STUDIES OF VESTIBULAR AND VISUAL-OCULAR MATURATION IN NORMAL CHILDREN

G.S.KENYON, FRCS, FRCSEd.

Submitted in 1989 to the University of Edinburgh for the degree of Doctor of Medicine.

TO MY PARENTS

Qui facit per alium facit per se

Some of the data included in this thesis has been published in preliminary form in an article entitled:

"Neuro-otological findings in normal children. Journal of the Royal Society of Medicine, 1988;81:644-648."

With this exception the findings have not been previously published or submitted for publication to any learned journal.

CONTENTS

DECLARATION OF ORIGINALITY

The work contained within this thesis is my own and the thesis has been composed entirely by myself. I have received no assistance except where specifically indicated in the list of acknowledgements contained herein.

G.S.KENYON.

ACKNOWLEDGEMENTS

I would like to thank the following, without whom this thesis would have been impossible.

1. Dr. Susan Snashall, Consultant Physician in Audiological Medicine, Guildford Hospitals for generously allowing me access to her department and use of test facilities.

2. Mrs. Lana Levens, Senior Chief Physical Measurement Technician, Department of Audiological Medicine, Guildford Hospitals for providing the necessary technical assistance during the performance of these tests and for accompanying me on several visits to local schools to explain the nature of the work to be undertaken.

3. Dr. Jonathan Murray, Consultant Otolaryngologist, Edinburgh Royal Infirmary, for his patient criticisms of the study format.

4. Mr Stephen Evans, Professor of Biometry and Medical Statistics, The London Hospital Medical College, London for his help in data processing and appraisal of the statistical analyses performed.

5. Dr. Christopher Kennard, Consultant Neurologist, The London Hospital, London for his criticisms of the sections dealing with the maturation of eye movements and their control by the cerebellum.

6. Mr. Stephen Archibald and Mr. Ian Berle, Departments of Medical Illustration at The Royal Surrey County Hospital, Guildford and The London Hospital, London for their help in the preparation of the illustrations.

7. The President, Annals Publishing Company for permission to reproduce Figure 1.0 which is taken from Pappas DG (1984), "Barany's History of Vestibular Physiology". The Annals of Otology, Rhinology and Laryngology, (supp. 110), 93, 3.

8. The publisher and author for permission to reproduce Figure 6.1 which is re-drawn from Figure 2.7, page 43. In: Rudge P (1983) Clinical Neuro-otology, Edinburgh: Churchill Livingstone.

9. The staff of the library at The Royal Surrey County Hospital, Guildford and of the Bibliography Department, The Royal Society of Medicine, London for their unfailing courtesy and for their help in providing literature searches and photocopies of original articles.

10. The headmasters and mistresses of the schools outlined in Appendix 1, who allowed me to speak to their parents and pupils in order to recruit subjects to the study, and who then gave leave to these volunteers in order that they could attend for investigation.

11. The parents and children who attended, often at personal inconvenience, and who made the study possible.

ABSTRACT

The vestibular system matures early in embryonic life but the neonate lacks postural control and co-ordination. From this it seems likely that vestibular responsiveness changes in infancy,and previous studies have suggested that such changes exist and continue throughout the childhood years. However the overall picture is unclear due to the heterogenicity of stimuli and recording techniques employed in different studies.

One of the other major sensory systems responsible for orientation is the visual apparatus,and it is recordings of eye movement which allow an assessment of vestibular responsiveness (through the vestibulo-ocular reflex). Thus vestibular maturation can only be put into a proper perspective by an appreciation of any parallel changes in visual-ocular control and by an understanding of the interaction between the visual and vestibular systems. Such co-operation implicates central control mechanisms including the cerebellum.

It is now clear that such an understanding is not merely of academic interest since vestibular and balance disorders in children are not as uncommon as was previously thought. If it is the case that the normal values and the range of normal data are different in childhood,then interpretation of the results obtained from the commonly applied tests is liable to be erroneous if adult norms are applied.

The present study was therefore conceived in an attempt to answer certain specific questions about the maturation of visual-ocular control mechanisms and of the vestibulo-ocular reflex in children. Specifically the slow phase velocity,amplitude and frequency of eye movements resulting from caloric stimulation and the results of testing various aspects of visual-ocular control (pursuit,saccadic and optokinetic responses) were studied. In addition the effect of optic fixation on the vestibular response and the interaction between the two systems through measurement of the

phenomenon of optokinetic after-nystagmus (OKAN) in response to full field stimulation was studied.

In order to do this one hundred normal children were recruited from schools in the Guildford area of Surrey and were studied and compared to twenty-one adult volunteers. The results suggest that there is a continuing evolution of vestibular responsiveness with age and suggest that central control of eye movements may also be immature.

PREFACE

As long ago as the beginning of the nineteenth century it was understood that body rotation could provoke vertigo or transient disequilibrium. It was also noted that these sensations were sometimes associated with movements of the eyes, but there was little evidence to connect these findings with the vestibular apparatus, and almost no appreciation of the role of this important system in human equilibration. In the century and a half that has elapsed since these preliminary findings we have come to understand something of the mechanisms responsible for the maintenance of normal postural stability, and now appreciate that this depends on the co-ordinated interaction of a sophisticated system of sensory afferents and motor effectors. As far as afferent information is concerned it is clear that the dominant sensory inputs come from the visual system, the vestibular apparatus and from touch and proprioceptive information from receptors within muscles and joints. In turn the effector arm is provided by the motor outflow of the peripheral neuromuscular system which is controlled and moderated by the pyramidal and extrapyramidal systems and by the cerebellum (Figure 0.1).

In normal circumstances central integration of this complex system is so comprehensive that it scarcely intrudes upon consciousness; in contrast a sudden derangement may produce such dramatic and incapacitating consequences that many of the activities considered essential to life are made impossible. Thus Cawthorne wrote: "Labyrinthine disturbance may make (a patient) feel that the end of the world has arrived, and I am told by sufferers of seasickness that in the acutest phase in the distress they wish it had" (Cawthorne, 1945).

It has been known for some time that the vestibular system is one of the first to develop in the human embryo, and early studies showed that the vestibular apparatus is histologically complete in the human foetus at 9. 5 weeks of gestation (Hooker, 1952). It is also known that myelination of the vestibular system is well advanced at 6 months and that the endolymphatic and bony labyrinths and vestibular nerve fibres

Figure 0.1

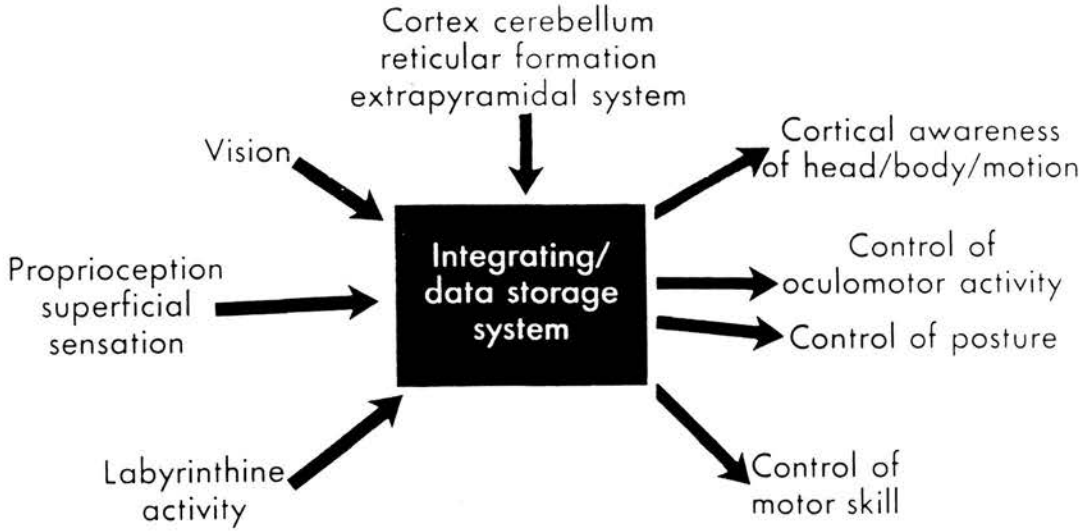


Diagram showing the main afferent input and effector mechanisms responsible for equilibration.

are mature at birth (Langworthy, 1933; Rosenhall, 1972; Bergstrom, 1973; Dayal, Farkashidy and Kokshanian, 1973). In addition there is evidence to support the concept that the system is physiologically responsive at an early stage; the large neurones of the vestibular nuclei are functional at 21 weeks of foetal life (Humphrey, 1965) and it is known that acceleratory stimuli in newborn infants results in deviation of the eyes in the direction in which the slow phase of nystagmus might be anticipated, even though the centrally induced fast component may not be present (Tibbling, 1969).

It is therefore clear that the vestibular system will react to stimulation both in utero and in the neonatal period, but in spite of this the normal infant lacks both the postural control and the co-ordination necessary for locomotion. In this respect the young child certainly lags behind many others in the animal kingdom. For instance some quadrupeds are able to follow the herd within minutes of birth while other species, including our Darwinian ancestors the great apes, exhibit advanced motor development at an early age when compared with the human infant. The normally growing child thus represents something of an enigma, for it would seem that he is born with an anatomically mature and functioning vestibular system which he is unable to put to immediate use. This paradox is put into even sharper focus by the range and complexity of subsequently acquired vestibular skills which emerge to override this unimpressive start. Thus man can so condition his vestibular system that he is able to learn to ride a bicycle or horse, skate and ski, sail and fly and, in some cases, live and work in the hostile environments provided by altered gravity in space or at the bottom of the sea. All this suggests that there must be age related changes in vestibular reactivity, and this process would appear to be ongoing since there is a repetitive self-stimulation of the vestibular system evident in most childhood games which obviously wanes with maturation.

In point of fact the possibility of differing responses in neonates, children and adults was recognised early in the history of vestibular investigation. The earliest reports are attributed to Bartels and Barany (Galebsky, 1927), and Galebsky personally

confirmed the presence of nystagmus in neonates in response to a rotatory stimulus and noted that the fast component of this response was weak and tended to disappear during sleep. He also elicited nystagmus by caloric irrigation and, although he failed to demonstrate optokinetic nystagmus, he quotes a personal communication from Barany who stated that he could elicit "A definite optical nystagmus in the newborn under certain conditions, viz. :the newborn must be awake, not distracted, not howl or spoil his linen, the lights must not be intense and the object fall on the fovea centralis".

While the need to investigate maturation changes was thus recognised by these early pioneers, it appears that most of the available data relating to normal vestibular responsiveness has been collected by testing adults. Perhaps the widely appreciated difficulties inherent in recording responses in children has deterred some investigators (Conraux and Collard, 1970; Picart, Conraux and Grenier, 1971; Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979; Cyr, 1980), and diffidence in performing tests on normal children when sequelae such as disorientation, vertigo or even pain could result may have proved a natural bar to others. However, as will be demonstrated in Chapter 2, even when studies have been undertaken the results have provided no very clear message as to the true nature of the maturation of vestibular performance in children. This is both because the vestibular stimuli used have often been unique to a particular laboratory, and because in many instances insufficient attention has been paid to monitoring the recording conditions used. Interpretation of the results obtained and repetition of the experiments is obviously difficult (or even impossible) if the stimulus used is not readily available, and failure to monitor the mental state or a willingness to allow recordings to be made in the light is widely known to alter the response patterns obtained (Wendt, 1951; Collins, 1974; Ornitz, Brown, Mason and Putnam, 1974; Levy, 1977). Indeed even simple eye closure suppresses the normal vestibulo-ocular reflex (Tjernstrom, 1973). All these sources of error are to some extent implicated in the majority of studies concerning vestibular reactivity in childhood, and in some instances there has even been a complete failure to record the

state of visual fixation. Inevitably this means that our current knowledge of the maturation of this response must be incomplete.

There are several reasons why this situation should be rectified. The need for normative data is emphasised by an increasing awareness of the possibility that children may present with neuro-otologic problems suggesting vestibular disorder or with vestibular symptomatology as a result of systemic disease (Haid, 1979; Eviatar and Eviatar, 1980): if the childhood response is different then to apply adult norms to interpret the results obtained is clearly inappropriate. Furthermore there is the suggestion that there are links between vestibular disturbance and developmental and behavioral disorder. Delayed onset neonatal vestibular challenge and motor retardation has been noted in both Down's Syndrome and cerebral palsy (Kravitz and Boehm, 1971), and one retrospective study has suggested that vestibular behaviour by head rocking will advance normal motor development such as crawling and pulling up to the standing position (Sallustro and Atwell, 1978). Such early stimulation may even influence the way in which an adult responds to a vestibular stimulus, and this possibility led Guedry to suggest that: "infants moved early in life have sensory information which can be associated with other experiences related to the movement" (Guedry, 1972). Of course these concepts are not new. Indeed Asclepiades of Bithynia (circa 124-140 BC) is credited as having employed the rocking beds which were in general use in his day to soothe restless infants and troubled adults (Mettler, 1947). But since we do not yet have an wholly accurate picture of the processes involved in vestibular maturation we are wholly unable to rationalise the prospect of vestibular stimulation as therapy.

This thesis was therefore conceived in an attempt to answer specific questions about the nature of the maturation changes in the vestibular system during childhood using standard and widely available stimulus and recording techniques. It also includes an assessment of visual motor skills, for these are also thought to display maturation changes (Gilligan, Mayberry, Stewart, Kenyon and Gaebler, 1981; Herman, Maulucci

and Stuyck, 1982; Larsby, Thell, Moller and Odkvist, 1988) and could, of course, directly influence the vestibulo-ocular reflex.

But an assessment of visual-ocular control also serves to give clues as to other maturation processes. For instance, the measurement of optokinetic after-nystagmus gives an insight into the integration of visual and vestibular information since after-nystagmus depends on subcortical optokinetic pathways and their interaction at the level of the vestibular nuclei. Such an integration of information from vestibular end organ and peripheral retina is considered to be of prime importance in visual-vestibular interaction (Gonshor and Melvill Jones, 1976; Koenig,Allum and Dichgans,1978; Lau, Honrubia, Jenkins, Baloh and Yee, 1978; Guedry, Lentz and Jell, 1979), and some have assumed an equivalence in the neurophysiological mechanisms underlying vestibular and peripheral retinal stimulation (Raphan and Cohen, 1978). Indeed, Guedry concluded that ... "it is not unreasonable to suppose that peripheral retinal stimulation by background movement routinely aids in the adjustment of the vestibulo-ocular reflex to the specific requirements of voluntary visual pursuit during head and whole body turning" (Guedry, 1979). These aspects of the physiology of the visual and vestibular systems will be discussed in more detail in subsequent chapters. However the thesis starts with an historical review of the development of our knowledge of visual and vestibular function.

CHAPTER 1

AN HISTORICAL REVIEW OF VESTIBULAR AND OCULAR-MOTOR PHYSIOLOGY

SUMMARY

The central role of the vestibular apparatus in normal equilibration and co-ordination was a mystery to many of the earliest investigators. Even now a full appreciation of the role of this important system and its integration with visual and other inputs to provide a composite picture of body awareness and position provides us with a considerable challenge.

The present chapter considers the evolution of our ideas about the vestibular apparatus and discusses the origins of the caloric test. It also relates the difficulties which the earliest investigators experienced in assessing ocular movements and, in particular, the problems they encountered in coming to terms with the concept of the conjugacy of eye movement.

A. THE VESTIBULAR SYSTEM

It was probably Erasmus Darwin who first observed the important connections between ocular movements and vestibular stimulation. He certainly noted "rolling movements" of the eyes in his studies of vertigo and observed that during these episodes subjects were prone to seeing movements of objects in a direction "contrary to previous rotation" (Darwin, 1794). But the first systematic experiments which investigated postural control date from the beginning of the nineteenth century when Purkinje published a dissertation on visual movements obtained by galvanic stimulation of the cerebellum (Purkinje, 1819). He later observed the same phenomena in a series of subjects, including himself, when rotated in a chair (Purkinje, 1820), but concluded that these ocular movements were the result of strain secondary to pressure on the cerebral contents and made no connection between vestibular stimulation and the accompanying nystagmus.

However at about the same time Flourens reported the effects of ablating various parts of the vestibular apparatus and its central connections in pigeons (Flourens, 1842). These experiments showed that cerebellectomy produced disturbance of co-ordination while cerebral destruction lead to lack of volition with maintenance of normal reflexes. Flourens also demonstrated that destruction of the superior semicircular canal caused the pigeon to fall forwards, removal of the posterior canal caused it to fall backwards and horizontal canal ablation caused lateral movement of the birds head with rotation of the body around a vertical axis. But again he failed to appreciate the role of the canals in the maintenance of equilibration, and instead concluded that the vestibular system provided a means of regulating directional movement.

There was then a hiatus in vestibular investigation until Brown-Sequard renewed interest in the subject by drawing attention to the vertigo caused by thermal stimulation of the ear by syringing with cold water (Brown-Sequard, 1860). This was followed by a article written by Prosper Meniere which linked the experimental work of Flourens together with a large number of clinical case histories and the autopsy report of a vertiginous girl (Meniere, 1861). Meniere concluded that the explanation of vertigo was not, as was commonly thought at this time, a form of "apoplectiform cerebral congestion", but that a better explanation could instead be provided by invoking a disorder of the semicircular canals. It has now been suggested that the postmortem findings he reported were not typical of endolymphatic hydrops and that he was instead observing haemorrhage into the labyrinth as the result of acute myeloid leukaemia (Fisher, 1956; Pappas and Galanos, 1982). But in spite of this the paper became a classic as it was the first to link the symptoms of vertigo and tinnitus with a labyrinthine lesion. This therefore heralded a new phase of research into the physiology of the semicircular canals.

The true significance of the semicircular canals was also realised by Goltz while he was Professor of Physiology at the University of Strassburg. He was one of the central figures in the antilocalisation school of neurophysiologists, and it is therefore

somewhat ironic to find that he was the first to report that head movement causes displacement of the endolymph (Goltz, 1870). He established the central role of the cupula which he realised was responsible for the balance of the head and, in turn, the equilibrium of the entire body. But it was the simultaneous researches of Crum-Brown in Edinburgh, Mach in Prague and Breuer in Vienna which advanced these ideas by showing that the semicircular canals are the sensory organs responsible for the perception of rotatory motion (Crum-Brown, 1874; Mach, 1875; Breuer, 1891). They also demonstrated that vestibular stimulation influences the muscles of the eyes and body, and Breuer observed that destruction of the peripheral labyrinth was associated with rotation of the head and with nystagmus beating to the contralateral ear (Breuer, 1874): he is thus generally accredited as being the first to describe vestibular nystagmus.

By this time there was a general awakening of interest in the functions of the vestibular system and, as a result, this period saw an explosion in our knowledge of the physiology of equilibration. For instance Bechterew published his classic series of experiments at this time. These demonstrated that a gradual loss of nystagmus and diminution of muscle imbalance would follow if sufficient time was allowed to elapse after unilateral labyrinthectomy and also showed that destructive surgery to the hitherto undamaged ear caused the symptoms and signs to re-appear (Bechterew, 1882). He also realised from these experiments that simultaneous bilateral labyrinthectomy was not associated with nystagmus, (although some muscle weakness and diminution of tone resulted), and in other experiments was able to demonstrate that the symptoms of vestibular imbalance would recur if the nuclei on the same side were damaged after recovery from unilateral labyrinthine ablation. By contrast no nystagmus resulted if the contralateral vestibule and ipsilateral vestibular nuclei were destroyed after unilateral labyrinthectomy, but he showed that nystagmus and muscle imbalance would follow if simultaneous bilateral labyrinthectomy was succeeded by unilateral ablation of the vestibular nuclei.

Ten years after this research Ewald, who had followed Goltz as Professor of Physiology in Strassburg, made a series of important observations based upon his research with pigeons (Ewald, 1892; 1898). Ewald's experimental method involved inducing endolymph flow by means of a pneumatic bulb attached to a fistulous opening in the semicircular canals. Some investigators considered this stimulus to be too violent but subsequent work has confirmed Ewald's findings (Fernandez and Goldberg 1971; Baloh, Honrubia and Konrad, 1977). His conclusions later became known as Ewald's first and second laws and stated that:

1. The eyes and head move in the direction of the stimulated canal as well as in the direction of endolymph flow.

2. A flow of endolymph towards the ampulla of the lateral canal (utriculo-petal) causes greater stimulation than flow away from the ampulla (utriculo-fugal) whereas in the superior and posterior canals the reverse is true.

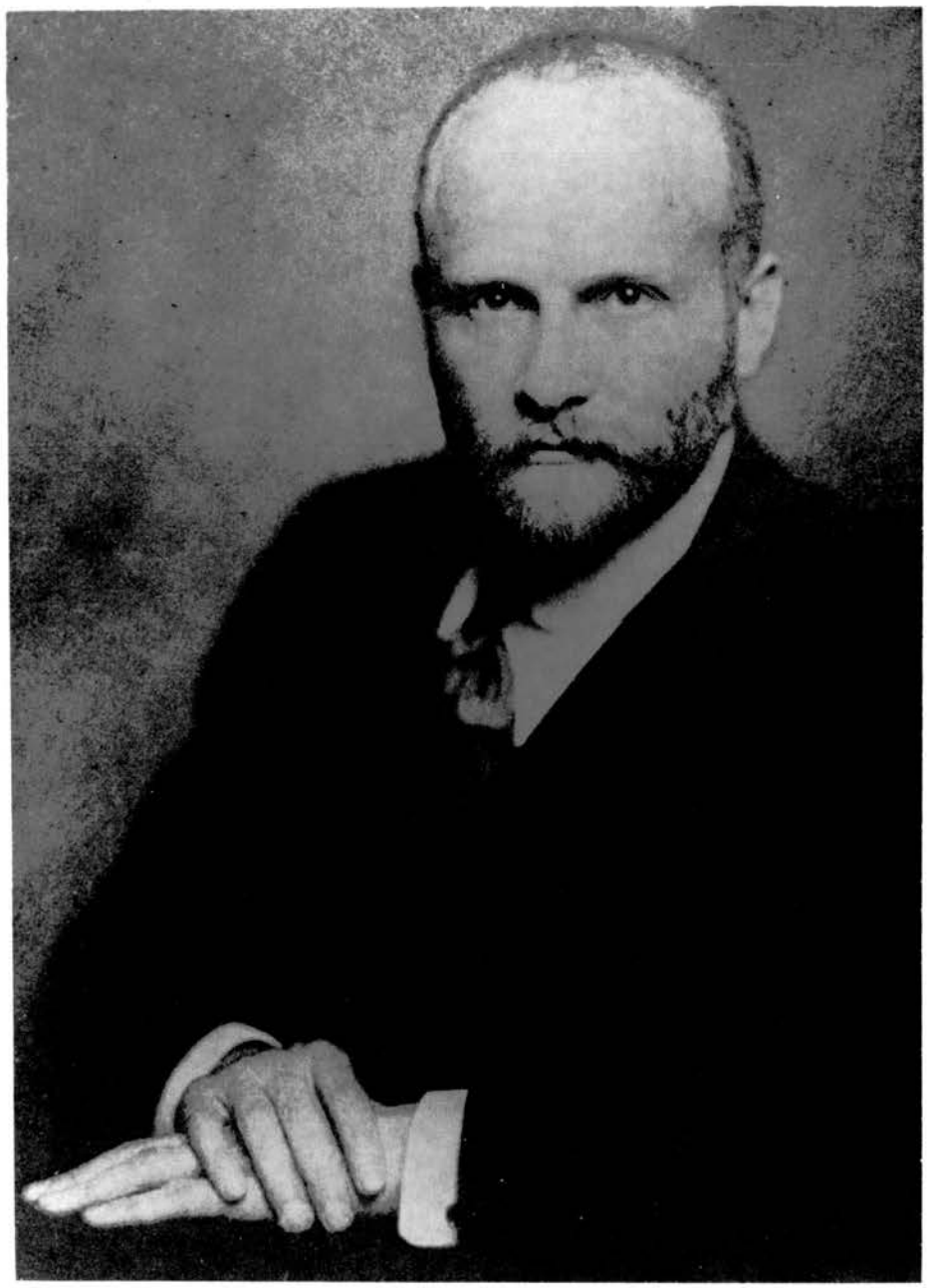
This work further emphasised the role of the semicircular canals but, by the time this work was published, there was already an increasing awareness of the need to investigate both the central and peripheral mechanisms of postural control, and research had started to move away from simple considerations of the motion of the endolymph and cupula. This was reflected in the work of Cyon in Paris and Hoegyes in Hungary both of whom, quite independently, started to study central vestibular pathways. They both showed the connections between individual semicircular canals and Cyon also investigated and wrote of the link between these pathways and nystagmoid movements of the eyes (Cyon, 1878). In addition Hoegyes demonstrated the areas of the central nervous system within which ocular nystagmus occurred (Hoegyes, 1881). Indeed it seems that he spent most of his lifetime in researching these pathways only to have his contributions go unnoticed by most of his contemporaries because he published in Hungarian:it was not until much later that his researches were translated into German (Jones, 1918).

These ideas were followed by experiments demonstrating the inhibitory influence of the cerebellum upon vestibular nystagmus and by studies which showed that ablation of one cerebral hemisphere causes a disparity in the strength of the nystagmus generated in response to a rotatory stimulus. This later phenomenon was first attributed to increased sensitivity of one labyrinth (Leider and Bauer, 1911) but is now thought to be due to inequality of central tonic influences (Fischer, 1956). Later the term "directional preponderance" was coined to describe this disparity. This terminology is generally attributed to Cawthorne and his co-workers even though they credit it to Barenne and de Kleyn (Cawthorne, Fitzgerald and Hallpike, 1942).

Advances in our understanding were also linked with the outstanding work of Robert Barany (Figure 1. 1). His contribution to the subject was immense, for he was the first to introduce testing of the vestibular apparatus and the first to interpret these tests in terms of disorders of the vestibular apparatus. His classic paper "Untersuchengen uber den vom Vestibularapparat des Ohres reflektorisch ausgelosten rhythischen Nystagmus und seine Begleiterscheinungen" was published in 1906 in volume 40 of the Monatschrift fur Ohrenheilkund. This essay introduced the concept of irrigation of the external meatus with large quantities of cold water as a clinical method of evaluating labyrinthine function, and he offered a theory to explain this phenomenon by suggesting that changes in temperature at the tympanic membrane are conducted to the semicircular canals through the temporal bone. He reasoned that the first labyrinthine structure to be stimulated would be the lateral canal, and that a change in temperature here would cause a change in specific gravity in adjacent fluids with convection currents and an endolymphatic flow. It seems that this explanation of the caloric response emanated from a childhood experience, and the following is Barany's description of this which is extracted from a speech given by him:

> "I remember the water heater, and my astonishment, as a child, when I found the water just above the fire quite cold, but right at the top, the bath-oven was so hot it burnt the fingers. The labyrinth now represented in my mind the water heater-ie. a vessel filled with fluid. The temperature of this fluid is naturally 37 degrees Centigrade-the body

Figure 1.1



Robert Barany

> temperature. I squirt cold water at the one side of the vessel. What must happen? What must naturally occur is that the water lying against this wall is cooled down; in this way it acquires a higher specific gravity than the surrounding water and sinks to the bottom of the vessel. On the other hand, water still at body temperature takes its place. If I syringe the ear with hot water, the motion must be precisely contrary. But the motion of the fluid must be altered if I alter the position of the vessel. And it must be changed to the exact opposite if I turn the vessel through 180 degrees. The test which had to be the crucial experiment for this theory occurred to me at once. If syringing the ears, be it with cold fluid or hot, succeeded in evoking nystagmus, precisely opposite in direction for two positions of the head differing by 180 degrees, then the theory must be the right one. I now went to the clinic and undertook the experiment. As it turned out, the anticipated result appeared with the greatest clearness. Two positions of the head, encompassing between them 180 degrees, gave directly opposite nystagmus reactions. . . "

Although this view was to prevail it did not gain immediate and widespread acceptance. Some authors expressed the opinion that the caloric reaction resulted from stimulation of the vestibular nerves (Bartels, 1911), and others considered that the response was secondary to a labyrinthine vascular reaction (Kobrak, 1918). It was also suggested that nystagmus could be produced by direct pressure of water on the labyrinth (van Caneghem, 1946) but Barany disproved this by demonstrating that irrigation with water at body temperature had no effect and that warm water reversed the direction of the response. It was also suggested that the amount of heat applied would be insufficient to cause temperature changes in the labyrinth, but this criticism was also shown to be erroneous by work which showed that syringing small quantities of cold water into the external auditory meatus of a cat was sufficient to cause paralysis of the postganglionic sympathetic fibres which are responsible for pupillary dilatation and which run over the lateral labyrinthine wall (de Kleijn, Socin and de Burlet, 1915; de Kleijn and Magnus, 1918).

Further work allowed Barany's explanation to gain greater credibility (Borries, 1920, 1922, 1925; Maier and Lion, 1921; Steinhausen, 1931). For example such studies visually demonstrated cupular movement in response to a caloric stimulus and showed that this movement would occur even if the temperature of the stimulus

differed from that of the body by only half a degree (Maier and Lion, 1921; Steinhausen, 1931). Barany's theory was also made attractive by elegant work which demonstrated that the duration of heat transmission in the temporal bone in response to a caloric stimulus corresponds with the latency and duration of the resultant nystagmus (Meurman, 1924; Schmalz, 1931).

However time has not dimmed further criticism and, although Barany's theory is still largely accepted, recent work has once more called the whole basis of the caloric reaction into question. For example it has been shown that body position alters the intensity of caloric nystagmus (Coates and Smith, 1967). But more damaging is the evidence from the American space programme which has clearly demonstrated that a caloric reaction can be elicited in zero gravity. In such circumstances convection cannot be the effective stimulus since such movement is gravity dependent. This work has inevitably led to some revision of our ideas about the caloric reaction and it has recently been suggested that a thermal stimulus results in an alteration of endolymph volume and that it is the resultant pressure gradient which acts to cause cupular deflection (Scherer and Clarke, 1985; Muller-Deile, Reker and Zell, 1986).

B. THE VISUAL SYSTEM

The earliest medical recordings of eye movement in normal subjects were published in the 16th Century (Bartisch, 1583), but for the next two hundred years the chief interest of most investigators centred around monocular strabismus and only passing reference was made to conjugate movements of the eyes. Even at the beginning of the nineteenth century things were slow to change and, while there were some reports of binocular movement, these tended to coincide and to become interspersed with the growing literature of the time on the movements induced by alterations in vestibular function. For example it seems certain that Darwin's studies cited at the beginning of this chapter were observations of nystagmus due to a peripheral vestibular lesion rather than a description of conjugate binocular movement.

However two contempories of Purkinje, Muller and Magendie, did make scientific contributions concerning conjugate eye movements. They pointed out that the ocular globes turned around a centre of rotation (Mueller, 1826; Magendie, 1824), and although it was later alleged that this concept had been considered two hundred years previously by the astronomer Kepler (Helmholtz, 1866), it is clear that these investigators speculated a great deal on the anatomical and physiological mechanisms behind such movements. Shortly after these papers the first experimental observations of smooth binocular movements were made and the results published (Muller, 1834).

The same period saw two other major developments. The first of these was a description of eye movements in response to visual stimuli by Purkinje (Purkinje, 1819). This report of what we now understand to be optokinetic nystagmus was made after observing crowds watching a procession of cavalry, and the same movements were later reported in subjects looking out of the window of a moving train (von Helmholtz, 1866; Javal, 1878). To this day such a means of invoking optokinetic nystagmus is widely quoted, and this has led to such movements being described by some as "railway" or "train" nystagmus. Here again Barany was pre-eminent since he was one of the first to describe the clinical testing of the optokinetic response by means of a rotating striped drum (Barany, 1920).

The second advance was the description by Bell of the upward mobility of the eyes which is seen with bilateral eyelid closure and which he described in patients with facial palsy. We now appreciate this as a normal phenomenon and understand that it is merely more obvious in the palsied face, but this report led to a succession of papers in which Bell demonstrated other eye movements and specific cranial nerve dysfunctions: included amongst these was the facial palsy which has come to be eponymously associated with his name (Bell, 1823, 1833).

It was also Helmholtz who, between 1856 and 1866, started research into vision and the co-ordination and conjugacy of eye movements. His work, which has since been translated and annotated by Southall (Southall, 1924), propagated the idea that

movement of the eyes is a learned skill. This work was accompanied by papers from Hering, a contemporary of Helmholtz, who performed accurate experiments and who made careful observations of the relationship between movements of the head and binocular movements of the eyes and concluded that the eyes are "yoked" and move as a unit (Hering, 1868, 1879). Again these concepts were not entirely new having been first suggested some years previously in a case report which is discussed in a later part of this section (Foville, 1858). Even so this work heralded a growing appreciation of the conjugacy of eye movements, and produced ideas which were later to be confirmed by clinical observations made on patients suffering from hemiplegia and epileptiform seizures (Jackson, 1866).

While such findings are rightly regarded as being amongst the first documented accounts of the conjugate eye movements, it is unfortunately true that much of the research undertaken during the last century was of a fragmentary nature and concentrated on case reports of abnormal movements in response to different central lesions. Pre-eminent in this respect were the French, whose papers described conjugate eye palsy associated with ipselateral and contralateral hemiplegia together with a number of crossed syndromes associated with brainstem lesions (Andral, 1834; Foville, 1858; Gubler, 1859). Reviewing this data one gets the impression that the concept of conjugacy of eye movement was still proving something of an enigma; certainly some authors were still searching for a single nerve that would move both eyes in one direction.

In point of fact it was one case report, already alluded to, which provided the basis for further advance in this field. Foville wrote of a forty three year old man who suddenly lost consciousness and who was later found to have sustained a left lower motor neurone facial palsy together with slewing of the tongue to the right, a right hemiplegia and bilateral gaze paresis on left lateral movement of the eyes (Foville, 1858). With the anatomical knowledge available at the time he attributed this clinical picture to a left pontine lesion, but he also gave considerable thought to the paralysis of adduction in the right eye and reasoned that this must be due to damage at the

point of origin of the third nerve which, he assumed, crossed to the other side "as all oculomotor fibres do". We now know that this explanation is untenable, but it was the first paper to point out that no "synergistic fibres" could exist in a "single nerve trunk" as had been previously thought, and this paper thus effectively demonstrated that crossed innervation had to occur within the brainstem. This concept served to provide the foundation of subsequent clinical, anatomical and electrophysiological studies of structures such as the median longitudinal fasiculus which are intimately involved in conjugate gaze.

In the vanguard of research in this area was Prevost whose clinical and experimental observations were later grouped together in a monograph (Prevost, 1868). His experimental methods in animal models consisted of direct cerebral incisions or the injection of tobacco grains in water into the cerebral circulation and this work, together with his clinical studies, led him to conclude that lesions of the cerebrum tend to result in ipselateral ocular deviation whereas lesions of the pons or cerebellum result in gaze deviation to the contralateral side. This theory was embodied in the literature of the day as "Prevost's rule" which stated that "the patient looks towards the lesion in cases of cerebral involvement and away from the lesion in cases with damage to the brainstem". Some of the points he made in discussion of his results remain valid today. For example he emphasised the close relationship between head and eye movements and observed that patients with stroke tend to have altered head posture together with transient abnormalities of eye movements. He also noted that bringing a forcefully deviated head to the midline enhances ocular deviation and, in attempts to correlate the findings of head and eye deviation with the site of the lesion, concluded that the damaged area was invariably located deep within the brain. He also speculated as to whether or not superficial lesions such as subdural haematoma had their influence by acting on the deeper central structures responsible for conjugate gaze. During the 1870's such centres were again inferred in writings of the effects of coma and anaesthesia upon eye movements (Mercier, 1877).

Although Prevost was unable to outline the cephalo-oculomotor pathways involved, his successors did manage a more anatomical analysis of the observable phenomena. Graux devoted his doctoral thesis to this problem, and was able to demonstrate a structure in the floor of the fourth ventricle of cats (apparently the median longitudinal fasiculus) which he noted was responsible for linking the abducens and oculomotor nuclei (Graux, 1878). His slides of human material were not as convincing as those he obtained from his animal work, but it was these studies together with others which stressed the importance of this structure, which led to the medial longitudinal fasiculus being recognised as the critical pathway for conjugate and horizontal gaze (Bennett and Savill, 1889; Monakow, 1895). Thereafter there were many other reports which centred around the importance of this structure. Some later papers included the observation that there could be preservation of convergence in cases of bilateral paralysis of conjugate horizontal gaze and, based on this work and on Foville's theories, many then argued that dissociation of conjugate gaze was associated with the functions of the medial longitudinal bundle. Later it was learned that the fasiculus could indeed transmit two types of information, one for contralateral horizontal gaze and the other for convergence (Spiller, 1924). Since this time the role of the pontine reticular formation in the genesis of these eye movements has also become apparent (Bender, 1980).

Of course it is true that these early clinical descriptions of cases were sketchy and the pathological lesions induced during experimental studies were often quite gross. Such methodology could only lead to errors and conflicting reports often resulted. In spite of this these early studies added a great deal to our understanding and, since the end of the nineteenth century, this knowledge has been immeasurably advanced by careful direct investigations of the excitability of various areas within the cerebral cortex and brainstem of the monkey and other experimental animals. The introduction of stereotactic surgery at the beginning of this century helped to enhance the precision given to such stimulation and ablation experiments and the detailed work on the anatomy, and physiology of the vestibular neurones controlling eye movements and the role of the pontine reticular formation by Lorente de No (Lorente de No, 1933),

provided the basis of much of our current understanding of the origin of visual-ocular function.

Studies of other aspects of eye movement were also first made in the nineteenth century. The first experiments assessing the velocity of movement measured the number of times a subject could look back and forth between two objects in a given time (Volkmann, 1846). Such work was repeated by students working under the direction of Helmholtz (Lamanski, 1869), and it was by then appreciated that the speed of eye movements could vary and could be either smooth or irregular. In spite of this it was not until nearly the turn of the century that the first detailed studies of fast eye movements were made and were recorded in response to the stimulus provided by viewing moving patterns on film (Stratton, 1902).

A year later a comprehensive classification of eye movements was presented by the American psychologist Dodge (Dodge, 1903). This systematic approach was a major milestone in our thinking and is still widely quoted. It divided horizontal eye movements into five types:

Type I	-	Rapid movement of the eye towards an object of interest which is eccentric upon the retina.
Type II	-	Pursuit movement.
Type III	-	Coordinated compensatory eye movements.
Type IV	-	Dash reactive compensatory eye movements.
Type V	-	Convergence or divergence.

The fast movements as envisaged by Dodge we now call saccades and the dash reactive movements we understand as the vestibulo-ocular reflex. But increasing knowledge has made it clear that slow movements are considerably more complex than he or anyone else at this time envisaged. For example we now know that there are two systems subserving differing optokinetic responses.

While further experimentation has increased our knowledge of the specific response patterns of the cerebrum and brain stem, and their roles in eye movements have become better appreciated, it has to be admitted that the morphological and physiological evidence of the pathways involved is still to some extent presumed and incomplete (Bender, 1980). However much of what is known will be discussed in subsequent chapters.

CHAPTER 2.

THE PHYSIOLOGY OF EQUILIBRATION.

An account of the known physiology of the systems concerned with balance, posture and eye movement.

SUMMARY

This chapter concentrates on the physiology of two of the main systems which influence position sense and which allow normal equilibration, posture and spatial orientation. These are the vestibular and visual apparatus.

A short section dealing with the effect of changing central control upon these vital functions is also included. In particular the influence of the cerebellum on vestibular and ocular function is discussed.

The other important sensors which provide information about body position are the proprioceptors. These are not discussed since their study was not considered here. Presumably they could also be liable to exhibit maturation effects in the children examined.

INTRODUCTION

Even casual observers are aware that eye and head movements are tightly linked. This interaction allows stabilisation of the visual image during head movement (the vestibulo-ocular reflex) and matching of the visual image to objects in the visual field (the optokinetic system). Obviously when the head is stationary the optokinetic reflex alone must be responsible for eye movement. The same must also be true when there has been a period of head movement at constant velocity, because in such circumstances endolymphatic stimulation ceases and ocular compensation for continued head movement relies on the optokinetic system. However when there is movement of the head together with movement of the visual surroundings the two systems are integrated, although the exact mechanisms which allow this to happen are still poorly understood.

What is clear is that the centres which allow for the integration of horizontal eye movements lie in the upper brainstem. The regions of the medial vestibular nucleus and nucleus propositus hypoglossus are of critical importance since lesions here upset the integration of a pure velocity signal to a mixed velocity and position command, and without this input the eyes move when stimulated but then drift back to their rest position due to the visco-elastic properties of the orbital contents. The same areas are responsible for the velocity and position commands which precede saccadic initiation. Indeed it seems that this area provides a final common pathway for the interpretation of all horizontally induced eye movements (Cannon and Robinson, 1986). The following account gives an overview of vestibular and visually induced eye movements and of their control mechanisms.

A. THE VESTIBULAR APPARATUS

i) The peripheral vestibular system

The sensory epithelium of the vestibular apparatus is located in the semicircular canals and in the maculae of the saccule and utricle; each of these receptors contains a mixture of sensory and supporting cells. The sensory cells are of two types. Type 1 are flask shaped and are surrounded by chalice like nerve terminals which transmit afferent information, and Type 11 are cylindrical with multiple button like neuronal elements which are thought to have an efferent function. In addition the sensory cells have two types of cilia; a single kinocilium and multiple (up to 110) thinner stereocilia (Spoendlin, 1964). Displacement of sensory cells towards the kinocilium results in stimulation and depolarisation while movement away from the kinocilium causes hyperpolarisation and inhibition (Flock, Jorgenson and Russell, 1973). In the maculae the sensory epithelium is less than 1mm squared and is overlaid by a gelatinous matrix composed of calcareous material into which the cilia are embedded. In the semicircular canals the ciliated and supporting epithelium forms the cristae ampullaris which lies at right angles to the longitudinal axis of the canal and is

topped by the cupula. This extends to fill the ampulla and forms a watertight swing-door seal with the adjacent canal wall (Igarishi, 1966).

The maximal stimulus for both these sensors is a force passing through the kinocilium and bisecting the stereocilia (von Bekesy, 1966). In the maculae the specific gravity of the otolith exceeds that of the surrounding endolymph in a ratio of 2.7:1; the force acting on this receptor at rest is thus equal to the product of the otolith mass and gravitational force. During movement this changes and an additional force is then developed in a direction which opposes head displacement. The effective stimulus is the resultant of these two forces, and the position of the statoconial membrane relative to the sensory epithelium thus varies according to the magnitude and direction of this shearing force (de Vries, 1950). By contrast there is no resting input to the underlying sensory epithelium in the semicircular canals since the specific gravity of the cupular mass is the same as that of the surrounding endolymph (Money,Bonen and Beatty,1971). During angular acceleration the inertia of the endolymph causes it to lag with respect to head movement and there is thus a flow of endolymph relative to the canal wall. This is resisted by the temporary deformation and elasticity of the cupula which results in stimulation, although it is not clear whether excitation is the result of simple cilial bending or fanning or whether it is due to pivotal rotation around the kinocilium.

In this way these organs function to transduce the forces associated with head acceleration and gravity into a biological signal according to Newton's second law (Force = Mass x Acceleration). The maculae sense gravitational forces and respond to linear acceleration whereas the semicircular canals function as sensors of angular acceleration. But while the appropriate stimulus to the canals may be an acceleratory force, the resultant efferent output indicates velocity. This is thought to be partially due to the anatomy of the system, because the diameter of the semicircular canals is small compared with their radius of curvature, and acceleration results in a laminar flow of endolymph which is proportional to head velocity (Jones and Milsum, 1965). But there is also modulation of the response in the neural output since otolith or

semicircular canal stimulation results in non uniform patterns of neural discharge due to subpopulations of nerves with different conduction velocities and adaption characteristics (Fernandez and Goldberg, 1971, 1976; Goldberg and Fernandez, 1971).

Afferent traffic is conducted centrally by myelinated fibres which pass to the large bipolar cells of Scarpa's ganglion in the internal auditory meatus. There is also a topographical arrangement at this site, for the superior portion of the ganglion contains large fibres originating from Type 1 cells on the crest of the cristae, and the inferior portion consists of fibres arising from the slopes of the cristae and from Type 11 cells.

ii) The central connections

The central projections of these cells take two major routes. An ascending branch synapses in the cerebellum and at the vestibular nuclei (especially the superior and medial elements) and a descending branch synapses on the inferior vestibular nuclei (Brodal, 1974). There are also efferent fibres, and these take origin from the area adjacent to the lateral and medial vestibular nuclei and from the region of the sixth nerve nucleus (Gacek and Lyon, 1974).

The four groups of cells which constitute the vestibular nuclei lie on the floor of the fourth ventricle (Brodal, 1974). These are named superior, lateral, medial and descending (or spinal), and each has distinct anatomical connections. The nuclei are both monosynaptically and polysynaptically activated, and there are complex and different firing patterns within them in response to ipselateral or contralateral stimulation of the canals or otolith organs (Schneider and Anderson, 1976; Peterson, 1970). An additional level of sophistication is provided by populations of cells subserving either dynamic or static responses (Schor, 1974).

Since no primary vestibular afferents cross the midline all commissural connections are either second or higher order neurones, but direct contralateral inhibition of the vestibular nuclei has been demonstrated (Shimazu and Precht, 1966), and it is now

apparent that commissural inhibitory connections also pass through the cerebellum (Furuya, Kawano and Schimazu, 1976). The existence of these inhibitory commissural fibres is thought to enhance the sensitivity of the vestibular system (Markham, Yagi and Curthoys, 1977); they also provide a mechanism for modulation and integration of vestibular information within the spinal cord.

The following organisation of the afferent input to the vestibular nuclei is widely quoted:

1. Superior nucleus:cristae of the semicircular canals and cerebellum.

2. Lateral nucleus:cerebellum and utricle together with some spinal and commissural afferents.

3. Medial nucleus:cristae of the semicircular canals and cerebellum together with some fibres from the reticular formation and the utricle.

4. Descending nucleus:utricle and saccule together with a small number of fibres from the cristae and from the cerebellum.

In turn the output of the vestibular nuclei passes through different long tracts to serve five main systems which are:

1. The oculomotor nuclei via the medial longitudinal fasiculus and reticular formation.

2. The motor horn cells in the spinal cord via the reticulospinal and vestibulospinal tracts and through the inferior part of the medial longitudinal fasiculus.

