derived from ANOVA)

		I	II	III	IV	V	VI
Latency	ipsi	<0,01	<0,01	<0,01	<0,01	-	<0,01
	contra	-	<0,01	<0,01	<0,01	<0,01	<0,25
Amplitude	ipsi	<0,01	<0,01	<0,01	<0,01	<0,01	<0,05
	contra	<0,05	<0,01	<0,01	<0,01	<0,01	<0,01

Table A5.50 ABR; Trial Effects

		I	II	III	IV	V	VI
Latency	ipsi	-	-	-	-	-	-
	contra	0,01	0,05	<0,05	-	-	<0,05
Amplitude	ipsi	-	-	-	-	-	-
	contra	-	-	-	-	-	-

Table A5.51

ABR; Comparison of left and right monaural ipsilateral recordings

Student's t-test (related measures)

Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	I	II	III	IV	V	VI
Latency	Ho	Ho	Ho	0,05	0,05	Ho
Amplitude	Ho	Ho	Ho	Ho	Ho	Ho

Table A5.52

ABR; Comparison of ipsi- and contralateral latencies

Student's t-test (related measures)

Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	II	III	V	VI	III-V
Males	,001	,001	,001	,02	,001
Females ,	001	,02	,001	,001	,001

Table A5.53

ABR; Latency differences between ipsi- and contralateral recordings

Sex	No, of Ears	Measure	Latency differences (ms) II	III	IV	V	VI	III-V
males	12	mean	0,07	0,14		0,18	0,04	0,27
females	12	mean	0,09	0,03		0,13	0,10	0,15
males & females	24	mean	0,08	0,09		0,16	0,06	0,21

Table A5.54

ABR; Comparison of ipsi- and contralateral amplitudes

Student's t-test for related measures

Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	II	III	V	VI
Males	,001	,001	,001	,10
Females ,	01	,001	,001	,05

Table A5.55

ABR; Amplitude differences between ipsi- and contralateral recordings

Sex	No, of Ears	Measure	Amplitude differences (nV) II	III	IV	V	VI
males	12	mean	22,3	106,1		72,0	17,0
females	12	mean	26,4	156,1		65,7	18,7
males & females	24	mean	24,3	131,0		69,0	13,7

Table A5.56

ABR; Comparison of monaural and binaural effects

(Significance of F values derived from ANOVA with repeated measures on one factor)

		I	II	III	IV	V	VI
Latency	(binaural)	-	003	12	-	-	02
	(monaural)	-	-	-	-	-	-
Amplitude	(binaural)	02	-	02	08	002	02
	(monaural)	-	-	-	-	-	-

Table A5.57

ABR; Amplitude differences for binaural and monaural recordings

Sex	No, of Ears	Measure	Amplitude differences (nV) all V	IV pres	Mon/Bin IV abs	ratio
males	12	mean	310	406	94	70
		s, d,	88	99		
females	12	mean	396	485	89	78
		s, d,	136	184		
males & females	24	mean	354	446	92	74
		s, d,	122	150		

Table A5.58 ABR; Comparison of male and female data

t-test for indepemdent measures

Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	I	II	III	IV	V	VI
Latency	0,001	0,001	0,001	0,01	0,05	Ho
Amplitude	0,05	0,05	0,01	Ho	Ho	0,02

Table A5.59 ABR; Mean differences (male - female) records

	Mean differences (ms) I	II	III	IV	V	I-V
Latency(ipsi)	0,23	0,26	0,38	0,18	0,19	0,06
Latency(contra)	0,24	0,22	0	0	0	0

Table A5.60 MLR; Comparison of ipsi- and contralateral latencies

t-test for related measures. Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	Po	Na	Pa	Nb	Po-Na	Na-Pa	Pa-Nb
Latency	Ho	,001	,002	,02			
Amplitude					Ho	,01	Ho

Table A5.61 MLR; Latency differences between ipsi- and contralateral recordings

No,of Ears	Measure	Latency differences (ms) Po	Na	Pa	Nb
24	mean	ns*	0,75	0,60	ns*
	s,d,		1,27	1,77	
			c>i	i>c	

* indicates not significant

Table A5.62

MLR; Amplitude differences between ipsi- and contralateral recordings

No, of Ears	Measure	Amplitude differences (nV) Po-Na	Na-Pa	Pa-Nb
22	mean	ns	42, 28	ns*
	s, d		51, 10	
			c>i	

* indicates not significant

Table A5.63

MLR; Comparison of male and female data

t-test for independent measures. Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$. Figures denote significance level at which the null hypothesis is rejected.

	Po	Na	Pa	Nb	Po-Na	Na-Pa	Pa-Nb
Latency	,02	0, 01	0, 01	Ho			
Amplitude					0, 01	Ho	Ho

Table 5.64

MLR; Mean differences male - female records

	No, of Ears	Measure	Differences (ms or nV)) Po	Na	Pa	Nb	Po-Na	Na-Pa	Pa-Nb
latency	24	mean	ns	1, 43	2, 32	ns	ms		
amplitude	24	mean				65	ns	ns	nV

*ns= values not significant at p < 0, 01

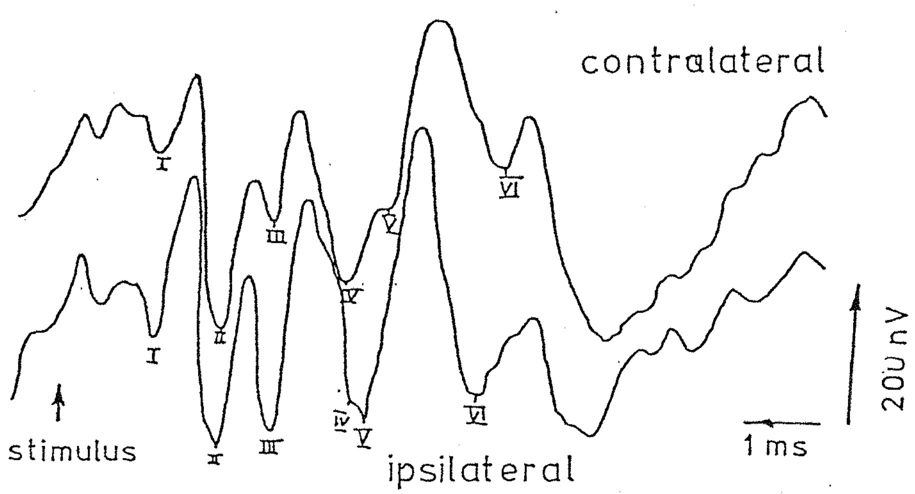


Fig A5.1 Comparison of ipsi-and contralateral records from one subject.