3. The cerebellum.

4. The autonomic nervous system.

5. The cerebral cortex (temporal lobe).

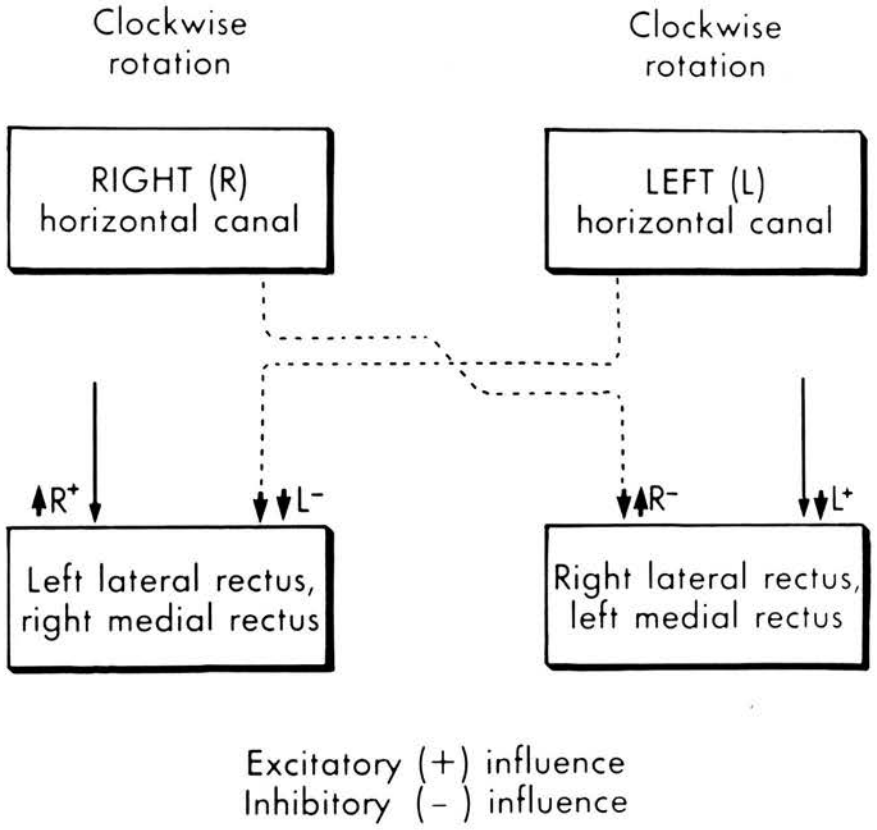
iii) The vestibulo-ocular reflex and vestibulo-ocular reflex suppression

The vestibulo-ocular reflex arc is of central importance in gaze stabilisation and consists of the vestibular receptor, primary, secondary and tertiary neurones and the relevant oculomotor muscle (Szentagothai, 1950). This reflex is also of clinical importance, since it forms the physiological basis for the slow component of the nystagmus induced by semicircular canal stimulation.

The basis of the vestibular response is that excitatory impulses in one semicircular canal produces reciprocal inhibition and an exact mirror image response in the canal paired with it in the contralateral ear. The neural connections between the individual canals and extraocular muscles which facilitate this have been characterised by stimulation and ablation experiments in laboratory animals (Lorente de No, 1933; Fluur, 1959; Cohen, Suzuki and Bender, 1964), and from this work it is known that each semicircular canal has connections to parts of the ipselateral vestibular nuclei. The afferent traffic is both excitatory and inhibitory. Thus rotation to the right results in endolymphatic flow to the left and ampullo-petal cupular deflection in the right horizontal semicircular canal; this output is excitatory. At the same time there is an ampullo-fugal flow in the left horizontal canal which and the resultant cupular deflection is inhibitory. Therefore equal and opposite information passes to the nuclei subserving the agonist and antagonist muscles, the lateral and medial recti Figure 2. 1), and the result is movement of the eyes to the left caused by contraction of the left lateral and right medial rectus muscles.

In spite of this apparently simple explanation the accounts provided in the literature vary somewhat in their descriptions of the brainstem connections of the vestibular apparatus, albeit that there seems no doubt that the major tract responsible for transmitting information to the ocular nuclei is the medial longitudinal fasiculus. This

Figure 2.1



Diagramatic representation of agonist and antagonist action of vestibular stimulation upon muscles responsible for eye movement in response to rotational stimuli.

pathway certainly handles all the excitatory and inhibitory information from the posterior canal and its central connections with the medial and superior vestibular nuclei. It also transmits inhibitory information from the superior canal as relayed through the superior vestibular nuclei, and passes inhibitory and excitatory stimuli from the horizontal canals to the lateral recti by way of the medial vestibular nuclei. The only other tracts involved are the superior peduncle of the cerebellum on each side (which relays excitatory information received from the superior vestibular nuclei and superior canals), and the accessory tract of Deiters (which transmits some excitatory information from the lateral vestibular nucleus to the ipselateral medial rectus in response to horizontal canal stimulation). It is by way of these pathways that the slow phase of the nystagmus which results from vestibular stimulation is generated. The fast phase is an involuntary saccade which appears to emanate from activity in the parapontine reticular formation (Raphan and Cohen, 1978), but while these cells clearly possess the ability to monitor vestibulo-ocular signals, the exact mechanism which causes this fast movement response is unclear.

Vestibulo-ocular reflex suppression

In the past it has always been assumed that the ability of the brain to suppress vestibular information when either subject or target are moving depends on simple addition of pursuit and vestibulo-ocular eye movement without modification of the vestibulo-ocular reflex (VOR). Modulation typically occurs when the subject attempts to fix on a moving target when he himself is rotating; this results in a reflex gain that is close to 1 at all frequencies up to 5 Hz. If however the subject attempts to fix on a target which rotates with him the gain is very low at low target velocities, and it was this observation which led some to suppose that the pursuit system was responsible for suppression (Barnes, Benson and Prior, 1978). This hypothesis received further support from clinical observations which implied that central lesions which impair pursuit also impair cancellation (Baloh, Lyerly and Yee, 1984).

Unfortunately humans rotated in the dark can increase or decrease their VOR gain by tracking an imagined fixed or moving target (Barr, Schultheis and Robinson, 1976;

Herman, 1982). In these instances smooth pursuit could not possibly be responsible for suppression since it is seen only when a moving target is present. More recent research has suggested that the brain contains a separate system which allows for rapid and voluntary regulation of the amplitude of eye movements induced by vestibular stimulation, and evidence for this started with the realisation that the characteristics of pursuit and vestibular eye movements are quite different. Pursuit movements are most efficient when the frequency of target movement is low; in these circumstances gain and phase approximate to unity. However, when the target velocity exceeds speeds of 60-70 degrees/second, or is made to oscillate at frequencies greater than 1-1.5 Hz, then the gain diminishes rapidly and a large phase lag develops. If target movement is unpredictable the performance of this response falls further (Larsby,Thell,Moller and Odkvist,1988).

By contrast, the vestibulo-ocular reflex shows a variable gain with an average of 0.7 in response to rotation in the dark at moderate frequencies (0.1-0.5 Hz) and, as speed decreases, the eyes show a phase lead and there is a decrease in the gain. Similarly as speed increases the response remains stable with phase remaining close to 0 and rising to 1 or above at a stimulus frequency between 1 and 2 Hz.

These differences are also revealed by simple clinical examination. Slow velocity eye movements in response to vestibular stimulation are enhanced by the abolition of optic fixation whereas pursuit is abolished. In addition, reports of disease selectively affecting one or other function imply differing mechanisms (Dell'Osso, Abel and Daroff,1981), and this work is further reinforced by experiments in monkeys which have appeared to identify the specific groups of neurones responsible for suppression. Moreover, such work has demonstrated that second order relay neurones carrying pursuit information are not active during vestibulo-ocular suppression (Tomlinson and Robinson, 1980, 1981; May and McCrea, 1985).

Even if an independent pathway acts to suppress the vestibulo-ocular reflex the mechanism is certainly imperfect for it is common to find that the induced

movements are not completely suppressed when testing the system in the dark with imagined targets (Maulucci and Herman, 1979). It may therefore be true that the pursuit system has a role to oppose the residual eye movements which remain after the gain has been reduced to negligible amounts. What seems certain is that the standard suppression test is not measuring the performance of the pursuit system per se although, as has been inferred, it certainly remains possible that such a test measures the combined action of this system in concert with another.

B. VISUAL-OCULAR CONTROL

i) Pursuit movements

Pursuit movements are low velocity tracking movements of the eyes which are used to follow a target and maintain a visual image on the fovea (Dodge, 1903). Animal work has shown that the receptive system for this movement comprises the retina, lateral geniculate body and striate cortex, and information from these sites is radiated to a large number of peristriate areas arranged in two main groups. These interpret target movement and colour, and pass information to the middle temporal area of the superior temporal sulcus from where it is relayed to the middle part of the superior temporal lobe and the inferior parietal cortex (Maunsell and van Essen, 1983). By this stage the information is encoded for target direction, position and velocity, and these centres then transmit the signal to the primitive cerebellum, the flocculus and nodulus (Suzuki and Keller, 1984). In turn these areas are involved in a system of reciprocal innervation with the vestibular nuclei and networks of neurones in the pontine tegmentum, and it is this upper brainstem system which generates and modulates pursuit movement through the ocular motor neurones.

ii) Saccadic movements

Saccadic movements are high velocity "all or none" movements of the eye which are voluntarily or involuntarily initiated to correct the direction of gaze and restore the visual image to the fovea. The velocities achieved in execution of these movements

are between 200 and 600 degrees/second with a variability which depends on the previous degree of ocular excursion (Robinson, 1964). After saccadic initiation there is a latent period before the movement begins of 150-200 milliseconds, and a succession of saccades show this same latent period between each movement.

The saccadic system is controlled by the frontal eye fields. Low intensity stimulation of this area in animals and man causes conjugate deviation of the eyes to the opposite side (Mott and Schaeffer, 1890; Penfield and Jasper, 1954; Brucher, 1964; Robinson and Fuchs, 1969), and it is a common observation that epileptiform movements originating in this area cause contralateral conjugate deviation of the eyes (Mott and Schaeffer, 1890; Robinson and Fuchs, 1969). Elegant demonstrations of the anatomical connections from these areas have shown that the majority of fibres pass from the frontal eye fields into the internal capsule adjacent to the globus pallidus and to the thalamus and zona inseta, fields of Forel and upper brainstem (Brucher, 1964). Information for horizontal and vertical saccades is then separately transmitted to the paramedian reticular formation in the pons and mesencephalon (Henn and Cohen, 1976; King, Fuchs and Magnin, 1981).

Mapping experiments have also shown that these areas contain separate phasic and tonic cell subgroups, and this fits the physiological requirements for fast movements which are for a pulse of energy to overcome the inertia of the orbital contents followed by a step to maintain the eye in eccentric gaze (King, Lisberger and Fuchs, 1976). These cells would appear to correspond to this theoretical "pulse-step" or "velocity-position" requirement, but the exact pathways from these centres to the ocular muscles are uncertain. It appears that excitatory stimuli for horizontal saccades are passed directly or indirectly through the medial longitudinal fasiculus (Buettner-Ennever and Henn, 1977). Less is known about inhibitory patterns.

iii) Optokinetic movements

Optokinetic nystagmus is the result of movement of the visual surroundings which produce a slip of the visual image on the retina. Since Barany's original observations of this phenomenon the response has been the subject of a large number of different studies.

The major contribution was undoubtably made by Ter Braak who was able to show that there are two sorts of stimulus and response patterns involved (Ter Braak, 1936). The first is an active or "look" response and is seen if a subject sits and follows an object moving across his visual field. This results in large amplitude eye movements with eye velocity tailored linearly to target velocity up to a speed of 60 degrees/second. The second is a passive or "stare" response which is seen when the subject attempts to maintain his eyes in central gaze as the stimulus passes:this results in small amplitude and high frequency nystagmus which falls behind target speed when the later exceeds 30 degrees/second.

Of equal importance was his work in experimental animals which also showed something of the differing physiology of these responses. Thus he demonstrated that a target which engaged the subjects interest produced a cortical reaction dependent on foveal vision which was abolished by decortication or ablation of the strial cortex (Ter Braak, 1936; Ter Braak and van Vliet, 1963). This is now known to be identical to pursuit (Magnusson,Pyykko and Norrving,1986). By contrast, non-pursuit nystagmus could also be identified and was found to be dependent on the vestibular nuclei and the entire visual field, especially the periphery. This subcortical response engages a hypothetical neuronal mechanism in the central nervous system known as the "velocity storage mechanism" (Ter Braak, 1963), and it is now believed that both the vestibulo-ocular reflex and the subcortical response share this mechanism which acts as an integrator (Demer and Robinson, 1983). As Ter Braak was able to show, this later response is unaffected by cerebral ablation (Ter Braak, 1936).

The validity of these suppositions have recently been reinforced following a series of clinical tests performed on patients with congenital achromotopsia and glaucoma and with central lesions of the parietal lobes or cerebellum (Yee, Baloh, Honrubia and Jenkins, 1982). Of course in normal clinical circumstances a visual stimulus will generate responses from both systems; a pure subcortical response will only be obtained when the normally dominant pursuit system breaks down.

iv) Optokinetic after-nystagmus

The phenomenon of optokinetic after-nystagmus (OKAN) reflects the subcortically mediated optokinetic response. Thus it is in some ways correlated to the gain in the vestibulo-ocular reflex (Zasorin, Baloh, Yee and Honrubia, 1983). There is a large literature concerning OKAN in experimental studies, but few clinical reports have made use of its measurement. Perhaps this is because some studies have suggested that it is absent in up to 20% of the normal population (Magnusson, Pyykko and Jantti 1985; Sakata, Ohutsu, Itoh and Teramoto, 1986).

C. THE CEREBELLUM

Disordered cerebellar control in animals has a profound effect on somatic musculature including eye control systems. In monkeys experimental cerebellar lesions, including total cerebellectomy, result in normal saccades and conjugate gaze but cause difficulties in maintenance of eccentric gaze and failure of pursuit (Westheimer and Blair, 1973). Caloric and optokinetic responses are also altered, and there is an asymmetry of response for both stimuli which is more marked towards the side of the lesion. In adults these abnormalities persist indefinitely to some extent, even though there is some minor compensatory drift towards a midline ocular posture with time. However in young animals the compensation is more immediate and complete and appears to involve both cerebellar and extra cerebellar influences.

Lesions of the flocculus are particularly important. They cause changes of the fixation index by reducing the suppressive effect of fixation on the vestibulo-ocular reflex in the light while leaving unaltered the nystagmus induced in the dark (Takemori and Cohen, 1974; Zee, 1984). It has been claimed that these effects are due to deranged pursuit (Liseberger and Fuchs, 1977), and arguments for and against the role of pursuit in vestibulo-ocular reflex suppression have been advanced in previous paragraphs.

Regardless of the brainstem pathways implicated, it does seem that there is incontrovertible evidence to implicate the flocculus in both these activities. Lesions in this area certainly cause abnormalities of vestibular nystagmus, and bilateral ablation of the flocculus reduces the slow component velocity of the foveate optokinetic response. This has resulted in the regions of the flocculus, paraflocculus, nodulus and uvula being known as the vestibulo-cerebellum. Yet in spite of this there is no change in after-nystagmus, and this implies that the passive or non-foveate system is quite unaffected (Tekemori and Cohen, 1974).

In addition there is evidence to suggest that the regions of the dorsal vermis and fastigial nuclei are of importance in the control of eye movements and particularly saccadic amplitude. Thus lesions in this region result in saccadic inaccuracy and macrosaccadic oscillations (Zee, 1984).

In medical practice pathologies tend to be less discrete than laboratory lesions. They are also less likely to be self limiting. Nonetheless, cerebellar pathology usually results in several characteristic abnormalities of movement, and included among these are gaze paretic nystagmus and other derangements of visual-ocular function such as the breakdown of the pursuit system which is interspersed with saccades. This so called saccadic intrusion or saccadic pursuit results in the eyes moving in a series of jerks in response to a target. In addition the gain of the system is altered so that pursuit is lost at lower target velocities than normal. Thus the eyes tend to move

ahead of rather than lag behind a target. To compensate saccades are inserted in the opposite rather than in the same direction as eye movement.

As far as saccadic movements per se are concerned there is a tendency for these to be inaccurate with hypermetria and a corrective movement to restore foveal position (Baloh, Konrad and Honrubia, 1975; Selhorst, Stark, Ochs and Hoyt, 1976; Zee, Yee, Cogan, Robinson and Engle,1976). The opposite response, (hypometria and additional fast movements in the same direction as the target), may also occur with large amplitude excursions (30-40 degrees).

It is of interest that these abnormalities are not always reflected in derangement of the large drum optokinetic response. This is often relatively well preserved even in patients who have grossly deranged pursuit. The gain of a full field optokinetic stimulus (eye velocity/stripe velocity) never declines to a value which is less than that of the pursuit system alone (Baloh, Konrad and Honrubia, 1975), and this presumably is because both foveate and peripheral field stimuli are involved. On the other hand the pure pursuit or foveal stimulus offered by a small drum often fails to produce an optokinetic response in cerebellar disease. In spite of this the unusual case of a man who suffered two consecutive hemi-cerebellectomies with a resultant absence of pursuit together with some preservation of optokinetic nystagmus serves to suggest that there is some separation of function (Estanol, Romero and Convera, 1979).

Thus a lack of cerebellar control results in gaze paretic nystagmus, saccadic pursuit and , commonly, hypermetric (or occasionally hypometric) saccades. These disorders may co-exist with abnormalities of large drum optokinetic responses, but often this is less marked than might be expected from consideration of the pursuit response alone. Small drum testing is more commonly affected, and in unilateral cerebellar lesions a directional preponderance of both optokinetic and caloric nystagmus is the usual result.

CHAPTER 3

THE MATURATION OF VESTIBULAR AND VISUAL-OCULAR RESPONSES

A review of previous studies contrasting differences in vestibular and visual-ocular function with age.

SUMMARY

Most of the information at present in the literature concerning childhood vestibular responses spans only a few years of development, and many of the available studies have used different stimulating and recording techniques.

In particular the means used to record responses has varied considerably. Thus nystagmus has been measured both with and without fixation or mental alerting. These differences in technique have made an overall view of the maturation of vestibular function difficult to obtain.

Knowledge concerning the development of visual function is even more fragmented. Little information exists from longitudinal studies which allows an insight into the development of the various movements concerned with visual ocular-control and there are no studies which have measured the phenomenon of optokinetic after-nystagmus.

The following review presents the current state of knowledge on this subject.

A. VESTIBULAR FUNCTION

i) Introduction

The effect of vestibular stimulation in neonates, infants and older children has been studied by a number of groups using differing stimulus techniques. Unfortunately such attempts at establishing normative data have often been marred because insufficient attention has been paid to the monitoring of either the stimulus or the recording conditions used. The obvious pitfalls have been failures to monitor the mental state of the patient or to appreciate that while drowsiness suppresses nystagmus a state of forced alertness does not necessarily ensure a stronger response (Torok, 1970; Collins, 1974).

It has been suggested that the ideal mental state should be one of "relaxed attentiveness", and that this can be encouraged and monitored by recording the patient's responses with infra-red viewers, electroencephalography (EEG) and electronystagmography (ENG) (Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979). The majority of investigations err significantly from this ideal and indeed many make no apparent attempt to assess the mental state or to encourage alertness in the subjects tested. In other instances there has been a willingness to allow recordings to be made with the eyes closed or blindfolded. Such recording methods are also erroneous for visual sensation in the absence of fixation can critically alter nystagmus (Wendt, 1951; Ornitz, Brown, Mason and Putnam, 1974; Collins, 1974; Levy, Proctor and Holzman, 1977), and this finding must count against the results of studies which have used equipment such as Frenzel's glasses. In addition eye closure results in a strong tendency for upward vertical movement of the eye which suppresses the normal vestibulo-ocular reflex (Tjernstrom, 1973).

For all these reasons nystagmus is only reliably recorded in the dark with fixation removed but this, in turn, intensifies the need for proper alerting. This is especially true when recording responses from young children, for these subjects are those who are most prone to becoming bored and somnolent in the dark.

If these criticisms were not in themselves sufficient it must be said that there are also doubts concerning investigations which record only the total duration of nystagmus or the number of beats which follow a set stimulus. Such work has resulted in questionable conclusions being made about vestibular reactivity. For instance it has been inferred that increasing age results in an increased vestibular responsiveness since the duration of the induced nystagmus appears to be less in childhood (Zelenka and Slaninova, 1966). It is clear that such measurements may reflect the intensity of the stimulus but it seems unwise and erroneous to rely on them in isolation to reflect the nature of maturational change (Fluur and Mendel, 1969). Finally, to record responses by visual inspection alone seems certain to result in error. Obviously duration and the effect of optic fixation are the only parameters which can be

assessed and, although some work has suggested that the duration of post rotatory responses measured by ENG and visual inspection correlate closely (Keating, 1979), it seems certain that direct visual measurements must be less accurate since they are bound to measure some non nystagmic elements.

The stimuli used are also sometimes difficult to compare. For example, most of the available information concerning vestibular responsiveness of children in mid childhood is based on studies of the duration of post-rotatory nystagmus following abrupt deceleration. Such responses are superimposed upon and modified by the per-rotatory stimulus, and they thus do not have the stability of a sinusoidal stimulus (Baloh and Honrubia, 1979). An ongoing response also has the disadvantage that it prevents the study of secondary nystagmus which is thought to be centrally generated and to be a measure of vestibular adaption (Malcolm and Melvill Jones, 1970; Sills,Honrubia and Baloh,1978).

For these reasons caloric testing, although hampered by many possible procedural errors, has some advantages. Not least of these is the fact that such tests have the advantage that the results are widely understood.

As far as recording eye movements is concerned it is clear that some of the criticisms advanced in discussion of vestibular testing are also of relevance. For example the evaluation of optokinetic and pursuit movements is also dependent upon the alertness and attention of the investigated subject (Magnusson, Pyykko and Jantti, 1985) and,in addition, psychological factors such as motivation, attention and training are of importance (Schalen, Enbom, Henriksson, Magnusson and Pyykko, 1988).

ii) Vestibular responses in neonates and the effect of prematurity

Following early studies of vestibular nystagmus in the neonate (Bartels, 1911), vestibular reactivity in newborn infants has been confirmed by a number of authors using modern methodology. Per-rotatory and post-rotatory nystagmus was measured in one study in neonates aged between three hours and ten days using the stimulus provided by an electrically driven rotating table (Lawrence and Feind, 1953). The responses were only assessed visually with measurements made in a lighted environment, but all subjects tested exhibited post-rotatory nystagmus which persisted for a variable period (three to thirty five seconds) in the alert co-operative individual. Others have used the same stimulus technique and have confirmed these findings using electronystagmography (Pendelton and Paine, 1961). It is of interest that both these studies showed severely depressed or even absent responses in neonates who had experienced anoxia or trauma at birth or who had been born to mothers who had received an anaesthetic, and nystagmus was also depressed in children who had hyperbilirubinaemia or evidence of severe neurological damage.

Although two later studies which tested the responses in this age group failed to demonstrate consistent nystagmus patterns in response to rotatory stimuli or caloric irrigation (Mitchell and Cambon, 1969; Tibbling, 1969), it seems likely that these failed because of difficulty in maintaining alertness. It is also likely that a lack of arousal was responsible for some reports suggesting that the fast phase of the response is absent in this group (Jongkees and Gasthuis, 1973), especially since it has been suggested that the sensitivity of the fast phase is directly related to the degree of attentiveness (Ron,Robinson and Skavenski,1972).

It is also clear that prematurity may alter the response. Although one group have demonstrated nystagmus in premature neonates (Pendelton and Paine, 1961), this finding has certainly not been repeated by other investigators. Two studies have examined cohorts of infants at varying gestational ages (small, appropriate and large for gestational age and premature). Although optic fixation was only abolished by blindfold, one study reported response rates as high as 83% (torsion swing) and 69%

(ice cold caloric) at between ten to seventy five days post partum in the group appropriate for gestational age (AGA), but these rates fell to 24% and 26% respectively in the group which were small for dates (SGA) and the premature group showed completely absent responses (Eviatar,Eviatar and Naray,1974). In all cases the results improved when the children were re-tested at between four and nine months post partum. Similar results were reported when the post rotatory response to an abrupt deceleration was examined in full term AGA and SGA infants between forty two and forty nine weeks post conceptual age (Rossi, Pignataro, Nino, Gaini, Sambataro and Oldini, 1979).

It therefore seems certain that vestibular reactivity can be confirmed in the neonate provided that care is taken to ensure that the conditions pertaining during testing are strictly controlled, and provided that parturition has been uneventful and the child is of appropriate gestational age.

iii) Vestibular responses in the first two years of life

When studies are undertaken in children within their first two years of life new problems emerge, for it is more difficult to obtain and maintain the attention and co-operation of one and two year old children.

Many studies of the vestibular system in this age group are performed with observations of eye movement made whilst the examiner rotates holding the child in his or her outstretched arms. One early study using this method reported sustained deviations of the eyes up to four months of age after which slow ocular oscillations were apparent:these were superseded at the age of seven months by smaller more rapid ocular movements which probably reflected the fast phase of a nystagmus response (McGraw, 1941). More recent reports include a study which examined eye movements during and following rotation in alert infants subjected to two complete rotations in ten seconds (Silverstein, 1965). Ten to eighteen nystagmus beats were recorded during rotation in all infants, even though post rotatory nystagmus was

observed only in children up to the age of five months. This contrasts with other work in which up to thirty seconds of post-rotatory nystagmus was recorded in infants aged six to nine months when rotated for one minute at either 30, 50 or 100 degrees/second (Kantner, Clark, Allen and Chase, 1976). Again the recording conditions utilised were not uniform. In the former study observations were made with no control of optic fixation (although some infants were later restudied with the use of Frenzel's glasses), and in the later paper optic fixation was abolished by the use of Frenzel glasses but no record was made of attempts to control alertness.

Unfortunately further work using a more constant and reproducible stimulus and a more reliable recording technique has not always helped to advance knowledge a great deal. For example, the nystagmus characteristics in this age group have been recorded using electronystagmography with the infants blindfolded and alert and in response to both caloric and torsion swing chair stimuli (Eviatar and Eviatar, 1979). The results using the chair showed no relationship between frequency and age, but both the amplitude and the slow phase velocity of the nystagmus increased from birth to six months and then remained stable until twenty four months. Using caloric stimulation the latency of the response decreased until the age of six months and the frequency, amplitude and slow phase velocity all increased from birth until nine months of age.

These results are at variance with the work of Aust and Goebel who in two separate papers recorded nystagmus patterns using an electromechanically controlled rotating chair (Goebel and Aust, 1978; Aust and Goebel, 1979). Nystagmus in response to acceleration and rotation at a constant speed (per-rotatory nystagmus) and abrupt deceleration (post-rotatory nystagmus) showed an increasing beat frequency during the per-rotatory period up to seven months of age but no changes in frequency during the post rotatory period. On the other hand amplitude increased in both phases from birth to seven months of age, although thereafter there were no measurable changes in either stimulus period.

The most recent work in this area has used a remotely controlled chair with a stimulus consisting of a period of linear acceleration followed by rotation at constant velocity in complete darkness (Ornitz, Kaplan and Westlake, 1985). Mental alerting was used and the EEG monitored to assess drowsiness. Nystagmus was measured using electronystagmography. This paper is discussed in more detail in a later part of this chapter, but it was of interest for it showed that the duration of the primary nystagmus is significantly lower in children aged between two and four months when compared to those aged twenty two to eighty four months. In addition the overall response shows a reduction in gain and increased time constants for the decay of the response with age.

The differences in these studies are impossible to explain accurately. As before the stimuli and recording techniques used are not uniform between laboratories. Clearly there are changes in the characteristics of the evoked nystagmus during the period from birth up to some point during the middle of the first year of life, but whether this is due to altered vigour of the vestibular apparatus per se or to changing central influences seems impossible to say.

iv) Studies of vestibular function limited to mid childhood

Post rotatory nystagmus has been measured in children aged between five and nine years and a mean duration of response of 19 ± 6.9 seconds observed (Ayres, 1975). A more recent report confirmed this figure, produced evidence of a high test-retest reliability and noted no diurnal variation in the results (Royeen, 1980). However both of these studies measured the response by visual inspection alone.

Similar studies with varying stimuli and recording techniques abound in the literature. One of these measured post-rotatory nystagmus in children aged between four and five years and supplemented visual observation of eye movement by the use of Frenzel's glasses (Steinberg and Rendle-Short, 1977). Again the stimulus was abrupt deceleration, and these authors recorded a mean duration of the post rotatory response

of 15. 6 seconds. Similar results were obtained when duration, number of beats and frequency of nystagmus were measured by electronystagmography (Ornitz, Brown, Mason and Putnam, 1974), but the results of this paper were also of interest as varying types of visual input during the period following deceleration were allowed. Rotation was in absolute darkness, but the subsequent recordings were made with or without fixation in the light as well as in darkness. The study reports that the frequency of the response was higher and the amplitude lower where conditions encouraged ocular fixation and, as might have been expected, the longest durations for the response were recorded in total darkness (22-26 seconds). In contrast the shortest response durations were in conditions which allowed both light and visual fixation, and intermediate responses were seen when fixation or light alone was allowed. Similar effects have been reported in adults (Levy, Proctor and Holzman, 1977).

v) Studies of vestibular function spanning the entire childhood years

a) Caloric stimulation

To date there have been three studies reporting changes in the vestibular response to caloric stimulation with age. Michishita (1967) used hot and cold water stimuli and measured the nystagmus duration, slow phase velocity and frequency in children aged from birth to fifteen years. The slow phase velocity was greatest during the first year of life, fell rapidly until the age of three years and then decreased more slowly until the age of fifteen. However the results for slow phase velocity were expressed in recording units and not in degrees per second and, as a result, the values obtained cannot be directly compared with other studies. During the same tests it was found that the duration of the nystagmus rose from an average of 300 seconds in the first year of life to 650 seconds between the ages of seven and nine. After this there was a gradual decrease towards adult values which were attained at between ten and fifteen years of age. Coincidentally the frequency of the response rose and fell. In this paper calculations for directional preponderance and canal paresis were also presented

and these showed that differences needed to exceed 35% and 25% respectively in order unequivocally to indicate disorder.

By contrast Peron used an air caloric and assessed eye movement using electronystagmography with recordings made in the light with Frenzel's glasses (Peron, 1980). He measured beat frequency and slow phase velocity in the thirty second period following the stimulus, and showed an increase in the velocity and frequency of the response with age. On the other hand some have demonstrated a decrease in latency, amplitude and maximum velocity with age (Kofanov, 1979), and there are, therefore, still some doubts as to the changes in the characteristics of this response with maturation.

b) Sinusoidal stimulation

There have also been three studies reporting the responses of children to sinusoidal stimulation. In one, infants under one year of age, children aged between one month and six years and mature adults were tested with a damped rotational test (Kaga, Suusuki, Marsh and Tanaka, 1981). The responses were recorded using electronystagmography, and it was found that the beat frequency and duration of the nystagmus both increased with age. In a similar study the threshold of the response to sinusoidal rotation was recorded in eighty children aged between six weeks and twelve years of age (Guerrier, Dejean, Basseres and Denise, 1970) but, although electronystagmography was used and attempts at mental alerting were made, no mention was made of the visual conditions in which the children were tested. This study found that the threshold declined from a value of 10 degrees/second in two month old infants to 4 degrees/second in five year olds, and also showed that there was a further decrease to 2 degrees/second by the age of twelve. These values are still high in contrast to the normal threshold in adults which is between 0.1 and 0.2 degrees/second; they are also contradicted by other work which has suggested a threshold of 0.23 degrees/second for five to ten year old children with a modest increase in adolescence and early adult life (Calseyde, Ampe and Depont, 1972).

c) Impulse and ramp acceleration

Several studies have used these stimuli to assess vestibular responses in children. In one nystagmus was measured in children in response to a stimulus comprising acceleration, movement at a constant velocity of 30 degrees/second for thirty seconds and abrupt deceleration. The duration, number of beats and maximum velocity were measured by electronystagmography (Michishita, 1967). The number of beats and nystagmus duration increased with age (40 seconds in the youngest subjects to 80 seconds in seven to nine year olds), and this was followed by a decrease to adult values (of 60 seconds) in ten to fourteen year olds. The maximum slow component velocity was highest in the very young infants and decreased rapidly until the age of two and thereafter more slowly up to fifteen years of age.

A similar study measuring nystagmus parameters in children in response to a short period of acceleration (66.7 degrees/second for 1.8 seconds) and a sustained period of movement at a constant velocity found that the fast and slow component velocities of the nystagmus and the amplitude of the response both decreased significantly with increasing age (Tibbling, 1969). At the same time the frequency of the nystagmus increased. The duration of the response was significantly reduced in the infants aged three to twelve months, and this was found to be the period in which the strongest nystagmus with the highest amplitudes and velocities occurred.

vi) The origins of the observed differences

Tibbling's arguments about the origins of these differences claim that the amplitude of the slow component should be seen as a centrally evoked parameter since it depends on interruption by the fast component which is a centrally induced saccade. She therefore concludes that the youngest children with the highest slow component velocities have the largest peripheral element to their response and the lowest central influence. At the same time she argues that the low nystagmus frequency seen in the youngest children must be a direct consequence of the high amplitude, since clearly it was impossible to attribute it to slow component velocity which was in any case

higher in the older children. However arguments against these conclusions were advanced in another study which measured the maturation sequences of primary and secondary nystagmus in children using ramp acceleration (10 degrees/second) followed by movement at a constant velocity of 180 degrees/second for three minutes (Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979). This study showed that the amplitude and slow and fast phase velocities of both primary and secondary nystagmus were largest in the youngest infants and reduced with age, and while the velocity of the secondary nystagmus was always less than the primary, the ratio of secondary nystagmus to primary nystagmus was considerably greater in infancy than in later childhood. These authors therefore argue that this suggests greater adaption (and greater central influence) in the very young with a reduction of this influence with maturation.

These papers are of importance for they highlight the difficulties experienced when attempts are made to extrapolate from observed phenomena. For example, the genesis of secondary nystagmus is not completely understood, but appears to be of central origin and to be responsible for modulating vestibular responsiveness; it is thus held to be a measure of vestibular adaption (Young and Oman, 1969; Malcolm and Melvill Jones, 1970; Sills, Honrubia and Baloh, 1978). The quantitative relationship between the slow phase velocities of primary and secondary nystagmus is thought to offer an assessment of vestibular adaption, with greater adaption resulting in relatively smaller primary and greater secondary nystagmus velocities (Malcolm and Melvill Jones, 1970). But here is no proof that this is so, any more than one can argue with conviction for or against Tibbling's conclusion.

Recent work in this field has continued to produce conclusions from measurements of phenomena which are not of proven origin. Thus much has been written about the gain and the time constants of response decay. These reports have shown decreasing gain (Herman, Maulucci and Stuyck, 1982; Yagi, Sekine and Shimizu, 1983; Ornitz, Kaplan and Westlake, 1985) and increasing time constants with age (Ornitz, Kaplan and Westlake, 1985).This later study measured gain and time constants of response

decay to a stimulus consisting of short period of acceleration followed by rotation at a constant velocity. The recording conditions were well controlled. The responses in infants (2-14 months), young children (22-84 months), older children (9-11 years) and adults were assessed, and the results showed that there was an overall decline in duration of response with a parallel reduction in gain and increase in the time constants with age. Whilst these results are of interest, the problem with them is that to argue the origin of the developmental effect from phenomena such as time constants and gain is spurious when the effector mechanisms concerned have not been positively identified. These authors argue that changing time constants implies altering activity in the brainstem reticular formation and that evolutionary changes in gain reflects altered activity of the vestibular nuclei. But we know that the vestibular nuclei are mature early in foetal life (Humphrey, 1965), and the arguments in favour of explaining the sites of origin of these phenomena are circumstantial. In addition, since decreased gain is normally associated with a decrease in time constants, these authors have had to argue that maturation involves dissociation of function with different rates of development for the vestibular nuclei and reticular formation. Such dissociation (with a decrease in gain and an increase in time constants) is apparently seen after medication with some drugs (Blair and Gavin, 1979), but to explain the maturation changes of the vestibulo-ocular reflex as the result of equal and opposite effects in contiguous brainstem neurones seems fundamentally unsound and begs the question as to why such closely allied structures would display such dichotomous maturation. Clearly these conclusions could well be erroneous. Indeed the authors acknowledge this and admit that these conclusions are "necessarily tentative".

vii) Conclusions

1. There is general agreement that the responses of the vestibular system exhibits maturational change and undergo modification throughout infancy and childhood and into the early adult years.

2. Many of the available studies have produced results which are in conflict one with another. In the majority of cases this is because the recording methods used have been poorly controlled. In addition comparisons are often difficult because differing stimuli have been employed.

3. Some authors have implied cause from effect. Thus conclusions have been drawn on the basis of analyzing secondary nystagmus patterns or other phenomena such as time constants and the gain of the response. Such conclusions may be valid but must be accepted with caution in the absence of a proper understanding of their origin.

B. VISUAL FUNCTION

Introduction

Previous reports have suggested that the development of the phylogenetically older vestibular system predates the visual system (Robinson, 1964). Unfortunately this conclusion is difficult to substantiate because, in contrast to the body of information which exists concerning vestibular maturation, the available knowledge of the development of the visual system is sparse. For instance, there is no longitudinal study available which compares saccadic eye movements at different ages and, although it is widely stated that most visual skills undergo considerable refinement in the post natal period, the exact rate of progression for individual movements is often disputed.

If other researches are considered then the importance of environmental stimulation in the development of visual motor responses becomes obvious. This is, as far as is known, in apparent contradistinction to the vestibular system. For example if central vision fails to develop then nystagmus commonly supervenes and when near vision is impossible due to hypermetropia convergence may be deficient. These examples show that the nervous system imprints learned visual responses on a background of

innate reactivity and demonstrates the degree of developmental delay which results when these responses are not correctly inaugurated.

i) Anatomy and acuity of the eye

In contrast with the vestibular system, all researchers agree that the eye is physically immature at birth. In the neonate the cornea is 80% and the eyeball 70% of the diameter of the adult, and these structures are still only 95% of the adult size at one and three years respectively (Duke-Elder and Cook, 1963). Differentiation of the fovea is not completed until four months of age, and myelination of the optic nerve is variable but is generally thought to be incomplete until the child is between seven months and two years of age (Magoon and Robb, 1981).

This immaturity is reflected in measurements of visual acuity in infants which is said to be the equivalent of 20/400 at birth and to improve to approximately 20/100 by the age of six months (Teller, 1974; Dobson and Teller, 1978). Other studies using visually evoked potentials have demonstrated acuity levels close to those of an adult by the age of six months (Greenwald, 1983), and these conclusions are also mirrored in the observed behavioral patterns of the neonate. These show that an infant will reach purposefully for small objects by the age of four months and will display accurate conjugate movements (implying an advanced development of visual function) by six months. Of course too much reliance cannot be placed on behavioral studies since a child may perform to a level required by the conceptual demands of a task rather than as a direct consequence of its visual content.

This fact was probably directly responsible for the erroneous assessments of visual function which were current before the 1970's (Parks, 1982) and, as with vestibular testing, it is probably true that these errors were compounded by inconsistencies due to inattention on the part of the test subjects. Whatever the explanation these conclusions are certainly in conflict with earlier estimates of acuity based on

graduated optokinetic stimuli which suggested that central vision is advanced at birth (Dayton, Jones, Aiu, Rawson, Steele and Rose, 1964).

ii) Fixation,convergence and conjugacy

The fixation reflex is present at birth (Hoyt, Nickel and Billson, 1982), but it has generally been assumed that it is feebly developed and that the eyes react poorly and only to a strong stimulus such as bright light. Nonetheless fixation responses are established early and are certainly well developed by the age of two months even when there is some initial immaturity.

By contrast it has been widely held that there is no evidence of convergence at birth. Such a response is not seen before the age of one month and, as was shown many years ago, is not well developed until the age of six months (Worth, 1903). Of course such movements are of importance in order to fixate objects which are of essential interest to the child, but even so it is probable that these are not clearly defined for him because of a lack of acuity and because of a lag in the accommodation response due to a delay in the development of the ciliary muscles. By the age of six months this response also starts to develop, and it seems likely that it matures quickly from this time.

With respect to conjugacy it seems accepted that the eyes of a healthy newborn infant are rarely aligned and conjugate and that, during the first few weeks of life, ocular movements will shift between orthoptropia (both eyes looking straight ahead) and esotropia (wall eyed) with the latter movement seeming to predominating (Hoyt, 1987). The anatomical and physiological mechanisms which are responsible and the exact frequency with which these movements occur has yet to be defined, but it is clear that these deviations are usually transient and that most neonates establish appropriate ocular alignment by the third to fourth post natal week.

iii) Pursuit movements

Some authors have claimed that ocular movements in the newborn are essentially random and non conjugate, and have suggested that there is no demonstrable ability to perform simple pursuit movements during the first few weeks of life (McGinnis, 1930). In spite of this other authors have reported that newly born infants are fully capable of following an isolated moving target. Certainly more recent reports of investigations performed in neonates born at term and aged between eight hours and ten days showed that most were capable of locating a moving target and maintaining fixation on it provided that they were fully awake and alert (Dayton, Jones, Aiu, Rawson, Steele and Rose, 1964).

Therefore it seems that pursuit is unstable in the neonate and that at this age pursuit movements are often interrupted by small saccades to correct retinal slippage. Such a reduction in pursuit capability has also been demonstrated in older children (Herman, 1982; Larsby,Thell,Moller and Odkvist,1988) who have been found to display low smooth pursuit gains and a resultant increase in saccadic intrusion, especially when stimulus predictability is reduced (Larsby, Thell, Moller and Odkvist, 1988).

This apart it seems agreed that by the age of five to six weeks a child will follow a light over a considerable range for a few seconds and, by the age of three months, will display a well developed following response (Greenwald, 1983). If this evidence is viewed in conjunction with the results of optokinetic testing outlined below then it seems possible that the neural centres concerned with whole field motion may mature slightly earlier than those which are concerned with pursuit of a discrete target on a stationary background.

iv) Saccadic movements

Recent researches have also investigated the maturation of the saccadic system. Movements of the eyes which are saccade-like are observed in sleeping and awake neonates and are even seen in blind infants, although it seems clear that the subsequent maturation of saccadic eye movements is delayed in such children. It is known that infant saccadic velocity is not as fast as that of an adult and that a typical saccade in an infant is hypometric and requires several subsequent minor adjustments to reach a target (Hainline, Turkel and Abramov, 1984). Here again the estimates in the literature may be at variance with the truth, for it is clear that the efficiency of saccadic movement depends to some extent on the interest aroused by the test object and hence the attention of the subject. In addition, since no longitudinal studies have been performed the point at which this response becomes adult-like is not known.

v) Optokinetic movements

Cortical optokinetic pathways and pursuit movements share the same physiological mechanisms so it is perhaps of little surprise to find that there is little argument concerning the neonates ability to generate the slow phase of this response (Dobson and Teller, 1978). Indeed such movements were reported many years ago as being present in the first days of life (McGinnis, 1930; Gorman, Cogan and Gellis, 1957).

As has already been inferred, there is only sparse and contradictory information concerning the evolution of the optokinetic response with age. Increasing reactivity in response to an optokinetic stimulus has been reported in one study (Stefansson and Imoto, 1986), whereas other studies have found a slight but insignificant negative correlation between age and eye velocity in response to such stimuli (Holm-Jensen, Skovgaard and Peitersen, 1981). In addition it is known that the performance of visual-ocular responses declines after the age of forty, and that the slow phase velocity of optokinetic nystagmus decreases at the rate of 11-12 degrees/second/ decade of life (Simons and Buttner, 1985; Magnusson and Pyykko, 1986). Symmetry

is not, however, thought to change with age (Magnusson, Pyykko and Norrving, 1986).

CONCLUSIONS

1. The eye and optic nerve mature anatomically in the post natal period. This is in contradistinction to the vestibular apparatus and nerve which are mature at birth.

2. Visual responses are relatively well developed at an early stage, albeit that they are showing maturational changes in the neonatal period. It seems likely that acuity, conjugacy, fixation and convergence are mature early in infant life. Although several reports have demonstrated immature pursuit during later childhood the rate of change, if any, in other observed parameters of visual-ocular control is largely unknown.

STATEMENT OF THE PROBLEM

The introductory chapters of this thesis have outlined past and present theories concerning the physiology of the vestibular and visual-ocular control systems and have presented a summary of our current knowledge of the development of ocular and vestibular response patterns during infancy and childhood.

From a preview of previous work it is apparent that:

1. Parameters of the vestibulo-ocular reflex change with age from infancy and through childhood to adult life.There is general agreement that the slow phase velocity decreases with age whether expressed as degrees/second or as a measurement of gain.But,while many papers have made mention of decreasing amplitude and increasing beat frequency with age, these parameters of the response have not been fully characterised in a large scale trial and the apparent dysrythmia of the childhood response has been ignored. In addition there is only a small volume of work which has utilised caloric irrigation as a vestibular stimulus and this has produced conflicting results. Since a caloric test is the most commonly available stimulus,it seems appropriate to use it to accumulate relevant data about the maturation of the vestibulo-ocular reflex.

2. With the possible exception of pursuit movements,there is a paucity of information concerning visual-ocular maturation in childhood.

3. Although some reports have suggested that it is enhanced in childhood,the effects of visual fixation upon the vestibular response has not been adequately characterised.In addition,the possibility that the widely quoted reduction in response duration might cause fixation to spuriously appear to be enhanced has not been investigated.

4. There are no studies available which have quantified visual-vestibular interaction in children by looking at possible maturation effects in measurements of optokinetic after-nystagmus (OKAN).

The present study therefore set out to investigate the following questions in children aged between five and fourteen years and to compare the responses to those obtained in adults.

1. What are the changes with maturation in the mean slow phase velocity,amplitude and frequency of caloric induced nystagmus in children aged between 5 and 14 years? (As a subsidiary the study looked at the effect of visual fixation upon the vestibulo-ocular reflex and measured the effect of such fixation at different ages).

2. Are there any parallel changes in pursuit movements?

3. Are there any parallel changes in saccadic movements?

4. Do optokinetic movements in response to foveal and full-field stimuli show any maturation changes?

5. Is it possible to record optokinetic after-nystagmus (OKAN) as a measure of visual-vestibular interaction,and does this show maturation change?

CHAPTER 4
STUDY DESIGN

Outline of the history and examination of the subjects included and the means used to test visual-ocular and vestibular function.

SUMMARY

In contrast to many large scale studies of physiological function in man it has to be made immediately clear that this work could contain little in the way of "control" tests. Clearly, since the purpose of the study was to elicit normal function, the patients could not be controlled in the commonly accepted sense. All that could be done to overcome this was to be exact in the criteria used for selection and to be scrupulous in verification of the results by applying test-retest criteria wherever this was possible.

This chapter outlines the criteria used for patient selection to the study. Some papers have asserted that vestibular and auditory impairments occur together and have selected patients on this basis (Bergenhuis, Perols and Lofqvist, 1988). However this is not invariably true and cochlear-vestibular dissociation is certainly possible. For this reason this study assumed vestibular function to be normal only when all other particulars (history, examination and audiology) led one to suspect that it would be so. It was considered that only in this way could a "normal" vestibular population be assured.

A. PATIENT SELECTION

Approval for the study was first sought and obtained from the Ethical Committee at the Royal Surrey County Hospital.

It was decided that equal cohorts of children between the ages of five and fourteen years should be evaluated;clearly subjects younger than this were unlikely to tolerate the rigors of the test procedures. It was also anticipated that each cohort would contain ten subjects. A total of one hundred normal children (ten cohorts of ten children) were therefore sought for inclusion. All these children were to be recruited from schools in the Guildford area, and a list of those schools who subsequently

agreed to participate is given in Appendix 1. In all instances the initial approach to the school was made through a letter of introduction sent to the Headmaster or Headmistress, and when such an approach resulted in a positive response, this was followed by a personal visit to explain the study design. Following this visit the parents of children in target age groups were circularised or approached by the school. In all instances written parental consent to inclusion in the study was obtained. This required a second personal visit to the school in order to explain the research to the parents.

It was obvious at the outset that criteria for acceptance into the study would have to be established. A questionnaire was therefore prepared which incorporated the main factors which are known to predispose to vestibular damage. Since many pathological processes which affect the inner ear and result in vestibular damage also cause a simultaneous hearing impairment, any child who gave a previous history compatible with a potential labyrinthine injury which had necessitated an assessment of the hearing was rejected even if, at the time of consideration for entry, there was no audiological evidence of residual damage. In effect this resulted in rejection of any child who had ever been referred for an opinion about their hearing unless the hearing loss had been subsequently proven to be due to secretory otitis media which had been successfully treated without recurrence. Since hearing loss is not, however, an invariable accompaniment of labyrinthine pathology, the entry criteria had also to exclude patients with disequilibrium in the absence of other aural symptoms. In this respect it was borne in mind that many children do not complain of vertigo or imbalance, either because they are too young to report such a symptom, or because they fail to realise that such a symptom is abnormal (Gates, 1980).

This assessment was combined with a clinical examination of all patients. The format of the questionnaire which was utilised for both history and examination is reproduced in Appendix 2. A detailed discussion of the rationale used in its preparation is given below.

1. HISTORY

The name, age (in months) and sex of the patient was first recorded. To this was added detail from the questionnaire as outlined below:

i) motor milestones

A simple assessment of motor milestones and balancing skills was made. It has been known for many years that lack of vestibular function in children is often asymptomatic due to enhanced compensatory processes (Dix, 1948), but it has been suggested that such a deficiency should be suspected in cases where there is inexplicable delay in acquisition of motor skills or where there is a history of spatial disorientation in the absence of visual clues eg. fear of the dark or of being blindfolded. For this reason the age at which the child sat and walked unaided was recorded together with the time at which he or she was able to accomplish relatively complex motor tasks such as using a bicycle without support. In addition the ability to participate in physical education at school was ascertained.

ii) infectious disease

Specific enquiry was made about a number of pre and post-natal infections which are known to hazard inner ear function. Nearly all the reports of labyrinthine damage as the result of these agents are concerned with the hearing sequelae, and it is not known in many instances whether these infections are also capable of selective damage to the vestibular apparatus. In this respect a compromise was necessary, for it would be clearly wrong to include a child who had suffered a severe infection with hearing loss and equally absurd, and indeed impractical, to exclude cases where there had been a subclinical or mild infection with no suspicion of labyrinthine damage.

The following account gives the known sequelae of the common viral exanthemas together with the policy which was adopted for patient selection based on these findings.

a) prenatal infection

Prenatal infection with herpes zoster may affect the ear and cause deafness, although specific reports as to incidence are not available (Veltri, Wilson, Sprinkle, Rodman and Kavesh, 1981). Similar infection with cytomegalovirus results in hearing loss in approximately 15% of cases and such a sensorineural loss can be progressive (Pappas, 1983). However, perhaps the most notorious sequelae result from inter-uterine infection with the rubella virus;this results in severe labyrinthine injury with a moderate to profound sensorineural deafness regardless of the stage of pregnancy at which the disease is contracted (Hardy, 1973). Cytomegalovirus infection in utero also results in labyrinthine damage and sensorineural deafness, and some have inferred that this agent is ten times more common than rubella as a cause of deafness in the newborn (Bergstrom, 1977).

In the light of this data all children born to mothers with a history of rubella during pregnancy were excluded. A similar total exclusion policy applied to children whose mothers had suffered with any of the known ototoxic viruses or who had a severe viral infection warranting a medical opinion during pregnancy, regardless of the subsequent hearing of the child. It was also decided that if the prenatal history was in anyway suspicious then the obstetric records were to be examined. In the absence of such records, or where any real doubt remained, the child was excluded.

b) postnatal infection

Post natal infection with the measles virus is suspected to cause deafness with cochlear and vestibular damage in 4-10% of those who have been exposed (Schuknecht, 1974). The insult is usually bilateral and severe. By contrast mumps often results in unilateral and mild sequelae, although some reports show that 5-25% of patients infected with this virus experience some degree of sensorineural impairment (Vuori, Lahikainen and Peltonen, 1962). Hearing loss may also accompany meningitis and, in those who survive such an infection, the risk of labyrinthine damage has been variously assessed as between 6 and 20-40% (Baldwin,

Sweiber and Freind, 1985). Acute otitis media may also cause permanent sequelae, and there is now evidence that the incidence of sensorineural deafness is 7-10% higher in individuals who have suffered this infection (Paparella, Morizono, Le, Mancini, Sipilla and Choo, 1984).

As has been already stated it would have been both undesirable and impractical to exclude cases where there had been mild or subclinical infection with any of the common viruses ie. mumps, measles, varicella zoster and cytomegalovirus. Mild cases were therefore retained, but if there had been any concern about the hearing at the time of infection the child was excluded, even if a subsequent audiological assessment showed there to be no damage. A similar policy was adopted with acute otitis media. By contrast patients with chronic otitis media were automatically excluded and, since meningitis is a relatively uncommon condition, it was considered safer to exclude any child with a past history suggestive of meningeal infection regardless of the present status of the hearing.

iii) head injury

Severe head injuries were another obvious exclusion and rejection from the study was extended to any child who might have suffered with a post concussional syndrome. This is thought to be more common in children than in their adult counterparts and results in vertigo (Eviatar and Eviatar, 1977).

Whiplash injuries were also relevant. In one series 43 out of 235 patients under the age of 25 years who had suffered such an injury experienced dizziness and vertigo (Toglia, Rosenberg and Ronis, 1970). Therefore exclusion was extended to all who had sustained such an injury.

iv) ototoxicity

The role of ototoxic drugs in vestibular damage in children has been investigated by a number of authors. Some reports have shown delayed head control in pre-term infants after treatment with aminoglycoside antibiotics (Eviatar and Eviatar, 1981) and, although nystagmus was an invariable accompaniment, such vestibular damage could be unilateral and was seen in the absence of hearing loss. In view of this a history of the use of such antibiotics prohibited entry to the study.

v) migraine

Both classical and basilar artery migraine are known to occur in children. Such cases normally have a strong family history of this condition (Watson and Steel, 1974; Eviatar and Eviatar, 1980; Busis, 1983). The presenting symptoms are protean but include vertigo, dizziness, vomiting attacks and periodic abdominal pain as well as headache. Vestibular involvement has been inferred by the report of caloric abnormalities in a proportion of children with basilar artery migraine (Eviatar and Eviatar, 1980) and, in view of this, no child with any one of the classical symptoms of migraine outlined above or with a strong positive family history was admitted to the study.

vi) kernicterus

Hyperbilirubinaemia is most commonly caused by Rhesus incompatibility, but other blood group anomalies and liver immaturity may also cause neonatal jaundice. When circulating bilirubin levels are high a bilirubin encephalopathy (kernicterus) results and, although the site of the lesion causing hearing loss is not known for certain, 20-40% of children so affected develop a sensorineural deafness. For this reason any child with a history of post natal icterus was excluded unless the affliction was obviously mild and self limiting.

vii) metabolic disease

The possibility of metabolic disease being a risk factor in the children entering this study seemed very remote. Congenital deafness with hypothyroidism (Pendred's Syndrome) and endemic hypothyroidism due to iodine deficiency have been shown to affect hearing in children and are presumed to disturb vestibular function (Yan-You and Shua-Hua, 1985). It was assumed that a history of such disorders would be clearly evident from the history.

Less obvious is hyperlipoprotinaemia Type 11 which can develop in infancy and be manifest by xanthomata and by an inner ear disorder which mimics Menieres disease (Pillsbury, 1981). Although non of these afflictions is known to cause vestibular dysfunction in isolation, a personal and family history was sought in each instance and in doubtful cases it was decided that blood samples would be taken.

Of more concern was the possibility that maternal diabetes was a risk factor which should result in exclusion but, since it has no proven role in the aetiology of congenital deafness (Fraser, 1976), this did not seem appropriate.

viii) seizures

Seizures with vertigo can occur as part of the aura of a grand mal fit, as vestibulogenic epilepsy or as vertiginous epilepsy (Behrman and Wyke, 1958; Alpers, 1960; de Jesus, 1980). Vestibulogenic epilepsy results in nystagmus since it originates in the brainstem reticular formation and is precipitated by vestibular stimulation. This contrasts with vertiginous epilepsy which is a variant of temporal lobe disease arising in the vestibular cortex and resulting in transient losses of consciousness and a postictal syndrome:there is no nystagmus. Because of this, and because of the possibility of epileptiform reactions from the caloric reaction, no child with a history of any type of seizure disorder was accepted into this study.

ix) birth history

Included among the perinatal risk factors known to cause labyrinthine damage are a number of conditions related to parturition. These have recently been redefined and include asphyxia requiring more than 10 minutes resuscitation and/or intensive care, very low birth weight and neonatal sepsis (Thiringer, Kankkunen, Liden and Niklasson, 1984). In all cases a detailed history of the birth of the child was obtained, and any history which suggested that a child might have been "at risk" in one of these categories was excluded.

x) family history

Any positive family history of early onset of sensorineural deafness in siblings and first degree relatives lead to exclusion.

xi) present history

A history was taken in every case to rule out recent otalgia or otorrhoea. In addition a history of apparent inattention or hearing difficulty at school was sought and specific enquiry made as to episodes of vertigo and tinnitus. A clear history of any of these symptoms acted as an exclusion.

No child was accepted who had a history suggesting previous perforation of the tympanic membrane since this would have raised questions as to the advisability of caloric irrigation. Children with a previous history of otalgia and hearing difficulty were included, but only if such disabilities appeared to have been caused by serous otitis media and to have resolved completely and without sequelae such as atelectasis, scarring or sclerosis.

2. CLINICAL EXAMINATION OF THE VISUAL-OCULAR AND VESTIBULAR SYSTEMS

i) tympanic membranes

Initial inspection was undertaken to ensure that there were no obvious abnormalities of the pinna. Minor deformities of contour or position (except for "bat ears") and abnormalities such as accessory ear tags served to exclude entry. Otoscopy was then undertaken (using a standard Welch-Allen otoscope) in order to ensure that the external meatus was not stenosed and to confirm that it had a normal contour and was free of wax. The tympanic membrane was also inspected and drum integrity and mobility assessed using an attached Siegle's speculum.

ii) audiological assessment

Simple tuning fork tests (Rinne and Weber tests) were performed in all cases using a 512 Hertz tuning fork. For performance of the Rinne test the routine clinical practice of comparing air conduction at the meatus and bone conduction at the mastoid process was utilised;for the Weber test the fork was placed on the upper lip. In all instances these simple tests were supplemented by a pure tone audiogram using a Peters AP6 audiometer which was recalibrated at three month intervals. In the event of doubt as to middle ear pressure or mobility of the tympanic membrane an impedance study, with assessment of the resultant tympanogram, was undertaken using an Amplivox Impedance Bridge Type 702. Measurements of acoustic reflex threshold were not undertaken.

iii) eye movements

Eye movements can be examined clinically by direct observation or by recording the nystagmus using electronystagmography.The methodology and use made of electronystagmography in this study are discussed below.

Before either test an assessment of the visual acuity was made and disparity in conjugacy tested. The eyes were examined at the outset for any limitation of gaze or convergence, and acuity was measured (with correction if necessary) using a Snellen chart at 12 feet distance. Convergence was assessed by moving an object in central gaze slowly towards the patients mid face, and the range of ocular movement by moving the object (a pen) in both horizontal and vertical planes. Conjugacy was assessed by using a simple patch test in which the patient was asked to fix on an object in central gaze while one or other eye was alternately covered; in this way any strabismus was revealed.

a) pursuit movements

Pursuit was clinically tested by asking the patient to look at an object held approximately 30 to 40 cms in front of the nose. The target was then moved slowly (less than 10 degrees/second) across the visual field in a horizontal and vertical plane and the smoothness of pursuit established. More formal examinations with ENG control were later undertaken using a rigid pendulum (vide infra).

b) saccadic movements

The commonly applied clinical method was used. The patient was asked to look rapidly between two objects held approximately 30 degrees to either side of the midline. For formal testing rapid movements between two fixed light sources was used (vide infra).

iv) gait and stance

Gait was assessed by asking the subject to walk between two points on a level floor with the eyes open and to then return to the start point with the eyes closed. Ten or so steps with heel-to-toe walking were then assessed again with the eyes open and closed.

Examinations of stance rely upon Romberg's test which was first developed for the assessment of posterior column dysfunction in tabes dorsalis (Romberg, 1846). The patient was asked to stand on a relatively small base by putting the feet together and then to maintain this posture with the eyes closed and the arms outstretched. This test was used in each case and was supplemented by introducing body movement by marching on the spot (Unterberger's test: Unterberger, 1938). This serves to unmask vestibular inequality since the subject tends to move towards the paretic side.

v) cerebellar testing

Simple tests for dysmetria and past pointing, asynergia and dysdiadochokinesia were performed. The subjects were asked to touch their nose and then the examiners outstretched index finger, to tap the back of each hand in turn with the other and to alternately pronate and supinate each hand.

B. ELECTRO-OCULOGRAPHY AND ELECTRO-NYSTAGMOGRAPHY

i) theoretical background

The following account gives something of the theoretical background to measurements and recording of eye movements as used in this study. This knowledge is based on previously well known and widely quoted research (Aschan, Bergstedt and Stahle, 1956).

There is a constant DC potential between the retina and cornea with the latter being positively charged with respect to the former. The source of the negative electrical charge of the retina is considered to be the pigment epithelium and is thought to result from active ion transport. The magnitude of the resultant difference is a function of the illumination of the eye, and a stable potential only occurs after an adaption period of twenty minutes. In this way the eye acts as a dipole with a

rotational axis which coincides with its optical axis. Electrodes placed around the orbit can measure this corneo-retinal potential, and eye movement towards an electrode causes it to become more positive whilst the contralateral electrode looses positivity. Movement thus causes a change in potential difference across the eye the magnitude of which is proportional to the sine of angular rotation. As nystagmoid movement involves relatively small angular excursions the effective relationship between eye movement and the resultant voltage change is virtually linear:voltage changes thus represent changes in eye position.

The change in corneo-retinal potential recorded from periorbital skin electrodes is approximately 40 microvolt per degree of angular deviation (McLay,Madigan and Omerod,1958). The recording instrument used consists of a preamplifier, amplifier and galvanometer which feeds an ink jet pen. Deflections of the pen are recorded on a paper strip which moves at a set speed and thus registers eye movements against time. Recording by means of AC amplifiers causes substantial amplitude loss the magnitude of which varies depending on the time constant of the machine used. With DC recording no amplitude loss occurs and pen deflection provides faithful reflection of eye position even during periods of sustained eye deviation (Hood, 1968). For this reason DC recordings are now widely regarded as being the best means of measuring the electronystagmogram.

ii) methodology used

In this study saucer shaped gold plated electrodes of 5 mm. diameter were used. The skin was first cleaned using acetone to ensure good electrode contact, and electrode jelly (Cambridge Instrument Company, Cambridge, England) used to fill the concave surface of the electrodes which were then attached to the skin using adhesive tape (Transpore, 3M Ltd.). Only horizontal eye movements were recorded and bitemporal electrode placement was therefore used in all cases:the leads were placed in a dependent position in order to minimise the possibility of movement and interference. The electrodes were attached to the skin 1cm from the outer canthi in line with the

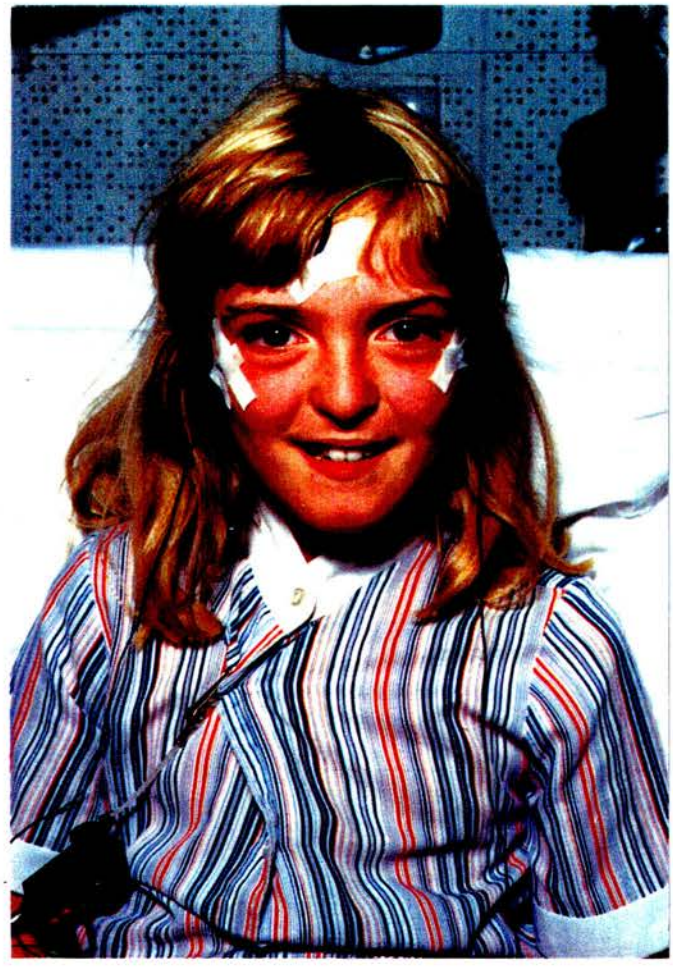
pupils, and a ground electrode placed in the centre of the forehead to minimise electrical interference from the recording apparatus (60 Hz). Figure 4. 1 shows the resultant electrode array and a large scale picture based on this figure was used during electrode placement to encourage acceptance of the test.

A twin channel ENG machine (Life-Tech 3002; Life-Tech, Houston, USA) was used to record eye movement (Figure 4. 2). Previous studies have shown that adventitious eye movements are common in the dark with both drift and saccadic movement liable to distort the traces obtained (Carpenter, 1977). Such movements are particularly common in children and are more readily distinguished if the DC recording mode is used (Snashall, 1983; Levens, 1988). For this reason the DC mode was used in all of the investigations performed in this study. A paper speed of 10 mm/second was used for all recordings with the exception of those made for the purposes of calibration:in this instance a speed of 5 mm/second was found to be satisfactory. In accordance with normal convention, movements of the eyes to the right were recorded by a vertical upward and to the left by vertical downward deflection.

The calibration used is referred to below. Drift was computed by repeated calibration between tests and was found to be negligible. It averaged 0.4 degrees/20 minutes (1. 2 degrees/hour), and was counteracted during tests by re-calibration in order to ensure recording accuracy. The speed of the paper used was also checked. Although it was set at 10 mm/second, this was periodically assessed by running a length of paper through the ENG machine for twenty seconds and recording the amount used/unit time. It was accurate at the stated speed and did not vary between tests.

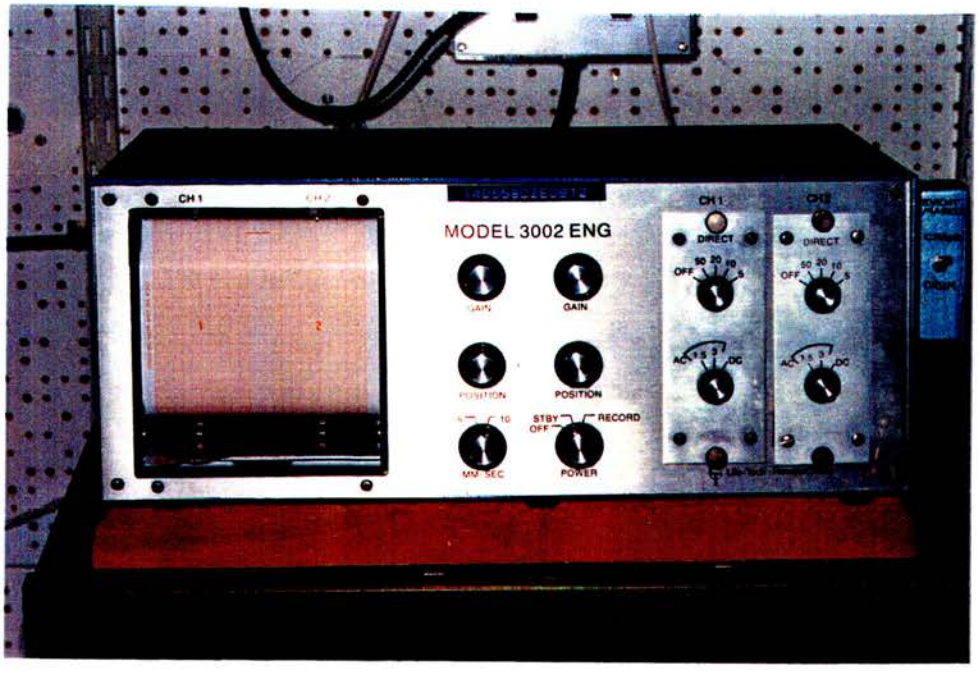
As with other studies, two main artefacts were encountered. These were due to electrical and bio-electrical phenomena. Inadequate electrode contact due to a loose electrode or loose connection between wire and electrode, insufficient electrode jelly or poorly cleansed skins caused artefacts with high frequency and uniform oscillations of the trace. Such an event was usually quite obvious but, in cases of doubt, could be readily identified using a skin resistance meter (EME Workshops, Guildford

Figure 4.1



Electrode display used for ENG recordings.

Figure 4.2



Electronystagmography machine

Hospitals). A loose ground electrode or close proximity of other electrical appliances produced a similar picture and were occasionally identified as the source of artefact. Bio-electrical events such as blinks were encountered but were readily recognised from the traces obtained. The high frequency spike activity which is said to be characteristic of muscle activity was not seen.

iii) calibration saccades

Calibration was performed with the child sitting supported on an examination couch and in a dimly lit room to minimise variation in corneo-retinal potential:a period of 20 minutes adaption to the ambient light was allowed before tests were started. Calibration angles of 30 degrees to right and left were used, and the gain adjusted such that 1mm. of pen deflection equalled 2 degrees of eye movement. In order to ensure accurate calibration five eye movements were recorded in each direction. Careful instructions to the child to hold the head still and move only the eyes were reinforced where necessary by a steadying hand on the head (Figure 4.3). This calibration was maintained throughout all recording with the exception of the caloric test, where it was altered such that 1 degree of eye movement corresponded to 1mm. of pen deflection.

C. THE ENG TEST BATTERY

Three main groups of tests were undertaken. All were performed in a dimly lit room. These were:

1. Tests of Pathological Nystagmus.
2. Tests of Visual-Ocular Control.
3. Caloric Irrigation with measurement of the Vestibulo-Ocular Reflex.

i) tests for pathological nystagmus

Testing for pathological nystagmus involved recordings from each child in the upright position with the eyes open, closed and open in the dark in both the primary position of gaze and with the eyes deviated 30 degrees to both right and left. Eye deviation with the eyes closed could be inferred from the electronystagmograph and was encouraged by a simple proprioceptive task. The child was asked to block out the light source with his or her thumb and to close the eyes whilst maintaining gaze down the outstretched limb (Figure 4.3). For tests performed in the dark an infra red viewer (Aural Aid Ltd; Figure 4.4) was found to be essential in order to avoid drifting of the eyes or excess head movement; such a viewer was therefore routinely employed in all tests.

Positional nystagmus was sought with the eyes closed and lying supine on the couch and in the right and left lateral positions. Each position was maintained for a minimum of twenty seconds. Artefact and excess eye movement was avoided by talking to the child and repetitively encouraging him to "look straight ahead" and to lie motionless throughout the recording.

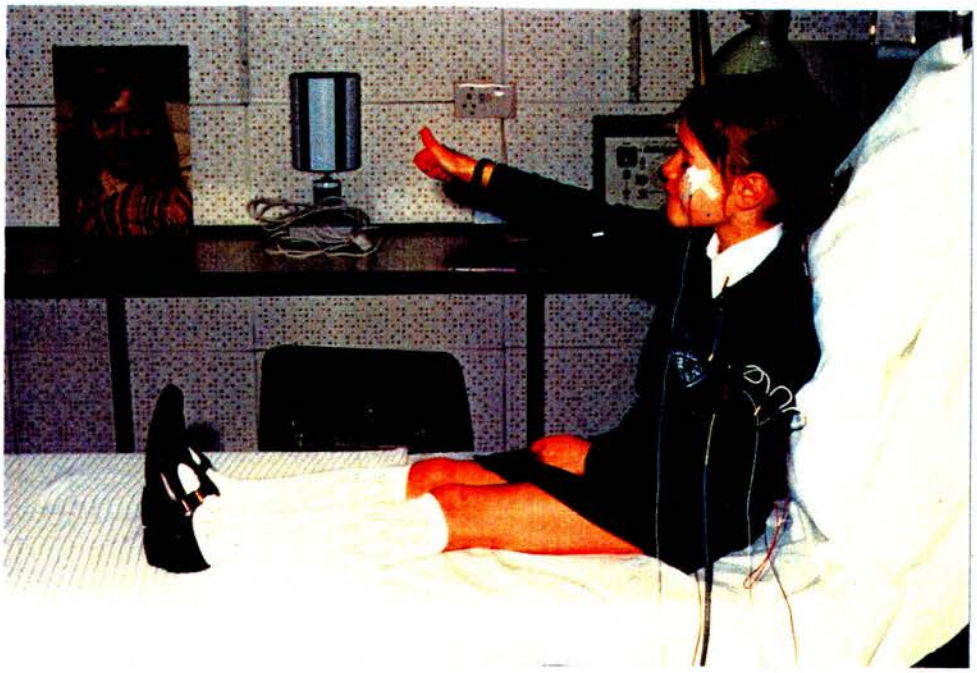
ii) tests of visual-ocular control

a) pursuit movements

Pursuit movements were tested by asking the child to track a rigid pendulum with an attached light source (Figure 4. 5). The point at which the distal end of the pendulum required to be moved in order to subtended an angle of 10 degrees from each side of the vertical was first ascertained and marked on the board behind the pendulum. All movements were recorded from this initial point.

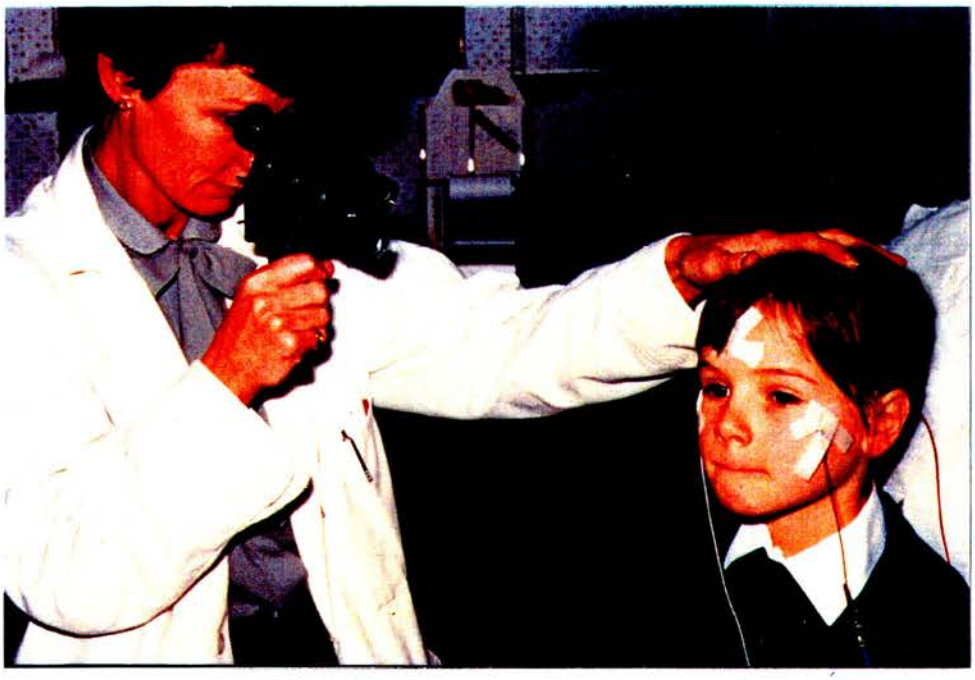
Accurate tracking during recording was encouraged by intermittently switching the pendulum light on and off in a random sequence and asking the child to report these changes. Such variability of the light source has been demonstrated to improve

Figure 4.3



Proprioceptive task used to ensure ocular deviation during recordings of gaze nystagmus.

Figure 4.4



Tests being performed using the infra red viewer.

attention for recording of pursuit movements in hyperactive children (Bala, Cohen, Norris, Gittleman and Kates, 1981), and the necessity of such a manoeuvre was readily apparent from preliminary tests performed in normal children (Figure 4.6).

b) saccadic movements

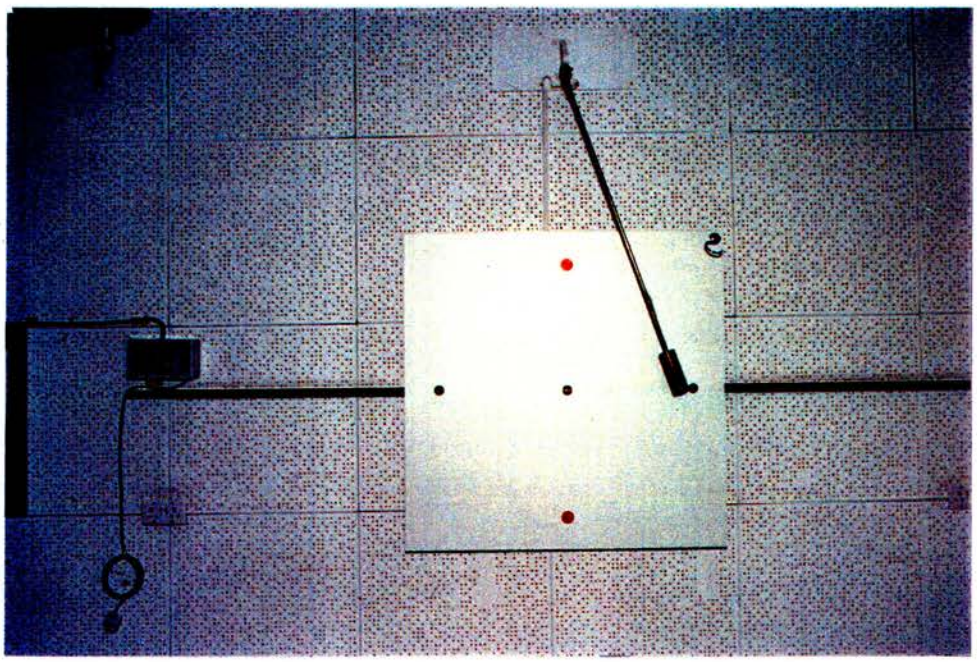
Saccadic movements were tested by asking the child to rapidly adjust and alternate gaze between a white light in central gaze and a yellow light subtending an angle of 10 degrees to the right in the same horizontal plane. After five such alternate movements the test was repeated with an exactly similar light at an angle of 10 degrees to the left. In a similar way, but with a different coloured light (red), saccadic movements were tested to a target subtending an angle of 30 degrees to the right and left of central gaze.

c) optokinetic movements

Two forms of optokinetic test (OKN) were used. Foveal stimulation was provided using a small drum of alternating black and white stripes (Figure 4. 7) held 40 cm. in front of the child and rotated in turn to the right and left for a minimum period of twenty seconds in each direction and at a speed of 132 degrees/second (22 r.p.m.). The drum was held in a vertical plane such that horizontal eye movements were recorded:vertical eye movements were not assessed. Speed of movement in each direction was checked between tests and no significant variation observed. As before a steadying hand on the head was found to be a useful adjunct, especially in young subjects who tended to move their heads in response to the stimulus. The child was instructed to "look the stripes", and it was found that this sort of constant verbal encouragement was necessary in order to prevent inattention and to ensure a satisfactory nystagmus pattern.

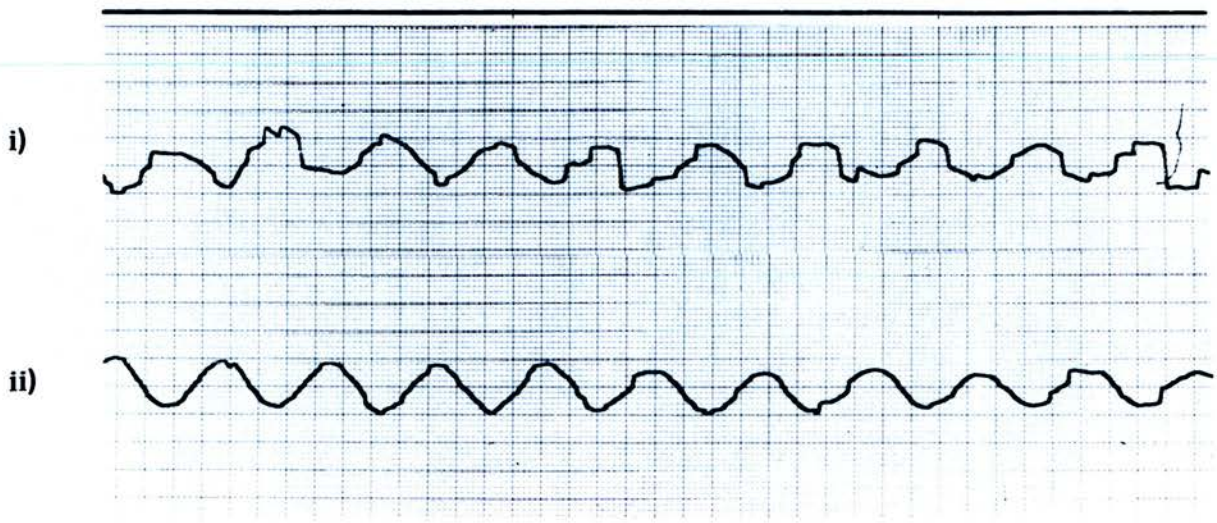
Nystagmus was also induced by a full field stimulus using a large drum with a diameter of 1.5 metres. This consisted of a curtain of animal print which was lowered around the child (Figure 4.8) and rotated at a constant speed to right or left. The child was encouraged actively to watch an animal (a ladybird) recurring at eye level; in this

Figure 4.5



Rigid pendulum used for tracking tests.

Figure 4.6



Traces obtained from nine year old in response to pendular tracking:

i) without intermittent light source

ii) with intermittent light source.

Figure 4.7

Small Drum used for Optokinetic Testing.

Figure 4.8

Large Drum used for Optokinetic Testing.

way an active pursuit response was encouraged. Again a minimum period of 20 seconds recording was achieved in each direction and, at the end of this time, the lights were switched off and after nystagmus (OKAN) sought and measured.

Because of possible variations in speed of rotation between tests each complete 360 degree rotation of the drum was recorded on the second channel of the ENG trace through a contact electrode at the top of the drum. In this way the actual speed of rotation could be calculated and measurements of the induced nystagmus corrected back to the notational or "ideal" speed. The validity of this correction technique had first to be assessed, and for this a group of 10 children and 5 adults whose ages were representative were tested from within the main study group (see Chapter 6).

With both forms of optokinetic stimulus the response was assessed by measurement of average slow phase velocity, amplitude and beat frequency in a representative part of the recording over at least a 15 second period.

iii) caloric irrigation with measurement of the vestibulo-ocular reflex

a) theoretical background

The bithermal caloric test has been the mainstay of vestibular investigation for the last thirty years. Thornval (Thornval,1917) was the first to report the use of this test in a clinical context and his methodology was later taken up by Fitzgerald and Hallpike who quantified the response and introduced the concepts of canal paresis and directional preponderance (Fitzgerald and Hallpike, 1942).The basic methods which these authors advocated has changed little in the intervening years. They described irrigation of each ear twice with water at 7 degrees above and below body temperature (ie. at 30 and 44 degrees Centigrade) in order to provide an equal and opposite labyrinthine stimulus,and measured the duration of the induced second degree nystagmus which resulted in the light.However,many workers now prefer to measure the duration of the response in the dark and light in order to establish a

fixation index, even though to do this requires either an infra red viewer or electronystagmography.

b) normal responses

The exact methodology varies between laboratories but in most cases water is irrigated into the ear over a period of 30 seconds. The response begins after approximately 20 seconds and reaches a peak after a further 40 seconds ie. by the end of the first minute. The nystagmus thereafter declines slowly and in most adults it will have disappeared after 3 minutes (Barber and Stockwell, 1980). Cool irrigation produces nystagmus with a fast phase away from the test ear; the converse is true for warm water.

c) canal paresis

To quantify a unilateral weakness the formula developed by Jongkees and Philipszoon is commonly used (Jongkees and Philipszoon, 1964). This defines a canal paresis as:

$$\frac{(RW+RC)-(LW+LC)x100}{RW+RC+LW+LC}$$

where RW, RC, LW, and LC are the peak slow phase velocities for responses to right warm, right cool, left warm and left cool irrigations respectively. In adults the widely quoted normal ranges for these parameters are 20-25% (Barber and Stockwell, 1980).

d) directional preponderance

Some patients have a directional bias with their response patterns. Thus, for example, right beating nystagmus may be greater than left beating. For this reason it is necessary to perform two irrigations to each ear. If this is not done preponderance cannot be calculated. The preponderance is also calculated on the basis of a formula derived by Jongkees and Philipszoon (1964). This is:

$$\frac{(RW+LC)-(LW+RC)x100}{RW+LC+LW+RC}$$

An upper limit of normal of 30% is widely accepted (Barber and Stockwell, 1980).

e) variability of response

With measurements of slow phase velocity large inter-individual variations in the results achieved from testing the vestibulo-ocular response have been reported (Baloh and Honrubia, 1979; Proctor and Glackin, 1985). These findings are true inter-individual differences and appear to be stable as tests are repeated. The possibility of this variation being due to a large number of variables including dimension of external meatus, subject height, race and diurnal variation has been investigated (Proctor and Glackin, 1985), but these authors concluded that the differences are most likely due to psychophysical variation.

iv) methodology employed

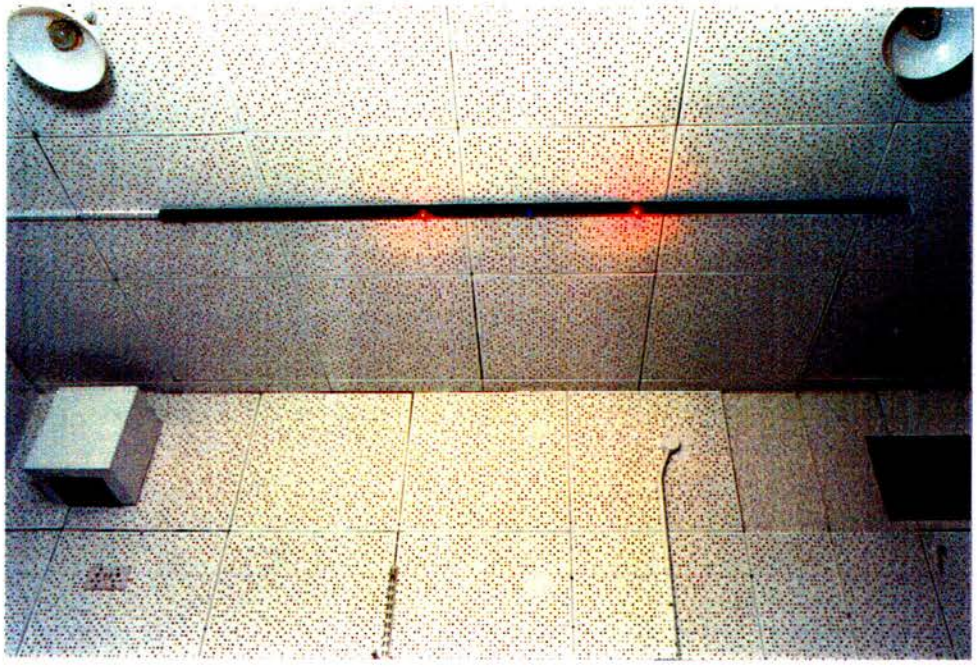
In this study sterile distilled water (Travenol Products, Thetford, Norfolk) was used to fill two Caloric irrigation tanks (Linco Industries Ltd. ; Figure 4. 9) which were used for the irrigations at 44 and 30 degrees Centigrade. This water was constantly circulated for a period of not less than thirty minutes to ensure that adequate heating or cooling had taken place and that no temperature gradient remained. Routine calibration of the thermostat and heating coils was undertaken every four months during the time of the study, and the temperature of the water checked during tests using a simple mercury thermometer. No gradient to the tip of the irrigation cannula was apparent when the water issuing from the cannula tip was tested.

Before the irrigations started the child was placed supine on an examining couch in dim light and with the head raised thirty degrees in order to bring the horizontal canals into vertical orientation. Calibration saccades were then made to overhead

Figure 4.9

Caloric Tanks.

Figure 4.10



Calibration lighting for caloric irrigation.

Figure 7.8

Regressions of SPV/age for individual caloric irrigations. Warm water.

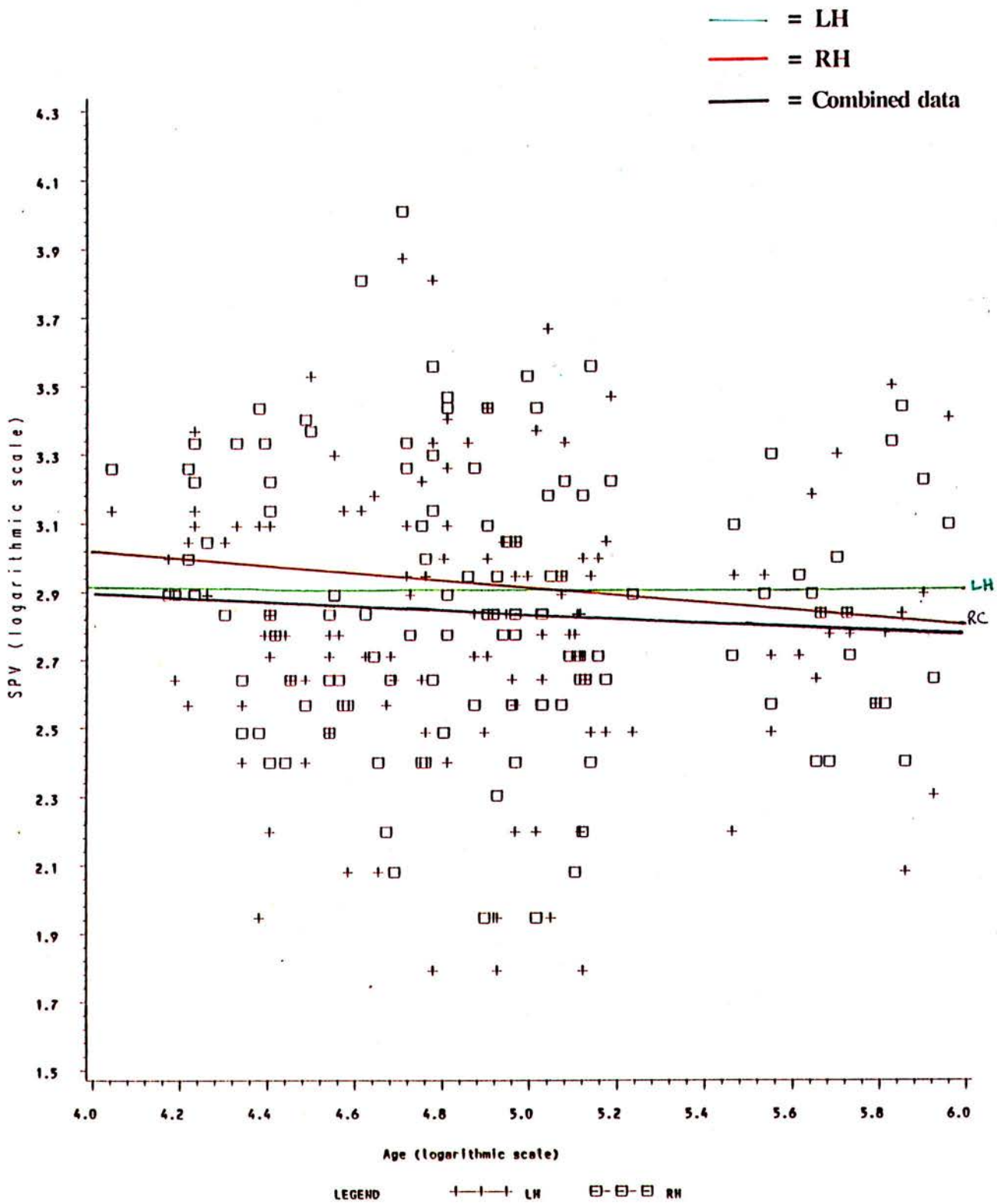
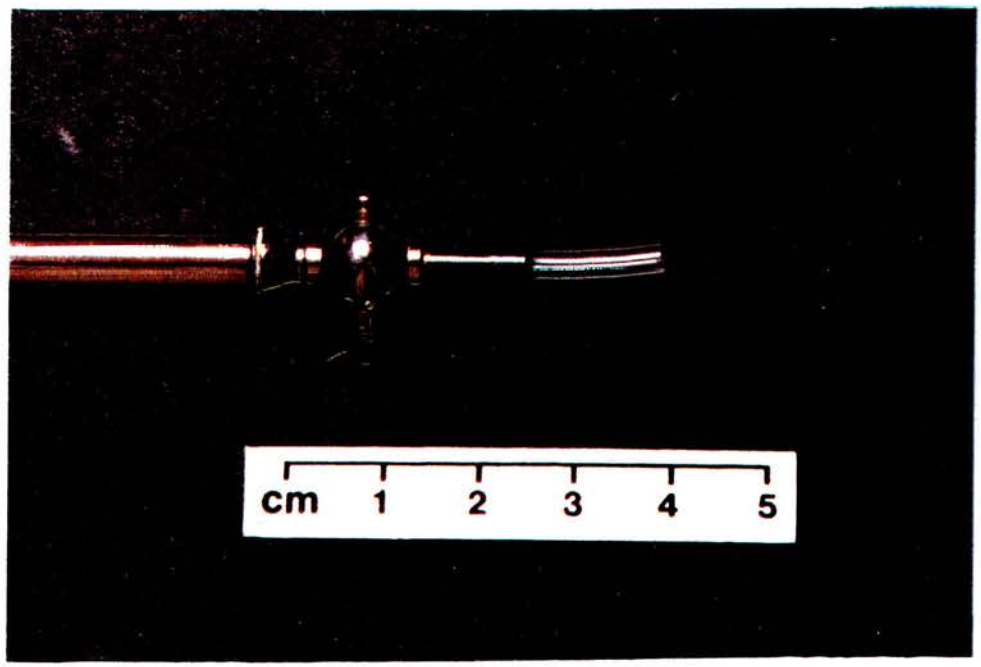


Figure 4.11



Irrigation cannula and disposable tip.