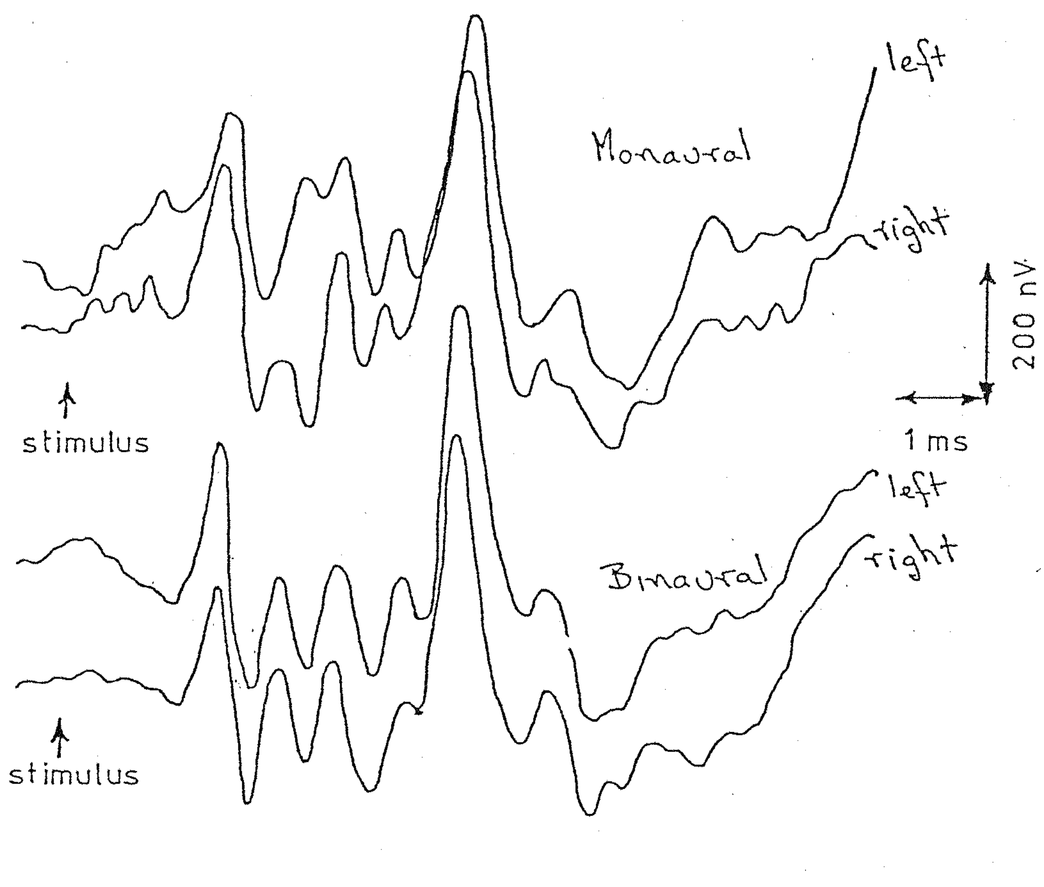


Fig A5.2 Comparison of monaural (right) and binaural records from one subject (right stimulation).

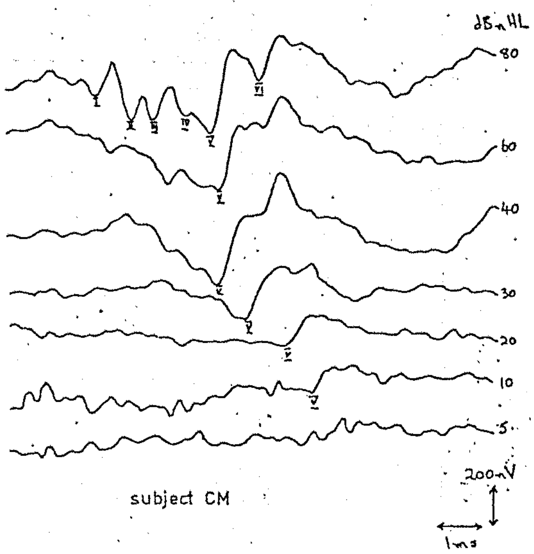


Fig A5.3 Example of ABR responses at intensities from 80dB HLto threshold (ipsilateral records) Recorded at $20s^{-1}$ click rate and .02-3kHz bandwidth.

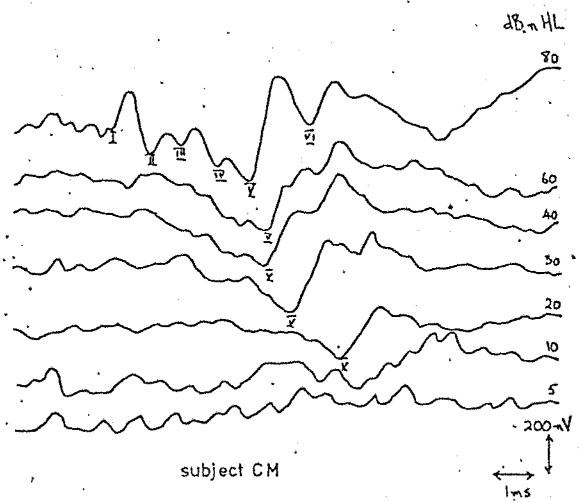


Fig A5.4 Example of ABR responses at intensities from 80dBnHL to threshold (contralateral records) Recorded at $20s^{-1}$ click rate and .02-3kHz bandwidth.

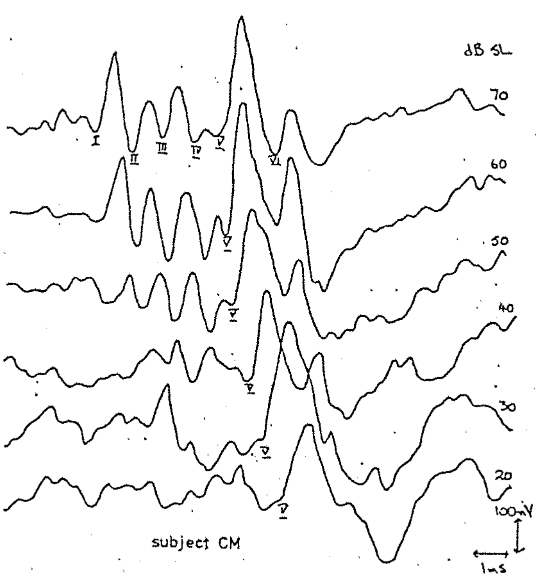


Fig A5.5 Example of ABR responses at intensities from 70 to 20dBSL (ipsilateral record). Recorded at $10s^{-1}$ click rate and 0.1-3kHz bandwidth.

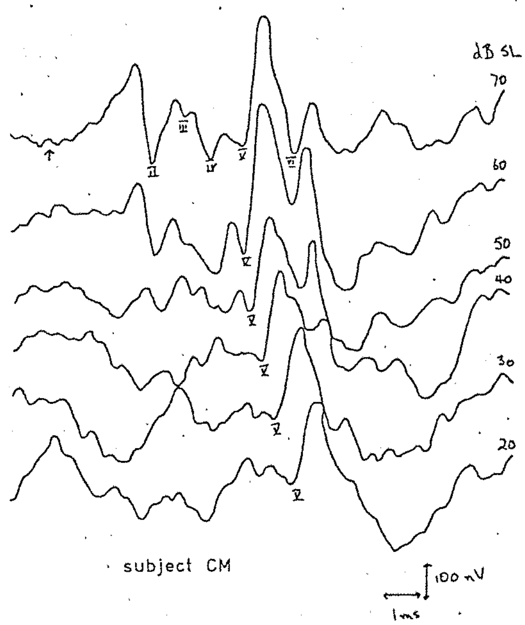


Fig A5.6 Example of ABR response at intensities from 70 to 20 dBSL (contralateral record). Recorded at $10s^{-1}$ click rate and .1-3kHz

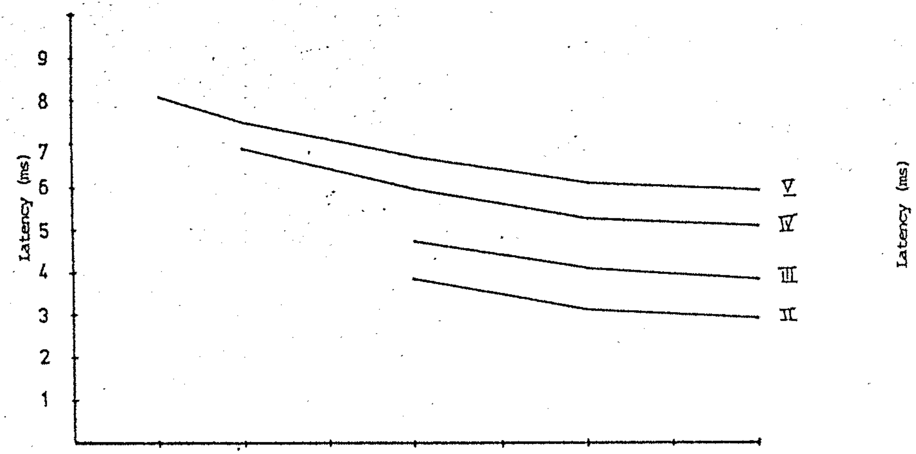


Fig A5.7 ABR Latency Intensity Function (ipsilateral, at $20s^{-1}$, .02 - 3 kHz)

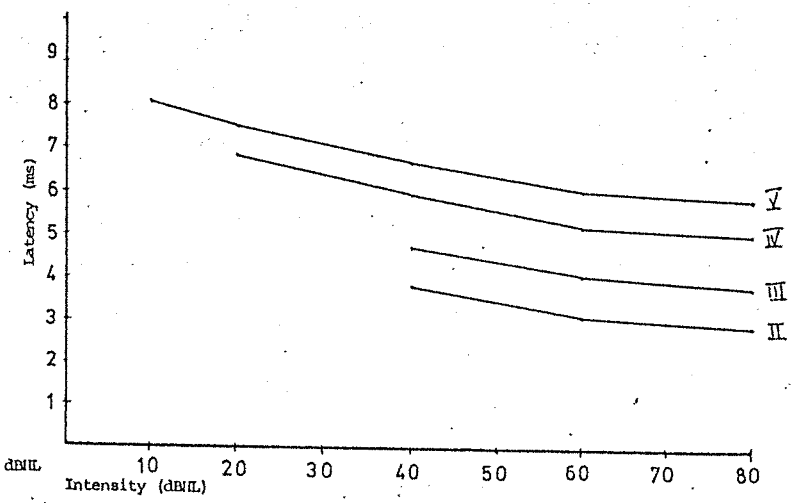


Fig A5.8 ABR Latency Intensity Function (contralateral, at $20s^{-1}$ and .02 - 3 kHz)

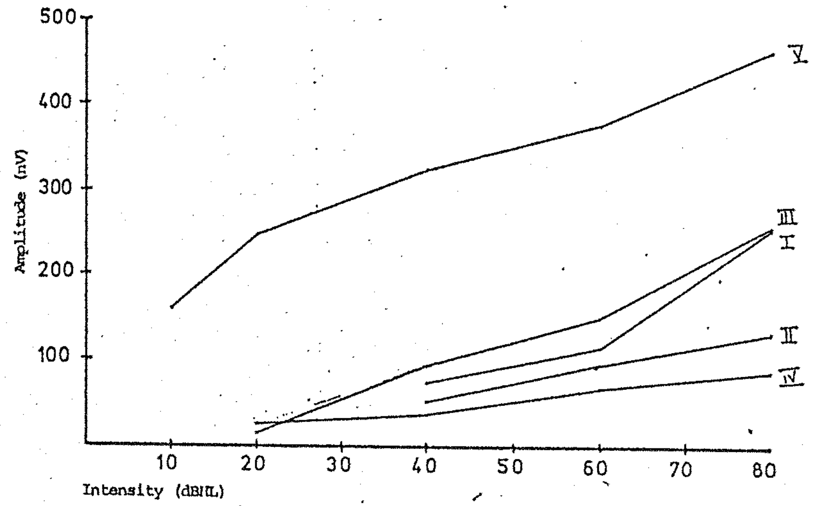


Fig A5.9 ABR Amplitude Intensity Function (ipsilateral, at $20s^{-1}$, .02 - 3 kHz)

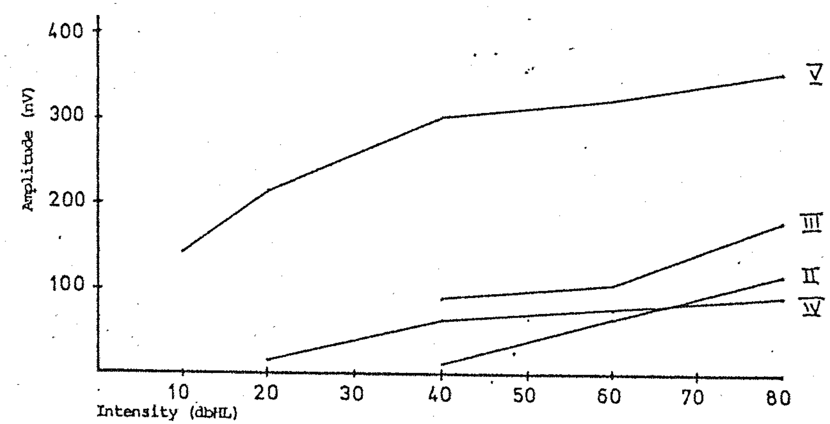


Fig A5.10 ABR Amplitude Intensity Function (contralateral, $20s^{-1}$, 0.02 - 3 kHz)