At ninety seconds dimmed overhead lights were switched on and an end point in the light sought and, if possible, recorded. The lights were then switched off again and an end point in the dark measured. In all instances the water used for irrigation was retained and its volume measured.

vi) calculation of response patterns

Measurements of eye movements in response to visual-ocular tasks and to caloric stimulation are tabulated at the end of Chapters 6 and 7. In each instance the response was assessed by calculation of the means obtained from measurements of a number of beats from each test.As a working rule a minimum of ten representative beats were measured from each of the traces obtained to obtain this data.

For pendular tracking tests the velocity of eye movement was calculated by drawing a tangential line on the trace to coincide with the maximum velocity of movement and computing velocity directly from the amplitude and duration of the response (velocity = measured amplitude/duration).As well as eye velocity,the frequency and velocity of the movement of the pendulum were also directly calculated from the trace and the gain then computed in each direction by comparison of the velocity of eye and pendular movement (eye velocity/target velocity). For optokinetic stimuli direct measurements were also made from the traces.Slow phase velocity was computed by direct calculation of the measured amplitude/duration in seconds of the slow phase of the response.The amplitude of the saccadic fast phase and the frequency of the response was also made directly from a representative section of the trace.

In the case of caloric stimulation the section from which measurements were made was always from the thirty second recording period outlined above ie.from the period 60-90 seconds after the start of irrigation.In this way the parameters which were derived were taken from the trace to coincide with the most vigorous part of the response pattern.For this test the tabulated values thus represent the means of several

individual nystagmus beats taken at the maximum point in the response sequence which thus coincides with the maximum slow phase velocity.

Such a method of recording and tabulating meaned figures in the presentation of the data appears to result, in many instances, in the normally accepted concordance between parameters being jeopardised. In individual measurements the relationship between velocity,amplitude and frequency (SPV = Amplitude x Frequency) is of course maintained but,as the result of beat to beat variation in the response and of the need to present results in individual cases as the tabulated mean of several recordings, this relationship may not always seem to be preserved.

CHAPTER 5

PATIENT ANALYSIS

An analysis of the patients included in the study and of those who were withdrawn or excluded.

SUMMARY

This chapter presents the accumulated data concerning the subjects who were included in the study together with the results of the clinical tests performed on these children.

It also discusses the subgroup of patients which was used for attaining test-retest data, and presents an analysis of those patients who were excluded from the study either on the basis of the history obtained or as a result of the clinical and audiometric tests performed.

INTRODUCTION

A total of one hundred and forty three subjects were recruited and considered for inclusion in the study. Of these twenty one were rejected after analysis of either the history or the clinical examination, and one child of six years failed to complete the examination and was withdrawn.

One hundred and twenty one individuals were therefore entered into the main study of vestibular and visual-ocular function; a statistical analysis of these subjects is presented here. Of equal importance are those who were excluded, and a description of these subjects is given separately towards the end of this chapter.

A. POPULATIONS INCLUDED

The total population for whom complete data was obtained consisted of one hundred children (46 males and 54 females) between the ages of five and fourteen years together with twenty one adults (11 male and 10 female) aged between twenty and thirty two years. All were Caucasian.

A computer based programme (Unistat; University Software, London, 1984) was employed to scan the age distributions of the patients included. The programme selected appropriate class intervals and lower bounds for the data with class intervals closed from below (including the lower limit) but open from above (excluding the upper limit).

The histograms of the ages of all the subjects included in the study are shown in Figure 5.1 and the relevant frequency distributions in Table 5.1. All data is in months post partum at the time of testing.As would be expected the data shows a bimodal distribution.When the data was compared by sex the skew for these two subgroups was comparable (male 1.335; female 1.272). In order to obtain the best straight line data fit,all subsequent regression analyses of the major data was performed with ages in months transformed to a natural logarithmic base ($\log_e$).

After acceptance into the study each subject was awarded a study number based on aged cohorts (e.g all nine children aged circa 5 years were arbitrarily given numbers from 1 to 9). This study number was used for subsequent identification of patients.

Figure 5.1a

Histograms of the patients included in the study (all patients)

a) Raw Data

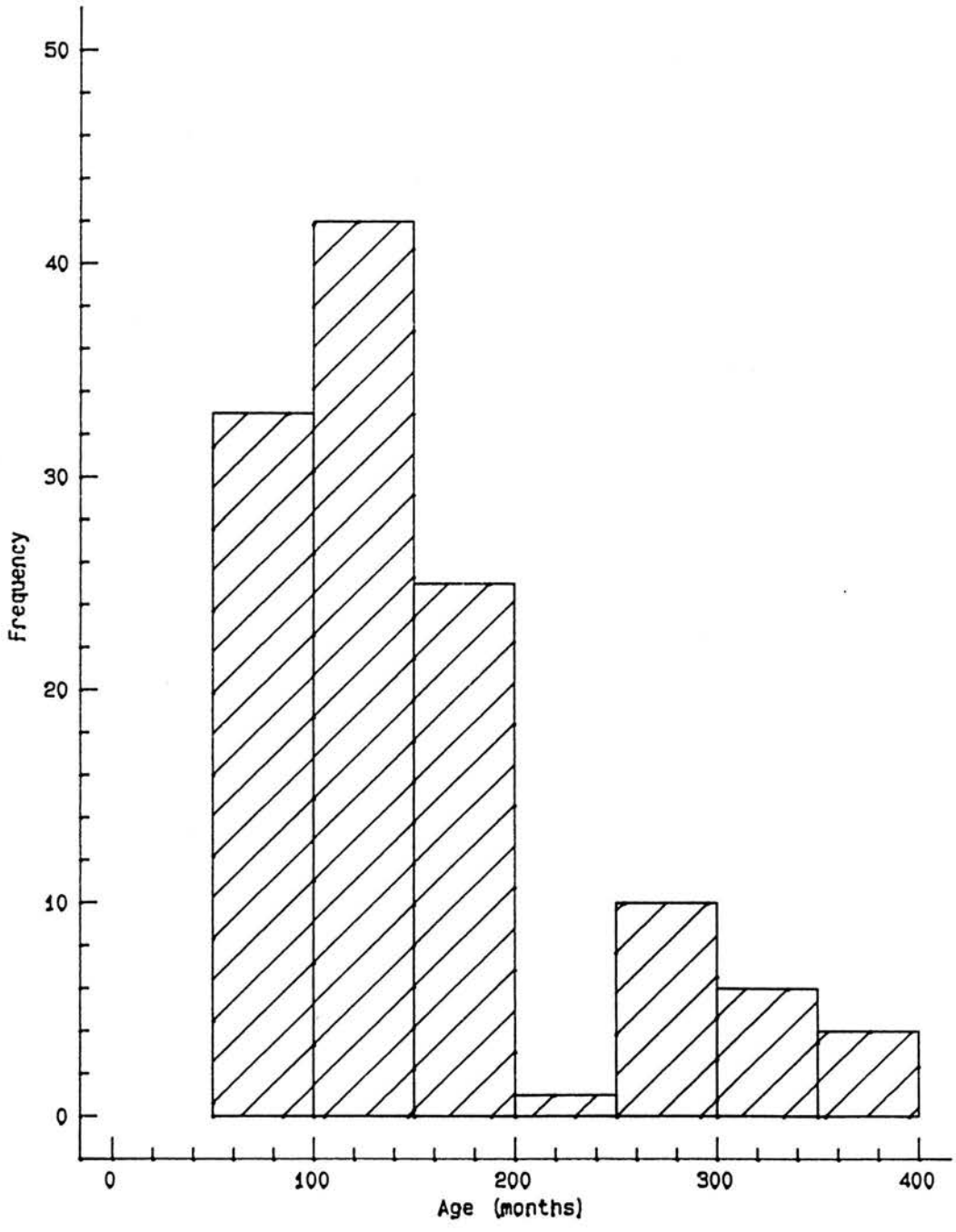
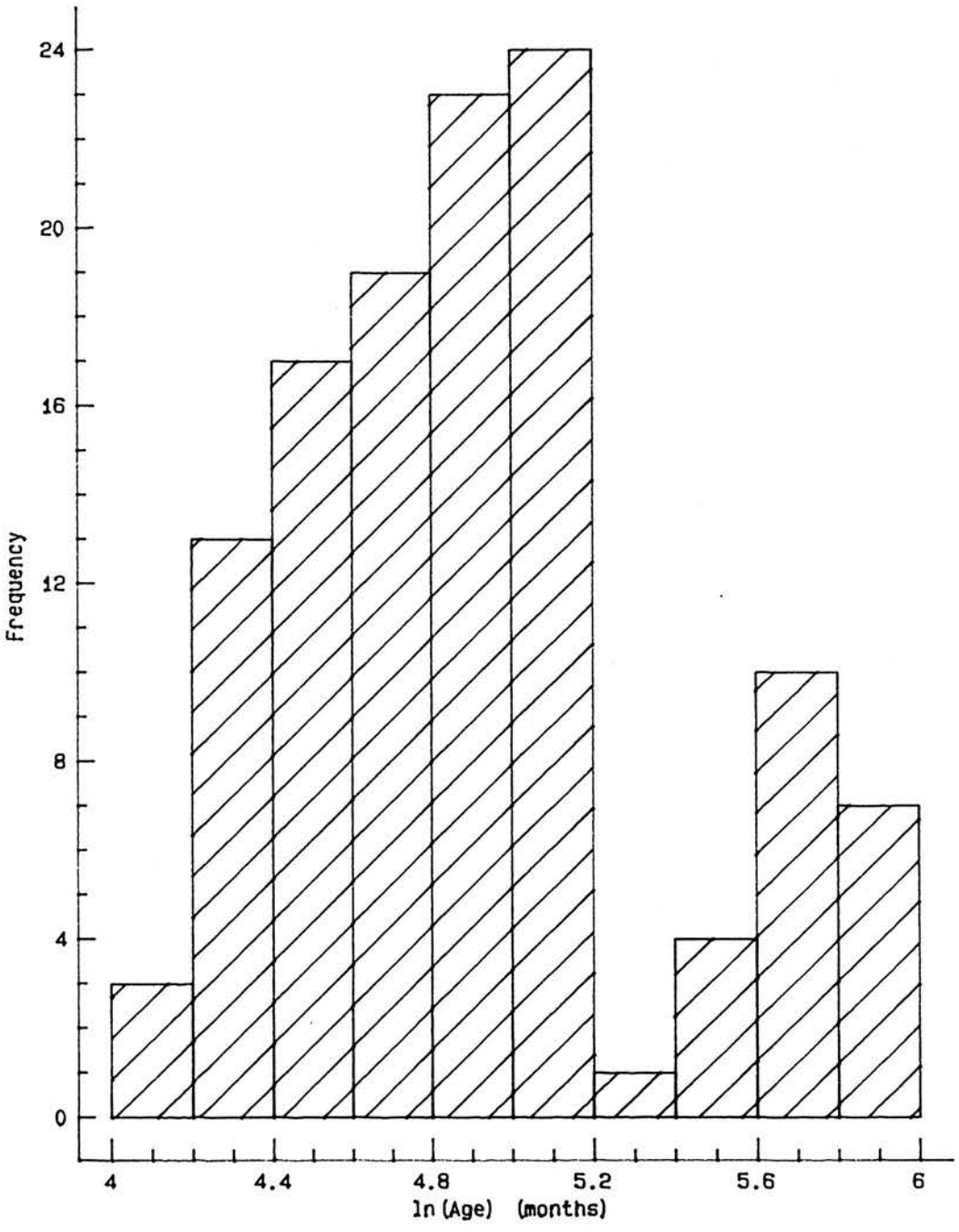


Figure 5.1b

Histograms of the patients included in the study (all patients)

b) Logged Data



i) History

The histories obtained from all of these subjects were based on the background information given in Chapter 4. Grouped data based on these histories is presented in tabular form in Tables 5.1 and 5.2. The first of these tables (Table 5.1) gives information concerning the birth of each patient and their subsequent neonatal development together with the ages at which major motor milestones were attained. Table 5.2 deals with previous infective diseases.

The remaining history was largely negative. In particular no patient had a personal history of migraine. Six subjects (patients 14, 23, 47, 65, 94 and 97) were said to have a first degree relative who had suffered with minor migraine type headaches but, on closer enquiry, through the patients' General Practitioner, a record of such illness was not substantiated. Certainly no treatment for migraine had, to the General Practitioner's knowledge, ever been required for the relatives of these individuals. These six subjects were therefore retained.

As far as the remaining history is concerned no patient had sustained significant trauma to the head. Some patients who had been mildly and very transiently icteric for up to 36 hours post partum were retained since this was clearly nothing other than minor physiological jaundice. No patients included had a history of ototoxic drug ingestion, and none had ever suffered with any sort of epileptic seizure. No patient included had a personal history of endocrine disease, and the only significant histories were of non insulin dependent diabetes and minor thyroid disorders in first degree relatives.

ii) Examination

No patient included in the study had any abnormality on clinical testing. In particular, all had normal visual acuity (if necessary with correction), and none displayed strabismus, nystagmus or clinical abnormalities of pursuit or saccadic eye movement. Gait, stance and Romberg and Unterberger's tests were normal in all subjects.

B. TEST-RETEST AND LARGE DRUM OPTOKINETIC TESTING

Sixteen children and eight adults who were included in the main study were re-examined in order to provide data as to the reproducibility of the tests undertaken. This subgroup consisted of 15 females and 9 males, and were patients numbered 3, 5, 13, 15, 24, 34, 46, 48, 52, 54, 74, 75, 76, 88, 99 and 100 (children) and 102, 115, 116, 117, 118, 119, 120 and 121 (adults).

Some of these same patients were also used to provide the data which was subsequently used for evolving regression equations to correct measurements made in response to stimulus variation when using the large Optokinetic drum. These were patients numbered 3, 5, 15, 46, 48, 54, 75, 88, 99, 100 (children) and 102, 112, 116, 119 and 121 (adults). A further discussion of this part of the test battery is given in Chapter 6.

C. ANALYSIS OF DATA

As has already been implied the data for each of the major tests undertaken was compared for maturation effect by regression analysis. Student's t test and Wilcoxon's signed rank test were also used, where appropriate, for some of the data comparisons. Test-retest data was compared in each instance by using Spearman's rank correlation coefficient (rho). The tests used are discussed in more detail in the relevant sections.

In all instances these analyses were made using a software package on a personal computer (Unistat; University Software, London, 1984: BBC B Computer).

D. PATIENTS EXCLUDED

i) History

The original approaches made to the schools submitting patients made it clear that a history of ear disease precluded entry to the study. As a result no patient with a positive personal or family history of ear disease came forward for consideration and no subject had to be excluded on these grounds.

Nine potential candidates to the study were excluded as a result of the history obtained. Three children were withdrawn as the result of events in the neonatal period. One had suffered hypoxia which had required assisted ventilation in a Special Care Baby Unit (SCBU) following a Caesarian section for placental insufficiency, and two further children were considered ineligible because of prematurity with either gross cyanosis at birth or apnoea requiring anaesthetic support with temporary intubation in the puerperium. In addition one child and two adults were excluded after giving a history of severe concussion requiring admission to hospital for observation, and a further child was ineligible because of a positive family and personal history of migraine requiring medication. One other child was excluded as she had been adopted and an accurate history of parturition was impossible, and one was ineligible as a result of having suffered from meningitis at the age of three years. No subject was excluded on the basis of developmental delay *per se*, and all had normal motor milestones.

ii) Examination

Five patients were excluded as the result of clinical neuro-otological testing. In one case this was due to an untreated and previously undocumented convergent strabismus, and another patient was found to have an unsuspected and mild unilateral high frequency sensorineural deafness. In the remaining three cases the subjects were excluded due to otoscopic evidence of serous otitis media which was confirmed on impedance bridge testing; in each case this had been symptomless.

iii) Pathological nystagmus

Seven patients were excluded as they appeared to exhibit either spontaneous or positional nystagmus. In one child a spontaneous nystagmus of 11 degrees/second was observed with the eyes open in the light and in the primary position of gaze and in three other cases transient nystagmus with slow phase velocities up to 8 degrees/second were found with the eyes closed and deviated thirty degrees to the right or left. In a further three cases positional nystagmus with a slow phase velocity of up to 8 degrees/second was recorded: in two cases this was apparent with the patient supine and in the remainder with the head in a lateral position. Although the limits for definition of pathological nystagmus are uncertain (Kenyon and Levens, 1987), for the purposes of this study these patients were unacceptable. Therefore no patient displaying any nystagmus during these recordings was included.

CONCLUSIONS

1. One hundred and forty three patients were initially considered for entry into the study.

2. One subject could not tolerate the test battery and was withdrawn.

3. Nine subjects were withdrawn as the result of the history obtained.

4. Five subjects were withdrawn as the result of clinical tests; the majority of these failed the screen provided by clinical examination of the ears or audiological testing.

5. Seven subjects were excluded as the result of finding spontaneous, gaze, or positional nystagmus on testing for pathological nystagmus.

6. A total of one hundred and twenty one patients satisfied the criteria for inclusion and completed the full test battery.

Table 5.1

Patient Number	Birth and Development			Milestones		
	Birth	Delivery	Puerperium	Sitting (months)	Walking (months)	Cycling (years)
1	Term	Cephalic	Normal	4	11	4
2	Term	Caesarian	Normal	5	13	3
3	Term	Cephalic	Normal	5	13	5
4	Term	Cephalic	Normal	6	11	3
5	Term (induced)	Cephalic	Normal	5	15	4
6	Term	Cephalic	Icterus (24hrs)	8	12	4
7	Term	Cephalic	Normal	5	13	4
8	Term	Cephalic	Normal	6	12	4
9	Term	Cephalic	Normal	6	12	5
10	Term	Cephalic	Icterus (24hrs)	8	14	3
11	Term	Cephalic	Icterus (36hrs)	6	11	5
12	Term	Cephalic	Normal	6	10	4
13	Term	Cephalic	Normal	5	12	5
14	Term (Caesarian)	Breech	Normal	6	12	4
15	Term	Cephalic	Normal	6	12	5
16	Term (Induced)	Cephalic	Normal	5	13	5
17	Term	Cephalic	Normal	6	14	6
18	2/52 pre term	Cephalic	Normal	5	13	6
19	Term	Cephalic	Normal	5	12	6
20	Term	Cephalic	Icterus (24hrs)	10	16	5
21	Term	Cephalic	Normal	4	10	6
22	Term	Cephalic	Icterus (36hrs)	4	9	3
23	Term	Cephalic	Normal	5	12	4
24	Term	Cephalic	Normal	6	18	6
25	Term	Cephalic	Normal	7	12	5

Table 5.1 (continued)

Patient Number	Birth and Development			Milestones		
	Birth	Delivery	Puerperium	Sitting (months)	Walking (months)	Cycling (years)
26	Term (Caesarian)	Cephalic	Normal	8	12	5
27	Term	Cephalic	Normal	5	13	3
28	Term	Cephalic (forceps)	Normal	7	12	4
29	Term	Cephalic	Normal	9	13	5
30	2/52 pre term	Cephalic	Icterus (24hrs)	5	12	4
31	Term	Cephalic	Normal	8	16	6
32	Term	Cephalic	Normal	4	10	4
33	Term	Cephalic	Icterus (36hrs)	7	14	4
34	Term	Cephalic	Normal	6	12	4
35	Term (Caesarian)	Cephalic	Normal	7	14	6
36	1/52 pre term	Cephalic	Normal	6	11	5
37	Term	Cephalic	Normal	5	12	6
38	Term	Cephalic	Normal	7	11	3
39	Term	Cephalic	Normal	7	12	5
40	Term	Cephalic	Icterus (48hrs)	4	13	4
41	Term	Cephalic	Icterus (48hrs)	5	18	5
42	Term	Cephalic	Normal	6	11	5
43	Term	Cephalic	Icterus (48hrs)	6	11	4
44	Term	Cephalic	Normal	6	15	8
45	Term	Cephalic	Normal	7	10	3
46	2/52 pre term	Cephalic	Normal	5	11	5
47	Term	Cephalic	Normal	5	9	4
48	Term	Cephalic	Normal	6	12	5
49	Term	Cephalic	Icterus (24hrs)	6	10	3

Table 5.1 (continued)

Patient Number	Birth and Development			Milestones		
	Birth	Delivery	Puerperium	Sitting (months)	Walking (months)	Cycling (years)
50	Term	Cephalic	Normal	5	12	5
51	Term	Cephalic	Normal	9	16	5
52	Term	Cephalic	Normal	5	10	4
53	Term	Cephalic	Normal	8	14	4
54	Term	Cephalic	Icterus (48hrs)	9	14	4
55	Term (Induced)	Cephalic	Normal	8	12	5
56	Term	Cephalic	Normal	9	17	7
57	Term	Cephalic	Normal	5	12	5
58	Term	Cephalic	Normal	6	13	5
59	Term	Cephalic	Icterus (24hrs)	6	10	5
60	Term	Cephalic	Normal	3	11	6
61	Term	Cephalic	Normal	8	13	5
62	Term	Cephalic	Normal	4	10	4
63	Term	Cephalic	Normal	6	11	4
64	2/52 pre term	Cephalic	Normal	6	13	3
65	Term	Cephalic	Icterus (24hrs)	7	12	4
66	2/52 pre term	Cephalic	Normal	3	8	3
67	Term	Cephalic	Normal	6	14	5
68	Term	Cephalic	Normal	5	12	5
69	Term	Cephalic	Normal	7	12	4
70	Term	Cephalic	Icterus (36hrs)	4	11	5
71	Term (Caesarian)	Breech	Normal	5	18	6
72	2/52 pre term	Cephalic	Icterus (72hrs)	7	12	5
73	Term	Cephalic	Normal	8	14	5
74	Term	Cephalic	Normal	6	12	5

Table 5.1 (continued)

Patient Number	Birth and Development			Milestones		
	Birth	Delivery	Puerperium	Sitting (months)	Walking (months)	Cycling (years)
75	2/52 post term	Cephalic	Normal	3	8	4
76	Term	Cephalic	Normal	3	10	6
77	Term	Cephalic	Normal	4	13	5
78	Term	Cephalic	Icterus (36hrs)	5	10	6
79	Term	Cephalic	Normal	6	11	5
80	Term	Cephalic	Normal	5	16	5
81	Term	Cephalic	Normal	7	20	4
82	Term	Cephalic	Normal	6	14	5
83	Term	Cephalic	Apnoea x1	5	11	6
84	Term	Cephalic	Normal	6	14	5
85	Term	Cephalic	Normal	5	10	3
86	Term	Cephalic	Normal	6	13	4
87	1/52 pre term	Cephalic	Normal	5	13	6
88	Term	Cephalic	Normal	9	11	5
89	Term	Cephalic	Normal	6	12	5
90	Term	Breech	Normal	9	12	6
91	Term	Cephalic	Normal	5	14	6
92	Term	Cephalic	Normal	6	11	7
93	Term	Cephalic	Icterus (24hrs)	6	18	4
94	Term	Cephalic	Icterus (72hrs)	5	12	4
95	Term (Caesarian)	Cephalic	Normal	3	11	6
96	2/52 post term	Cephalic	Normal	5	7	8
97	Term	Cephalic	Normal	6	14	7
98	Term (Caesarian)	Cephalic	Normal	3	9	4
99	Term	Cephalic	Normal	6	13	4

Table 5.1 (continued)

Patient Number	Birth and Development			Milestones		
	Birth	Delivery	Puerperium	Sitting (months)	Walking (months)	Cycling (years)
100	Term	Cephalic	Normal	5	13	5
101	Term	Cephalic	Normal	6	14	6
102	Term (Caesarian)	Cephalic	Normal	5	11	5
103	2/52 pre term	Cephalic	Normal	5	15	4
104	Term	Cephalic	Normal	6	13	4
105	Term	Cephalic	Normal	5	13	3
106	Term	Cephalic	Normal	5	11	4
107	Term	Cephalic	Normal	6	11	4
108	Term	Cephalic	Icterus (36hrs)	5	11	8
109	Term	Cephalic	Normal	6	11	5
110	Term	Cephalic	Normal	6	13	4
111	Term	Cephalic	Normal	8	13	5
112	Term (Caesarian)	Cephalic	Normal	5	13	4
113	Term	Cephalic	Normal	5	11	6
114	Term	Cephalic	Normal	5	15	4
115	Term (Caesarian)	Cephalic	Normal	6	8	4
116	Term	Cephalic	Apnoeic x 2	3	12	5
117	Term	Cephalic	Normal	4	13	4
118	Term	Cephalic	Normal	6	11	3
119	Term	Cephalic	Icterus (36hrs)	8	13	4
120	Term	Cephalic	Normal	5	13	3
121	Term	Cephalic	Normal	4	8	4

Table 5.2

History of Infectious Disease in each Subject Studied
(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
1	-	24	36	24	-	-	-
2	-	48	-	-	-	-	-
3	-	-	-	-	-	-	-
4	12	-	24	-	-	-	-
5	-	36	-	48	-	-	-
6	-	36	36	-	-	-	-
7	-	-	-	-	12	-	-
8	-	-	36	12	-	-	-
9	12	-	-	-	48	-	-
10	14	-	14	-	-	-	-
11	-	24	24	-	24	-	-
12	36	48	66	18	-	-	-
13	48	-	60	-	27	-	-
14	-	-	-	-	15	-	-
15	-	60	60	-	-	-	-
16	-	-	38	-	-	-	-
17	-	48	36	24	-	-	-
18	20	-	60	38	-	-	-
19	-	-	48	-	-	-	-
20	-	-	60	-	-	-	-
21	72	-	36	-	36+38	-	-
22	-	-	36	42	-	-	-
23	72	-	48	-	-	-	-
24	-	66	84	-	48	-	-

Table 5.2 (continued)

History of Infectious Disease in each Subject Studied

(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
25	-	-	18	-	60	-	-
26	18	-	48	-	-	-	-
27	-	-	-	-	-	-	-
28	-	-	48	60	-	-	-
29	-	-	-	-	-	-	-
30	-	-	72	-	-	-	-
31	-	-	36	60	-	-	-
32	84	-	36	-	-	-	-
33	60	0	36	-	-	-	-
34	72	24	24	36	-	-	-
35	24	-	24	30	-	-	-
36	-	84	72	-	-	-	-
37	-	-	36	-	-	-	-
38	-	-	36	-	-	-	-
39	-	-	36	48	-	-	-
40	-	-	72	94	-	-	-
41	72	60	72	-	-	-	-
42	-	-	60	-	-	-	-
43	-	-	5	-	-	-	-
44	-	-	12	-	-	-	-
45	-	36	72	-	-	-	-
46	-	36	24	-	-	-	-
47	72	36	72	-	-	-	-
48	-	-	12	-	-	-	-

Table 5.2 (continued)

History of Infectious Disease in each Subject Studied

(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
49	-	48	-	36	-	-	-
50	48	36	48	-	-	-	-
51	-	-	60	72	-	-	-
52	-	72	72	84	-	-	-
53	72	96	83	84	-	-	-
54	60	-	-	-	-	-	-
55	60	60	72	-	3	-	-
56	60	60	36	72	-	-	-
57	-	-	-	-	-	-	-
58	60	84	12	30	-	-	-
59	-	-	84	-	-	-	-
60	-	-	96	-	-	-	-
61	-	-	-	48	-	-	-
62	-	-	120	131	-	-	-
63	-	-	72	-	-	-	-
64	-	-	84	-	-	-	-
65	-	60	48	-	-	-	-
66	-	60	60	-	-	-	-
67	-	-	-	-	-	-	-
68	48	-	48	-	-	-	-
69	-	72	31	8	-	-	-
70	-	-	36	-	-	-	-
71	72	3	84	-	-	-	-
72	-	-	-	-	-	-	-

Table 5.2 (continued)

History of Infectious Disease in each Subject Studied

(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
73	-	48	-	60	-	-	Whooping Cough (78)
74	-	-	60	60	-	-	-
75	-	48	60	72	-	-	-
76	48	72	60	48	0	-	Scarlet Fever (80)
77	84	84	84	-	-	-	-
78	72	96	72	60	-	-	-
79	60	72	80	84	-	-	-
80	-	-	48	-	-	-	-
81	-	-	72	48	-	-	-
82	-	-	48	60	-	-	-
83	-	36	54	-	-	-	-
84	-	-	11	-	-	-	-
85	-	120	-	-	-	-	-
86	-	-	-	-	-	-	-
87	72	-	48	36	-	-	-
88	-	-	72	-	-	-	-
89	-	-	48	-	-	-	-
90	-	-	131	96	-	-	-
91	-	30	96	-	-	-	-
92	72	-	60	48	-	-	-
93	60	-	36	-	-	-	-
94	48	-	36	72	-	-	-

Table 5.2 (continued)

History of Infectious Disease in each Subject Studied
(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
95	72	72	72	-	-	-	-
96	96	96	-	-	-		-
97	48	36	48	48	-	-	-
98	24	-	36	48	-	-	-
99	-	-	-	24+48	-	-	-
100	48	72	36	-	-	-	-
101	60	96	72	-	-	-	-
102	48	36	24	48	36	-	-
103	48	72	24	24	-	-	-
104	-	-	48	-	120	-	-
105	36	60	24	-	-	-	-
106	-	-	-	-	-	-	-
107	-	-	36	-	-	-	-
108	36	48	24	-	-	-	-
109	48	36	76	24	-	-	-
110	48	36	72	-	-	-	-
111	-	-	-	-	36	-	-
112	48	36	48	36	-	-	T.B.(120)
113	36	24	24	-	-	-	-
114	36	24	48	-	-	-	-
115	48	36	48	-	-	-	Brucellosis (38)
116	36	24	36	36	-	-	Hepatitis (120)

Table 5.2 (continued)

History of Infectious Disease in each Subject Studied

(age in months post partum)

Patient Number	Measles	Mumps	Zoster	Rubella	Otitis Media	Meningitis	Other
117	-	24	2	-	-	-	-
118	48	-	36	36	-	-	-
119	48	24	36	48	-	-	-
120	48	-	48	60	-	-	Glandular Fever (192)
121	36	-	48	-	-	-	-

CHAPTER 6

RESULTS
VISUAL-OCULAR FUNCTION

The results of tests performed to assess visual-ocular control.

SUMMARY

The results of testing visual-ocular control in the 121 subjects included in the study are presented in this chapter. Each subject completed a series of tests specifically designed to test pursuit and saccadic movements as well as foveal and full field optokinetic reactions. These results are presented here together with the results of examinations undertaken to assess test-retest reliability.

Also included are the results obtained measuring optokinetic after-nystagmus and a comparison of the results of directional preponderance measurements obtained by testing small drum (foveal) and large drum (full field) optokinetic responses.

In order to ensure reproducibility of the stimulus used for pursuit and optokinetic testing the equipment used was tested on several occasions prior to starting the definitive examinations. The results of these tests are presented in the introductory section.

INTRODUCTION

The preliminary testing of the equipment used produced the following results.

i) Pendular tracking

The frequency of pendular movement approximated closely to 0.5 Hz and the peak velocity to 20.5 degrees/second; there was no decay in this movement during the time of the test. Variations in frequency and velocity of target movement were small and, since calibration stability was high, are presumed to result from minor discrepancies in pendular excursion at the outset of the test. Every precaution to give greater precision to the measurements was made, but the degree of pendular movement was obviously likely to show minor degrees of intra-test variation.

ii) Optokinetic testing: small drum

With small drum optokinetic testing the rotational speed in each direction was assessed at the outset of the tests by timing the number of "passes" made in one minute by a coloured strip of crayoned paper placed in parallel to one stripe of the drum. The results of this test, which was repeated on a number of occasions throughout the duration of the experiments, showed that the speed of drum rotation did not vary either between tests or in response to changes in direction of drum rotation. In both instances it was constant at 22 revolutions/minute (132 degrees/second). The responses to drum rotation to the left (nystagmus fast phase to the right) and to the right (nystagmus fast phase to the left) could therefore be tabulated for each child without correction of observed values for variation in stimulus velocity.

iii) Optokinetic testing: large drum

In a random series of experiments using the large drum performed prior to patient testing it became apparent that the velocity of large drum movement in each direction could vary between recordings. This was proved by measuring drum rotation on the second channel of the E. N. G. machine using an electrode attached to the top of the drum. Each 360 degree rotation was marked on the trace and, knowing the paper speed, the drum speed for each recording could be established. Variation was seen in spite of accurately setting the rheostat which controlled drum rotation, and the discrepancy seen and measured could be as great as 10 degrees/second.

Previous work in adults has shown that in clinical work, with intact foveate vision, eye velocity parallels stimulus velocity up to a speed of approximately 30 degrees/second. At speeds in excess of this the gain (eye velocity/stimulus velocity) starts to fall (Figure 6.1; Rudge, 1983). However it has also been suggested that a high stimulus velocity may reveal pathologies better than does a lower velocity (Jung and Kornhuber, 1964). The stimulus velocity for which this drum was routinely set was 72 degrees/second. From Figure 6.1 it can be seen that with normal vision at this velocity the gain has almost plateaued, and it therefore seemed likely that small

variations in drum speed would have resulted in only marginal changes in eye velocity. However it was clear that these results could not be simply accepted and applied uncritically to tests performed in childhood.

In addition, in order to characterise the response more fully, some recordings were to be made at a lower speed. For these tests a speed close to 45 degrees/second (7.5 r.p.m.) was chosen. Presumably small alterations in drum speed would then be liable to result in more marked changes in eye velocity. It was therefore necessary to establish the criteria by which all measurements at both speeds could be corrected.

There was a further problem with this test for it was apparent from reading the literature that there was no available data which correlated varying drum speed with the amplitude and frequency of the resultant response. It seemed clear that changes in stimulus speed were, within certain limits, likely to result in predictable changes in the velocity of eye movement. But the effects on the frequency and particularly on the amplitude (which is a centrally mediated saccade) are undocumented.

In order to try and overcome this problem preliminary experiments were undertaken in a group of ten children and five adults who were subjects included in the main study and whose ages were representative of the total population tested. The responses to a variety of stimulus velocities above and below 72 and 45 degrees/second were first measured (Tables 6.1 and 6.2) and the relationship between the relevant parameter and stimulus velocity was then explored by simple linear regression analysis. The results obtained are presented in greater detail in the relevant section.

RESULTS

A. PURSUIT

i) Maturation of response

Recordings of pendular tracking were made in every case. Knowing the speed of paper movement, the velocity and frequency of pendular movement could be calculated and, by measurement of the slope of the trace obtained by ocular pursuit, the peak velocity of eye movement to right and left assessed. A minimum of five eye movements in each direction were assessed, and the mean obtained. Hence the mean gain for each movement (eye velocity/target velocity) could be computed. The results are shown in Table 6.3 together with the patient study numbers and ages at the time of measurement.

It was immediately apparent that the correlation between eye movement and pendular movement was high ie. movements of the pendulum were accurately mirrored in movements of the eyes. This was confirmed by measurements of gain (which approximate to unity). It was also apparent that the velocity of pendular movement to the left was slightly in excess of movement to the right and this minor bias was confirmed both from the summated data given at the foot of Table 6.3 and from a simple regression analysis comparing gain to the right and left.The relevant scatter diagram for this regression together with the line of best fit is shown in Figure 6.0. As would be expected the correlation between the two movements is strong ($R2 = 0.9841$) and,although there is an undoubted bias to the left,this was clearly insignificant.This was also proved using a Student's t test for paired data the ($t = 1.511$ for velocity and 1.532 for gain; $p > 0.1$ for both movements).

Of course of principal importance was the need to establish or refute a maturation effect. In order to do this, linear regressions of the velocity and gain of eye

Figure 6.0

Pendular Tracking:

Regression comparing Gain of Movement to Left and Right

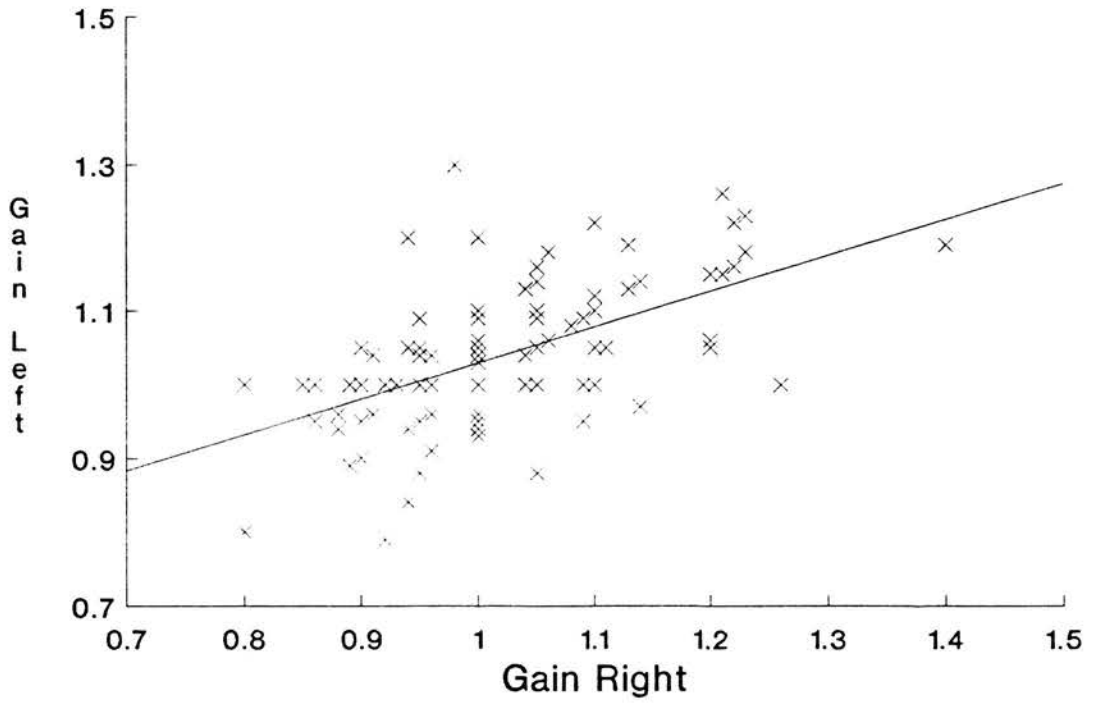
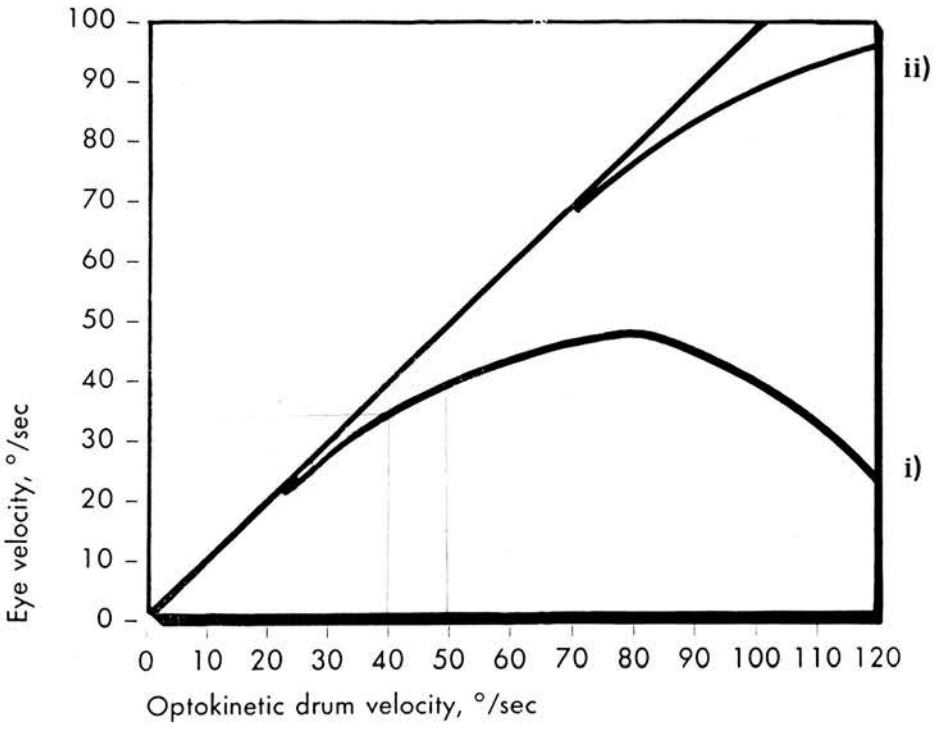


Figure 6.1



Relationship between slow phase velocity of ocular movement and drum velocity:

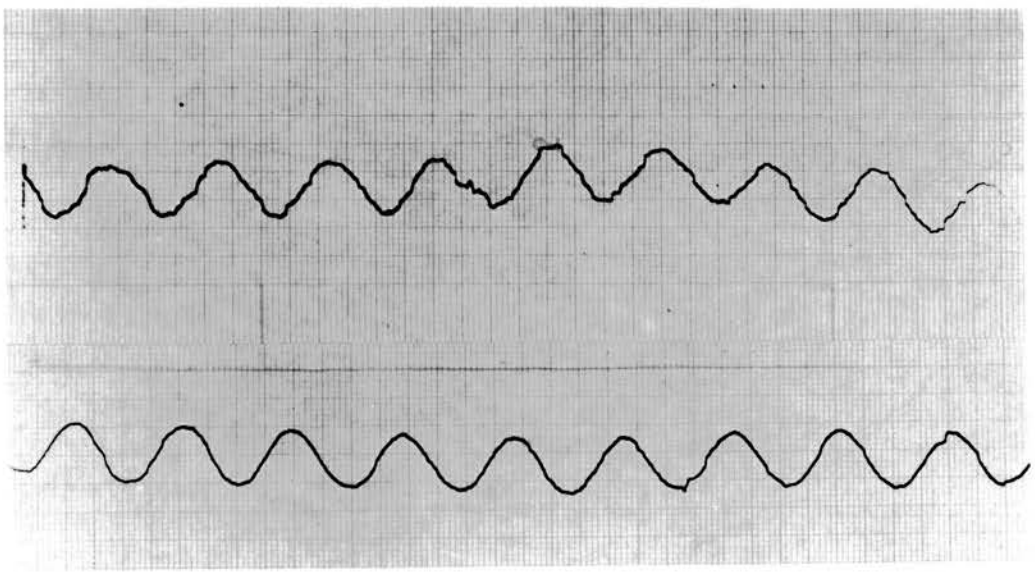
i) normal subjects

ii) patients with central scotoma

Figure 6.2

i)

ii)



Pendular Tracking in a child.

i) saccadic intrusion.

ii) normal smooth pursuit.

movements were performed against age as the independent variable.Regressions were performed with this variable in natural logarithms ($\log_e$). The results of these analyses are shown at the foot of Table 6.3. In each instance the square of the correlation coefficient (R_2) is close to 0 which confirms that the data is not related to age and that there is no maturation change in pursuit eye movements at this velocity.

Although there was no maturation effect from measuring velocity and gain of movement, there was a minor degree of bilateral saccadic intrusion evident when the youngest patients were tested (Figure 6.2). This finding is documented in Table 6.5. It was not apparent when testing older children or adults.

ii) Test-retest

All measurements were repeated in twenty four patients specified in Chapter 5 one month after their first visit and, using Spearman's correlation coefficient (rho), it is readily apparent that the gain and velocity of such movements show a high test-retest reliability (Table 6.4).

B. SACCADES

i) Maturation of response

Each patient was tested for movements to targets subtending angles of both ten and thirty degrees from central gaze. A tendency to both under and overshoot the target and then readjust was apparent in some patients (Figure 6.3). However, hypometria was always transient and rapidly disappeared with testing: it did no reappear when the same subject was retested. In contrast hypermetria was evident and persistent in some cases, especially in the youngest patients tested (Table 6.5). As with saccadic pursuit this feature was observed with diminishing frequency as age advanced. In addition hypermetria was more easily seen in tests requiring a larger ocular excursion to 30 degrees. This is at variance with previous researches which have suggested that

the normal range effect would predict undershoot (ie. a hypo rather than hypermetric movement) which would be less apparent with greater target distance (Kapoula, 1985).