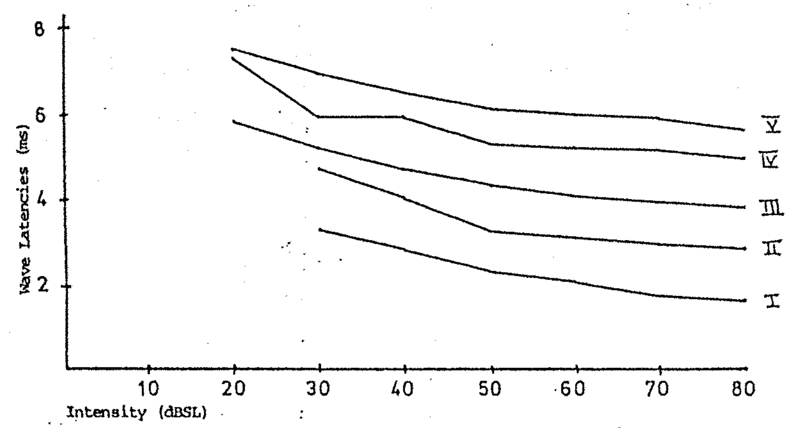


Fig A5.11 ABR Latency Intensity Function (ipsilateral, .10s^{-1}, 0.1 - 3 kHz)

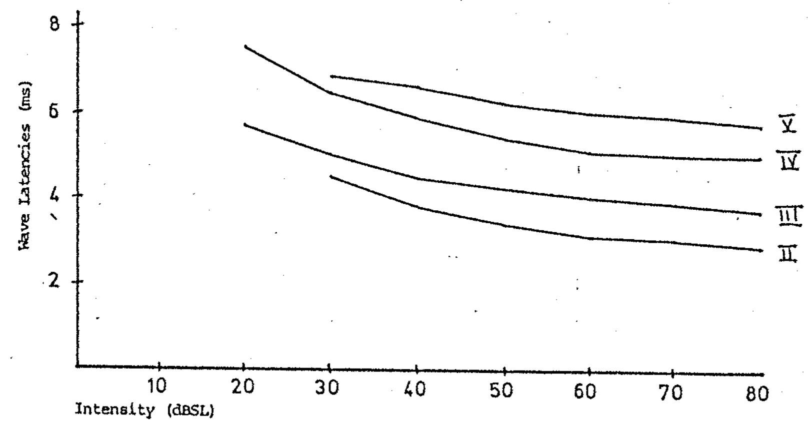


Fig A5.12 ABR Latency-Intensity Function (contralateral, at 10s^{-1}, 0.1 - 3 kHz)

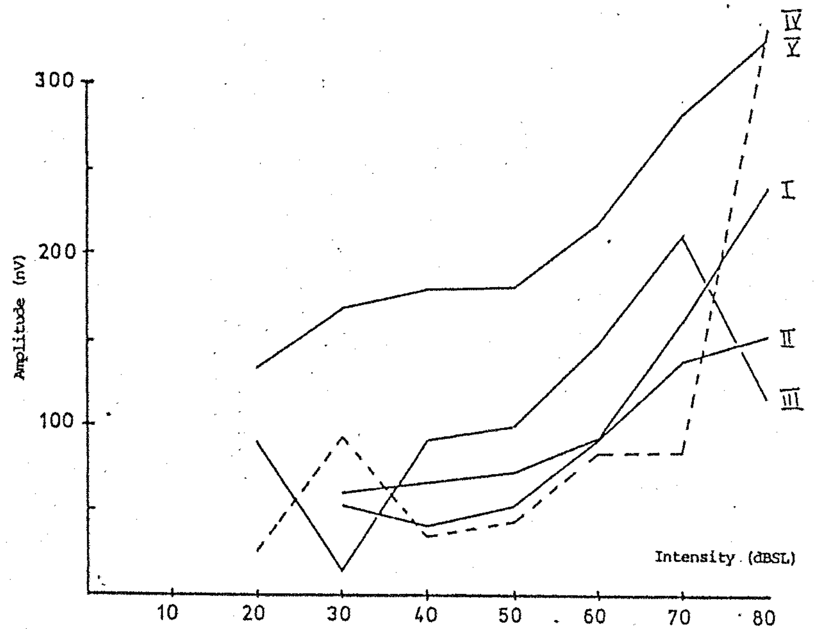


Fig A5.13 ABR Amplitude Intensity function (ipsilateral at 10^{-1}, 0.1 - 3 kHz)

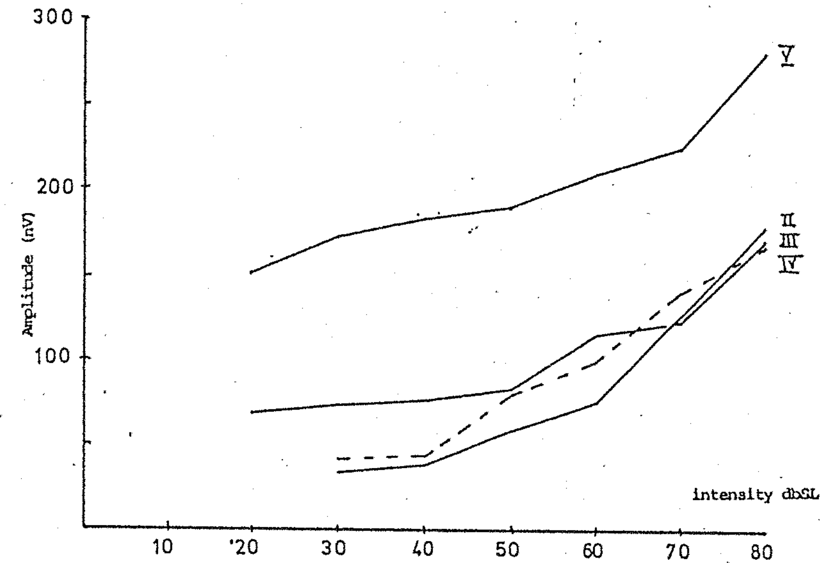


Fig A5.14 ABR Amplitude Intensity Function (contralateral at 10^{-1}, 0.1 - 3 kHz)

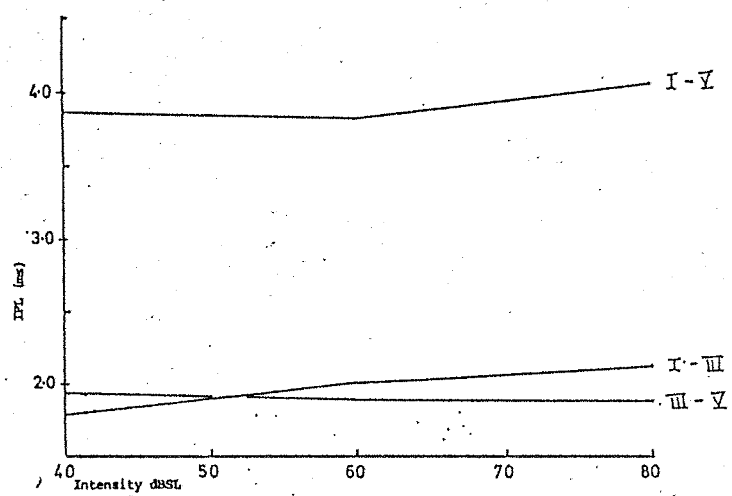
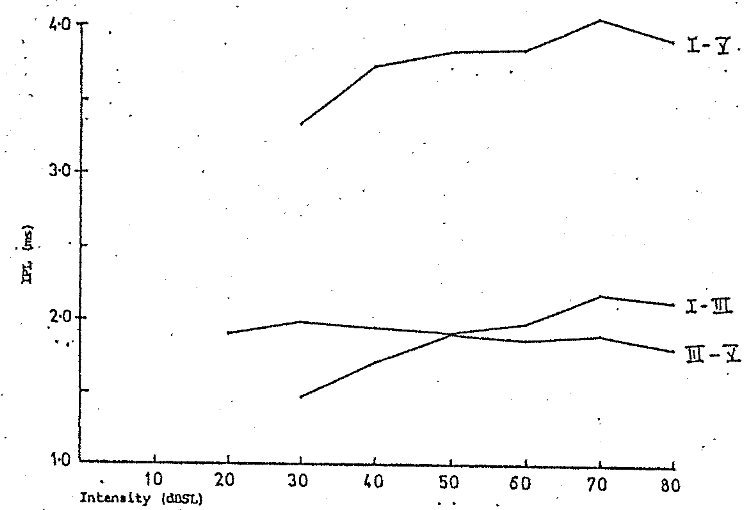


Fig A5.15 ABR IPL - Intensity Function (ipsilateral, at 20^{-1}, 0.02 - 3 kHz)



ABR IPL - Intensity Function (ipsilateral, at 10^{-1}, .1 - 3kHz)

Fig A5.16

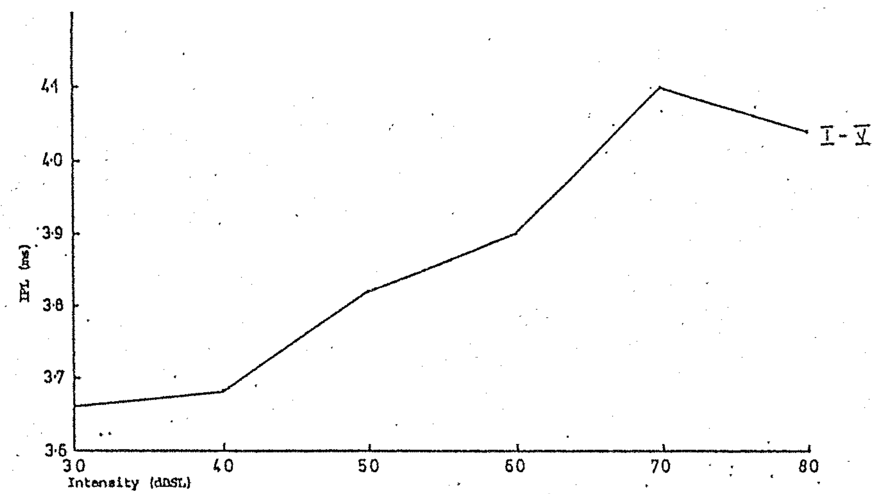


Fig A5.17 ABR IPL - Intensity Function (ipsilateral at 10^{-1}, 0.1 - 3kHz) derived from the means of the absolute peak latency vs intensity functions.