C. OPTOKINETIC TESTING: SMALL DRUM

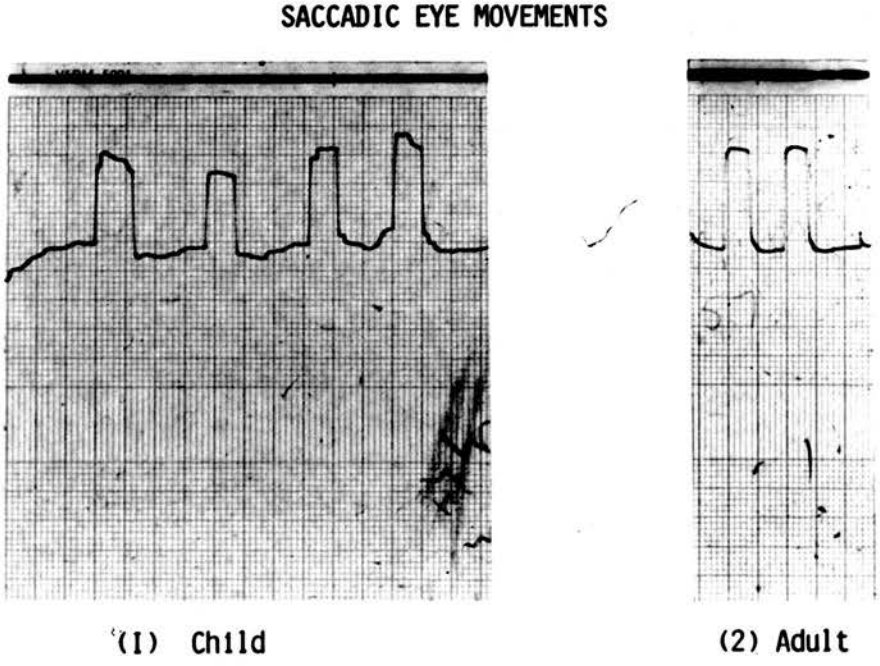
i) Maturation of response

Nystagmus parameters were first measured in response to optokinetic stimulation using a foveal stimulus. All measurements were performed with mental alerting and instructions to concentrate on the centre of the drum.

The raw results are presented in Table 6.6. The whole Table contains information which is the result of paired recordings in each subjects. In each case nystagmus slow phase velocity and saccadic amplitude and frequency was recorded with nystagmus beating to the left (drum movement to the right) preceding nystagmus to the right. The ages of each of the individuals (in months) is also tabulated, and the means and standard deviations for each parameter recorded at the foot of the Table.

There was no immediately discernable pattern of change in response to increasing age but, in order to confirm this impression, regressions of each parameter against age as the independent variable were performed. The skew given by pattern analysis of each measured parameter before and after natural logarithmic transformation ($\log_e$) is given at the foot of Table 6.6. Regression was performed with these parameters (independent variables) together with age (dependent variable) in natural logarithmic base. The results are given at the foot of Table 6.6, and the squares of the correlation coefficients (R_2) obtained confirm a lack of change in slow phase velocity, amplitude or frequency of this type of optokinetic nystagmus with age.

Figure 6.3



Saccadic Movement in a child.

1) **a mixed hypometric and hypermetric response in a child.**
2) **normal response in an adult.**

ii) Test-retest

Test-retest data for this stimulus are presented in Table 6.7 and are again compared with Spearman's rank correlation coefficient (rho). It is readily apparent that the results obtained with tests using a small drum were consistent and show a reproducibility of the responses obtained.

D. OPTOKINETIC TESTING: LARGE DRUM

1. Experiments with varying stimulus velocity

As with small drum testing, all measurements of large drum optokinetic tests were performed with constant mental stimulation and instructions to watch one of the animals (a ladybird) which recurred at eye level. A ''look'' response equivalent to pursuit was therefore elicited.

The relationship between drum velocity and the resultant velocity of eye movement is known to become progressively more non-linear above a stimulus speed of 30 degrees/second.This work has already been alluded to above (Rudge,1983).As far as this study was concerned it was obviously important to establish the relationship between the parameters which were measured and the stimulus velocity,for it was only in this way that the most appropriate means could be identified for correcting the measured values in response to variations in stimulus speed.

Therefore the data acquired from the preliminary testing of fifteen subjects who were included in the main study was used to explore this relationship further.These subjects (ten children and five adults) are specified in Chapter 5.They were deliberately exposed to stimulus velocities around 72 and 45 degrees/second, and the results obtained for each parameter (velocity, amplitude and frequency) together with the drum velocities at which the measurements were made are tabulated in Tables 6.1 and 6.2.The data obtained from these preliminary studies was then pooled and assessed by simple linear regression analysis using a model based on the equation:

observed parameter= a x drum speed + constant.

Scatter diagrams for each of the measured variables are shown in Figure 6.4 together with the lines of "best fit". It is clear from the plots so obtained that a simple linear fit is possible for each of the three parameters over the stimulus velocity range specified:in no case did the curve become parabolic at higher drum velocities. The greatest scatter is seen in amplitude measurements and this is reflected in the squares of the correlation coefficients for each measurement (R_2:Velocity = 0.66479:Amplitude = 0.2915:Frequency = 0.6382).

In the main experiments which looked for a maturation effect with age,the observed values were therefore corrected for variations in stimulus speed by using simple proportionality alone.

Figure 6.4

i) Regression of Slow phase velocity/Drum Speed

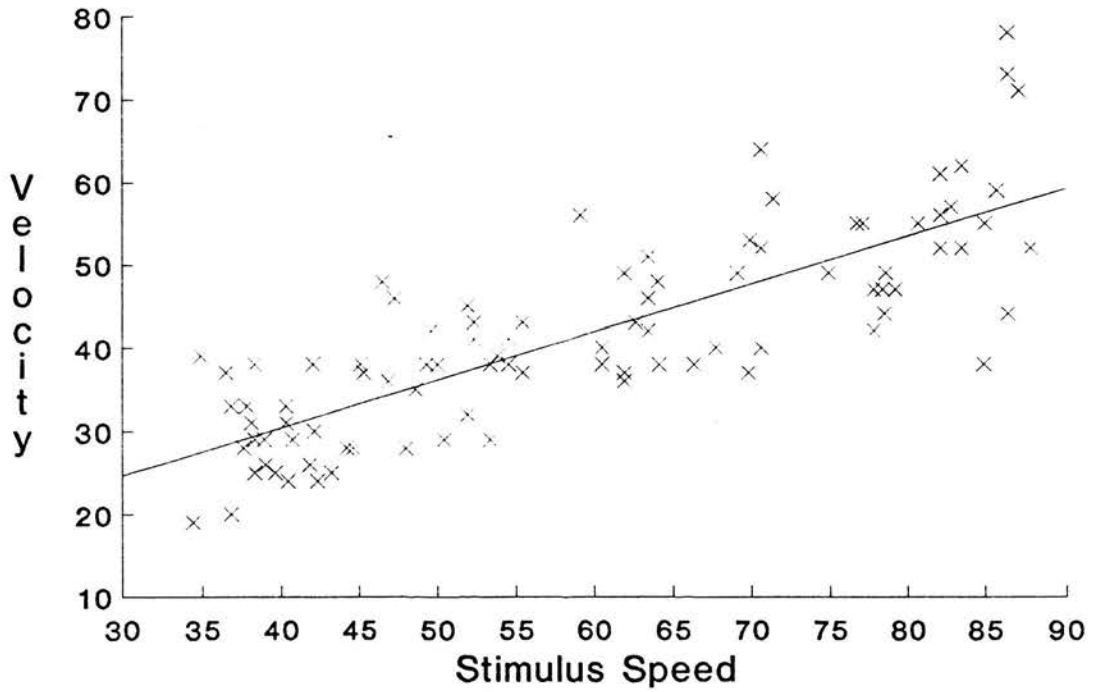


Figure 6.4

ii) Regression of Amplitude/Drum Speed

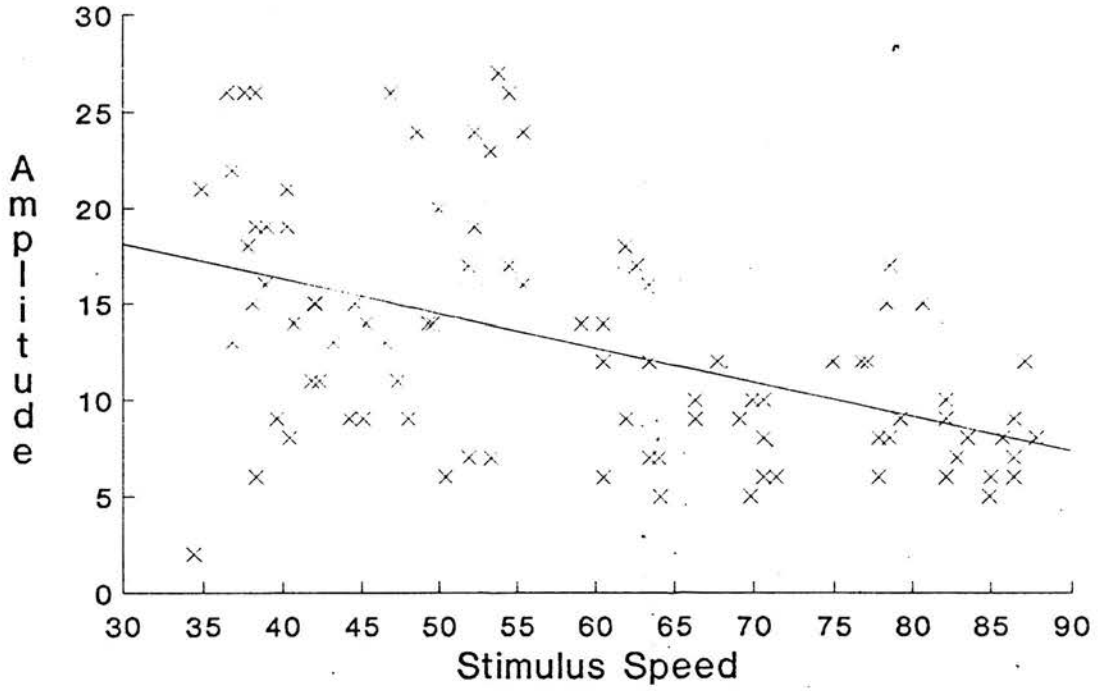
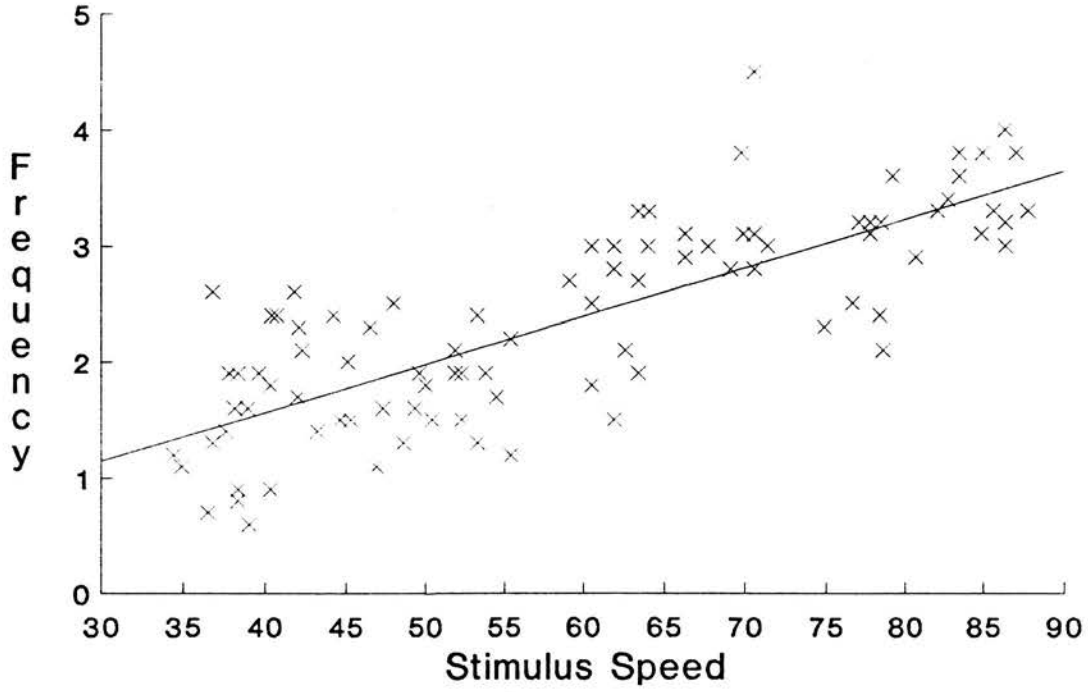


Figure 6.4

iii) Regression of Frequency/Drum Speed



2. Optokinetic responses

i) Maturation of response

In the light of the data presented previously the observed data was corrected,if necessary,to a predicted value at the notational speeds of either 45 or 72 degrees/second by simple proportionality. The values thus derived together with the measurements of speed of drum rotation for each of the patients are shown in Tables 6.8 and 6.9.

The corrected data was then analyzed for each speed of rotation studied. The results are given at the foot of Tables 6.8 and 6.9. As with the foveal task provided by small drum stimulation there was no apparent maturational change with age, but this impression was confirmed by regression analysis. As before regressions were undertaken with the relevant parameter entered in logarithmic base. As can be seen from the coefficients obtained (R_2), the results confirm a lack of maturation change.

ii) Test-retest

Test-retest data was also obtained at 72 degrees/second. The results obtained after correction are shown in Table 6.10. Again there is an obvious reproducibility of the stimulus using Spearman's rank correlation coefficient.

iii) Optokinetic after-nystagmus

Optokinetic after-nystagmus was measured in each instance using the large drum. This parameter was only measured at stimulus speeds around 72 degrees/second.

The results were assessed by recording the slow phase velocity of the nystagmus recorded in the dark (after-nystagmus) and comparing this speed with the corrected velocity of movement attained during stimulation. The ratio eye velocity in the

dark/eye velocity with stimulation then served to provide a fixation suppression index (FSI) for movement in each direction.

The results are given in Table 6.11. It is of interest that such a response appears to be more evident in childhood (subjects 1-100) than in a comparable series of adults (subjects 101-121). This accords with previous researches in adults where the response has been difficult to define in some cases (Magnusson, Pyykko and Jantti, 1985; Sakata, Itch and Teramoto, 1986).

The response was also assessed for maturation with age by linear regression analysis. The method used was as outlined above. Again there is no maturation effect with age.

iv) Test: retest

Test-retest data was again collated by use of Spearman's rank correlation coefficient (rho). The results are shown in Table 6.12 where it is again apparent that there is a high degree of test-retest reliability.

3. Directional preponderance

Measurements of directional preponderance of the small and large drums (at 72 degrees/second) were made in each instance. Preponderance was calculated from the equation:

$$\frac{SPV(L)-SPV(R)\ x100}{SPV(L)+SPV(R)}$$

where SPV equals the mean slow phase velocity recorded to right and left respectively.

The results confirm a lack of maturational change in preponderance with age for both large and small drum stimulation (Table 6.13). However, comparisons between stimuli were also made and these showed that there is a difference in preponderance for a foveal or full field task which was confirmed using Student's t test for paired data. It is readily apparent that this is the result of the greater values obtained for preponderances measured using the small drum (foveal) task in children.

CONCLUSIONS

1. There are suggestions of maturation effects in children between the ages of 5 and 14 years when testing pursuit and saccadic movements. Young children display a tendency to produce a somewhat broken pursuit pattern (saccadic pursuit) and hypermetric saccades. However the results obtained using different optokinetic stimuli shows no maturation effect.

2. Test-Retest Reliability is high for each of the measured parameters.

3. Foveal and full field stimuli are effective in eliciting a response provided that suitable alerting is maintained. However, a difference in directional preponderance is seen between the two stimuli.

4. Optokinetic after-nystagmus is easier to observe in childhood but shows no maturation effect. The neuronal pathways concerned with the subcortical optokinetic response (peripheral retina, accessory optic tract with its nuclei and the vestibular nuclei) can therefore be presumed to be fully mature by the age of five years.

Table 6.1

Optokinetic Testing; Large Drum
Preliminary Test Results
at differing Drum Speeds (around 72°/sec)

Drum Speed (°/sec)	S.P.V (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
64.0	48	7	3.0
87.1	71	12	3.8
64.1	38	5	3.3
83.5	52	8	3.8
70.6	64	10	2.8
86.4	73	9	3.0
60.5	40	14	1.8
71.4	58	6	3.0
86.4	78	7	3.2
69.8	37	5	3.8
63.4	51	12	2.7
78.6	49	17	2.1
62.6	43	17	2.1
87.8	52	8	3.3
66.3	38	9	2.9
82.1	52	9	3.3
74.9	49	12	2.3
63.4	46	16	1.9
82.1	56	6	3.3
60.5	40	12	2.5
77.8	47	8	3.2
69.1	49	9	2.8
85.7	59	8	3.3
82.8	57	7	3.4
79.2	47	9	3.6

Table 6.1 (continued)

Optokinetic Testing; Large Drum
Preliminary Test Results
at differing Drum Speeds (around 72°/sec)

Drum Speed (°/sec)	S.P.V (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
78.5	44	8	3.2
61.9	37	18	1.5
67.7	40	12	3.0
61.9	36	9	2.8
78.4	47	15	2.4
80.7	55	15	2.9
59.1	56	14	2.7
77.1	55	12	3.2
86.4	44	6	4.0
70.6	40	6	4.5
76.7	55	12	2.5
70.6	52	8	3.1
61.9	49	9	3.0
83.5	62	8	3.6
85.0	55	6	3.8
60.5	38	6	3.0
63.4	42	7	3.3
84.9	38	5	3.1
77.8	42	6	3.1
66.3	38	10	3.1
82.1	61	10	3.3
69.9	53	10	3.1

Table 6.2

Optokinetic Testing; Large Drum
Preliminary Test Results
at differing Drum Speeds (around 45°/sec)

Drum Speed (°/sec)	S.P.V (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
40.3	33	21	0.9
46.5	48	13	2.3
42.0	38	15	1.7
53.3	29	7	2.4
48.0	28	9	2.5
55.4	43	16	2.2
44.2	28	9	2.4
47.3	46	11	1.6
49.6	42	14	1.9
36.8	33	22	2.6
43.2	25	13	1.4
38.9	29	16	1.6
40.7	29	14	2.4
42.1	30	15	2.3
40.3	31	19	1.8
50.4	29	6	1.5
51.9	32	17	1.9
44.6	28	15	1.5
53.3	38	23	1.6
51.9	45	7	2.1
36.8	20	13	1.3
36.5	37	26	0.7
45.1	38	9	2.0
41.8	26	11	2.6
38.1	31	15	1.6

Table 6.2 (continued)

Optokinetic Testing; Large Drum

Preliminary Test Results

at differing Drum Speeds (around 45°/sec)

Drum Speed (°/sec)	S.P.V (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
39.6	25	9	1.9
34.4	19	20	1.2
42.3	24	11	2.1
38.3	25	26	0.8
40.4	24	8	2.4
50.0	38	20	1.8
54.5	41	26	1.7
54.5	38	17	1.7
48.6	35	24	1.3
55.4	37	24	1.2
37.8	33	18	1.9
39.0	26	19	0.6
52.3	43	24	1.5
49.3	38	14	1.6
38.3	38	6	1.9
53.8	39	27	1.9
45.3	37	14	1.5
37.6	28	26	1.4
46.9	36	26	1.1
38.3	29	19	0.9
52.3	41	19	1.9
34.9	39	21	1.1

Table 6.3

Pendular Tracking

Study Number	Age (Months)	Velocity of Eye Movement Left (°/sec)	Right (°/sec)	Pendular Movement Frequency (Hz)	Velocity (°/sec)	Gain Left	Right
1	69	24	23	0.40	19	1.26	1.21
2	69	15	16	0.57	16	0.93	1.00
3	66	22	18	0.50	22	1.00	0.80
4	57	18	18	0.50	18	1.00	1.00
5	65	24	20	0.50	18	1.30	0.98
6	68	19	18	0.50	18	1.05	1.00
7	74	29	24	0.50	24	1.20	1.00
8	68	24	22	0.52	21	1.14	1.05
9	69	23	21	0.51	19	1.21	1.10
10	83	19	24	0.52	19	1.00	1.26
11	76	21	23	0.52	24	0.88	0.95
12	77	16	16	0.52	18	0.89	0.89
13	71	19	21	0.50	19	1.00	1.10
14	77	24	24	0.50	25	0.96	0.96
15	81	22	20	0.55	22	1.00	0.90
16	82	15	18	0.50	17	0.88	1.05
17	82	16	18	0.52	19	0.84	0.94
18	82	18	20	0.50	17	1.05	1.20
19	80	19	18	0.50	16	1.19	1.13
20	80	20	19	0.50	19	1.05	1.00
21	94	23	22	0.54	23	1.00	0.96
22	89	22	20	0.53	20	1.10	1.00
23	85	22	23	0.50	22	1.00	1.05
24	95	21	24	0.52	22	0.95	1.09
25	90	19	17	0.54	19	1.00	0.89
26	94	23	22	0.55	22	1.03	1.00
27	89	18	18	0.50	17	1.06	1.06
28	82	25	22	0.50	24	1.04	0.91
29	86	21	17	0.55	18	1.20	0.94
30	94	22	22	0.50	20	1.10	1.10
31	109	21	21	0.54	17	1.23	1.23
32	104	27	23	0.53	22	1.20	1.00
33	98	16	16	0.50	18	0.80	0.80
34	96	16	18	0.50	15	1.06	1.20
35	101	23	23	0.55	24	0.96	0.96

Table 6.3 (continued)

Pendular Tracking

Study Number	Age (Months)	Velocity of Eye Movement Left (°/sec)	Right (°/sec)	Pendular Movement Frequency (Hz)	Velocity (°/sec)	Gain Left	Right
36	102	18	20	0.50	18	1.00	1.10
37	105	22	21	0.52	21	1.04	1.0
38	97	20	20	0.50	18	1.10	1.10
39	108	20	20	0.52	22	0.90	0.90
40	112	13	12	0.58	12	1.10	1.00
41	107	20	21	0.55	20	1.00	1.05
42	117	22	19	0.53	21	1.05	0.90
43	116	16	16	0.50	14	1.14	1.14
44	111	22	20	0.50	21	1.05	0.95
45	116	23	22	0.50	22	1.04	1.00
46	119	23	24	0.52	23	1.00	1.04
47	112	21	23	0.50	21	1.00	1.09
48	113	23	23	0.50	21	1.09	1.09
49	117	20	18	0.55	19	1.05	0.95
50	119	20	22	0.52	20	1.00	1.10
51	129	18	20	0.52	18	1.00	1.10
52	131	18	20	0.54	18	1.00	1.10
53	123	22	20	0.50	20	1.10	1.00
54	119	20	21	0.53	21	0.95	1.00
55	119	20	20	0.55	20	1.00	1.00
56	123	20	19	0.52	19	1.05	1.00
57	123	22	21	0.55	23	0.96	0.91
58	131	20	20	0.53	19	1.05	1.05
59	123	20	18	0.52	19	1.05	0.95
60	122	20	18	0.52	19	1.05	0.95
61	144	21	22	0.55	23	0.91	0.96
62	140	21	21	0.52	21	1.00	1.00
63	137	20	18	0.53	20	1.00	0.90
64	135	20	20	0.52	20	1.00	1.00
65	134	20	19	0.50	19	1.05	1.00
66	141	25	22	0.52	21	1.19	1.04
67	138	22	20	0.50	18	1.22	1.10
68	138	28	24	0.52	28	1.00	0.85
69	135	23	22	0.50	21	1.09	1.05
70	143	22	20	0.55	21	1.04	0.95
71	135	19	17	0.52	16	1.18	1.06

Table 6.3 (continued)

Pendular Tracking

Study Number	Age (Months)	Velocity of Eye Movement Left (°/sec)	Right (°/sec)	Pendular Movement Frequency (Hz)	Velocity (°/sec)	Gain Left	Right
72	151	16	16	0.52	17	0.94	0.94
73	153	23	22	0.52	23	1.00	0.95
74	144	22	21	0.50	22	1.00	0.95
75	147	16	15	0.50	17	0.94	0.88
76	148	24	24	0.51	23	1.04	1.04
77	151	26	24	0.51	23	1.13	1.04
78	155	18	18	0.52	17	1.05	1.05
79	144	22	22	0.50	18	1.22	1.22
80	153	23	23	0.52	21	1.09	1.09
81	160	24	22	0.52	23	1.04	0.96
82	165	20	18	0.52	19	1.05	0.94
83	156	28	26	0.52	28	1.00	0.93
84	167	21	20	0.54	22	0.95	0.90
85	167	21	22	0.52	20	1.05	1.10
86	166	14	16	0.51	14	0.97	1.14
87	167	20	19	0.51	20	1.00	0.95
88	163	19	20	0.51	18	1.05	1.11
89	161	21	21	0.52	22	0.95	0.95
90	160	21	20	0.50	20	1.05	1.00
91	171	28	26	0.55	28	1.00	0.93
92	168	24	23	0.52	24	1.00	0.96
93	177	22	21	0.55	22	1.00	0.95
94	168	26	26	0.50	24	1.08	1.08
95	174	21	20	0.52	19	1.10	1.05
96	177	19	18	0.55	18	1.06	1.00
97	171	24	24	0.52	24	1.00	1.00
98	188	24	22	0.55	24	1.00	0.92
99	169	22	23	0.50	19	1.15	1.20
100	179	24	22	0.52	23	1.04	0.96
101	388	21	22	0.50	18	1.16	1.22
102	366	23	23	0.52	24	0.96	0.96
103	307	26	27	0.52	27	0.96	1.00
104	258	26	26	0.52	23	1.13	1.13
105	258	20	21	0.52	17	1.18	1.23
106	283	21	18	0.52	21	1.00	0.86
107	254	23	21	0.52	21	1.09	1.00
108	348	24	23	0.52	22	1.09	1.05

Table 6.3 (continued)

Pendular Tracking

Study Number	Age (Months)	Velocity of Eye Movement Left (°/sec)	Velocity of Eye Movement Right (°/sec)	Pendular Movement Frequency (Hz)	Pendular Movement Velocity (°/sec)	Gain Left	Gain Right
109	275	21	19	0.52	18	1.16	1.05
110	295	19	22	0.50	24	0.79	0.92
111	286	18	19	0.52	19	0.95	1.00
112	351	24	21	0.52	22	1.09	0.95
113	335	22	20	0.52	23	0.95	0.86
114	300	28	26	0.52	28	1.00	0.92
115	309	18	19	0.52	19	0.94	1.00
116	375	18	18	0.54	17	1.05	1.05
117	237	20	20	0.52	19	1.05	1.05
118	236	25	24	0.52	24	1.04	1.00
119	340	22	20	0.52	22	1.00	0.90
120	328	22	23	0.52	19	1.15	1.21
121	289	23	21	0.52	24	0.96	0.88
Mean	152.5	21.2	20.7	0.5	20.5	1.03	1.01
SD	79.2	3.1	2.6	0.02	3.0	0.09	0.09
Skew	1.35	0.004	-0.15	-0.97	0.25	-0.92	0.35
Skew($\log_e$)	0.5	-0.5	-0.65	-1.60	-0.3	-0.65	-0.09
R_2	-	0.03	0.04	0.02	0.05	-0.008	-0.007

Table 6.4

Pendular Tracking: Test/Retest (Gain)

Patient	Test		Retest	
Number	Left	Right	Left	Right
3	1.00	0.80	0.94	0.90
5	1.3	0.98	0.87	0.91
13	1.00	1.10	1.04	0.91
15	1.00	0.90	1.10	1.00
24	0.95	1.09	1.10	1.04
34	1.06	1.20	1.09	1.09
46	1.00	1.04	1.00	1.10
48	1.09	1.09	1.10	1.00
52	1.00	1.10	0.80	0.80
54	0.95	1.00	1.04	1.19
74	1.00	0.95	0.95	1.00
75	0.94	0.88	1.06	1.05
76	1.04	1.04	0.02	1.00
88	1.03	1.08	1.10	1.05
99	1.15	1.20	0.96	0.98
100	1.04	0.96	1.00	1.09
102	0.96	0.96	1.00	0.98
115	0.94	1.00	1.00	0.91
116	1.0	1.05	0.92	1.00
117	1.05	1.05	1.00	1.00
118	1.04	1.00	0.95	0.88
119	1.0	0.90	1.00	1.04
120	1.15	1.20	1.05	1.00
121	0.91	0.88	0.80	0.90

Spearman's rank correlation coefficient (rho):

Left (Columns 2 + 4) rho = 0.995

Right (Columns (3 + 5) rho = 0.994

$p<0.001$ for both Left and Right

Table 6.5

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

\+ = Hypermetric Saccade or Saccadic pursuit

– = normal Saccade or pursuit

Patient Number	Age (Months)	Pursuit	Sacccades 10°	30°
1	69	+	+	+
2	69	-	-	+
3	66	+	+	+
4	57	+	-	-
5	65	-	+	+
6	68	-	-	-
7	74	-	-	-
8	68	-	-	+
9	69	+	-	+
10	83	-	+	+
11	76	-	-	+
12	77	-	-	-
13	71	-	+	+
14	72	-	-	+
15	81	+	+	+
16	82	+	-	-
17	82	-	-	-

Table 6.5 (continued)

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

Patient Number	Age (Months)	Pursuit	Sacccades 10°	30°
18	82	-	-	+
19	80	-	-	+
20	80	-	-	+
21	94	-	+	+
22	89	+	+	+
23	85	-	+	+
24	95	-	-	+
25	90	+	+	+
26	94	+	-	+
27	89	+	-	+
28	82	-	-	-
29	86	+	-	-
30	94	-	-	-
31	109	+	-	+
32	104	+	-	+
33	98	+	-	+
34	96	+	-	+
35	101	+	-	+
36	102	-	-	+
37	105	-	-	+
38	97	-	-	+

Table 6.5 (continued)

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

Patient Number	Age (Months)	Pursuit	Sacccades 10°	Sacccades 30°
39	108	+	-	+
40	112	+	-	+
41	107	-	-	+
42	117	-	-	+
43	116	+	-	+
44	111	+	-	+
45	116	-	-	+
46	119	-	-	+
47	112	+	-	+
48	113	-	-	-
49	131	+	+	+
50	117	-	-	+
51	119	+	-	+
52	129	+	+	+
53	131	-	-	-
54	123	-	-	+
55	119	-	-	+
56	119	-	-	-
57	123	-	-	+
58	131	-	-	-
59	123	-	-	-

Table 6.5 (continued)

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

Patient Number	Age (Months)	Pursuit	Sacccades 10°	Sacccades 30°
60	122	-	-	-
61	144	+	-	-
62	140	-	-	-
63	137	-	-	-
64	135	-	-	-
65	134	-	-	-
66	141	-	-	-
67	138	-	-	-
68	138	-	-	+
69	135	-	-	-
70	143	-	-	-
71	135	-	-	-
72	151	-	-	-
73	153	-	-	-
74	144	+	-	-
75	144	-	-	+
76	148	+	-	-
77	151	+	-	-
78	155	+	-	-
79	144	-	-	-
80	153	-	-	-

Table 6.5 (continued)

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

Patient Number	Age (Months)	Pursuit	Sacccades 10°	30°
81	160	-	-	-
82	165	-	-	-
83	156	-	-	-
84	167	-	-	+
85	167	-	-	+
86	166	+	-	-
87	176	+	-	-
89	161	-	-	+
90	160	-	-	-
91	171	-	-	-
92	168	-	-	-
93	177	+	-	-
94	168	-	-	-
95	174	-	-	-
96	177	-	-	-
97	171	-	-	+
98	188	-	-	-
99	169	-	-	-
100	179	-	-	-
101	388	-	-	-

Table 6.5 (continued)

Visual-ocular Control: Recording of hypermetric saccades and saccadic pursuit in subjects studied

Patient Number	Age (Months)	Pursuit	Sacccades 10°	30°
102	366	-	-	-
103	307	-	-	-
104	258	-	-	-
105	258	-	-	-
106	283	-	-	-
107	254	-	-	-
108	348	-	-	-
109	275	-	-	-
110	295	-	-	-
111	286	-	-	-
112	351	-	-	-
113	335	-	-	-
114	300	-	-	-
115	309	-	-	-
116	375	-	-	-
117	287	-	-	-
118	340	-	-	-
119	328	-	-	-
120	286	-	-	-
121	226	-	-	-

Table 6.6

Optokinetic Testing: Small Drum

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
1	69	23	8	2.4	24	7	1.6
2	69	11	5	2.2	10	3	2.3
3	66	21	6	1.7	24	8	1.8
4	57	10	8	1.4	11	8	1.4
5	65	20	5	2.2	15	5	1.7
6	68	11	6	1.6	9	6	0.9
7	74	18	5	2.3	11	4	2.0
8	68	14	5	2.1	12	5	1.1
9	69	16	5	2.1	16	4	2.8
10	83	13	4	2.0	10	6	1.4
11	76	17	5	2.7	21	4	2.8
12	77	26	6	2.2	19	5	2.1
13	71	12	4	1.8	9	4	1.8
14	77	14	8	1.8	17	8	1.8
15	81	13	4	2.1	11	5	1.6
16	82	23	7	2.7	26	7	2.6
17	82	13	4	1.8	11	6	1.4
18	82	15	4	2.5	19	6	2.0
19	80	15	4	2.1	12	5	2.0
20	80	11	5	1.8	11	4	2.1
21	94	16	5	1.9	14	8	1.4
22	89	13	5	2.4	21	4	2.5
23	85	13	5	2.0	17	4	2.0
24	95	22	5	1.7	15	5	1.7
25	90	18	4	2.0	17	6	1.7
26	94	13	6	1.4	22	8	2.2
27	89	11	6	2.3	18	6	1.9
28	82	15	6	2.2	24	7	2.1
29	86	15	5	2.3	15	5	1.7
30	94	18	5	2.2	29	6	2.1
31	109	24	6	2.4	20	6	2.4
32	104	15	5	2.1	11	4	2.1
33	98	13	5	1.5	16	8	1.8
34	96	17	6	1.5	26	6	2.3

Table 6.6 (continued)

Optokinetic Testing: Small Drum

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
35	101	32	7	2.6	40	7	2.8
36	102	10	5	1.4	14	5	2.0
37	105	19	6	2.3	22	5	2.4
38	97	18	5	2.0	17	4	1.9
39	108	16	5	1.9	15	5	2.0
40	112	22	5	2.4	22	5	2.6
41	107	22	7	2.3	23	6	2.6
42	117	13	4	2.4	16	6	2.2
43	116	6	3	1.6	5	3	1.4
44	111	14	7	1.7	9	6	1.2
45	116	19	6	2.8	23	8	2.2
46	119	15	5	2.3	15	4	2.1
47	112	15	5	1.9	17	5	1.8
48	113	14	4	1.8	14	3	1.8
49	117	15	4	2.9	13	5	1.7
50	119	22	6	2.7	17	5	1.8
51	129	17	6	2.1	22	6	2.6
52	131	16	6	1.6	13	4	1.7
53	123	24	7	2.6	24	9	2.3
54	119	32	8	2.7	30	8	2.9
55	119	10	7	1.4	9	6	1.7
56	123	20	6	2.2	16	4	2.0
57	123	16	6	2.5	16	6	1.8
58	131	18	4	2.0	22	3	1.8
59	123	10	4	1.9	9	3	1.9
60	122	18	4	2.3	21	5	2.4
61	144	18	7	2.0	13	5	2.1
62	140	11	4	1.5	10	3	1.9
63	137	15	4	2.6	18	4	2.9
64	135	15	7	1.5	16	5	1.5
65	134	12	4	2.5	12	5	2.1
66	141	14	4	2.2	8	4	1.7
67	138	20	6	2.0	20	5	2.3
68	138	27	7	2.4	24	8	2.1

Table 6.6 (continued)

Optokinetic Testing: Small Drum

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
69	135	16	4	2.5	15	4	2.8
70	143	18	8	2.1	17	7	2.2
71	135	14	4	1.9	15	4	2.4
72	151	15	6	1.7	8	2	1.8
73	153	10	3	2.2	16	3	2.0
74	144	28	6	2.9	26	7	2.3
75	144	17	4	2.3	28	6	2.7
76	148	15	3	2.7	14	4	2.7
77	151	13	4	2.5	15	5	2.3
78	155	22	7	2.3	24	5	2.2
79	144	32	5	2.7	20	5	3.1
80	153	16	4	1.6	25	5	2.3
81	160	25	5	2.4	22	5	2.5
82	165	9	4	1.7	10	4	2.4
83	156	24	6	2.4	29	7	2.5
84	167	15	4	2.2	13	4	2.0
85	167	9	3	1.8	11	3	1.7
86	166	21	4	2.7	26	4	3.4
87	167	11	3	2.3	13	5	2.2
88	163	11	4	2.3	16	3	2.3
89	161	14	3	2.6	18	4	3.0
90	160	18	4	3.2	14	3	2.4
91	171	26	6	2.6	29	6	2.8
92	168	19	6	2.1	13	5	2.1
93	177	21	5	2.1	17	4	2.1
94	168	27	6	2.4	28	11	2.2
95	174	17	4	2.2	16	5	2.0
96	177	19	5	2.1	15	6	2.1
97	171	23	8	2.6	28	5	2.3
98	188	25	7	2.3	22	8	2.2
99	169	17	5	2.3	17	4	2.3
100	179	17	6	2.2	23	6	2.2
101	388	20	4	2.2	19	4	2.2
102	366	21	6	2.2	21	5	2.6

Table 6.6 (continued)

Optokinetic Testing: Small Drum

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient	Age	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency
Number	(months)	(°/sec)	(degrees)	(b.p.s.)	(°/sec)	(degrees)	(b.p.s.)
103	307	21	5	2.5	21	5	2.8
104	258	13	4	2.2	15	5	2.3
105	258	15	4	2.1	18	5	2.1
106	283	11	6	2.3	12	5	2.8
107	254	14	4	2.1	13	3	2.2
108	348	27	7	2.4	26	7	2.2
109	275	24	6	2.3	23	3	2.3
110	295	16	4	2.4	13	3	2.5
111	286	9	3	2.5	10	3	2.2
112	351	17	5	2.4	21	5	2.6
113	335	18	4	3.6	23	4	2.9
114	300	22	4	2.6	21	6	2.8
115	309	31	8	2.7	28	6	2.9
116	375	20	3	3.6	20	4	3.7
117	237	11	3	3.0	8	3	2.2
118	236	16	7	1.6	19	6	1.7
119	340	24	6	3.2	27	5	3.1
120	328	22	9	2.0	21	7	2.1
121	289	10	6	2.0	7	7	2.7
Mean	152.5	17.3	5.20	2.20	17.7	5.2	2.20
SD	79.2	5.4	1.40	0.40	6.20	1.6	0.50
Skew	1.35	0.65	0.43	0.40	0.50	0.7	0.20
Skew($\log_e$)	0.5	-0.2	-0.10	-0.30	-0.40	-0.03	-0.70
R_2	-	0.03	0.03	0.1	0.02	0.02	0.20

Table 6.7

Optokinetic Testing; Small Drum: Test/Retest

Patient Number	TEST						RETEST					
	Left Beating Nystagmus			Right Beating Nystagmus			Left Beating Nystagmus			Right Beating Nystagmus		
	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency
3	21	6	1.7	24	8	1.8	24	9	1.9	21	8	1.9
5	20	5	2.2	15	5	1.7	19	4	2.4	18	6	2.9
13	12	4	1.8	9	4	1.8	14	8	1.9	11	5	1.6
15	13	4	2.1	11	5	1.6	10	9	1.2	11	7	1.4
24	22	5	1.7	15	5	1.7	16	8	1.9	14	6	1.3
34	17	6	1.5	26	6	2.3	12	6	1.0	25	4	1.0
46	15	5	2.3	15	4	2.1	11	6	1.6	13	6	0.9
48	14	4	1.8	14	3	1.8	19	8	1.9	17	9	1.9
52	16	6	1.6	13	4	1.7	21	4	2.9	11	4	2.9
54	32	8	2.7	30	8	2.9	25	9	1.4	26	3	1.4
74	28	6	2.9	26	7	2.3	21	4	1.8	19	4	1.9
75	17	4	2.3	28	6	2.7	15	7	2.1	14	8	2.1
76	15	3	2.7	14	4	2.7	13	4	2.1	11	7	1.5
88	11	4	2.3	16	3	2.3	15	3	2.2	15	4	2.1
99	17	5	2.3	17	4	2.3	21	4	2.7	20	5	2.3
100	17	6	2.2	23	6	2.2	16	4	2.2	17	5	2.3
102	21	6	2.2	21	5	2.6	20	6	2.9	19	8	2.2
115	31	8	2.7	28	6	2.9	24	7	2.9	26	5	3.4

Table 6.7 (continued)

Optokinetic Testing; Small Drum: Test/Retest

	TEST						RETEST					
Patient	Left Beating Nystagmus			Right Beating Nystagmus			Left Beating Nystagmus			Right Beating Nystagmus		
Number	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency	S.P.V.	Amplitude	Frequency
116	20	3	3.6	20	4	3.7	19	4	3.0	19	5	3.4
117	11	3	3.0	8	3	2.2	11	8	2.3	9	5	2.8
118	16	7	1.6	19	6	1.7	14	8	2.2	19	7	1.9
119	24	6	3.2	27	5	3.1	24	6	2.3	23	3	2.3
120	22	9	2.0	21	7	2.1	27	4	2.3	21	6	2.0
121	20	6	2.0	7	7	2.7	14	4	2.1	13	6	2.2

Spearman's rank correlation coefficient (rho):

			p
Left Beating Nystagmus;	S.P.V.	0.8239	<0.01
	Amplitude	0.9309	<0.001
	Frequency	0.9959	<0.001
Right Beating Nystagmus;	S.P.V.	0.8178	<0.01
	Amplitude	0.9465	<0.001
	Frequency	0.9946	<0.001

Table 6.8

Optokinetic testing; Large Drum (72°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
1	69	49	12	2.1	50	11	2.2
2	69	37	9	2.6	50	7	2.1
3	66	38	9	2.3	45	8	2.0
4	57	39	7	2.7	55	9	2.0
5	65	38	13	2.9	56	16	1.7
6	68	61	19	3.3	56	25	1.9
7	74	69	15	3.0	75	22	1.9
8	68	55	17	2.0	59	18	2.2
9	69	33	15	2.1	29	7	2.5
10	83	47	12	2.2	35	12	2.2
11	76	53	9	3.6	44	19	2.2
12	77	53	18	2.3	50	15	2.1
13	71	46	12	2.0	60	12	2.0
14	77	52	10	3.1	63	13	2.8
15	81	42	10	2.6	47	13	1.8
16	82	48	14	3.0	52	14	2.5
17	82	55	12	2.9	59	15	2.9
18	82	51	9	2.6	49	12	2.3
19	80	49	9	2.8	48	12	2.4
20	80	43	14	2.4	45	11	1.9
21	94	60	11	2.5	57	19	1.9
22	89	51	11	3.1	61	12	2.6
23	85	48	10	2.7	44	13	1.8
24	95	57	16	2.1	52	13	2.1
25	90	50	9	3.0	56	13	2.0
26	94	51	14	2.0	57	17	2.1
27	89	38	11	2.3	50	9	1.9
28	82	72	13	3.1	75	14	3.1
29	86	32	8	3.7	24	12	3.3
30	94	38	9	2.7	42	21	2.2
31	109	49	9	3.2	39	8	3.1
32	104	43	13	2.6	56	8	2.4
33	98	45	13	1.5	43	16	1.8
34	96	34	26	1.9	39	16	2.3

Table 6.8 (continued)

Optokinetic testing; Large Drum (72°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
35	101	45	12	2.5	59	9	3.5
36	102	44	7	4.2	43	6	2.4
37	105	51	8	2.7	58	13	2.9
38	97	46	6	2.7	48	5	3.7
39	108	51	13	2.3	47	12	2.4
40	112	35	15	2.4	45	14	2.5
41	107	57	12	3.4	55	14	2.4
42	117	44	9	3.3	46	14	2.5
43	116	38	12	2.5	36	9	2.1
44	111	46	20	2.1	36	19	1.5
45	116	46	16	2.8	46	17	2.6
46	119	45	15	2.1	42	17	1.8
47	112	49	7	2.6	69	9	2.9
48	113	44	15	1.3	53	17	1.5
49	117	50	10	3.9	47	10	3.6
50	119	50	13	2.5	43	14	2.9
51	129	46	9	3.1	43	15	2.2
52	131	72	18	2.0	64	13	1.9
53	123	76	13	2.9	80	16	2.6
54	119	72	9	3.5	72	15	3.4
55	119	45	13	2.6	55	10	1.9
56	123	54	12	2.1	44	13	2.1
57	123	40	8	2.7	43	7	3.4
58	131	55	11	3.2	52	5	4.0
59	123	39	11	2.6	28	10	2.1
60	122	42	8	2.5	43	13	3.1
61	144	35	10	2.8	27	8	2.4
62	140	55	12	1.2	47	12	2.4
63	137	45	11	3.2	48	9	2.7
64	135	50	11	2.6	73	12	3.4
65	134	31	11	2.3	32	11	1.9
66	141	49	10	2.3	55	13	1.7
67	138	31	15	2.0	36	17	2.0
68	138	59	16	3.3	79	15	3.1

Table 6.8 (continued)

Optokinetic testing; Large Drum (72°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
69	135	44	10	4.2	55	9	3.7
70	143	43	7	2.8	51	9	2.7
71	135	43	10	2.6	42	9	2.8
72	151	43	12	2.1	43	10	2.5
73	153	65	14	3.1	64	13	2.6
74	144	65	11	3.2	63	12	3.4
75	144	53	6	3.7	57	11	2.8
76	148	50	10	4.2	43	10	3.1
77	151	71	8	2.7	65	15	2.2
78	155	48	9	2.1	46	12	2.5
79	144	53	12	2.6	51	13	2.2
80	153	59	7	3.4	54	11	2.8
81	160	54	12	2.5	54	10	3.1
82	165	50	10	3.6	51	8	3.0
83	156	69	18	2.9	74	14	3.0
84	167	62	10	2.8	66	12	2.9
85	167	42	9	3.2	45	11	2.6
86	166	39	10	3.1	41	8	3.4
87	167	47	8	2.8	46	15	2.2
88	163	39	10	3.3	38	11	2.5
89	161	41	8	3.8	48	7	3.3
90	160	54	10	3.1	46	9	3.1
91	171	77	9	3.6	80	18	2.8
92	168	54	14	3.0	46	18	2.5
93	177	49	11	3.0	54	10	3.1
94	168	57	12	2.6	56	13	2.8
95	174	60	11	2.5	55	13	2.1
96	177	70	12	3.4	68	12	3.0
97	171	79	15	3.4	78	29	2.4
98	188	62	9	3.2	49	11	3.0
99	169	44	8	3.4	46	9	3.1
100	179	51	17	1.9	45	17	2.0
101	388	61	9	2.8	54	15	2.4