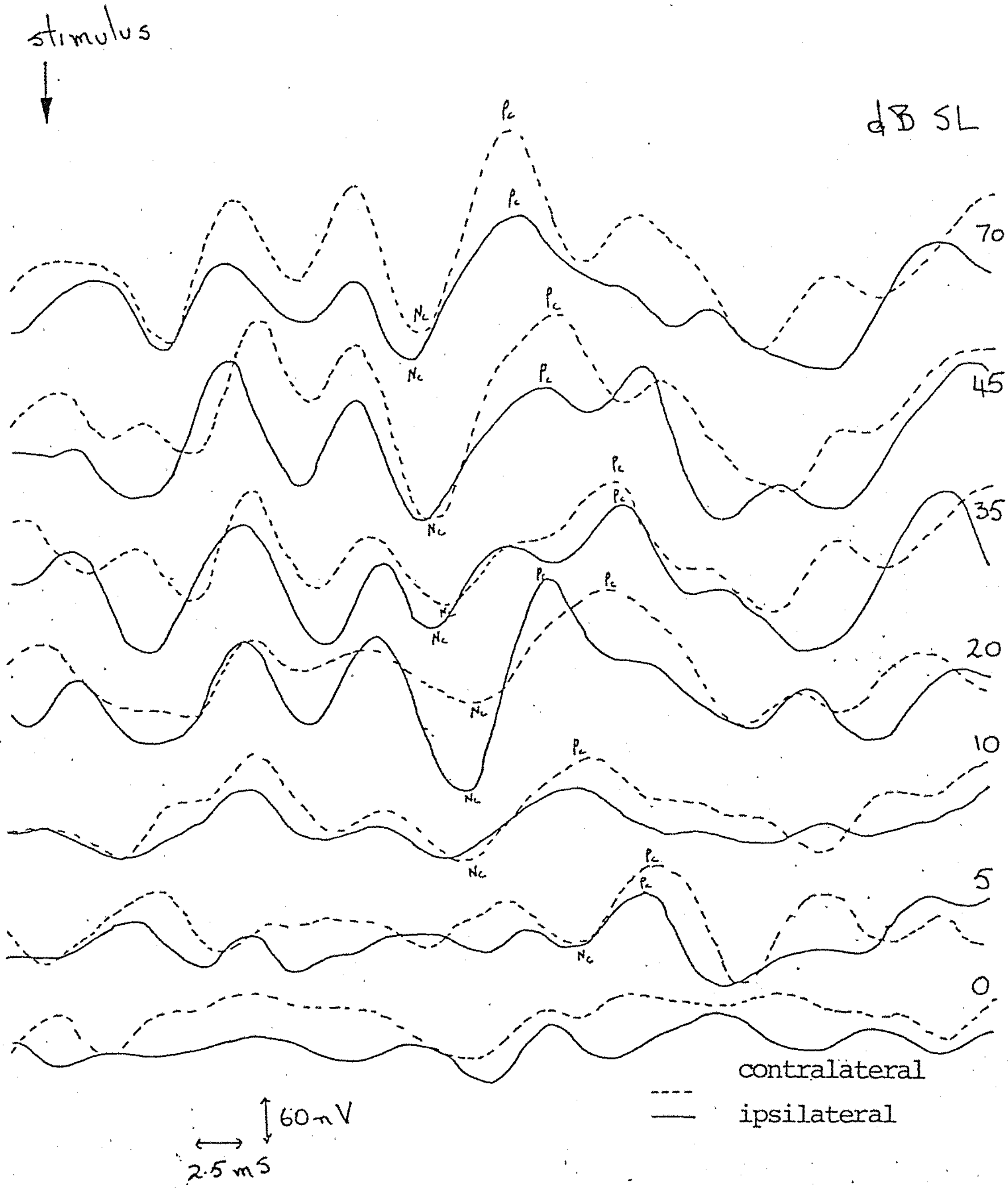


Fig A5.18 MLR at intensities from 70 dBSL to threshold. Monaural stimulation (subject MB).

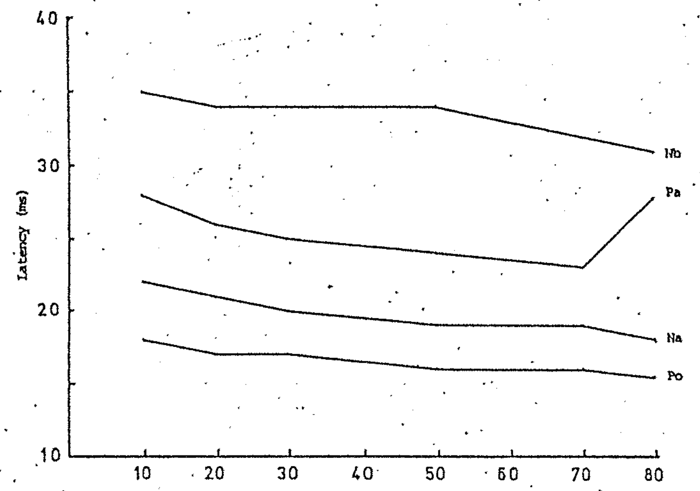


Fig A5.19 MLR Latency - intensity function (ipsilateral)

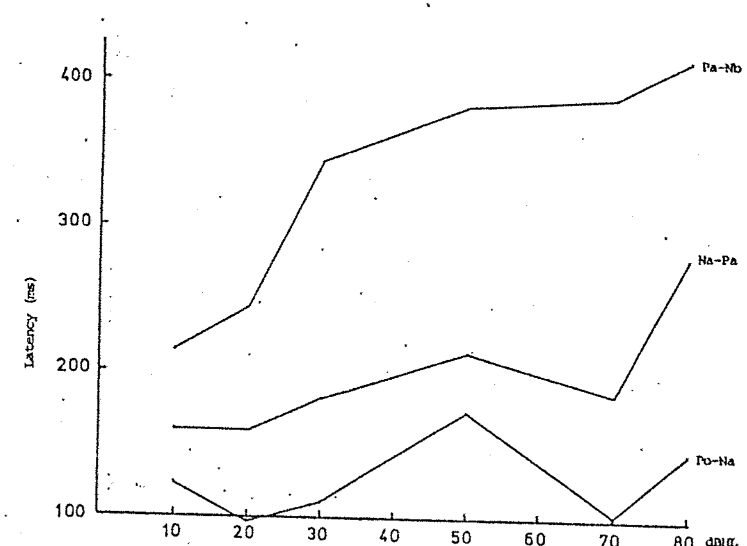


Fig A5.20 MLR amplitude intensity function (ipsilatoral)

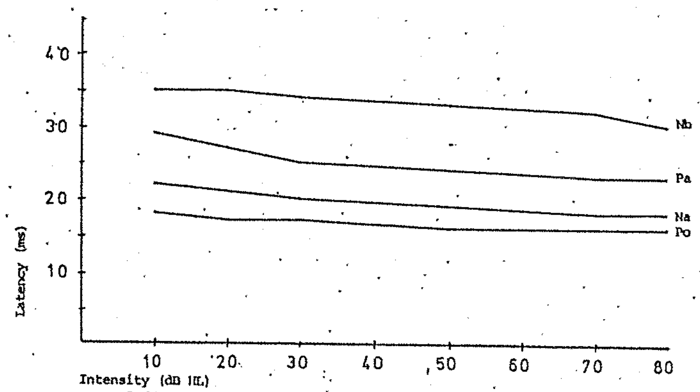


Fig A5.21 MLR latency intensity function (contralateral)

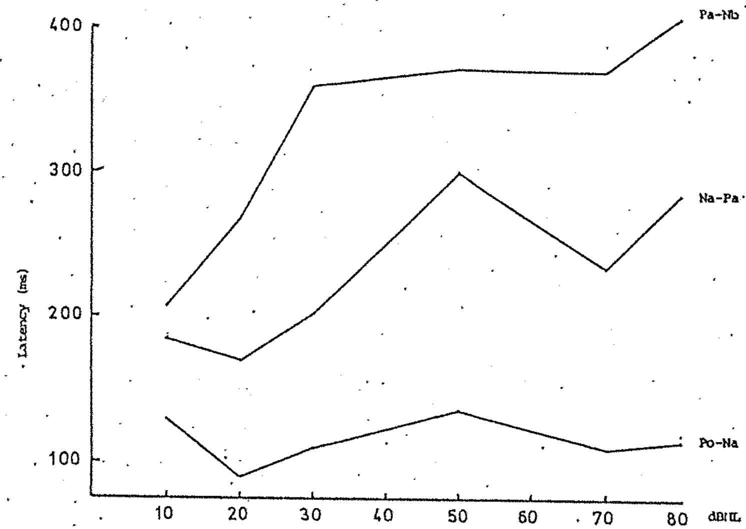


Fig A5,22 MLR amplitude intensity function (contralateral)

APPENDIX 6

AUDITORY ELECTROPHYSIOLOGICAL MEASURES: ANALYSES OF VARIANCE

CONTENTS

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ABSOLUTE LATENCIES; IPSILATERAL

Wave I

Source	SS	df	F
Between treatments	0.01	2	0.58
Between blocks	0.89	11	3.18
Residual	0.19	22	
Total	0.69	35	

The variance between subjects at the 0.01 level is significant. The variance between trials is not significant.