Table 6.8 (continued)

Optokinetic testing; Large Drum (72°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
102	366	47	10	2.8	60	5	2.9
103	307	45	11	3.2	57	16	2.4
104	258	52	8	2.8	54	9	3.0
105	258	48	9	2.6	45	9	3.0
106	283	47	9	2.9	67	9	2.6
107	254	39	10	3.6	45	7	4.1
108	348	71	9	3.3	84	10	3.2
109	275	53	5	3.0	61	11	3.0
110	295	45	5	3.5	47	7	3.5
111	286	40	6	3.8	46	8	3.3
112	351	41	9	2.5	43	11	2.8
113	335	46	7	2.9	52	8	3.5
114	300	59	8	2.9	66	9	3.3
115	309	38	19	1.9	48	17	2.5
116	375	41	9	3.0	53	13	3.0
117	237	43	9	3.1	44	9	3.0
118	236	47	13	2.7	51	9	2.9
119	340	53	6	3.7	57	10	2.8
120	328	44	19	2.1	46	12	2.4
121	289	49	15	2.4	50	12	2.5
Mean	152.5	49.7	11.2	2.8	51.8	12.2	2.6
SD	79.2	7.8	2.7	0.5	8.8	3.1	0.5
Skew	1.35	0.78	1.1	-0.02	0.5	0.9	0.28
Skew($\log_e$)	0.5	0.24	0.07	-0.8	-0.03	-0.14	-0.15
R_2	-	0.01	0.07	0.04	0.02	0.05	0.2

Table 6.9

Optokinetic testing; Large Drum (45°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
2	69	41	17	1.1	40	11	2.4
4	57	36	19	1.2	39	12	2.3
5	65	33	11	1.9	29	9	2.0
7	74	51	10	2.6	49	10	2.8
8	68	40	12	2.5	44	16	1.9
10	83	28	10	1.4	22	8	2.1
12	77	48	10	2.2	38	15	1.8
13	71	28	9	2.5	34	9	2.1
15	81	42	13	2.0	40	12	1.7
17	82	38	10	2.8	43	10	1.8
25	90	32	15	1.6	33	12	2.6
29	86	32	11	2.0	32	14	1.9
31	109	35	14	2.2	28	15	1.8
35	101	37	16	2.1	30	18	1.0
40	112	41	13	1.9	40	10	1.9
42	117	38	15	1.7	34	15	1.7
51	129	31	16	1.6	35	26	1.3
53	123	36	26	1.8	35	15	1.3
58	131	41	15	1.4	37	15	1.6
61	144	42	15	1.7	44	9	1.4
62	140	37	7	1.9	34	15	1.3
63	137	47	10	1.9	49	13	2.0
64	135	33	15	2.0	37	16	1.8
66	141	34	21	2.0	36	14	1.5
67	138	38	18	1.5	43	11	1.6
70	143	31	23	1.4	31	18	2.2
72	151	28	11	1.7	39	15	1.8
76	148	44	8	2.5	40	8	2.1
78	155	32	12	1.2	39	14	1.9
80	153	40	11	2.0	29	9	2.0
81	160	29	10	2.8	26	10	1.9
82	165	33	14	1.9	41	17	1.8
83	156	35	12	2.1	45	12	2.0
84	167	33	21	1.9	32	8	2.1

Table 6.9 (continued)

Optokinetic testing; Large Drum (45°/sec)

		Left Beating Nystagmus			Right Beating Nystagmus		
Patient Number	Age (months)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)	SPV (°/sec)	Amplitude (degrees)	Frequency (b.p.s)
86	166	38	10	1.8	42	10	1.5
91	171	39	18	1.7	37	10	2.1
92	168	34	17	1.9	34	10	2.3
93	177	49	17	2.4	44	18	1.9
95	174	34	22	1.3	39	16	2.4
100	179	34	18	1.9	35	20	1.4
101	388	45	20	2.0	39	21	2.0
102	366	45	15	2.3	42	14	2.4
103	307	35	16	2.2	35	19	2.3
104	258	29	17	1.0	30	21	1.4
106	283	35	9	2.1	37	10	3.0
107	254	20	11	2.2	22	11	2.8
108	348	41	15	2.1	40	11	2.5
109	275	43	15	2.1	40	16	1.9
110	295	42	18	2.0	42	15	2.7
111	286	27	18	1.6	35	18	1.5
112	351	39	20	1.0	43	14	1.4
113	335	37	18	1.7	41	21	1.0
114	300	29	20	0.5	33	17	1.1
115	309	35	24	1.2	39	24	1.6
116	375	38	21	1.8	41	26	1.7
117	237	42	19	1.9	46	17	1.4
118	236	41	24	1.7	40	10	3.0
119	340	30	15	2.0	29	16	1.9
120	328	31	23	1.3	31	21	1.3
121	289	28	20	1.4	30	25	1.1
Mean	185.9	36.4	15.5	1.8	36.9	14.5	1.9
SD	81.4	7.1	3.8	0.35	4.8	3.7	0.37
Skew	0.6	-0.09	0.2	-0.3	-0.36	0.68	0.35
Skew($\log_e$)	-0.09	-0.48	-0.3	-1.6	-0.83	-0.10	-0.26
R_2	-	0.009	0.2	0.04	0.001	0.19	0.02

Table 6.10

Optokinetic Testing; Large Drum: Test/Retest (72°/sec)

Patient Number	TEST						RETEST					
	Left Beating Nystagmus			Right Beating Nystagmus			Left Beating Nystagmus			Right Beating Nystagmus		
	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency
3	38	9	2.3	45	8	2.0	42	11	2.1	40	9	2.3
5	38	13	2.9	56	16	1.7	40	11	2.7	42	18	2.1
13	46	12	2.0	60	12	2.0	46	14	2.1	59	13	2.9
15	42	10	2.6	47	13	1.8	48	11	3.4	51	17	2.1
24	57	16	2.1	52	13	2.1	48	16	2.0	52	12	2.2
34	34	26	1.9	39	16	2.3	38	18	2.1	40	14	2.3
46	45	15	2.1	42	17	1.8	43	17	2.4	41	19	2.3
48	44	15	1.3	53	17	1.5	46	7	2.3	46	13	2.0
52	72	18	2.0	64	13	1.9	50	19	2.7	58	16	2.2
54	72	9	3.5	72	15	3.4	65	9	3.3	64	17	3.1
74	65	11	3.2	63	12	3.4	68	13	2.6	59	14	3.1
75	53	6	3.7	57	11	2.8	51	9	3.1	54	14	2.7
76	50	10	4.2	43	10	3.1	56	13	3.6	59	9	3.1
88	39	10	3.3	38	11	2.5	40	12	3.6	44	9	3.3
99	44	8	3.4	46	9	3.1	47	11	2.8	45	11	2.9
100	51	17	1.9	45	17	2.0	45	15	2.4	46	15	2.7
102	47	10	2.8	60	5	2.9	39	19	2.9	56	10	2.8
115	38	19	1.9	48	17	2.5	41	12	1.6	49	12	2.0

Table 6.10 (continued)

Optokinetic Testing; Large Drum: Test/Retest (72°/sec)

Patient Number	TEST						RETEST					
	Left Beating Nystagmus			Right Beating Nystagmus			Left Beating Nystagmus			Right Beating Nystagmus		
	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency	SPV	Amplitude	Frequency
116	41	9	3.0	53	13	3.0	47	12	3.2	50	13	3.1
117	43	9	3.1	44	9	3.0	38	5	2.9	49	10	2.8
118	47	13	2.7	51	9	2.9	42	12	2.4	46	10	3.1
119	53	6	3.7	57	10	2.8	51	10	2.7	57	12	2.1
120	44	19	2.1	46	12	2.4	47	11	2.4	42	14	2.3
121	49	15	2.4	50	12	2.5	51	11	1.9	54	9	1.9

Spearman's rank correlation coefficient (rho):

			p
Left Beating Nystagmus;	SPV	0.7310	<0.01
	Amplitude	0.5980	<0.01
	Frequency	0.74251	<0.01
Right Beating Nystagmus;	SPV	0.6854	<0.01
	Amplitude	0.7423	<0.01
	Frequency	0.6572	<0.01

Table 6.11

Optokinetic Testing; After-Nystagmus

Patient Number	Age (Months)	Nystagmus SPV (°/sec) Left	Nystagmus SPV (°/sec) Right	After-Nystagmus SPV (°/sec) Left	After-Nystagmus SPV (°/sec) Right	Fixation Suppression Index Left	Fixation Suppression Index Right
1	69	49	50	10	10	0.2	0.2
2	69	37	50	15	5	0.4	0.1
3	66	38	45	17	7	0.5	0.2
4	57	39	55	11	6	0.2	0.1
5	65	38	56	13	0	0.4	0.0
6	68	61	56	17	0	0.3	0.0
7	74	69	75	15	19	0.2	0.3
8	68	55	59	15	12	0.2	0.2
9	69	33	29	10	3	0.3	0.1
10	83	47	35	5	0	0.3	0.0
11	76	53	44	0	0	0.1	0.0
12	77	53	50	17	0	0.0	0.0
13	71	46	60	24	4	0.3	0.1
14	77	52	63	14	0	0.5	0.0
15	81	42	47	8	4	0.3	0.1
16	82	48	52	0	11	0.2	0.2
17	82	55	59	16	11	0.0	0.2
18	82	51	49	14	10	0.3	0.2
19	80	49	48	10	10	0.3	0.2
20	80	43	45	11	0	0.2	0.0
21	94	60	57	15	11	0.3	0.2
22	89	51	61	20	9	0.4	0.2
23	85	48	44	15	6	0.3	0.1
24	95	57	52	10	0	0.2	0.0
25	90	50	56	10	6	0.2	0.1
26	94	51	57	0	11	0.0	0.2
27	89	38	50	0	7	0.0	0.2
28	82	72	75	0	8	0.0	0.1
29	86	32	24	11	10	0.4	0.4
30	94	38	42	4	4	0.1	0.1
31	109	49	39	25	8	0.5	0.2
32	104	43	56	8	11	0.2	0.2
33	98	45	43	5	9	0.1	0.2
34	96	34	39	4	4	0.1	0.1
35	101	45	59	5	6	0.1	0.1

Table 6.11 (continued)

Optokinetic Testing; After-Nystagmus

Patient Number	Age (Months)	Nystagmus SPV (°/sec) Left	Nystagmus SPV (°/sec) Right	After-Nystagmus SPV (°/sec) Left	After-Nystagmus SPV (°/sec) Right	Fixation Suppression Index Left	Fixation Suppression Index Right
36	102	44	43	9	0	0.2	0.0
37	105	51	58	5	14	0.1	0.3
38	97	46	48	9	5	0.2	0.1
39	108	51	47	10	0	0.2	0.0
40	112	35	45	7	14	0.2	0.3
41	107	57	55	17	6	0.3	0.2
42	117	44	46	18	5	0.4	0.1
43	116	38	36	9	8	0.2	0.2
44	111	46	36	9	7	0.2	0.2
45	116	46	46	9	5	0.2	0.1
46	119	45	42	5	4	0.1	0.1
47	112	49	69	14	17	0.3	0.3
48	113	44	53	9	13	0.2	0.3
49	117	50	47	10	10	0.2	0.2
50	119	50	43	5	4	0.1	0.1
51	129	46	43	14	9	0.3	0.2
52	131	72	64	0	0	0.0	0.0
53	123	76	80	14	15	0.2	0.2
54	119	72	72	29	7	0.4	0.1
55	119	45	55	17	17	0.4	0.3
56	123	54	44	0	0	0.0	0.0
57	123	40	43	0	13	0.0	0.3
58	131	55	52	8	6	0.2	0.1
59	123	39	28	16	0	0.4	0.0
60	122	42	43	13	9	0.3	0.2
61	144	35	27	8	5	0.2	0.2
62	140	55	47	5	11	0.1	0.2
63	137	45	48	9	10	0.2	0.2
64	135	50	73	5	12	0.1	0.2
65	134	31	32	6	7	0.2	0.2
66	141	49	55	10	8	0.2	0.2
67	138	31	36	3	4	0.1	0.1
68	138	59	79	12	8	0.2	0.1
69	135	44	55	10	0	0.2	0.0
70	143	43	51	0	0	0.0	0.0

Table 6.11 (continued)

Optokinetic Testing; After-Nystagmus

Patient Number	Age (Months)	Nystagmus SPV (°/sec) Left	Nystagmus SPV (°/sec) Right	After-Nystagmus SPV (°/sec) Left	After-Nystagmus SPV (°/sec) Right	Fixation Suppression Index Left	Fixation Suppression Index Right
71	135	43	42	9	7	0.2	0.2
72	151	43	43	11	12	0.3	0.3
73	153	65	64	14	7	0.2	0.1
74	144	65	63	13	13	0.2	0.2
75	144	53	57	11	6	0.2	0.1
76	148	50	43	5	16	0.1	0.4
77	151	71	65	0	0	0.0	0.0
78	155	48	46	9	6	0.2	0.1
79	144	53	51	6	5	0.1	0.1
80	153	59	54	18	11	0.3	0.2
81	160	54	54	11	11	0.2	0.2
82	165	50	51	10	10	0.2	0.2
83	156	69	74	7	10	0.1	0.2
84	167	62	66	5	0	0.1	0.0
85	167	42	45	0	0	0.0	0.0
86	166	39	41	8	0	0.2	0.0
87	167	47	46	0	5	0.0	0.1
88	163	39	38	12	0	0.3	0.0
89	161	41	48	6	4	0.2	0.1
90	160	54	46	0	5	0.0	0.1
91	171	77	80	9	0	0.1	0.0
92	168	54	46	22	5	0.4	0.1
93	177	49	54	25	11	0.5	0.2
94	168	57	56	0	6	0.0	0.1
95	174	60	55	8	9	0.1	0.2
96	177	70	68	10	8	0.2	0.1
97	171	79	78	8	16	0.1	0.2
98	188	62	49	19	8	0.3	0.2
99	169	44	46	0	0	0.0	0.0
100	179	51	45	0	5	0.0	0.1
101	388	61	54	0	0	0.0	0.0
102	366	47	60	0	0	0.0	0.0
103	307	45	57	0	0	0.0	0.0
104	258	52	54	11	0	0.2	0.0
105	258	48	45	5	5	0.1	0.1

Table 6.11 (continued)

Optokinetic Testing; After-Nystagmus

Patient Number	Age (Months)	Nystagmus SPV (°/sec) Left	Nystagmus SPV (°/sec) Right	After-Nystagmus SPV (°/sec) Left	After-Nystagmus SPV (°/sec) Right	Fixation Suppression Index Left	Fixation Suppression Index Right
106	283	47	67	0	0	0.0	0.0
107	254	39	45	6	7	0.2	0.2
108	348	71	84	7	9	0.1	0.1
109	275	53	61	6	9	0.1	0.2
110	295	45	47	4	4	0.1	0.1
111	286	40	46	0	0	0.0	0.0
112	351	41	43	0	0	0.0	0.0
113	335	46	52	6	5	0.1	0.1
114	300	59	66	12	0	0.2	0.0
115	309	38	48	0	10	0.0	0.2
116	375	41	53	8	11	0.2	0.2
117	237	43	44	9	18	0.2	0.4
118	236	47	51	14	5	0.3	0.1
119	340	53	57	14	23	0.3	0.4
120	328	44	46	9	9	0.2	0.2
121	289	49	50	0	20	0.0	0.4
Mean	152.5	49.7	51.8	8.8	6.7	0.18	0.14
S.D.	79.2	10.3	11.5	6.4	5.2	0.13	0.1
R_2	-	-	-	0.09	0.007	0.12	0.004

Table 6.12

Optokinetic Testing: After-Nystagmus; Test/Retest (72°/sec)

Patient	Test		Retest	
Number	Left	Right	Left	Right
3	0.50	0.20	0.40	0.30
5	0.40	0.00	0.40	0.00
13	0.50	0.10	0.30	0.20
15	0.20	0.10	0.30	0.10
24	0.20	0.00	0.30	0.10
34	0.10	0.10	0.10	0.10
46	0.10	0.10	0.20	0.20
48	0.20	0.30	0.30	0.20
52	0.00	0.00	0.10	0.00
54	0.40	0.10	0.30	0.10
74	0.20	0.20	0.20	0.20
75	0.20	0.10	0.10	0.10
76	0.10	0.40	0.10	0.30
88	0.30	0.00	0.30	0.20
99	0.00	0.00	0.10	0.00
100	0.00	0.10	0.00	0.10
102	0.00	0.00	0.00	0.00
115	0.00	0.20	0.00	0.10
116	0.20	0.40	0.20	0.40
117	0.20	0.40	0.10	0.10
118	0.30	0.10	0.20	0.20
119	0.30	0.40	0.30	0.40
120	0.20	0.20	0.20	0.20
121	0.00	0.40	0.10	0.40

Spearman's rank correlation coefficient (rho):	p
Left (Columns 2 + 4) rho = 0.8556	<0.001
Right (Columns (3 + 5) rho = 0.7333	<0.001

Table 6.13

Optokinetic Testing; Directional Preponderances
Children

Patient Number	Age	Small Drum	Large Drum	Patient Number	Age	Small Drum	Large Drum	Patient Number	Age	Small Drum	Large Drum
1	69	2	1	36	102	17	1	71	135	3	1
2	69	5	15	37	105	7	7	72	151	30	0
3	66	24	9	38	97	3	2	73	153	25	1
4	57	5	17	39	108	3	4	74	144	4	2
5	65	14	19	40	112	0	13	75	144	24	4
6	68	10	4	41	107	2	2	76	144	3	8
7	74	24	4	42	117	10	2	77	148	7	5
8	68	8	4	43	116	9	3	78	151	4	2
9	69	0	7	44	111	22	12	79	155	23	2
10	83	13	9	45	116	10	0	80	144	22	5
11	76	11	9	46	119	0	3	81	153	6	0
12	77	15	3	47	112	6	17	82	160	5	1
13	71	14	13	48	113	0	9	83	165	9	4
14	77	10	8	49	117	7	3	84	156	7	3
15	81	8	6	50	119	13	8	85	167	10	4
16	82	6	4	51	129	13	7	86	166	1	3
17	82	6	4	52	131	10	6	87	167	8	1
18	82	12	2	53	123	0	3	88	163	19	1
19	80	11	1	54	119	3	0	89	161	13	8
20	80	0	2	55	119	5	10	90	160	12	8
21	94	7	3	56	123	11	10	91	171	5	2
22	89	24	9	57	123	0	4	92	168	19	8
23	85	13	4	58	131	10	3	93	177	11	5
24	95	18	5	59	123	5	17	94	168	2	1
25	90	17	6	60	122	8	1	95	174	3	4
26	94	26	6	61	144	16	13	96	177	12	2
27	89	24	14	62	140	5	8	97	171	10	1
28	82	23	2	63	137	9	3	98	188	6	12
29	86	0	14	64	135	3	19	99	169	0	2
30	94	24	8	65	134	0	2	100	179	15	6
31	109	9	11	66	141	27	6				
32	104	13	13	67	138	0	8		Mean	10.1	6.07
33	98	3	2	68	138	6	15		S.D.	7.7	4.8
34	96	7	7	69	135	3	11				
35	101	14	14	70	143	3	9				

Table 6.13 (continued)

Optokinetic Testing; Directional Preponderances

Adults

Patient Number	Age	Small Drum	Large Drum
101	388	3	6
102	366	0	12
103	307	0	12
104	258	7	2
105	258	9	3
106	283	4	18
107	254	4	7
108	348	2	8
109	275	2	7
110	295	10	2
111	286	5	7
112	351	11	2
113	355	12	6
114	300	2	6
115	309	5	12
116	375	0	13
117	237	16	1
118	236	9	4
119	340	6	4
120	328	2	2
121	289	18	1
Mean	-	6.1	6.4
S.D.	-	5.2	4.7
R_2 (All data)	-	0.05	0.002

Student's t test (small drum/large drum):

$t = 2.8021 \quad p<0.01$

CHAPTER 7

RESULTS
VESTIBULO-OCULAR FUNCTION

The results of tests performed to assess the maturation of the vestibular system.

SUMMARY

The data collected as the result of testing the vestibulo-ocular reflex by caloric irrigation is presented in this chapter. As with Chapter 6 the text includes the results of experiments designed to assess test-retest reliability.

The introductory section which follows gives some preliminary thoughts concerning the reproducibility of the stimulus used, and this is followed by a description of the results attained by caloric testing and the effects of optic fixation at various ages. Also included are assessments made of canal paresis and directional preponderance of the slow phase velocity measurements.

INTRODUCTION

For these experiments the calibration was altered using overhead lights such that 1mm of pen deflection equalled 1 degree of ocular excursion. As with other tests the subjects were examined in the dark after a period of adaption in dimly lit surroundings to minimise variation in corneo-retinal potential. In order to ensure that there was no inadvertent recording error the infra-red viewer was used as part of the examination in the dark: in this way head and eye movement, including eye closure, was discouraged.

The criteria for deciding the amount of water which provided an adequate stimulus are not apparent from the literature. Methodology differs between laboratories and there is no agreement as the amount of water required/unit time to stimulate the labyrinth. Everyone agrees that the temperature gradient depends upon the conducting properties of the tympanic membrane and middle ear and the amount of thermal energy delivered. Making the assumption that the conducting properties of the drum and middle ear are constant between subjects, the anatomical variable must be meatal size and the stimulus variables the water temperature and the irrigation time. The two

stimulus variables were constant and adequately controlled, so it follows that the amount of water used, and hence the stimulus strength, should depend principally upon meatal size.

This still begs the question as to what can be accepted as an adequate stimulus. In order to try and ascertain this a preliminary series of tests were performed using the same apparatus to measure the amount of water that is required to stimulate the labyrinth. The output of the system used was 450 ml/minute, and it was found in these preliminary tests that irrigations in children with apparently normal (i.e. not obviously narrowed) meati utilised at least 180 ml/30 seconds. This stimulus appeared adequate in that all children receiving this amount of water experienced objective vertigo and all such irrigations produced nystagmus. In addition warm water irrigations with this stimulus produced a flush sign which could be readily viewed at otoscopy. By contrast children who received only 150-160 mls/30 seconds did not always experience subjective symptoms, nystagmus, or an adequate flush sign. It was therefore decided that no irrigation would be accepted which fell below 180 ml/30 seconds.

A. SPONTANEOUS AND LATENT NYSTAGMUS

The first investigation undertaken was an examination of eye movements in each subject in response to positioning the child for caloric testing i.e lying supine on a couch with the head raised by thirty degrees. Recordings were made for a minimum of thirty seconds in the dark. These measurements acted as a control for the tests which followed.

No child who was accepted displayed any spontaneous or latent nystagmus when placed in this position.

B. CALORIC IRRIGATION

Further details of the test used in each case have been previously outlined (Chapter 4). To recapitulate, mental alerting and the same irrigation sequence was used throughout, and the nystagmus recorded between sixty and ninety seconds in complete darkness using electronystagmography. The tympanic membrane was examined after each warm water irrigation to ensure that there was an adequate flush sign, and the water used collected in a kidney dish so that its volume could be measured. The amount of water used in each irrigation is show in table 7.1.

The raw data collected as the result of tests performed is shown in Table 7.2. In an exactly similar way to the methods used for analysis of the data of visual-ocular control, descriptive statistics were applied to each measured parameter and the skew of the data ascertained prior to regression analysis.

The results of these analyses showed that greater symmetry is given to all of the data after transformation to a natural logarithmic base ($\log_e$). This is confirmed by the skew recordings given at the foot of Table 7.3 and is also readily demonstrated by the resultant histograms for each variable (Figures 7.1 and 7.2). Since age measurements achieve greater symmetry when transformed to a logarithmic base (Chapter 5), the regressions used for both dependent (velocity, amplitude and frequency) and independent (age) variables was performed on logarithmic data.

A previous analysis of the data obtained without logarithmic transformation has suggested that a curvilinear regression with a quadratic term gives the best data fit (Kenyon, 1988). However, a more mathematically valid approach demands an analysis of the skew of the data before regression is undertaken, and it is apparent from the data presented here that each coefficient attains greater symmetry when transformed to a natural logarithmic base. Such a transformation makes invalid the use of a simple multivariate approach and this was therefore abandoned in favour of a linear equation for the purposes of the analysis presented here.

As will be seen this has the disadvantage that such a data fit predicts that the velocity and amplitude will decline such that they might appear to approach zero with increasing age (at the point where the regression line bisects the abscissa). However the analysis is not attempting to predict, and its only need is to ascertain whether each variable alters with age over a circumscribed (and relatively short) time interval. It was therefore decided that a simple linear fit, with logged data, would be appropriate to answer questions posed here concerning the maturation changes of each parameter with age.

i) Maturation of response

In each instance the grouped data was first plotted against age in months. The scatter diagrams and regression lines which result are shown in Figures 7.3, 7.4 and 7.5 and the coefficients which characterise these equations are shown in Table 7.4. In all instances the coefficients of the gradients which result attain statistical significance. For velocity measurements the sqaure of the correlation coefficient which results is small (R_2 = 0.0401; Table 7.4), and this demonstrates that age only contributes an extremely small ammount to the change seen in this variable (circa 0.4% of the overall change seen). For amplitude measurements the same coefficient is much higher (0.4973; Table 7.4), and it follows that variation in this parameter appears to have had a considerably greater overall effect on the maturation of the vestibular response and accounts for nearly 50% of the overall change seen. For analysis of frequency the square of the correlation coefficient has an intermediate value but is again quite high (0.3069; Table 7.4). It follows that this variable is also of importance in the maturation of the overall response.

ii) Effect of differing temperature gradients

A separate analysis of the results obtained by warm and cold water irrigation also provides data of interest. Regressions of grouped data attained from warm and cold water irrigations were first plotted separately against age in months (Figure 7.6 and

7.7). The coefficients for the resultant regression equations are shown in Table 7.4 and it is apparent that the colder of the two stimuli employed was responsible for the majority of the maturation effect seen in this parameter. The reasons for this discrepancy remain unclear.

It was certainly the subjective impression at the time of testing that the nystagmus resulting from the stimulus provided by the first calorisation (warm: left) tended to be weak by comparison with other tests. In order to investigate whether this was in fact the case, regressions of the individual slow phase velocities of the warm responses were also undertaken.

The results are shown in Figure 7.8 and it is clear that this impression was in fact correct. Although the squares of the correlation coefficients for the two warm irrigations are comparable (Table 7.5; $R_2 = 0.003$ and 0.004), it is in fact the case that the first irrigation tended to produce a totally insignificant effect on the overall maturation of the response. By contrast, the cold water irrigations appear to be nearly equally responsible for most of the, admittedly small, change in slow phase velocity which results with age (Figure 7.9).

iii) Test-retest reliability

In order to establish the reliability of this data a subgroup of the patients assessed were retested two months after their first attendance. The results are shown in Table 7.6 together with the coefficient which results using Spearman's rank correlation coefficient (rho). It is readily apparent that the correlation is high and that there is thus a high degree of test-retest reliability in the data. This implies that the large scatter seen in the data for each variable is the result of inter and not intra-subject variation.

Figure 7.1

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (unlogged).

i) Slow phase velocity

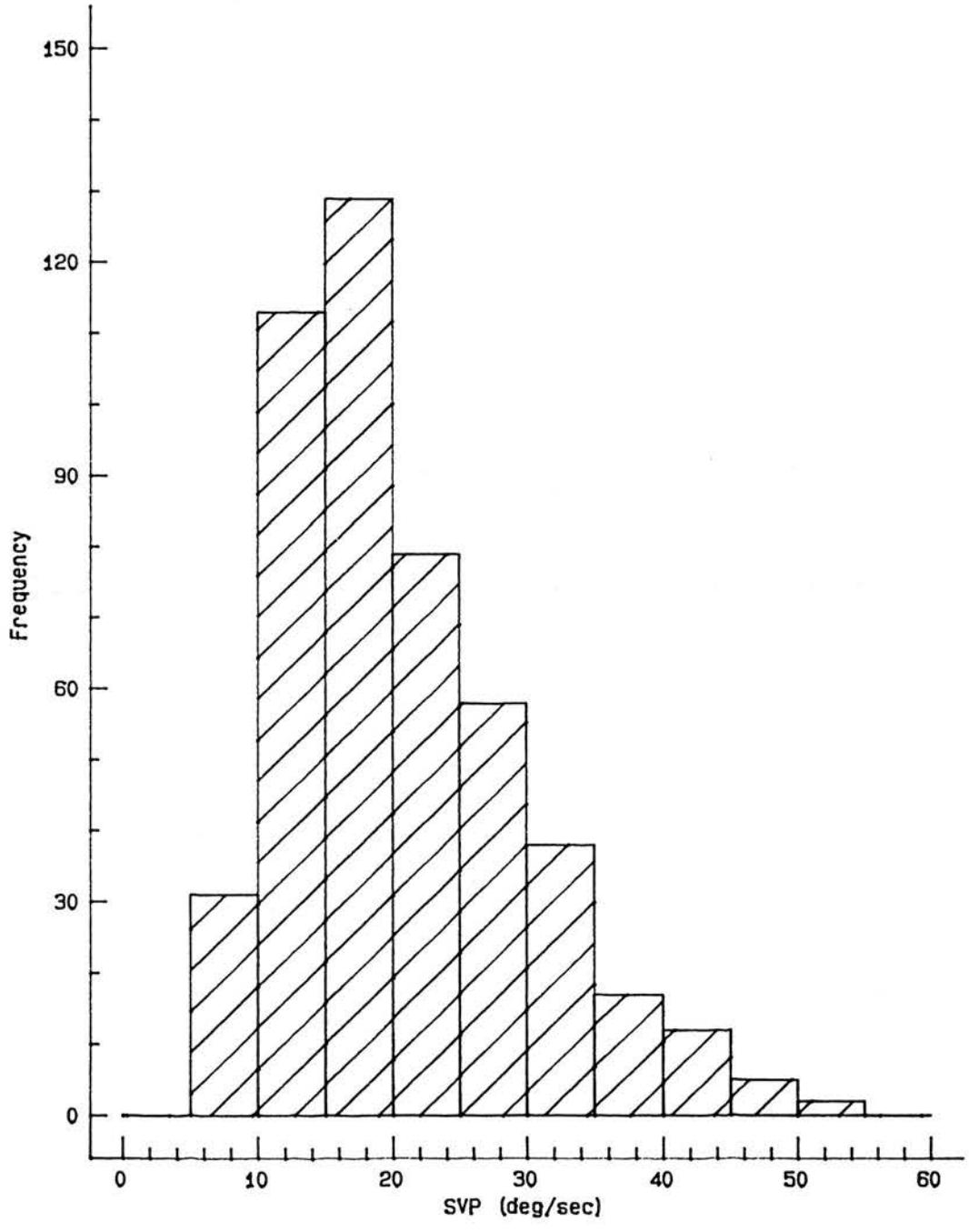


Figure 7.1

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (unlogged).

ii) Amplitude

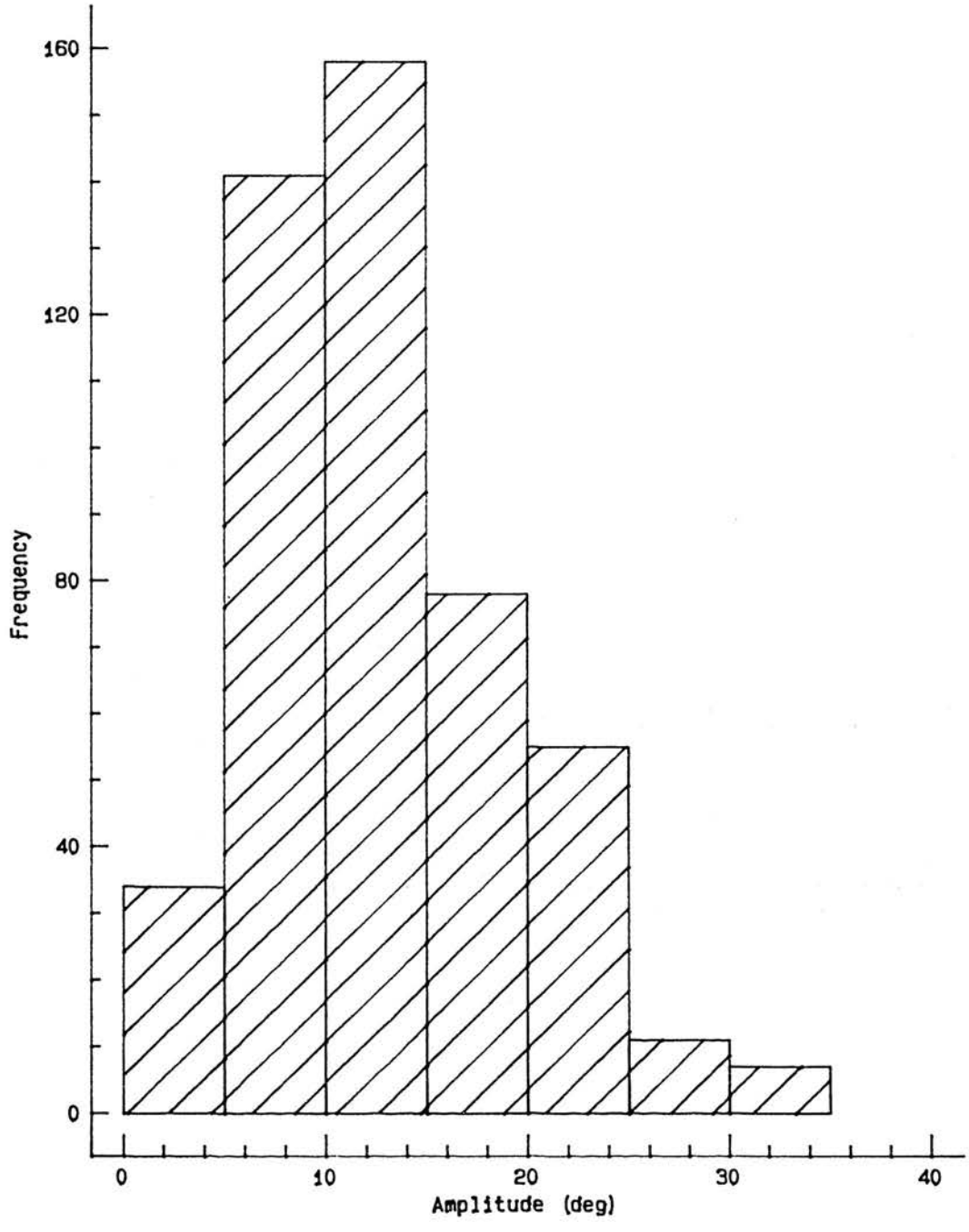


Figure 7.1

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (unlogged).

iii) Frequency

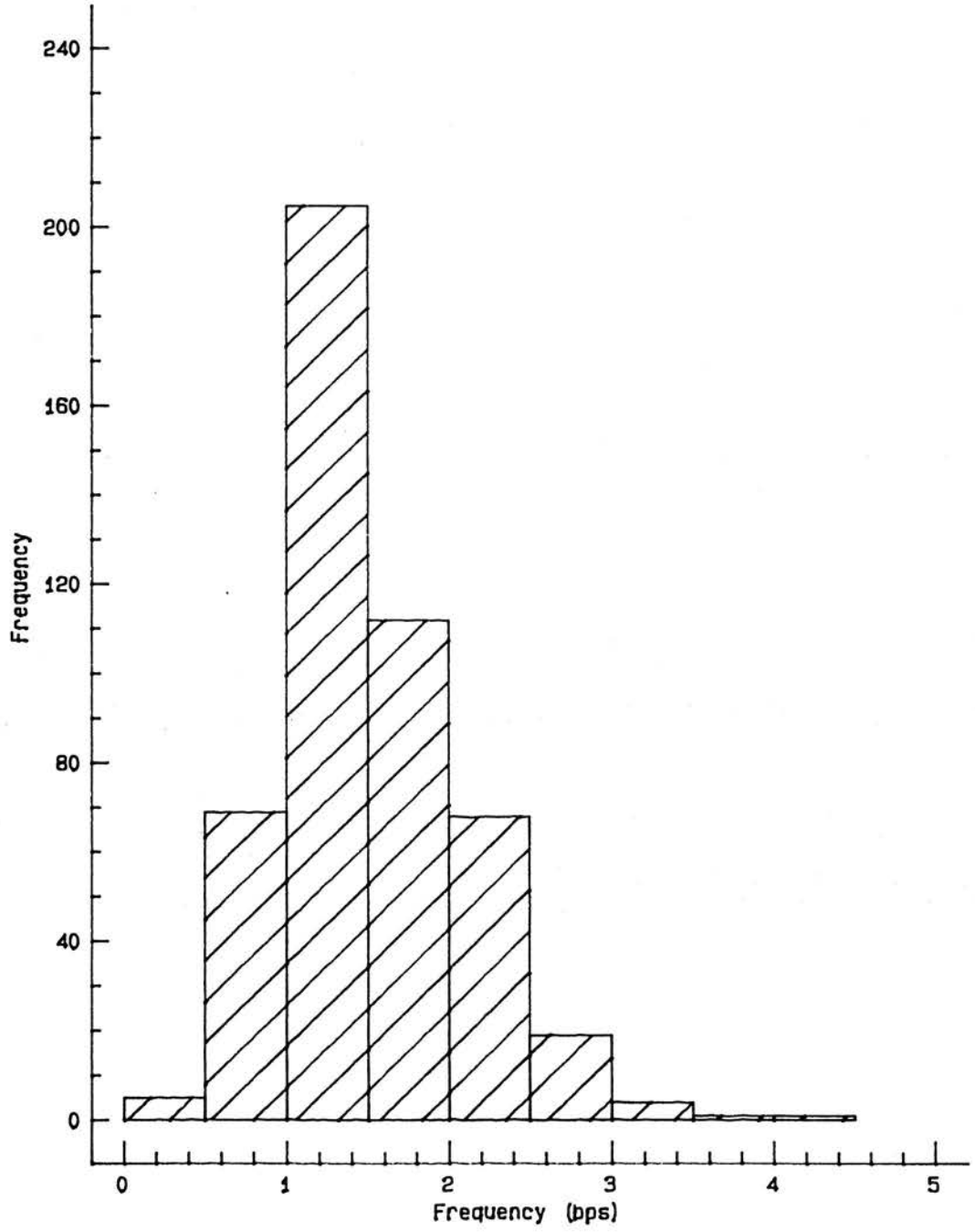


Figure 7.2

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (logged).

i) Slow phase velocity

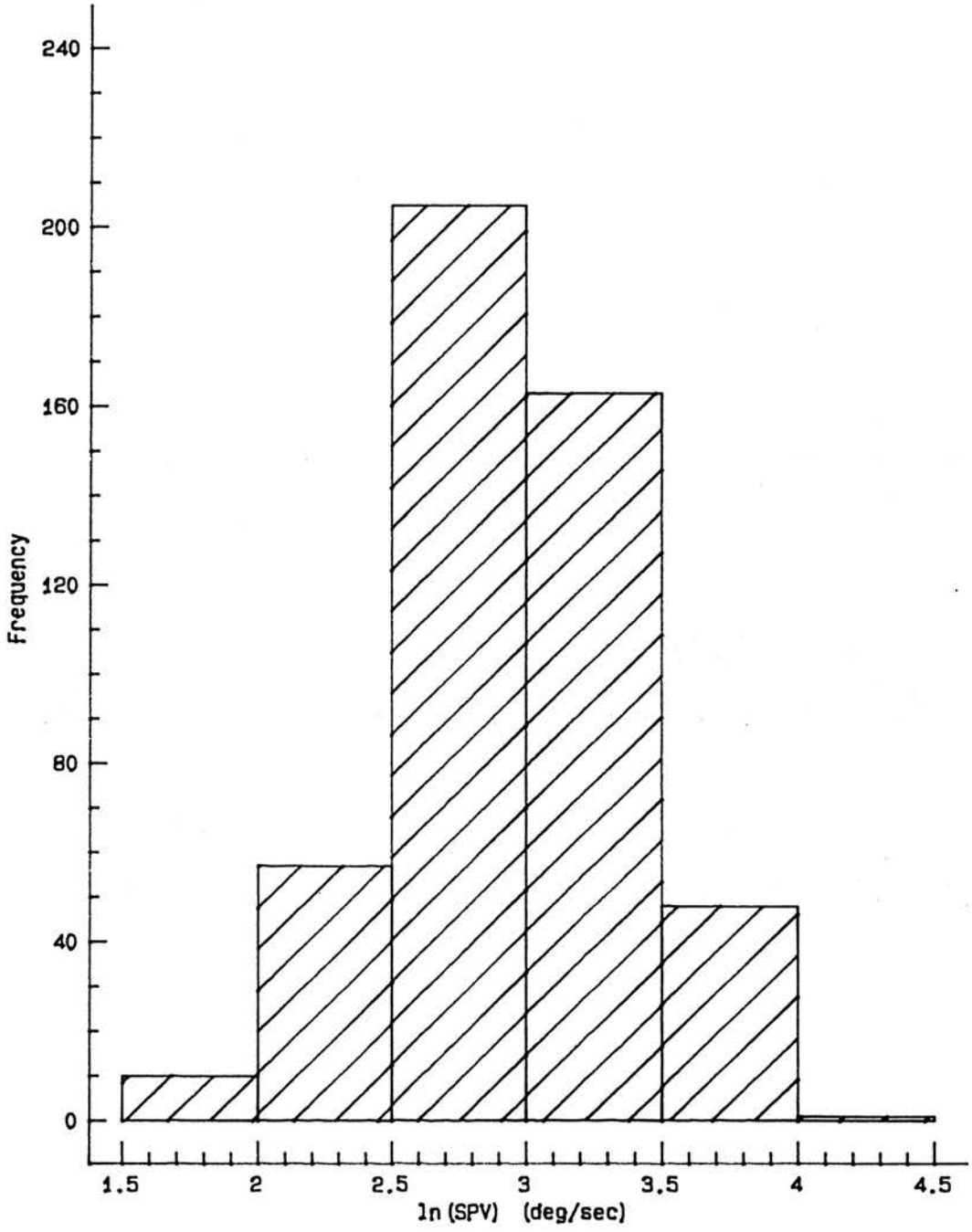


Figure 7.2

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (logged).

ii) Amplitude

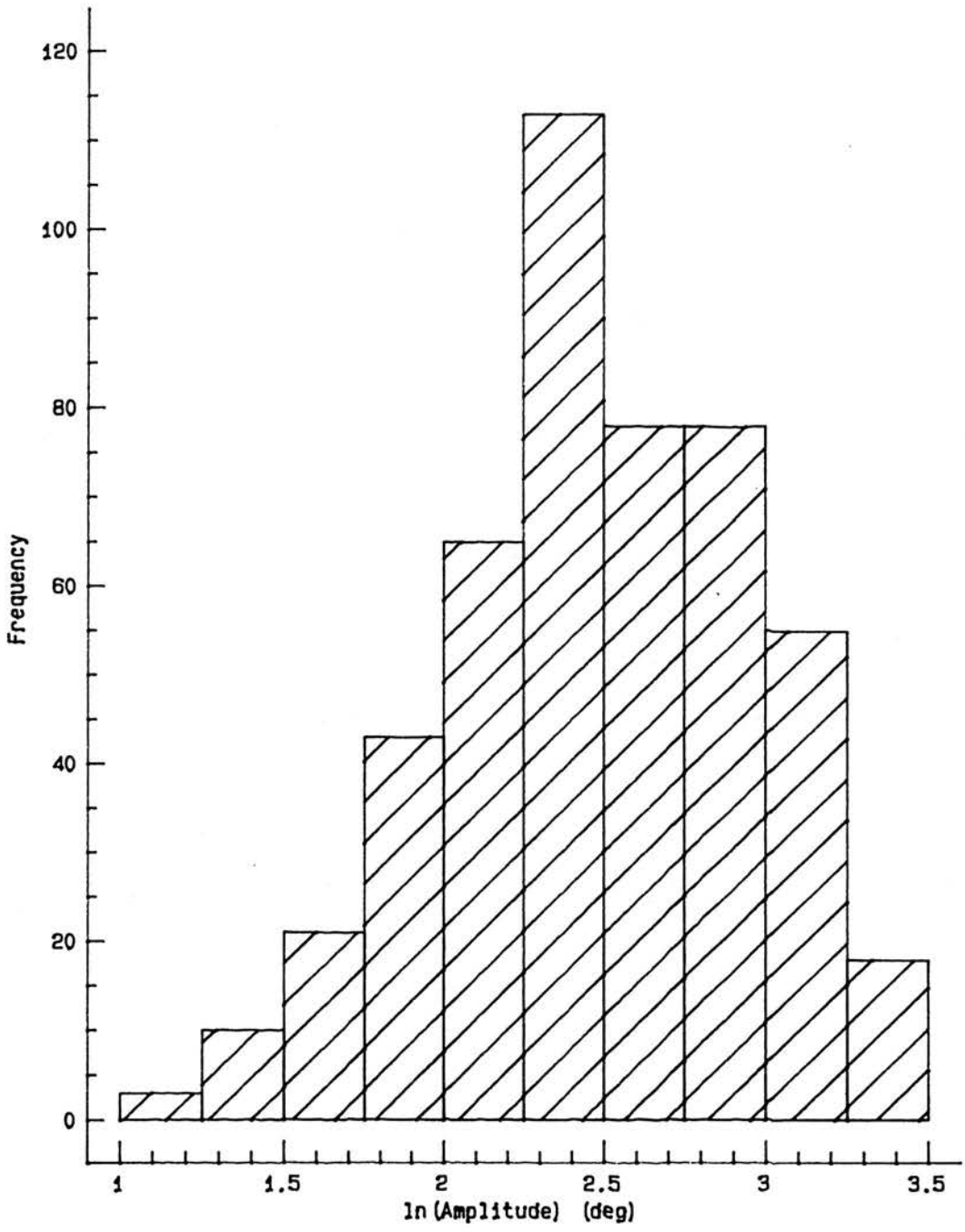
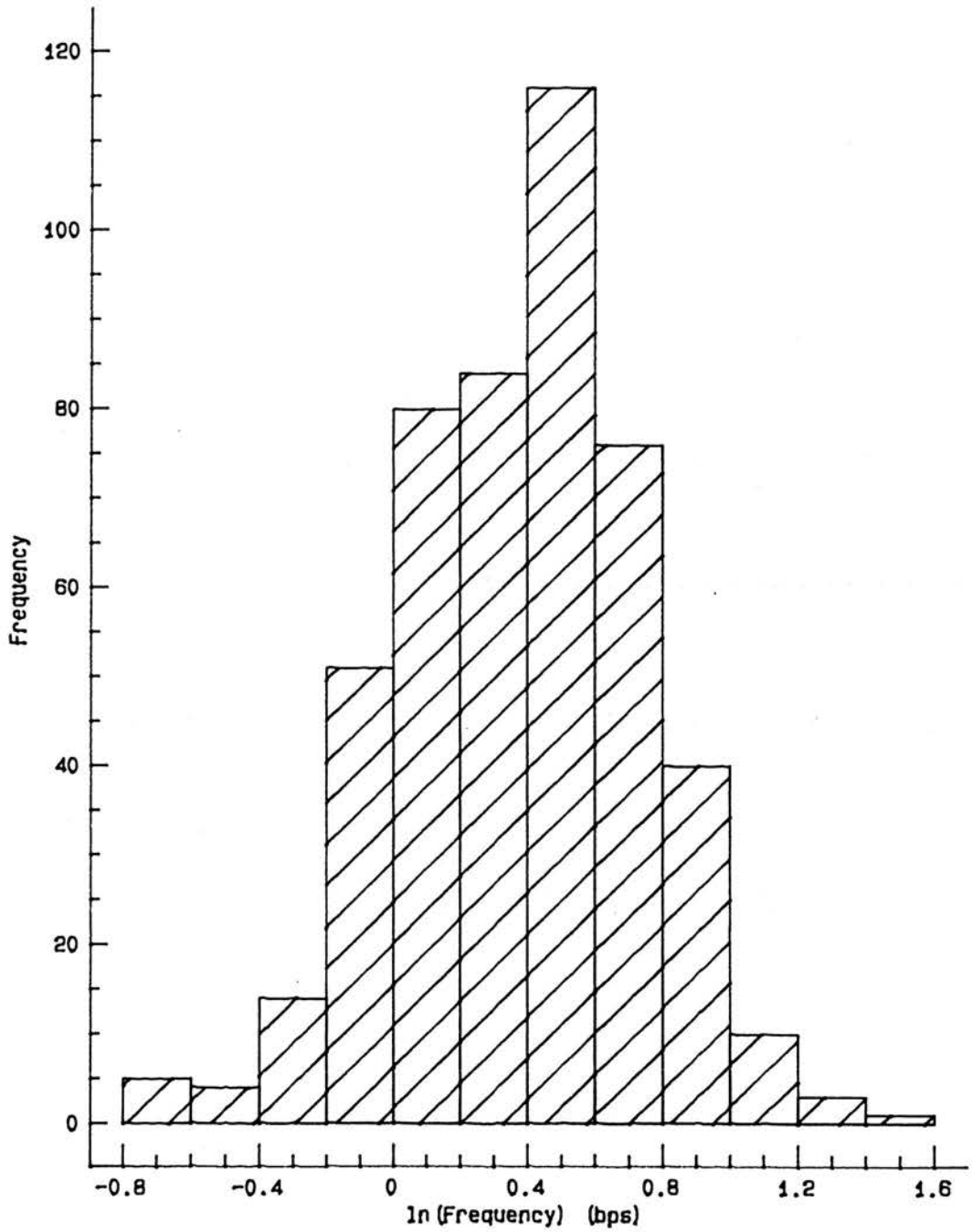


Figure 7.2

Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (logged).

iii) Frequency



These findings are in accord with previous observations which have suggested that the large scatter seen in such data is due to inter rather than intra-subject variation (Baloh and Honrubia, 1979; Proctor and Glackin, 1985).

iv) Variation by sex of patient

The results of slow phase velocity recordings made in male and female subjects were separately compared and are shown in Table 7.7. No major differences were obvious from comparisons of the means and standard deviations of each of the variables, but in order to confirm this the values of slow phase velocity attained for males and females was compared using Student's t test. The results show that no obviously significant differences are apparent (Table 7.7: $t=1.4816$; $0.5>p>0.1$) which is a finding in agreement with previous researches (Wall, Black and Hunt, 1984; Proctor and Glackin, 1985; Bergenius, Perols and Lonfqvist, 1988).

v) Canal paresis and directional preponderance

Measurements of canal paresis and directional preponderance were made and the results are given in Table 7.8. Simple linear regression analysis shows that there is no apparent pattern to the maturation of the either parameter with age (Table 7.8: $R_2=0.002$ for each variable). However, the data for canal paresis has an obviously greater variability in childhood and, as might be expected, this parameter does show a statistically significant difference from the same recordings made in adults (Table 7.8: $t=2.9793$; $p<0.01$).

These findings are collaborated in a separate and independent study (Levens, 1988). Since, when testing adults, many authors regard a canal paresis of greater than 25% and a directional preponderance of greater 30% as significant (Barber and Stockwell, 1980), it seems certain that these figures will have to be revised upwards when interpreting the data obtained in children.

Figure 7.3

Regression of slow phase velocity/age (log$_e$).

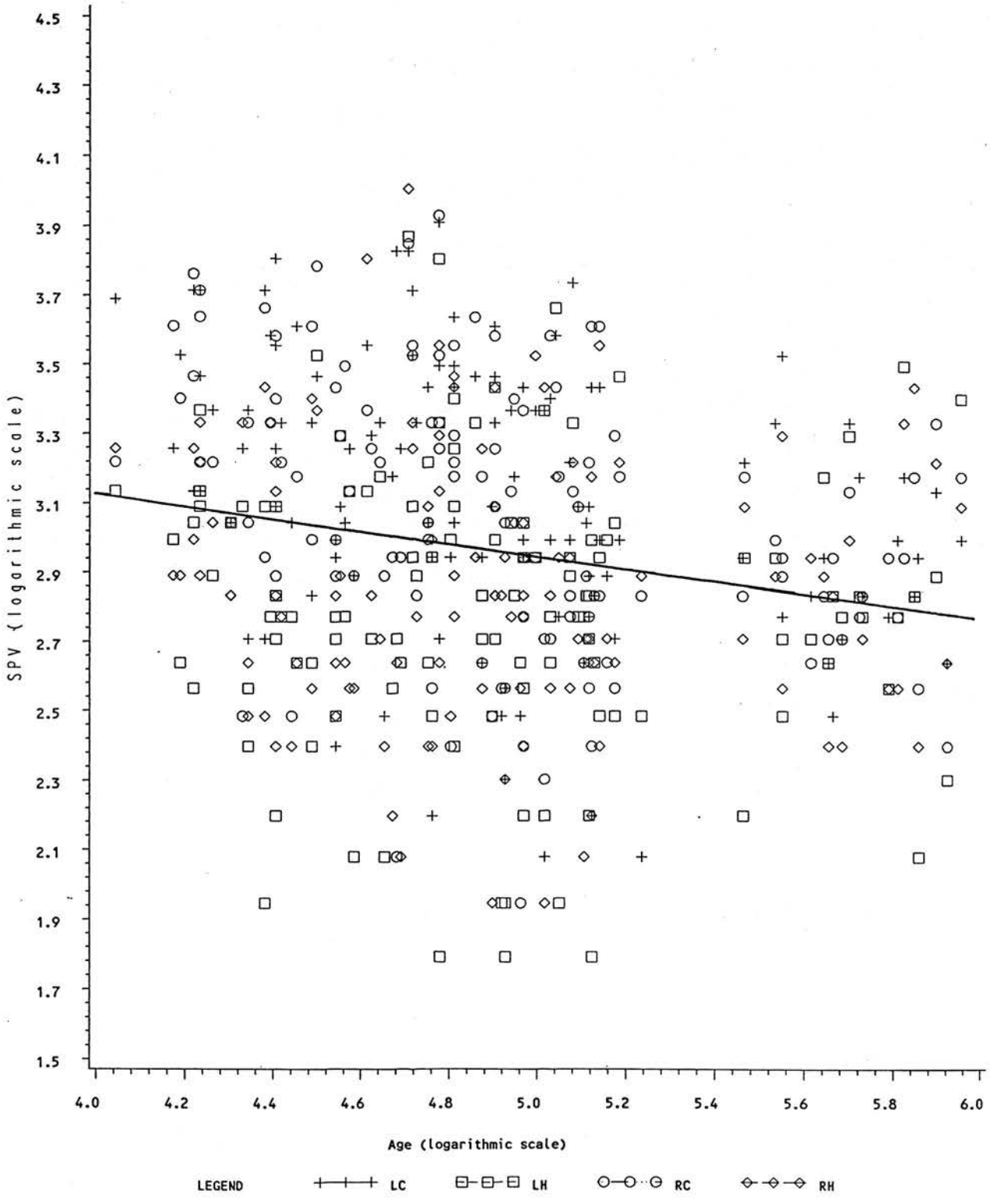


Figure 7.4

Regression of amplitude/age ($\log_e$).

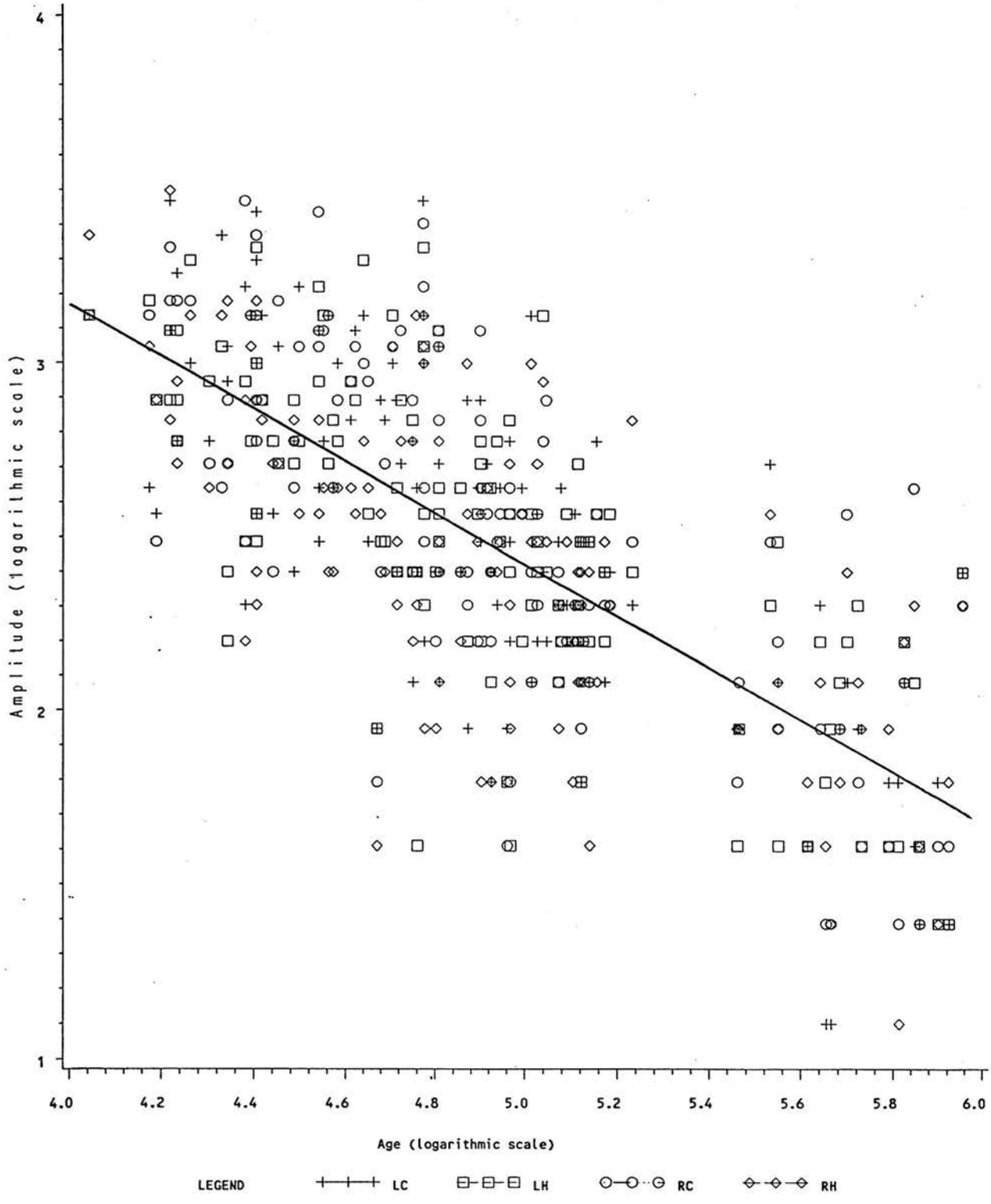
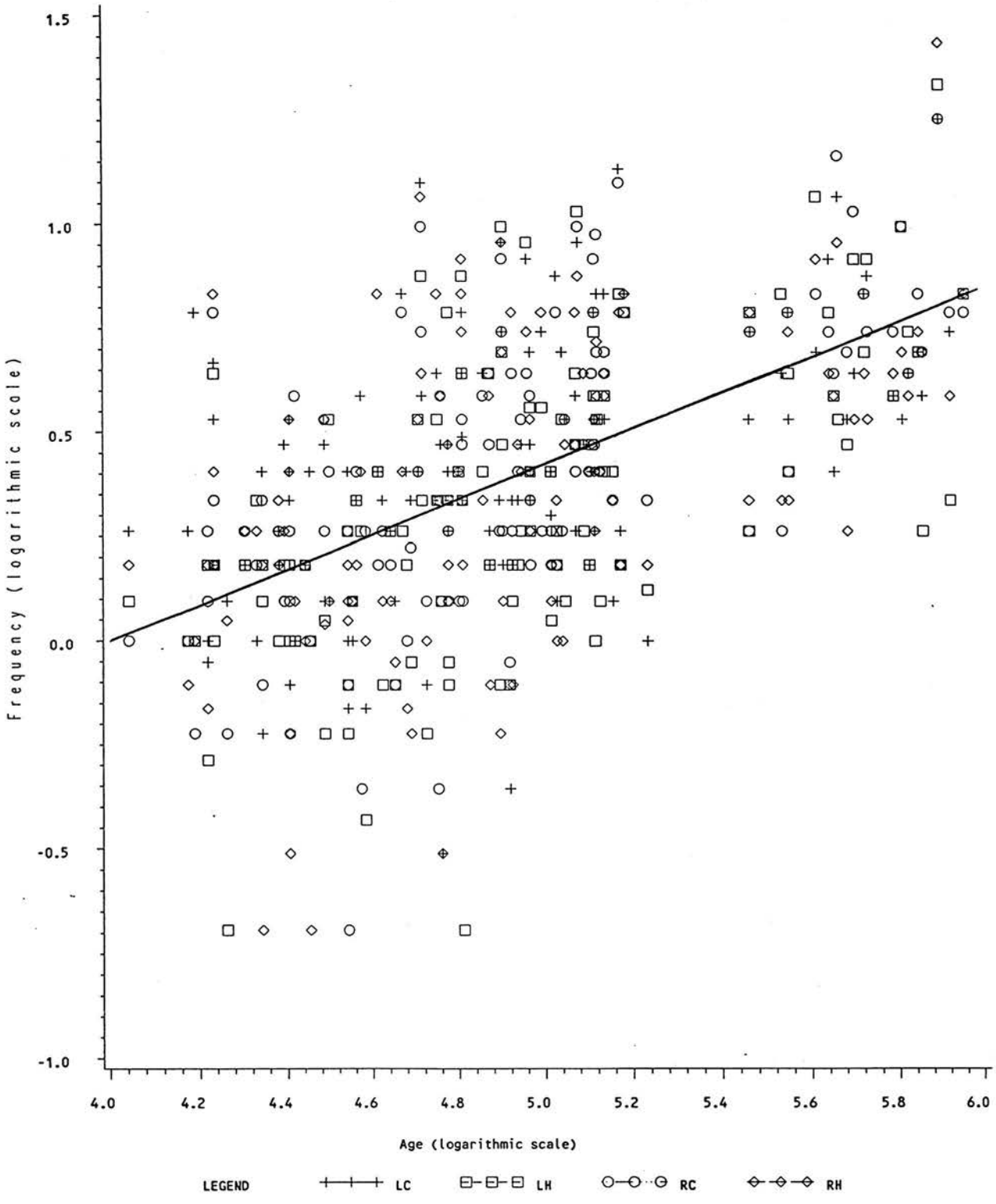


Figure 7.5

Regression of frequency/age (log.).



C. EFFECT OF VISUAL FIXATION

In the majority of the subjects tested the effect of visual fixation at ninety seconds was measured. This measurement was not made in all patients because of difficulties during testing in some individuals.

The results with the study number of the individuals tested together with their ages and response to fixation are presented in Table 7.9. It is immediately apparent that the majority of children tended to respond to fixation with an abolition of nystagmus which made recording an end point in the light impossible. Sometimes nystagmus then failed to reappear when darkness again supervened, but this also occasionally occurred in adults tested in a similar manner.

The duration of the nystagmus in the dark in children was also recorded and compared to the same data obtained in adults. When comparison was made it was apparent that the duration was less in children and this finding was statistically significant using calculations based on differences between means (S.E. Difference = 5.1149; $p<0.001$).

These results suggest that many children display enhanced visual-ocular reflex suppression and this appears to go hand in glove with a reduction in response duration.

Figure 7.6

Regressions of SPV/age for each thermal stimulus (log.). Warm water.

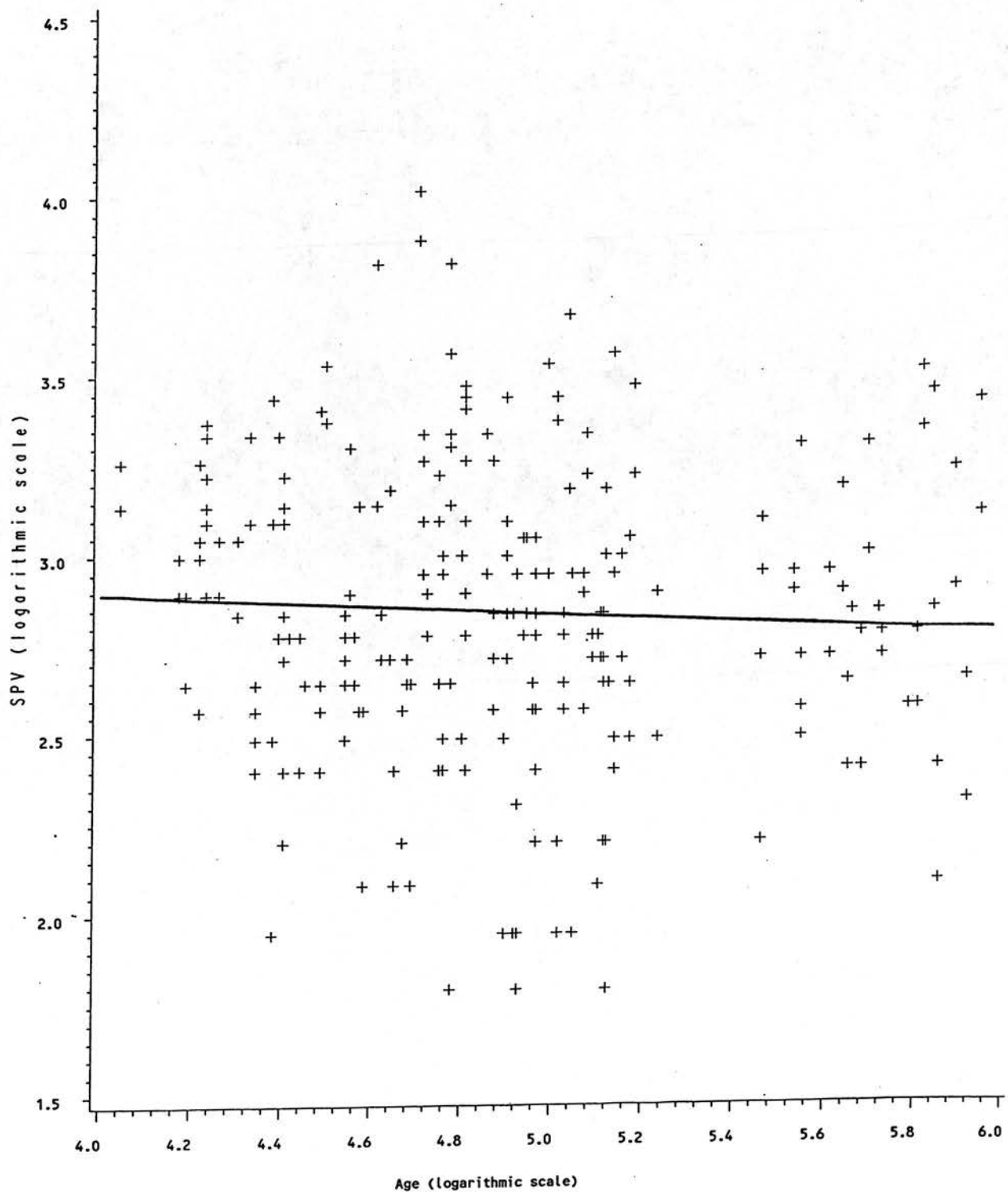


Figure 7.7

Regressions of SPV/age for each thermal stimulus (log_e). Cold water.

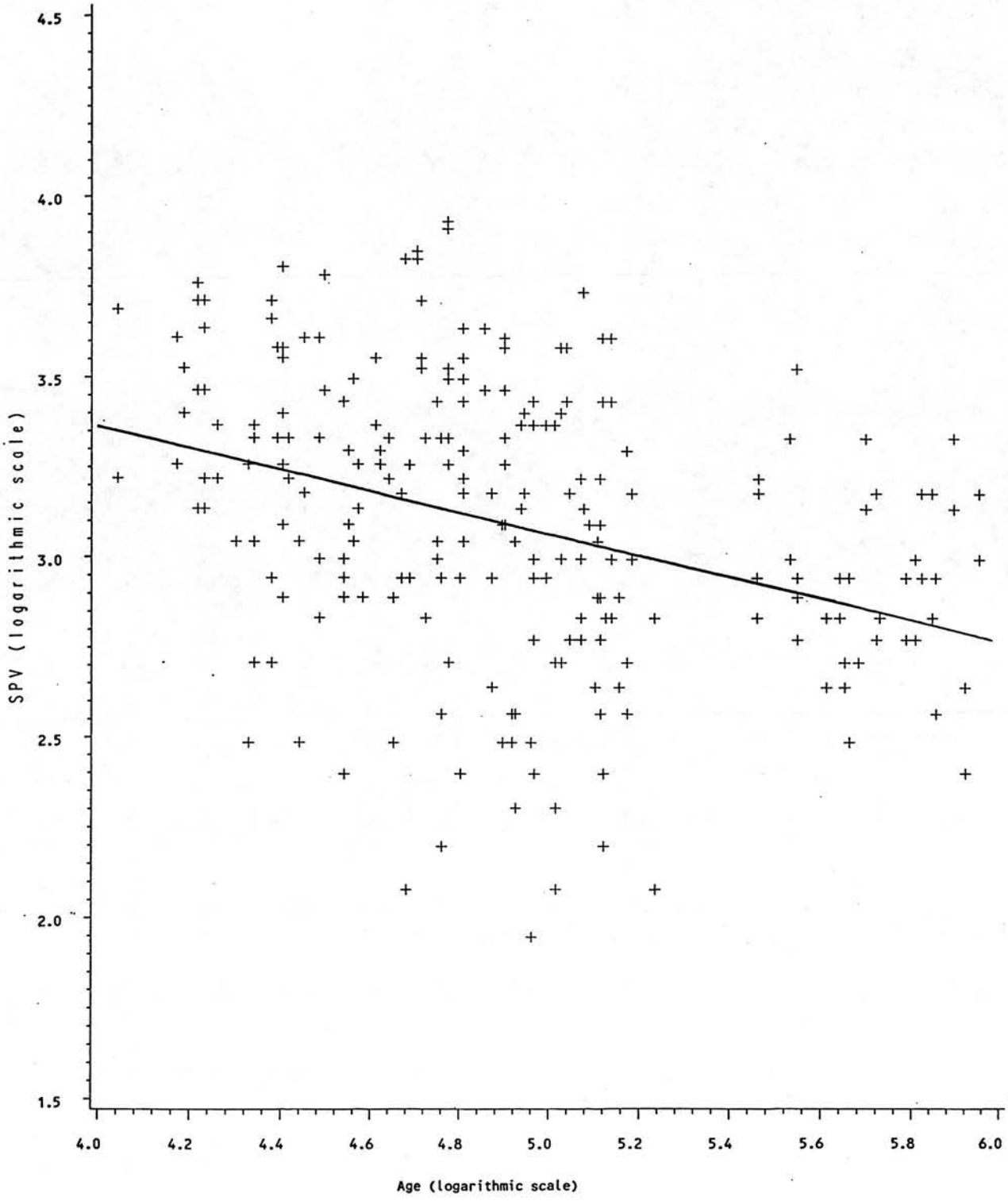


Figure 7.8

Regressions of SPV/age for individual caloric irrigations. Warm water.

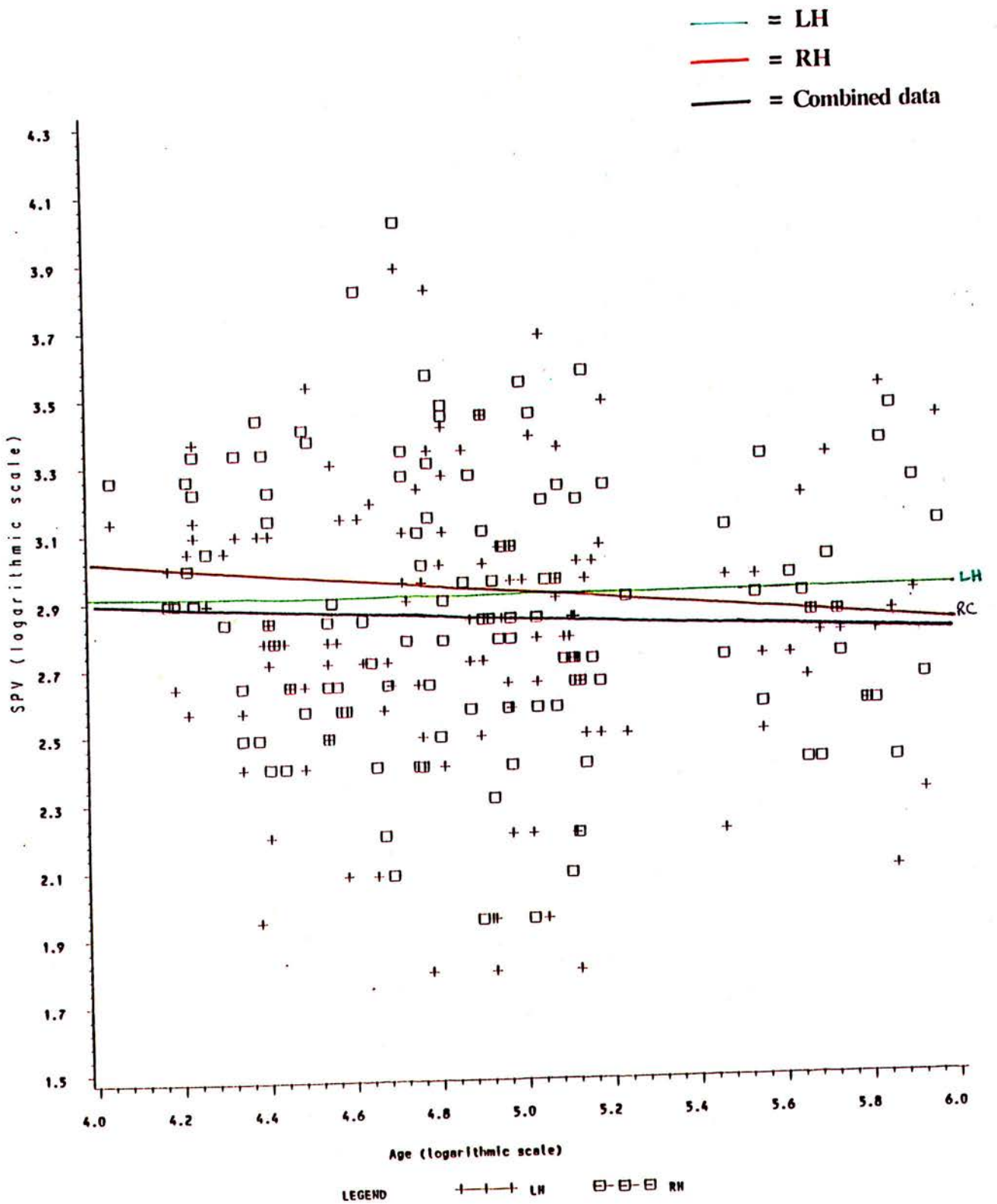
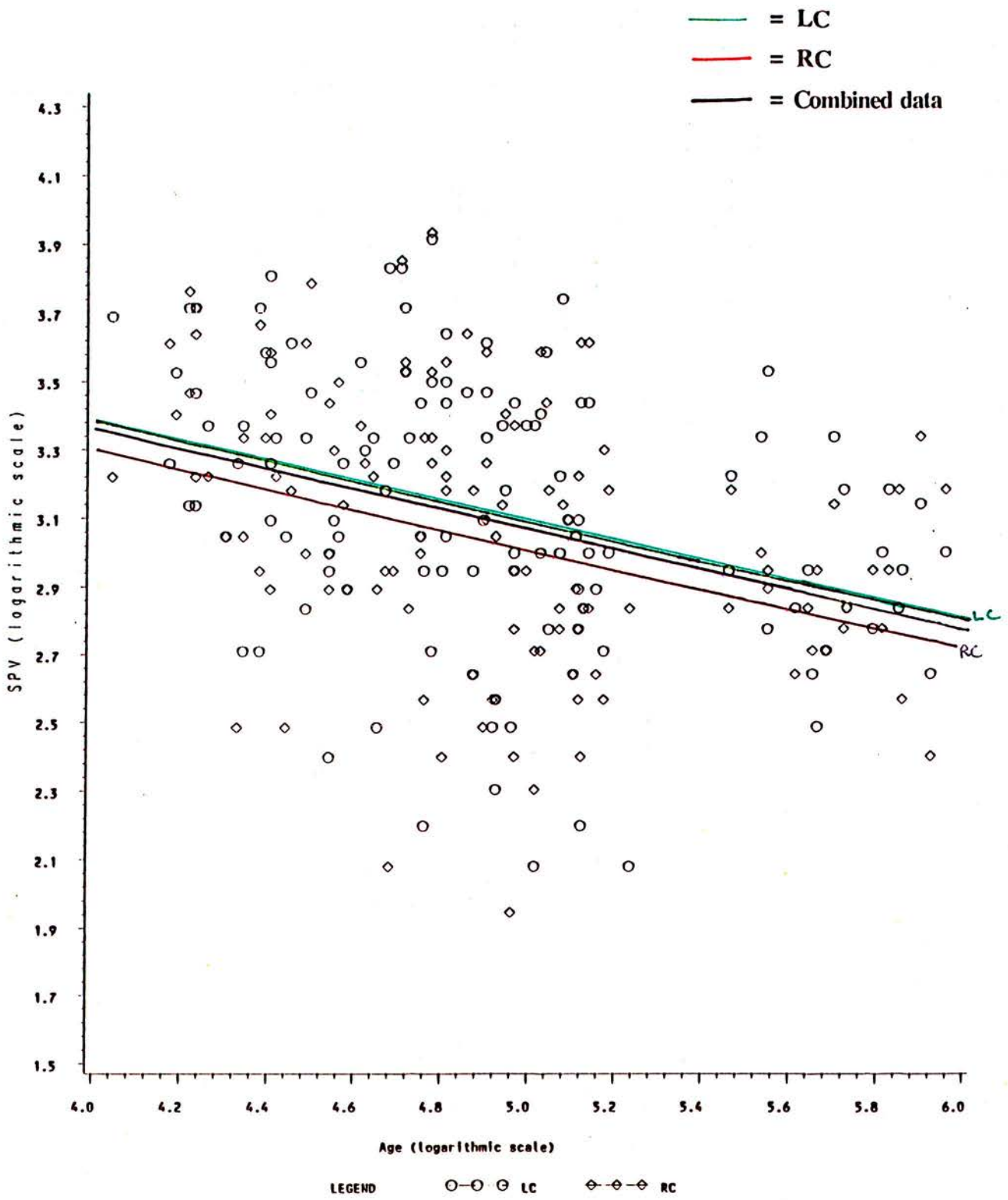


Figure 7.9

Regressions of SPV/age for individual caloric irrigations. Cold water.



CONCLUSIONS

1. The vestibulo-ocular reflex assessed by caloric irrigation shows age related effects in that there are maturation changes in slow phase velocity, amplitude and frequency between the ages of five and fourteen years. These effects appear to continue into adult life.

2. There is a diminished effect following the first caloric irrigation which appears to be at least partially responsible for the warm irrigations showing no significant change with maturation.

3. There is no variation by sex of patient.

4. There is a large scatter in the data and this is due to intra and not inter subject variation.

5. There is a significant difference between canal paresis measurements made in children and adults. The same is not so for measurements of directional preponderance, but both variables produced values in children which exceeded the upper limits normally quoted in adults.

6. The effect of optic fixation introduced during recording is not constant and is apparently to be enhanced in young children. The duration of the response is, *pari passu*, significantly reduced in children.

Table 7.1

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
1	220	200	200	200
2	190	200	200	200
3	200	180	190	180
4	195	205	200	200
5	190	200	200	200
6	185	185	190	190
7	200	200	190	180
8	200	200	200	200
9	200	195	180	195
10	200	200	200	200
11	220	210	200	220
12	190	195	200	210
13	185	185	180	200
14	190	190	180	200
15	180	190	190	190
16	200	200	200	200
17	200	190	200	190
18	200	180	180	180
19	200	200	210	200
20	200	190	190	190
21	180	190	180	180
22	200	200	200	200

Table 7.1 (continued)

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
23	190	200	190	190
24	205	200	200	200
25	190	200	220	250
26	180	190	200	200
27	200	180	180	195
28	190	180	190	190
29	190	190	190	200
30	190	200	180	190
31	200	180	200	190
32	180	185	180	180
33	190	180	190	190
34	190	190	190	190
35	180	190	190	200
36	200	200	190	200
37	200	200	200	200
38	200	200	180	200
39	200	180	200	190
40	190	180	190	200
41	180	180	200	200
42	200	190	210	210
43	190	190	180	200
44	200	200	200	190

Table 7.1 (continued)

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
45	190	200	200	190
46	180	180	195	200
47	200	200	190	200
48	210	200	200	190
49	190	190	190	190
50	190	190	210	210
51	190	190	190	190
52	190	180	190	190
53	200	190	190	190
54	200	200	210	180
55	185	200	200	200
56	200	200	200	190
57	190	200	200	200
58	180	200	200	200
59	195	200	200	195
60	180	190	200	190
61	150	290	190	190
62	180	190	200	220
63	190	190	220	215
64	190	210	200	190
65	200	190	180	190
66	190	200	200	200

Table 7.1 (continued)

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
67	200	190	200	200
68	190	200	200	200
69	160	170	200	200
70	190	200	180	185
71	185	205	190	190
72	195	200	180	180
73	200	190	210	210
74	200	190	200	200
75	190	200	200	220
76	200	190	210	200
77	200	200	200	180
78	190	180	180	200
79	190	190	190	210
80	200	190	190	200
81	180	180	210	210
82	190	190	210	210
83	180	200	200	200
84	190	170	210	240
85	190	190	210	210
86	200	190	210	200
87	185	180	200	200
88	190	190	200	200

Table 7.1 (continued)

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
89	190	200	200	200
90	180	180	230	230
91	190	170	220	250
92	200	180	200	200
93	190	190	200	200
94	200	190	200	200
95	180	180	200	210
96	200	200	200	200
97	180	180	190	200
98	200	200	180	200
99	200	190	200	210
100	180	180	200	200
101	180	180	230	250
102	190	190	230	200
103	200	200	210	200
104	210	200	200	200
105	180	180	200	200
106	210	200	220	220
107	180	200	220	240
108	200	210	210	210
109	180	180	200	190
110	180	200	200	200

Table 7.1 (continued)

Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls)

Patient Number	Caloric Irrigation (mls)			
	LH	RH	RC	LC
111	190	180	210	210
112	200	210	200	210
113	190	190	200	210
114	200	200	200	210
115	180	180	210	200
116	190	190	205	210
117	180	180	190	180
118	190	180	180	190
119	190	190	180	200
120	190	190	200	195
121	180	190	210	220

LH = Left warm

RH = Right warm

RC = Right cold

LC = Left cold

Table 7.2

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
69	22	22	1.0	28	19	1.50	41	24	1.4	32	26	1.2
69	29	16	1.9	25	15	2.30	38	16	2.8	41	16	1.9
66	14	18	1.0	18	18	1.00	30	12	0.8	34	13	2.2
57	23	23	1.1	26	29	1.20	25	33	1.0	40	23	1.3
65	20	24	1.0	18	21	0.90	37	23	1.0	26	14	1.3
68	21	22	1.2	20	17	1.20	32	24	1.1	41	32	1.0
74	21	19	1.2	17	14	1.30	21	15	1.3	21	16	1.2
68	13	18	0.8	26	33	0.85	43	28	1.3	23	22	0.9
69	23	18	1.2	18	19	1.20	25	16	1.2	23	16	1.7
83	16	18	1.0	16	17	1.10	25	18	1.8	28	23	1.0
76	22	21	1.4	28	23	1.30	12	14	1.2	26	29	1.0
77	11	11	1.2	12	15	1.20	28	15	1.4	29	19	1.5
71	18	27	0.5	21	23	1.05	25	24	0.8	29	20	1.1
77	13	9	1.1	14	24	0.50	21	18	0.9	15	21	0.8
81	16	16	1.2	28	21	1.30	28	23	1.1	36	23	1.6
82	9	13	1.0	25	10	1.50	18	16	1.1	26	13	1.7
82	22	28	1.0	11	24	0.60	30	23	0.8	35	27	0.9
82	15	12	1.2	23	11	1.70	36	29	1.3	22	20	1.5

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
80	7	12	1.0	12	9	1.20	19	12	1.3	15	10	1.3
80	22	19	1.0	31	18	1.40	39	32	1.3	41	25	1.2
94	16	19	1.3	14	13	1.10	20	21	0.9	20	14	1.5
89	14	18	0.8	30	16	1.70	37	16	1.7	28	11	1.6
85	16	16	1.2	11	15	1.00	12	11	1.2	21	13	1.2
95	27	23	1.1	18	14	1.10	27	22	1.1	22	16	1.0
90	34	16	1.7	29	13	1.10	44	21	1.5	32	25	1.1
94	15	25	0.8	12	13	1.05	18	31	0.5	19	22	1.0
89	11	15	1.5	13	17	1.40	20	14	1.3	17	16	1.1
82	17	20	1.0	17	18	0.80	18	18	1.1	45	31	1.4
86	14	15	1.0	14	15	0.50	24	24	1.0	37	21	1.5
94	12	19	0.9	17	17	1.20	31	22	1.3	11	12	0.8
109	14	12	1.0	8	11	0.80	19	15	1.2	26	17	1.4
104	24	27	1.3	15	16	1.10	25	20	1.2	28	23	1.3
98	8	16	0.6	13	14	1.00	18	18	1.3	18	20	0.8
96	16	15	1.4	14	11	1.20	33	23	1.5	21	23	1.4
101	23	19	1.5	45	14	2.30	29	19	1.2	35	17	1.5
102	15	18	0.9	17	13	1.10	26	21	1.3	27	22	1.4

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
105	8	13	0.9	11	14	0.95	18	19	0.9	12	12	1.1
97	23	17	1.3	13	11	1.50	23	14	0.7	26	14	1.8
108	15	12	1.2	14	13	0.85	8	11	1.0	46	18	1.5
112	22	11	2.4	28	10	2.90	34	11	2.7	41	11	3.0
107	13	7	1.3	9	5	1.50	19	6	2.2	24	7	2.3
117	19	5	1.1	11	23	0.60	13	11	1.1	9	11	0.6
116	25	17	1.7	22	16	2.30	21	18	1.4	31	16	1.4
111	48	23	1.7	55	21	1.70	47	21	1.5	46	20	1.5
116	14	11	1.3	11	9	1.40	20	11	0.7	21	8	1.9
119	45	28	0.9	23	23	1.20	34	30	1.1	50	32	1.5
112	19	14	1.4	26	12	1.90	35	11	2.1	34	18	1.8
113	18	18	0.8	16	16	1.00	17	22	1.1	28	15	0.9
117	12	11	1.4	20	10	1.80	28	11	1.8	19	14	1.6
119	28	13	1.4	27	20	1.10	26	12	1.4	33	20	1.3
129	28	14	1.5	19	9	1.40	38	11	1.8	32	11	1.9
131	17	9	1.9	26	20	1.80	24	10	1.9	19	18	1.2
123	26	13	1.9	31	16	2.30	27	21	1.4	33	15	1.9
119	6	10	0.9	14	7	1.20	28	14	1.4	15	9	1.6

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
119	45	21	2.2	35	21	1.60	51	25	1.3	33	23	1.4
123	30	14	2.4	32	11	2.50	35	17	1.7	31	11	2.2
123	11	12	0.5	16	8	2.10	24	11	1.6	21	8	1.6
131	15	9	1.2	13	13	0.90	14	11	1.6	14	7	1.3
123	22	22	1.4	18	12	1.20	25	22	1.1	38	21	1.4
122	20	11	1.5	12	7	1.50	11	9	1.1	19	11	1.5
144	21	17	1.5	21	15	1.30	16	14	1.2	31	16	1.6
140	21	16	1.2	16	11	1.60	23	12	1.5	29	10	1.4
137	7	14	0.9	17	14	0.90	13	13	0.9	12	15	0.7
135	15	16	1.6	17	14	1.10	22	22	1.3	28	18	1.2
134	12	13	0.9	7	12	0.80	12	9	1.3	22	14	1.4
141	17	12	1.3	21	12	1.50	30	13	1.7	24	14	1.6
138	7	14	1.1	10	11	0.90	13	11	1.3	13	11	1.4
138	6	8	1.2	19	6	2.20	21	9	1.9	10	6	1.2
135	20	9	2.7	22	6	2.60	26	14	2.5	37	13	2.6
143	14	6	2.6	13	6	2.10	7	5	1.9	12	7	2.5
135	31	15	2.0	31	13	2.00	36	17	2.1	32	12	2.1
151	9	10	1.0	7	12	1.1	10	8	1.2	8	8	1.3

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
153	16	11	1.3	17	12	1.40	36	13	2.2	30	9	2.4
144	9	5	1.3	11	7	1.30	11	6	1.5	19	9	1.4
144	13	13	1.3	16	8	1.70	19	14	1.4	20	9	2.0
148	19	9	1.7	34	13	2.20	19	13	1.3	29	14	2.1
151	29	13	1.5	31	20	1.20	15	11	1.3	29	23	1.5
155	39	23	1.7	24	19	1.00	31	16	1.3	36	11	2.0
144	19	11	1.7	17	10	1.50	29	13	1.8	19	12	1.5
153	14	12	1.2	13	15	1.00	15	10	1.2	20	13	1.1
160	19	10	1.6	19	10	2.20	17	11	1.6	20	10	1.8
165	16	9	1.2	8	6	1.50	14	9	1.5	14	9	1.2
156	7	11	1.1	19	12	1.60	24	18	1.7	16	9	1.7
167	17	15	1.8	15	8	1.70	16	9	2.2	16	10	1.7
167	15	9	2.1	14	11	1.30	25	10	2.5	22	9	2.2
166	17	9	1.6	15	9	1.60	18	10	1.9	21	13	1.5
167	9	10	1.0	15	10	1.50	13	9	1.6	18	10	1.3
163	16	13	1.3	15	12	1.90	22	9	1.6	22	10	1.6
161	28	9	2.8	25	10	2.40	23	9	2.7	42	14	2.6
160	18	8	1.9	13	7	1.60	16	8	1.5	25	12	1.3

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
171	12	9	1.5	35	11	1.80	37	10	2.0	31	12	1.7
168	20	12	1.7	24	11	1.80	37	10	2.0	31	12	1.7
177	21	11	2.3	14	12	2.20	27	10	3.0	15	8	3.1
168	6	6	1.8	9	8	2.05	11	7	2.6	9	6	2.3
174	20	13	1.5	15	8	1.40	14	13	1.4	18	16	1.1
177	12	9	1.2	14	12	1.20	13	10	1.2	15	11	1.3
171	19	12	1.8	11	5	1.90	17	8	1.9	20	8	2.3
188	12	11	1.1	18	17	1.20	17	12	1.4	8	10	1.0
169	14	12	1.1	14	8	1.50	17	9	1.5	17	9	1.7
179	32	13	2.2	25	10	2.30	24	10	2.2	20	11	2.3
388	30	11	2.3	22	10	2.30	24	10	2.2	20	11	2.3
366	18	4	3.8	25	4	4.20	28	5	3.5	23	6	3.5
307	17	10	2.0	17	8	1.90	16	6	2.3	24	7	2.3
258	15	12	1.5	13	8	1.40	18	9	1.5	16	8	1.7
258	12	5	1.9	27	7	2.10	19	7	2.2	34	8	2.2
283	24	9	2.2	18	8	1.90	17	7	2.1	19	10	2.5
254	19	10	2.3	18	13	1.40	20	12	1.3	28	15	1.9
348	17	8	2.0	31	10	2.10	24	14	2.3	17	5	2.0

Table 7.2 (continued)