Wave II

Source	SS	df	F
Between treatments	0.01	2	0.833
Between blocks	1.02	11	15.5
Residual		0.14	22
Total		1.17	35

The variance between subjects at the 0.01 level is significant. The variance between trials is not significant.

Wave III

Source	SS	df	F
Between treatments	0.07	2	0.043
Between blocks	15.60	11	1.746
Residual		17.87	22
Total		2.34	35

The variance between subjects at the 0.01 level is significant. The variance between trials is significant, $0.25<p<0.10$.

Wave IV

Source	SS	df	F
Between treatments	0.002	2	0.143
Between blocks	0.58	6	0.143
Residual		0.08	12
Total		0.62	20

The variance between subjects is not significant. The variance between trials is not significant.

Wave V (all values)

Source	SS	df	F
Between treatments	0.01	2	0.385
Between blocks	1.82	11	12.690
Residual		0.28	22 0.130
Total		2.11	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave V (values where Wave IV is absent, omitted)

Source	SS	df	F
Between treatments	0.01	2	0.833
Between blocks	0.13	11	0.006
Residual		0.13	22
Total		0.27	35

The variance between subjects is not significant. The variance between trials is not significant.

Wave VI

Source	SS	df	F
Between treatments	0.01	2	0.160
Between blocks	5.44	11	1.628
Residual		6.69	22 0.304
Total		12.14	35

The variance between subjects is significant at the $0.25<p<0.01$ level. The variance between trials is not significant.

ABSOLUTE LATENCIES ; CONTRALATERAL

Wave I

Source	SS	df	F
Between treatments	0.02	2	1.050
Between blocks	1.97	11	15.786
Residual		0.25	22
Total		2.24	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave II

Source	SS	df	F
Between treatments	0.66	2	1.571
Between blocks	0.94	11	40.140
Residual		0.99	22
Total		2.59	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is significant at the $p<0.01$ level.

Wave III

Source	SS	df	F
Between treatments	0.05	2	4.868
Between blocks	2.16	11	42.510
Residual		0.10	22
Total		2.31	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is significant at the $p<0.05$ level.

Wave IV

Source	SS	df	F
Between treatments	0.022	2	2.222
Between blocks	2.04	11	41.48
Residual		0.098	22
Total		2.156	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave V (where JIV is present)

Source	SS	df	F
Between treatments	0.03	2	1.41
Between blocks	0.41	10	3.948
Residual		0.21	20
Total		0.66	32

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is significant at the $p<0.05$ level.

Wave VI

Source	SS	df	F
Between treatments	0.06	2	0.913
Between blocks	0.56	11	1.614
Residual		0.69	22
Total		1.30	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is significant at the $p<0.25$ level.

PEAK-TO-PEAK AMPLITUDES : IPSILATERAL

Wave I

Source	SS	df	F
Between treatments	978	2	0.448
Between blocks	80650	11	6.715
Residual		24027	22
Total		105711	35

The variance between subjects is significant at the p<0.01 level. The variance between trials is not significant.

Wave II

Source	SS	df	F
Between treatments	112	2	0.21
Between blocks	33586	11	11.51
Residual		5837	22
Total		39535	35

The variance between subjects is significant at the p<0.01 level. The variance between trials is not significant.

Wave III

Source	SS	df	F
Between treatments	865	2	1.017
Between blocks	65036	11	13.900
Residual		9536	22
Total		75257	35

The variance between subjects is significant at the p<0.01 level. The variance between trials is not significant.

Wave IV

Source		SS	df F
Between treatments	3642	2	0.200
Between blocks	61096	11	11.150
Residual		8633	22
Total		52805	35

The variance between subjects is significant at the p<0.01 level. The variance between trials is not significant.

Wave V (all values of JV)

Source	SS	df	F
Between treatments	42.40	2	0.22
Between blocks	113439	11	10.92
Residual		20777	22
Total		134259	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave VI

Source	SS	df	F
Between treatments	413	2	0.064
Between blocks	98907	11	2.77
Residual		71332	22
Total		27988	35

The variance between subjects is significant at the $p<0.05$ level. The variance between trials is not significant.

PEAK-TO-PEAK AMPLITUDES ; CONTRALATERAL

Wave I

Source	SS	df	F
Between treatments	1759	2	1.684
Between blocks	17852	11	3.107
Residual		11490	22
Total		31102	35

The variance between subjects is significant at the $p<0.05$ level. The variance between trials is not significant.

Wave II

Source	SS	df	F
Between treatments	803	2	1.478
Between blocks	43656	11	14.614
Residual		5974	22
Total		50434	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave III

Source	SS	df	F
Between treatments	62.17	2	0.0459
Between blocks	53667	11	7.211
Residual		14884	22
Total		68613	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave IV

Source	SS	df	F
Between treatments	112	2	0.171
Between blocks	63226	11	19.277
Residual		61559	22
Total		69898	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave V

Source	SS	df	F
Between treatments	515	2	0.679
Between blocks	72008	11	17.270
Residual		8338	22
Total		80861	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

Wave VI

Source	SS	df	F
Between treatments	651	2	0.703
Between blocks	20670	11	4.059
Residual		10191	22
Total		31512	35

The variance between subjects is significant at the $p<0.01$ level. The variance between trials is not significant.

MONAURAL AND BINAURAL LATENCY COMPARISONS

Wave I

Source	SS	df	F
Between treatments	0.10	1	2.25
Between blocks	0.01	2	0.06
Interaction		0.02	2 0.18
Residual		2.97	66
Total		2.97	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave II

Source	SS	df	F
Between treatments	0.28	1	9.80
Between blocks	0.00	2	0.04
Interaction		0.01	2 0.19
Residual		1.89	66
Total		2.19	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave III

Source	SS	df	F
Between treatments	0.09	1	1.54
Between blocks	0.02	2	0.17
Interaction		0.02	2 0.17
Residual		4.02	66
Total		4.15	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave IV

Source	SS	df	F
Between treatments	0.01	1	0.20
Between blocks	0.02	2	0.12
Interaction		0.01	2 0.06
Residual		0.01	66
Total		4.53	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave V

Source	SS	df	F
Between treatments	0.16	1	2.67
Between blocks	0.01	2	0.06
Interaction		0.04	2 0.34
Residual		3.97	66
Total		4.18	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave VI

Source	SS	df	F
Between treatments	0.31	1	2.60
Between blocks	0.32	2	1.32
Interaction		0.21	2 0.89
Residual		7.88	66
Total		8.72	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

MONAURAL AND BINAURAL AMPLITUDE COMPARISONS

Wave I

Source	SS	df	F
Between treatments	84225	1	6.04
Between blocks	953	2	0.03
Interaction	2198	2	0.08
Residual		919912	66
Total		1007318	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave II

Source	SS	df	F
Between treatments	287029	1	19.31
Between blocks	792	2	0.03
Interaction		960	2 0.03
Residual		981021	66
Total		1269803	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at $p<.01$.

Wave III

Source	SS	df	F
Between treatments	84255	1	6.04
Between blocks	953	2	0.03
Interaction		2198	2 0.08
Residual		919912	66
Total		1007313	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at p<.01.

Wave IV

Source	SS	df	F
Between treatments	12456	1	0.082
Between blocks	3360	2	0.16
Interaction		1124	2 0.05
Residual		1125	66
Total		711310	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at p<.01

Wave V

Source	SS	df	F
Between treatments	259680	1	10.59
Between blocks	1684	2	0.03
Interaction		5621	2 0.11
Residual		1618758	66
Total		1885744	71

The variance between stimulating conditions is significant at the level p<.01. The variance between trials and the interaction is not significant at p<.01

Wave VI

Source	SS	df	F
Between treatments	24090	1	5.46
Between blocks	6041	2	0.68
Interaction		814	2 0.09
Residual		291102	66
Total		322046	71

The variance between stimulating conditions, the variance between trials and the interaction is not significant at p<.01.

APPENDIX 7

AUDITORY ELECTROPHYSIOLOGICAL MEASURES: FURTHER STATISTICAL ANALYSES

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ABR; INDIVIDUAL EAR DATA COMPARISONS

Latency values, recorded ipsilaterally

	I	II	III	IV	V	VI
t statistic	1.166	0.877	0.616	2.406	1.943	1.45
df	11	11	11	6	11	11
Δ	0.045	0.024	0.028	0.106	0.0875	0.0608
s.d.	0.1337	0.955	0.159	0.125	0.1560	0.1450

Amplitude values, recorded ipsilaterally

	I	II	III	IV	V	VI
t statistic	1.09	1.21	0.16	0.35	0.65	0.43
df	11	11	11	6	11	11
Δ	19.5	11.75	2	44.42	11.83	2.33
s.d.	61.74	33.58	43	33.60	63.21	18.88

Latency values, recorded contralaterally

	I	II	III	IV	V	VI
t statistic	0.67	0.26	0.35	0.84	0.13	0.46
df	11	11	11	11	11	11
Δ	0.02	0.01	0.01	0.04	0.01	0.03
s.d	0.13	0..11	0.13	0.16	0.30	0.23

Amplitude values, recorded contraterally

	I	II	III	IV	V	VI
t statistic	0.01	1.73	0.10	1.42	1.24	1.31
df	11	11	11	11	11	11
Δ	0.67	20.17	1	17.75	22.33	10.50
s.d.	24.24	40.56	33.39	43.22	62.10	27.72

In all cases:
using t-test for related measures
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

A.7.2 ABR; MALE AND FEMALE DATA COMPARISONS

Latency values, recorded ipsilaterally

	I	II	III	IV	V	VI
t statistic	4.76	5.095	6.03	3.32	2.11	1.75
df	11	11	11	7	11	11
Δ	0.23	0.26	0.34	0.22	0.19	0.10
s.d.	0.17	0.17	0.19	0.19	0.32	0.19

Amplitude values, recorded ipsilaterally

	I	II	III	IV	V	VI
t statistic	2.30	1.86	2.89	1.71	1.76	2.69
df	11	11	11	7	11	11
Δ	32.67	16.42	56.17	34.63	42.50	22.00
s.d.	49.13	30.64	67.39	57.48	83.78	28.30

A.7.3 ABR: COMPARISON OF MEAN LATENCY DIFFERENCES FOR IPSILATERAL AND CONTRALATERAL DATA

Male subjects, latency values

	II	III	V	VI	III-V
t statistic	5.19	4.48	6.03	2.35	5.87
df	35	35	35	35	35
Δ	0.09	0.10	0.34	0.09	0.30
s.d.	0.08	0.06	0.19	0.10	0.21

Female subjects, latency values

	II	III	V	VI	III-V
t statistic	6.25	2.14	4.81	5.88	4.93
df	35	35	35	35	35
Δ	0.10	0.06	0.22	0.09	0.20
s.d.	0.06	0.09	0.19	0.10	0.18

In all cases:
using t-test for related measures
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

A.7.4 ABR: COMPARISON OF MEAN LATENCY DIFFERENCES FOR LEFT AND RIGHT RECORDINGS TO BINAURAL STIMULATION

(using t-test for related measures)
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

	I	II	III	IV	V	VI	I-III	III-V	I-V
t	1.03	2.67	2.00	2.25	2.07	1.03	1.50	2.25	1.50
df	35	35	35	35	35	35	35	35	

A.7.5 MLR; COMPARISON OF MALE AND FEMALE DATA

Latency

(using t-test for independent measures)
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

	Po	Na	Pa	Nb
t	2.47	3.24	2.75	0.94
df	22	22	22	22
Δ	0.89	1.43	2.32	0.64
s.d.	0.49	1.04	2.06	2.25

Amplitude

(using t-test for independent measures)
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

	Po-Na	Na-Pa	Pa-Nb
t	2.68	0.43	1.44
df	22	22	22
Δ	66.70	18.60	103.21
s.d.	62.79	99.10	157.00

A.7.6 MLR: COMPARISON OF IPSILATERAL AND CONTRALATERAL DATA

Latency

(using t-test for related measures)
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

	Po	Na	Pa	Nb
t	0.10	4.12	3.33	2.27
df	24	24	24	24
Δ	0.76	0.56	1.30	1.11
s.d.	0.95	0.85	1.49	1.06

Amplitude

(using t-test for related measures)
Ho: $\mu_1=\mu_2$ and H_1: $\mu_1\neq\mu_2$.

	Po-Na	Na-Pa	Pa-Nb
t statistic	0.34	2.73	0.79
df	22	22	22
Δ	42.54	87.72	85.09
s.d.	36.45	72.72	153.44