Results of Caloric Irrigation; Unlogged

	Age	Left Warm			Right Warm			Left Cold			Right Cold		
	(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
	275	15	5	2.9	19	6	2.50	14	5	2.3	17	5	2.0
	295	16	8	1.6	11	6	1.30	15	7	2.0	15	7	1.7
	286	14	6	1.8	11	5	1.80	15	4	1.9	14	3	1.5
	351	8	5	1.3	11	5	2.00	13	4	2.0	19	4	1.8
	300	16	5	2.7	13	3	2.00	16	4	2.7	20	6	1.7
	300	27	9	2.5	20	11	1.70	23	13	2.8	28	8	1.9
	309	16	5	2.5	15	7	1.70	17	5	2.1	17	7	2.4
	375	10	4	1.4	14	6	1.80	11	5	2.2	14	4	2.1
	237	19	7	2.2	22	7	2.20	24	8	2.1	25	7	2.1
	236	9	5	1.3	15	7	1.40	17	6	1.3	19	7	1.7
	340	33	9	2.1	28	9	1.80	19	8	1.9	24	8	1.9
	328	13	5	1.8	13	7	1.90	19	5	2.1	16	6	1.8
	289	17	7	1.7	17	4	2.60	19	4	3.2	12	3	2.9
Mean	152.5	18.2	13.3	1.5	18.9	12.6	1.53	23.1	13.9	1.6	24.4	13.7	1.63
S.D.	79.2	7.9	5.6	0.56	7.8	5.5	0.56	8.9	6.7	0.56	9.2	6.5	0.51
Skew	1.331	1.3	0.6	1.1	1.4	0.9	1.1	0.7	0.9	0.5	0.77	0.8	

Table 7.3
Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
4.23	3.09	3.09	0.00	3.33	2.94	0.40	3.71	3.17	0.33	3.46	3.25	0.18
4.23	3.36	2.77	0.64	3.21	2.70	0.83	3.63	2.77	1.02	3.71	2.77	0.66
4.18	2.63	2.89	0.00	2.89	2.89	0.00	3.40	2.48	-0.22	3.52	2.56	0.78
4.04	3.13	3.13	0.09	3.25	3.36	0.18	3.21	3.49	0.00	3.68	3.13	0.26
4.17	2.99	3.17	0.00	2.89	3.04	-0.10	3.61	3.13	0.00	3.25	2.63	0.26
4.21	3.04	3.09	0.18	2.99	2.83	0.18	3.46	3.17	0.09	3.71	3.46	0.00
4.30	3.04	2.94	0.18	2.83	2.63	0.26	3.04	2.70	0.26	3.04	2.77	0.18
4.21	2.56	2.89	-0.28	3.25	3.49	-0.16	3.76	3.33	0.26	3.13	3.09	-0.05
4.23	3.13	2.89	0.18	2.89	2.94	0.18	3.21	2.77	0.18	3.13	2.77	0.53
4.41	2.77	2.89	0.00	2.77	2.83	0.09	3.21	2.89	0.58	3.33	3.13	0.00
4.33	3.09	3.04	0.33	3.33	3.13	0.26	2.48	2.63	0.18	3.25	3.36	0.00
4.34	2.39	2.39	0.18	2.48	2.70	0.18	3.33	2.70	0.33	3.36	2.94	0.40
4.26	2.89	3.29	-0.69	3.04	3.13	0.04	3.21	3.17	-0.22	3.36	2.99	0.09
4.34	2.56	2.19	0.09	2.63	3.17	-0.69	3.04	2.89	-0.10	2.70	3.04	-0.22
4.39	2.77	2.77	0.18	3.33	3.04	0.26	3.33	3.13	0.09	3.58	3.13	0.47
4.40	2.19	2.56	0.00	3.21	2.30	0.40	2.89	2.77	0.09	3.25	2.56	0.53
4.40	3.09	3.33	0.00	2.39	3.17	-0.51	3.40	3.13	-0.22	3.55	3.29	-0.10

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
4.40	2.70	2.48	0.18	3.13	2.39	0.53	3.58	3.36	0.26	3.09	2.99	0.40
4.38	1.94	2.48	0.00	2.48	2.19	0.18	2.94	2.48	0.26	2.70	2.30	0.26
4.38	3.09	2.94	0.00	3.43	2.89	0.33	3.66	3.46	0.26	3.71	3.21	0.18
4.54	2.77	2.94	0.26	2.63	2.56	0.09	2.99	3.04	-0.10	2.99	2.63	0.40
4.48	2.63	2.89	-0.22	3.40	2.77	0.53	3.61	2.77	0.53	3.33	2.39	0.47
4.44	2.77	2.77	0.18	2.39	2.70	0.00	2.48	2.39	0.18	3.04	2.56	0.18
4.55	3.29	3.13	0.09	2.89	2.63	0.09	3.29	3.09	0.09	3.09	2.77	0.00
4.49	3.52	2.77	0.53	3.36	2.56	0.09	3.78	3.04	0.40	3.46	3.21	0.09
4.54	2.70	3.21	-0.22	2.48	2.56	0.04	2.89	3.43	-0.69	2.94	3.09	0.00
4.48	2.39	2.70	0.40	2.56	2.83	0.33	2.99	2.63	0.26	2.83	2.77	0.09
4.40	2.83	2.99	0.00	2.83	2.89	-0.22	2.89	2.89	0.09	3.80	3.43	0.33
4.45	2.63	2.70	0.00	2.63	2.70	-0.69	3.17	3.17	0.00	3.61	3.04	0.40
4.54	2.48	2.94	-0.10	2.83	2.83	0.18	3.43	3.09	0.26	2.39	2.48	-0.16
4.69	2.63	2.48	-0.05	2.07	2.39	-0.22	2.94	2.70	0.22	3.25	2.83	0.33
4.64	3.17	3.29	0.26	2.70	2.77	0.09	3.21	2.99	0.18	3.33	3.13	0.26
4.58	2.07	2.77	-0.43	2.56	2.63	0.00	2.89	2.89	0.26	2.89	2.99	-0.16
4.56	2.77	2.70	0.33	2.63	2.39	0.18	3.49	3.13	0.40	3.04	3.13	0.33
4.61	3.13	2.94	0.40	3.80	2.63	0.83	3.36	2.94	0.18	3.55	2.83	0.40

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
4.62	2.70	2.89	-0.10	2.83	2.56	0.09	3.25	3.04	0.26	3.29	3.09	0.33
4.65	2.07	2.56	-0.10	2.39	2.63	-0.05	2.89	2.94	-0.10	2.48	2.48	0.09
4.57	3.13	2.83	0.26	2.56	2.39	0.40	3.13	2.63	-0.35	3.25	2.63	0.58
4.68	2.70	2.48	0.18	2.63	2.56	-0.16	2.07	2.39	0.00	3.82	2.89	0.40
4.71	3.09	2.39	0.87	3.33	2.30	1.06	3.52	2.39	0.99	3.71	2.39	1.09
4.67	2.56	1.94	0.26	2.19	1.60	0.40	2.94	1.79	0.78	3.17	1.94	0.83
4.76	2.94	1.60	0.09	2.39	3.13	-0.51	2.56	2.39	0.09	2.19	2.39	-0.51
4.75	3.21	2.83	0.53	3.09	2.77	0.83	3.04	2.89	0.33	3.43	2.77	0.33
4.70	3.87	3.13	0.53	4.00	3.04	0.53	3.85	3.04	0.40	3.82	2.99	0.40
4.75	2.63	2.39	0.26	2.39	2.19	0.33	2.99	2.39	-0.35	3.04	2.07	0.64
4.77	3.80	3.33	-0.05	3.13	3.13	0.18	3.52	3.40	0.09	3.91	3.46	0.40
4.71	2.94	2.63	0.33	3.25	2.48	0.64	3.55	2.39	0.74	3.52	2.89	0.58
4.72	2.89	2.89	-0.22	2.77	2.77	0.00	2.83	3.09	0.09	3.33	2.70	-0.10
4.76	2.48	2.39	0.33	2.99	2.30	0.58	3.33	2.39	0.58	2.94	2.63	0.47
4.77	3.33	2.56	0.33	3.29	2.99	0.09	3.25	2.48	0.33	3.49	2.99	0.26
4.85	3.33	2.63	0.40	2.94	2.19	0.33	3.63	2.39	0.58	3.46	2.39	0.64
4.87	2.83	2.19	0.64	3.25	2.99	0.58	3.17	2.30	0.64	2.94	2.89	0.18
4.81	3.25	2.56	0.64	3.43	2.77	0.83	3.29	3.04	0.33	3.49	2.70	0.64

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
4.77	1.79	2.30	-0.10	2.63	1.94	0.18	3.33	2.63	0.33	2.70	2.19	0.47
4.77	3.80	3.04	0.78	3.55	3.04	0.47	3.93	3.21	0.26	3.49	3.13	0.33
4.81	3.40	2.63	0.87	3.46	2.39	0.91	3.55	2.83	0.53	3.43	2.39	0.78
4.81	2.39	2.48	-0.69	2.77	2.07	0.74	3.17	2.39	0.47	3.04	2.07	0.48
4.87	2.70	2.19	0.18	2.56	2.56	-0.10	2.63	2.39	0.47	2.63	1.94	0.26
4.81	3.09	3.09	0.33	2.89	2.48	0.18	3.21	3.09	0.09	3.63	3.04	0.33
4.80	2.99	2.39	0.40	2.48	1.94	0.40	2.39	2.19	0.09	2.94	2.39	0.40
4.96	3.04	2.83	0.40	3.04	2.70	0.26	2.77	2.63	0.18	3.43	2.77	0.47
4.94	3.04	2.77	0.18	2.77	2.39	0.47	3.13	2.48	0.40	3.36	2.30	0.33
4.91	1.94	2.63	-0.10	2.83	2.63	-0.10	2.56	2.56	-0.05	2.48	2.70	-0.35
4.90	2.70	2.77	0.47	2.83	2.63	0.09	3.09	3.09	0.26	3.33	2.89	0.18
4.89	2.48	2.56	-0.10	1.94	2.48	-0.22	2.48	2.19	0.26	3.09	2.63	0.33
4.94	2.83	2.48	0.26	3.04	2.48	0.40	3.40	2.56	0.53	3.17	2.63	0.47
4.92	1.94	2.63	0.09	2.30	2.39	-0.10	2.56	2.39	0.26	2.56	2.39	0.33
4.92	1.79	2.07	0.18	2.94	1.79	0.78	3.04	2.19	0.64	2.30	1.79	0.18
4.90	2.99	2.19	0.99	3.09	1.79	0.95	3.25	2.63	0.91	3.61	2.56	0.95
4.96	2.63	1.79	0.95	2.56	1.79	0.74	1.94	1.60	0.64	2.48	1.94	0.91
4.90	3.43	2.70	0.69	3.43	2.56	0.69	3.58	2.83	0.74	3.46	2.48	0.74

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
5.01	2.19	2.30	0.04	1.94	2.48	0.09	2.30	2.07	0.18	2.07	2.07	0.30
5.03	2.77	2.39	0.26	2.83	2.48	0.33	3.58	2.56	0.78	3.40	2.19	0.87
4.96	2.19	1.60	0.26	2.39	1.94	0.26	2.39	1.79	0.40	2.94	2.19	0.33
4.96	2.56	2.56	0.26	2.77	2.07	0.53	2.94	2.63	0.33	2.99	2.19	0.69
4.99	2.94	2.19	0.55	3.52	2.56	0.78	2.94	2.56	0.26	3.36	2.63	0.74
5.01	3.36	2.56	0.40	3.43	2.99	0.18	2.70	2.39	0.26	3.36	3.13	0.40
5.04	3.66	3.13	0.53	3.17	2.94	0.00	3.43	2.77	0.26	3.58	2.39	0.69
4.96	2.94	2.39	0.55	2.83	2.30	0.40	3.36	2.56	0.58	2.94	2.48	0.40
5.03	2.63	2.48	0.18	2.56	2.70	0.00	2.70	2.30	0.18	2.99	2.56	0.09
5.07	2.94	2.30	0.47	2.94	2.30	0.78	2.83	2.39	0.47	2.99	2.30	0.58
5.10	2.77	2.19	0.18	2.07	1.79	0.40	2.63	2.19	0.40	2.63	2.19	0.18
5.04	1.94	2.39	0.09	2.94	2.48	0.47	3.17	2.89	0.53	2.77	2.19	0.53
5.11	2.83	2.70	0.58	2.70	2.07	0.53	2.77	2.19	0.78	2.77	2.30	0.53
5.11	2.70	2.19	0.74	2.63	2.39	0.26	3.21	2.30	0.91	3.09	2.19	0.78
5.11	2.83	2.19	0.47	2.70	2.19	0.47	2.89	2.30	0.64	3.04	2.56	0.40
5.11	2.19	2.30	0.00	2.70	2.30	0.40	2.56	2.19	0.47	2.89	2.30	0.26
5.09	2.77	2.56	0.26	2.70	2.48	0.64	3.09	2.19	0.47	3.09	2.30	0.47
5.08	3.33	2.19	1.02	3.21	2.30	0.87	3.13	2.19	0.99	3.73	2.63	0.95

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

Age	Left Warm			Right Warm			Left Cold			Right Cold		
(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
5.07	2.89	2.07	0.64	2.56	1.94	0.47	2.77	2.07	0.40	3.21	2.48	0.26
5.14	2.48	2.19	0.40	3.55	2.39	0.58	3.61	2.30	0.69	3.43	2.48	0.53
5.12	2.99	2.48	0.53	3.17	2.39	0.58	3.61	2.30	0.69	3.43	2.48	0.53
5.17	3.04	2.39	0.83	2.63	2.48	0.78	3.29	2.30	1.09	2.70	2.07	1.13
5.12	1.79	1.79	0.58	2.19	2.07	0.71	2.39	1.94	0.97	2.19	1.79	0.83
5.15	2.99	2.56	0.40	2.70	2.07	0.33	2.63	2.56	0.33	2.89	2.77	0.09
5.17	2.48	2.19	0.18	2.63	2.48	0.18	2.56	2.30	0.18	2.70	2.39	0.26
5.14	2.94	2.48	0.58	2.39	1.60	0.64	2.83	2.07	0.64	2.99	2.07	0.83
5.23	2.48	2.39	0.12	2.89	2.83	0.18	2.83	2.48	0.33	2.07	2.30	0.00
5.12	2.63	2.48	0.09	2.63	2.07	0.40	2.83	2.19	0.40	2.83	2.19	0.53
5.18	3.46	2.56	0.78	3.21	2.30	0.53	3.04	2.39	0.58	3.09	2.19	0.64
5.96	3.40	2.39	0.83	3.09	2.30	0.83	3.17	2.30	0.78	2.99	2.39	0.83
5.90	2.89	1.38	1.33	3.21	1.38	1.43	3.33	1.60	1.25	3.13	1.79	1.25
5.72	2.83	2.30	0.69	2.83	2.07	0.64	2.77	1.79	0.83	3.17	1.94	0.83
5.55	2.70	2.48	0.40	2.56	2.07	0.33	2.89	2.19	0.40	2.77	2.07	0.53
5.55	2.48	1.60	0.64	3.29	1.94	0.74	2.94	1.94	0.78	3.52	2.07	0.78
5.64	3.17	2.19	0.78	2.89	2.07	0.64	2.83	1.94	0.74	2.94	2.30	0.91
5.53	2.94	2.30	0.83	2.89	2.56	0.33	2.99	2.48	0.26	3.33	2.70	0.64

Table 7.3 (continued)

Results of Caloric Irrigation; Logged (Log_e)

	Age	Left Warm			Right Warm			Left Cold			Right Cold		
	(months)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)	S.P.V. (°/sec)	Amplitude (degrees)	Frequency (b.p.s.)
	5.85	2.83	2.07	0.69	3.43	2.30	0.74	3.17	2.63	0.83	2.83	1.60	0.69
	5.61	2.70	1.60	1.06	2.94	1.79	0.91	2.63	1.60	0.83	2.83	1.60	0.69
	5.68	2.77	2.07	0.47	2.39	1.79	0.26	2.70	1.94	0.69	2.70	1.94	0.53
	5.65	2.63	1.79	0.58	2.39	1.60	0.58	2.70	1.38	0.64	2.63	1.09	0.40
	5.86	2.07	1.60	0.26	2.39	1.60	0.69	2.56	1.38	0.69	2.94	1.38	0.58
	5.81	2.77	1.60	0.99	2.56	1.09	0.69	2.77	1.38	0.99	2.99	1.79	0.53
	5.70	3.29	2.19	0.91	2.99	2.39	0.53	3.13	2.56	1.02	3.33	2.07	0.64
	5.73	2.77	1.60	0.91	2.70	1.94	0.53	2.83	1.60	0.74	2.83	1.94	0.87
	5.92	2.30	1.38	0.33	2.63	1.79	0.58	2.39	1.60	0.78	2.63	1.38	0.74
	5.46	2.94	1.94	0.78	3.09	1.94	0.78	3.17	2.07	0.74	3.21	1.94	0.74
	5.46	2.19	1.60	0.26	2.70	1.94	0.33	2.83	1.79	0.26	2.94	1.94	0.53
	5.82	3.49	2.19	0.74	3.33	2.19	0.58	2.94	2.07	0.64	3.17	2.07	0.64
	5.79	2.56	1.60	0.58	2.56	1.94	0.64	2.94	1.60	0.74	2.77	1.79	0.58
	5.66	2.83	1.94	0.53	2.83	1.38	0.95	2.94	1.38	1.16	2.48	1.09	1.06
Mean	4.9	2.8	2.5	0.34	2.9	2.4	0.4	3.06	2.5	0.41	3.12	2.5	0.44
S.D.	0.5	0.43	0.5	0.4	0.4	0.5	0.4	0.4	0.5	0.34	0.39	0.5	0.3
Skew	0.5	0.2	-0.4	-0.1	0.2	-0.3	-0.3	-0.2	-0.3	-0.08	-0.4	-0.4	-0.2

Table 7.4

Coefficients for regression ($\log_e y = m\log_e x + c$)

All Data

	S.P.V.	P	Amplitude	P	Frequency	P
m	-0.182	<0.01	-0.743	<0.001	0.423	<0.001
Constant	4.724		4.616		-1.8376	
R_2	0.0401		0.4973		0.3069	
S.E. Regression	0.411		0.344		0.292	

SPV Only

	Warm	P	Cold	P
m	-0.0518	=0.04	-0.2725	<0.001
Constant	2.143		7.617	
R_2	0.0037		0.0963	
S.E. Regression	0.4115		0.37401	

Table 7.5

Caloric Irrigation; Warm/Cold: SPV (°/sec)

LH = Left warm LC = Left cold

RH = Right warm RC = Right cold

	Slow Phase Velocities			
Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
69	22	28	41	32
69	29	25	38	41
66	14	18	30	34
57	23	26	25	40
65	20	18	37	26
68	21	20	32	41
74	21	17	21	21
68	13	26	43	23
69	23	18	25	23
83	16	16	25	28
76	22	28	12	26
77	11	12	28	29
71	18	21	25	29
77	13	14	21	15
81	16	28	28	36
82	9	25	18	26
82	22	11	30	35
82	15	23	36	22
80	7	12	19	15

Table 7.5 (continued)

Caloric Irrigation; Warm/Cold: SPV (°/sec)

	Slow Phase Velocities			
Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
80	22	31	39	41
94	16	14	20	20
89	14	30	37	28
85	16	11	12	21
95	27	18	27	22
90	34	29	44	32
26	15	12	18	19
89	11	13	20	17
82	17	17	18	45
86	14	14	24	37
94	12	17	31	11
109	14	8	19	26
104	24	15	25	28
98	8	13	18	18
96	16	14	33	21
101	23	45	29	35
102	15	17	26	27
105	8	11	18	12
97	23	13	23	26
108	15	14	8	46
112	22	28	34	41
107	13	9	19	24

Table 7.5 (continued)

Caloric Irrigation; Warm/Cold: SPV (°/sec)

	Slow Phase Velocities			
Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
117	19	11	13	9
116	25	22	21	31
111	48	55	47	46
116	14	11	20	21
119	45	23	34	50
112	19	26	35	34
113	18	16	17	28
117	12	20	28	19
119	28	27	26	33
129	28	19	38	32
131	17	26	24	19
123	26	31	27	33
119	6	14	28	15
119	45	35	51	33
123	30	32	35	31
123	11	16	24	21
131	15	13	14	14
123	22	18	25	38
122	20	12	11	19
144	21	21	16	31
140	21	16	23	29
137	7	17	13	12

Table 7.5 (continued)

Caloric Irrigation; Warm/Cold: SPV (°/sec)

	Slow Phase Velocities			
Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
135	15	17	22	28
134	12	7	12	22
141	17	21	30	24
138	7	10	13	13
138	6	19	21	10
135	20	22	26	37
143	14	13	7	12
135	31	31	36	32
151	9	7	10	8
153	16	17	36	30
144	9	11	11	19
144	13	16	19	20
148	19	34	19	29
151	29	31	15	29
155	39	24	31	36
144	19	17	29	19
153	14	13	15	20
160	19	19	17	20
165	16	8	14	14
156	7	19	24	16
167	17	15	16	16
167	15	14	25	22

Table 7.5 (continued)

Caloric Irrigation; Warm/Cold: SPV (°/sec)

	Slow Phase Velocities			
Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
166	17	15	18	21
167	9	15	13	18
163	16	15	22	22
161	28	25	23	42
160	18	13	16	25
171	12	35	27	24
168	20	24	37	31
177	21	14	27	15
168	6	9	11	9
174	20	15	14	18
177	12	14	13	15
171	19	11	17	20
188	12	18	17	8
169	14	14	17	17
179	32	25	21	22
388	30	22	24	20
366	18	25	28	23
307	17	17	16	24
104	15	13	18	16
258	12	27	19	34
106	24	28	17	19
254	19	18	20	28

Table 7.5 (continued)

Caloric Irrigation; Warm/Cold: SPV (°/sec)

		Slow Phase Velocities			
	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
	348	17	31	24	17
	275	15	19	14	19
	295	16	11	15	15
	286	14	11	15	14
	351	8	11	13	19
	335	16	13	16	20
	300	27	20	23	28
	309	16	15	17	17
	375	10	14	11	14
	237	19	22	24	25
	236	9	15	17	19
	340	33	28	19	24
	328	13	13	19	16
	289	17	17	19	12
Mean	152.5	18.1	18.9	22.9	24.3
S.D.	79.2	7.9	7.8	8.8	9.2
Skew	1.33	1.3	1.34	0.75	0.53
Skew ($\log_e$)	0.5	-0.17	0.15	-0.17	-0.36
R_2	-	0.003	0.004	0.10	0.09

Table 7.6

Caloric Irrigation: Test/Retest (SPV °/sec)

Patient	Test				Retest			
Number	LH	RH	RC	LC	LH	RH	RC	LC
3	14	18	30	34	16	18	30	36
5	20	18	37	26	19	17	30	30
13	18	21	25	29	18	20	25	22
15	16	28	28	36	15	26	27	30
24	27	18	27	22	23	19	25	20
34	16	14	33	21	18	13	32	20
46	45	43	34	50	27	20	30	38
48	18	16	17	28	19	14	18	30
52	17	26	24	19	15	23	21	20
54	6	14	28	15	8	14	26	20
74	9	11	11	19	10	11	9	17
75	13	16	19	20	11	15	20	19
76	19	34	19	29	17	31	17	21
88	16	15	22	22	15	15	20	20
99	14	14	17	17	13	16	16	16
100	32	25	21	22	31	23	20	20
102	18	25	28	23	17	17	20	22
115	16	15	17	17	16	14	17	18
116	10	14	11	14	10	14	13	18
117	19	22	24	25	18	23	24	22
118	9	15	17	19	10	16	16	19
119	33	28	19	24	32	26	20	23
120	13	13	19	16	13	15	19	15
121	17	17	19	12	14	12	18	14

Spearman's rank coefficient (rho)

	p
LH = 0.8330	<0.001
RH = 0.8661	<0.001
RC = 0.8113	<0.001
LC = 0.5657	=0.02

Table 7.6 (continued)

Caloric Irrigation: Test/Retest (Amplitude/°)

Patient	Test				Retest			
Number	LH	RH	RC	LC	LH	RH	RC	LC
3	22	19	24	26	19	22	20	23
5	24	21	23	14	26	22	23	15
13	27	23	24	20	24	23	21	19
15	16	21	23	23	20	20	23	23
24	23	14	22	16	22	19	20	18
34	15	11	23	23	18	15	24	26
46	28	23	30	32	30	23	32	32
48	18	16	22	15	26	20	20	19
52	9	20	10	18	9	20	16	21
54	10	7	14	9	10	8	14	10
74	5	7	6	9	8	8	5	9
75	13	8	14	9	10	9	15	13
76	9	13	13	14	10	13	14	14
88	13	12	9	10	13	13	10	11
99	12	8	9	9	12	10	9	9
100	13	10	11	9	14	11	12	10
102	4	4	5	6	3	4	5	5
115	5	7	5	7	5	5	5	4
116	4	6	5	4	6	5	5	4
117	7	7	8	7	6	5	8	6
118	5	7	6	7	7	8	7	9
119	9	9	8	8	10	6	9	5
120	5	7	5	6	5	8	5	6
121	7	4	4	3	6	3	5	3

Spearman's rank coefficient (rho)

	p
LH = 0.9357	<0.001
RH = 0.9574	<0.001
RC = 0.8665	<0.001
LC = 0.9600	<0.001

Table 7.6 (continued)

Caloric Irrigation: Test/Retest (Frequency/bps)

Patient	Test				Retest			
Number	LH	RH	RC	LC	LH	RH	RC	LC
3	1.0	1.5	1.4	1.2	0.8	1.3	1.2	1.5
5	1.0	0.9	1.0	1.3	0.9	1.3	1.4	1.6
13	0.5	1.05	0.8	1.1	0.5	1.0	1.4	1.3
15	1.2	1.3	1.1	1.6	0.9	1.0	1.3	1.2
24	1.1	1.1	1.1	1.0	0.8	1.3	1.0	1.0
34	1.4	1.2	1.5	1.4	1.3	1.2	1.2	1.0
46	0.95	1.2	1.1	1.5	1.6	1.1	1.0	0.9
48	0.8	1.0	1.1	0.9	0.95	1.3	0.9	1.0
52	1.9	1.8	1.9	1.2	2.0	1.9	1.4	1.4
54	0.9	1.2	1.4	1.6	1.0	1.4	1.4	1.5
74	1.3	1.3	1.5	1.4	1.2	1.3	1.4	1.9
75	1.3	1.7	1.4	2.0	1.2	1.1	1.5	1.9
76	1.75	2.2	1.3	2.1	1.9	2.0	1.2	2.0
88	1.3	1.9	1.6	1.6	1.5	2.0	2.0	2.1
99	1.1	1.5	1.5	1.7	1.0	1.6	1.3	1.9
100	2.2	1.7	1.8	1.9	2.0	1.9	1.9	2.4
102	3.8	4.2	3.5	3.5	3.0	3.7	3.9	3.6
115	2.5	1.7	2.1	2.0	2.2	1.8	2.6	2.7
116	1.4	1.8	2.2	2.1	1.5	1.4	2.0	2.0
117	2.2	2.2	2.1	2.1	2.3	2.2	2.2	2.0
118	1.3	1.4	1.3	1.7	1.6	1.4	1.9	1.5
119	2.1	1.8	1.9	1.9	2.0	2.1	2.0	2.0
120	1.8	1.9	2.1	1.8	1.9	2.0	2.0	2.1
121	1.7	2.6	3.2	2.9	1.8	2.4	2.8	3.0

Spearman's rank coefficient (rho)

	p
LH = 0.993	<0.001
RH = 0.9993	<0.001
RC = 0.8990	<0.001
LC = 0.9889	<0.001

Table 7.7

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Male)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
2	69	29	25	38	41
4	57	23	26	25	40
5	65	20	18	37	26
6	68	21	20	32	41
7	74	21	17	21	21
8	68	13	26	43	23
9	69	23	18	25	33
10	83	16	16	25	28
11	76	22	28	12	26
12	77	11	12	28	29
14	77	13	14	21	15
18	82	15	23	36	22
22	89	14	30	37	28
27	89	11	13	20	17
30	94	12	17	31	11
34	96	16	14	33	21
35	101	23	45	29	35
38	97	23	13	23	26
40	112	22	28	34	41

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Male)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
44	111	48	55	47	46
45	116	14	11	20	21
47	112	19	26	35	34
48	113	18	16	17	28
49	117	12	20	28	19
51	129	28	19	38	32
52	131	17	26	24	19
53	123	26	31	27	33
55	119	45	35	51	33
56	123	30	32	35	31
57	123	11	16	24	21
58	131	15	13	14	14
60	122	20	12	11	19
63	137	7	17	13	12
64	135	15	17	22	28
66	141	17	21	30	24
67	138	7	10	13	13
68	138	6	19	21	10
73	153	16	17	36	30
79	144	19	17	29	19

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Male)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
81	160	19	19	17	20
86	166	17	15	18	21
89	161	28	25	23	42
90	160	18	13	16	25
91	171	12	35	27	24
94	168	6	9	11	9
100	179	32	25	21	22
101	388	30	22	24	20
103	307	17	17	16	24
105	258	12	27	19	34
106	283	24	18	17	19
109	275	15	19	14	19
112	351	8	11	13	19
113	335	16	13	16	20
114	300	27	20	23	28
115	309	16	15	17	17
375	116	10	14	11	14
119	340	33	28	19	24
Mean	154.1	18.9	20.7	24.7	24.8
S.D.	72.9	8.5	8.6	9.5	8.7

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Female)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
1	69	22	28	41	32
3	66	14	18	30	34
13	71	18	21	25	29
15	81	16	28	28	36
16	82	9	25	18	26
17	82	22	11	30	35
19	80	7	12	19	15
20	80	22	31	39	41
21	94	16	14	20	20
23	85	16	11	12	21
24	95	27	18	27	22
25	90	34	29	44	32
26	94	15	12	18	19
28	82	17	17	18	45
29	86	14	14	24	37
31	109	14	8	19	26
32	104	24	15	25	28
33	98	8	13	18	18
36	102	15	17	26	27
37	105	8	11	18	12

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Female)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
39	108	15	14	8	46
41	107	13	9	19	24
42	117	19	11	13	9
43	116	25	22	21	31
46	119	45	23	34	50
50	119	28	27	26	33
54	119	6	14	28	15
59	123	22	18	25	38
61	144	21	21	16	31
62	140	21	16	23	29
65	134	12	7	12	22
69	135	20	22	26	37
70	143	14	13	7	12
71	135	31	31	36	32
72	151	9	7	10	8
74	144	9	11	11	19
75	144	13	16	19	20
76	148	19	34	19	29
77	151	29	31	15	29
78	155	39	24	31	36

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Female)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
80	153	14	13	15	20
82	165	16	8	14	4
83	156	7	19	24	16
84	167	17	15	16	16
85	167	15	14	25	22
87	167	9	15	13	18
88	163	16	15	22	22
92	168	20	24	37	31
93	177	21	14	27	15
95	174	20	15	14	18
96	177	12	14	13	15
97	171	19	11	17	20
98	188	12	18	17	8
99	169	14	14	17	17
102	366	18	25	28	23
116	375	15	13	18	16
107	254	19	18	20	28
108	348	17	31	24	17
110	295	16	11	15	15
111	286	14	11	15	14

Table 7.7 (continued)

Caloric Irrigation; Data by Sex of Subject

		Slow Phase Velocities (Female)			
Patient Number	Age (months)	LH (°/sec)	RH (°/sec)	RC (°/sec)	LC (°/sec)
117	237	19	22	24	25
118	236	9	15	17	19
120	328	13	13	19	16
121	289	17	17	19	12
Mean	151.0	17.5	17.3	21.4	23.9
S.D.	70.2	7.4	6.8	7.9	9.9

Student's t test (male/female): t=1.4816 0.5>p>0.1

Table 7.8

Caloric Irrigation; Canal Paresis and Directional Preponderances

Children

Patient Number	Age (months)	Canal Paresis	Directional Preponderance	Patient Number	Age (months)	Canal Paresis	Directional Preponderance	Patient Number	Age (months)	Canal Paresis	Directional Preponderance
1	69	12	2	21	94	3	3	41	107	14	2
2	69	5	1	22	89	23	6	42	117	14	5
3	66	0	8	23	85	23	8	43	116	13	7
4	57	12	12	24	95	1	12	44	111	4	3
5	65	9	13	25	90	5	12	45	116	6	3
6	68	9	8	26	94	6	3	46	119	24	4
7	74	5	5	27	89	8	2	47	112	7	5
8	68	31	17	28	82	2	28	48	113	11	16
9	69	0	7	29	86	15	15	49	117	22	1
10	83	4	4	30	94	48	34	50	119	7	5
11	76	7	23	31	109	19	16	51	129	3	13
12	77	0	3	32	104	13	7	52	131	16	5
13	71	2	5	33	98	26	9	53	123	1	9
14	77	11	8	34	96	4	12	54	119	33	8
15	81	10	4	35	101	12	21	55	119	1	12
16	82	18	30	36	102	25	1	56	123	5	2
17	82	24	0	37	105	18	6	57	123	11	3
18	82	23	6	38	97	15	12	58	131	4	4
19	80	17	2	39	108	30	4	59	123	17	9
20	80	5	8	40	112	1	10	60	122	26	0

Table 7.8

Caloric Irrigation; Canal Paresis and Directional Preponderances

Children							
Patient Number	Age (months)	Canal Paresis	Directional Preponderance	Patient Number	Age (months)	Canal Paresis	Directional Preponderance
61	144	17	17	81	160	4	4
62	140	12	1	82	165	15	15
63	137	22	2	83	156	30	3
64	135	5	10	84	167	4	4
65	134	43	9	85	167	3	5
66	141	11	2	86	166	10	7
67	138	6	6	87	167	20	7
68	138	43	2	88	163	1	1
69	135	8	11	89	161	19	14
70	143	13	9	90	160	19	9
71	135	5	3	91	171	20	24
72	151	0	9	92	168	9	2
73	153	7	5	93	177	7	25
74	144	12	20	94	168	14	3
75	144	4	6	95	174	13	2
76	148	5	25	96	177	2	7
77	151	12	15	97	171	16	7
78	155	15	8	98	188	27	5
79	144	10	14	99	169	0	0
80	153	10	6	100	179	8	6
					Mean	12.4	8.3
					S.D.	9.9	6.9

Table 7.8 (continued)

Caloric Irrigation; Canal Paresis and Directional Preponderances

Adults

Patient Number	Age (months)	Canal Paresis	Directional Preponderance
1	388	6	14
2	366	13	2
3	307	11	11
4	258	0	6
5	258	0	33
6	283	5	10
7	254	10	8
8	348	20	9
9	275	2	13
10	295	11	1
11	286	4	7
12	351	17	2
13	300	12	2
14	300	12	4
15	309	2	2
16	375	2	14
17	237	2	4
18	236	7	13
19	340	10	0
20	328	5	5
21	289	11	11
	Mean	7.7	8.1
	S.D.	5.6	7.3
	R_2 (all data)	0.002	0.002

Student's t test (children/adults):

Canal Paresis $t=2.9793$ $p<0.01$

Directional Preponderance $t = 0.1073$ N.S.

Table 7.9

Vestibulo-Ocular Function: Results of Optic Fixation at 90 seconds

Patient Number	Age (Months)	End Point (Seconds)							
		Light						Dark	
1	69	-	-	-	-	-	-	125	-
3	66	-	-	-	-	110	120	-	135
5	65	-	-	-	-	-	125	125	-
6	68	-	-	-	-	115	-	140	130
7	74	-	-	-	-	-	130	-	130
8	68	-	-	-	-	-	-	125	-
10	83	-	-	-	-	120	105	-	120
11	76	-	-	-	-	-	120	-	120
14	77	-	-	-	-	-	-	100	-
15	82	-	-	-	-	-	-	-	120
17	82	-	-	-	-	-	140	-	115
18	82	-	-	-	-	-	-	135	130
19	80	-	-	-	-	110	-	-	110
20	80	-	-	-	-	130	150	150	140
21	94	-	-	-	-	110	150	150	140
22	89	-	-	-	-	140	123	125	175
25	90	-	-	-	-	125	130	145	135
26	94	-	-	-	-	115	125	-	125
28	82	-	-	-	-	130	135	130	140
31	109	-	-	-	-	240	105	105	125
35	101	-	-	-	-	110	130	115	135
36	102	-	-	-	-	240	110	130	130
37	105	-	-	-	-	115	130	110	140

Table 7.9 (continued)

Vestibulo-Ocular Function: Results of Optic Fixation at 90 seconds

Patient Number	Age (Months)	End Point (Seconds)							
		Light				Dark			
38	97	-	-	-	-	115	130	110	140
41	107	-	-	-	-	115	115	130	135
42	117	-	-	-	-	144	130	145	110
49	117	-	-	-	-	125	140	145	165
50	119	-	-	-	-	120	120	130	135
51	129	-	-	-	-	125	130	135	140
54	120	-	-	-	-	-	-	115	130
57	123	-	-	-	-	125	125	125	130
58	131	-	-	-	-	-	-	-	110
60	122	-	-	-	-	-	-	117	-
62	140	120	100	110	95	130	130	130	135
63	137	-	-	-	-	122	120	165	125
68	138	-	-	-	-	-	110	110	115
69	135	-	-	-	-	125	120	120	122
73	153	-	-	-	-	135	130	165	160
74	144	-	-	-	-	-	130	105	120
75	144	-	-	-	-	-	115	115	125
76	148	-	-	-	-	-	135	105	147
79	144	-	-	-	-	140	125	145	145
80	153	-	-	-	-	130	125	120	110
81	160	-	-	-	-	150	165	140	145
82	165	-	-	-	-	145	150	130	130
83	156	-	-	-	-	-	170	170	225

Table 7.9 (continued)

Vestibulo-Ocular Function: Results of Optic Fixation at 90 seconds

Patient Number	Age (Months)	End Point (Seconds)							
		Light				Dark			
84	167	-	-	110	-	105	97	130	105
85	167	-	-	-	-	105	103	105	130
86	166	-	-	-	-	130	125	130	130
87	167	-	-	-	-	-	122	145	125
88	163	-	90	-	-	135	130	142	130
89	161	-	90	-	-	135	130	142	130
90	160	-	-	-	-	130	95	112	125
91	171	-	-	110	115	130	125	135	130
92	168	-	-	-	-	155	130	135	145
93	177	-	-	-	-	120	-	130	115
94	168	-	-	-	-	-	110	115	130
95	174	115	95	110	113	135	125	130	140
96	177	-	-	-	-	-	-	130	120
97	171	-	-	-	-	115	-	115	130
98	188	-	-	-	-	125	130	130	111
99	169	-	-	-	-	130	130	155	157
100	179	-	-	-	-	123	116	165	155
101	388	90	125	160	155	120	170	225	225
102	366	-	-	-	-	140	140	160	150
103	307	-	110	105	100	165	170	200	190
104	258	110	97	125	119	215	190	200	205
105	258	-	100	95	97	165	155	150	160

Table 7.9 (continued)

Vestibulo-Ocular Function: Results of Optic Fixation at 90 seconds

Patient	Age	End Point (Seconds)							
Number	(Months)	Light				Dark			
106	283	95	105	105	100	125	175	170	165
107	254	-	-	-	130	170	165	155	150
108	348	105	115	130	155	165	180	190	155
109	275	102	-	-	105	160	165	170	170
110	295	110	100	98	100	150	125	130	135
111	286	-	-	-	-	130	135	120	115
112	351	-	110	104	155	140	200	180	165
113	335	90	105	105	110	170	165	190	190
114	300	105	105	110	104	165	150	190	180
115	309	110	115	105	100	160	140	170	140
116	375	105	-	-	-	125	165	170	125
117	287	100	118	115	-	135	135	170	130
118	340	110	105	100	-	150	175	155	160
119	328	115	110	100	100	150	145	160	165
120	286	-	100	110	100	160	140	170	144
121	236	127	130	140	150	155	180	205	210

Where dash is recorded no end point was observed.

End points in dark (mean):

Children	Adults
105.80±53.7	163.56±26.6

Difference 57.76 S.E. Difference 5.1149 $p<0.001$

CHAPTER 8
DISCUSSION

The relevance of the results achieved for future testing and for our understanding of equilibration in children.

SUMMARY

This chapter considers the results obtained from the work presented here and contrasts the findings with the existing body of world knowledge on the subject.

In conclusion the chapter tries to present a unified picture of these findings in the context of childhood development and attempts to predict future research in this area.

INTRODUCTION

Human development involves a large number of predictable and integrated maturational changes which embrace many aspects of behaviour including language and personal-social milestones. It is these skills as much as anything which characterise maturation from neonate to fully fledged adult. However, it is also true that many aspects of early development are measured in terms of success or failure in performance of motor tasks which require or implicate vestibular input. For example the disappearance of certain primitive reflexes and the emergence of mature responses to positional testing are used to predict gestational age (Dubowitz,Dubowitz and Goldberg,1970), and early human development is routinely charted by noting the ability to sit, stand and walk unaided. From the work presented here it would seem that this development of motor skills is reflected in changes in the vestibular response and in some minor aspects of visual-ocular control, and it also seems that altered cerebellar influences could be responsible for some of these effects. These aspects are discussed in subsequent sections.

A. THE VESTIBULO-OCULAR REFLEX

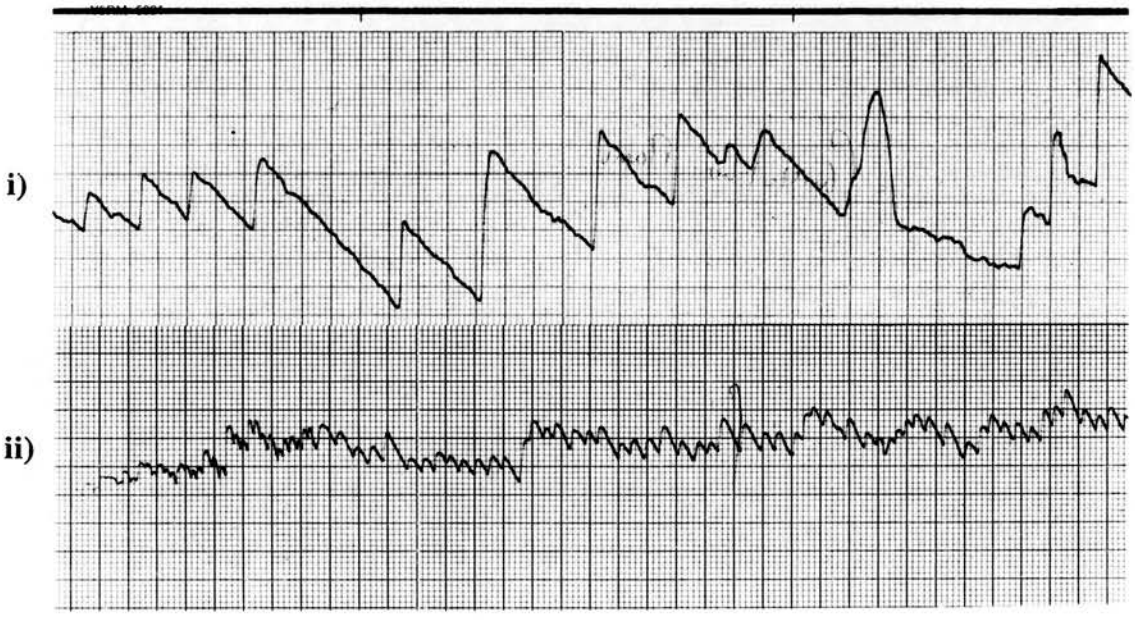
i) the results of caloric testing

The slow phase velocity of the vestibulo-ocular response was found to decline slowly with age. This has been reported in previous studies (Michishita, 1967; Kofanov, 1979; Kaga, Susuki, Marsh and Tanaka, 1981; Tibbling, 1969; Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979; Ornitz, Kaplan and Westlake, 1985). In this respect this study confirms the findings of these authors.

At the same time amplitude measurements decrease and the overall frequency of the response increases. Indeed, such findings may be appreciated from simple visual observation of traces obtained from irrigation of a five year old child and a twenty five year old man (Figure 8. 1). These two parameters have not always been measured in previous work but, once again, the findings of this study do fit with much of what has been written in the past (Michishita, 1967; Tibbling, 1969; Kofanov, 1979; Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979; Peron, Courtin, Aubert, Dehesdin, Andrieu-Guitrancourt, 1980; Kaga, Suusuki, Marsh amd Tanaka, 1981). There are thus definite age related changes in the commonly measured nystagmus parameters after vestibular stimulation using caloric irrigation.

Further analysis shows that the changes in slow phase velocity measurements were only significant because of the results obtained with the cooler caloric stimulus. This finding is not in accord with previous studies which shown that warm water provides the larger stimulus gradient (Cawthorne and Cobb, 1954) and which have demonstrated that a cold water challenge provides a greater stimulus only if response duration is assessed; the converse is usually only true if slow phase velocity is measured (Rudge, 1983; Proctor and Glackin, 1985; Sills, Baloh and Honrubia, 1987). The reasons for the differences seen in this study are unclear.

Figure 8.1



Traces obtained in response to caloric irrigation:

i) in a five year old male child.

ii) in a twenty-five year old male adult.

ii) data scatter

Previous studies have shown that the large data scatter obtained in measurements of slow phase velocity of the caloric response are due to inter rather than intra-subject variation, although no readily defined reasons for the origins of these differences have been provided (Proctor and Glackin, 1985). Analysis was therefore performed in order to ascertain whether the source of the large data scatter seen in this study was the result of similar variation.

Linear regression of the results from each thermal stimulus showed similar constants and gradient coefficients for each test, and test-retest data shows reproducibility with high correlation coefficients. Taken together these pieces of information prove that the scatter is the result of inter rather than intra-subject variation and this validates the supposition that the stimulus used provided a reproducible vestibular challenge. These findings are in accord with previous studies in the world literature which have drawn attention to a great inter-individual variation in caloric responsiveness and high degrees of test-retest reliability (Baloh and Honrubia, 1979).

iii) the effect of visual fixation

Although the tests performed were not specifically designed to look at the length of the responses obtained, the duration in the dark and light was assessed in a number of cases. It was apparent that the introduction of light ninety seconds after the start of the test often abolished the response in younger children (Figure 8. 2), and in some cases this was accompanied by complete suppression of the nystagmus such that it would not return after resumption of recording in the dark. This finding was certainly not apparent in adults where fixation, even if it abolished the nystagmus temporarily, would not so inhibit the response that further nystagmus and an end point would be impossible to define and measure.

This finding could be the result of enhanced vestibulo-ocular reflex suppression per se or may simply be due to response fatigue. Previous reports have suggested that response durations are reduced in young children both after caloric irrigation,

sinusoidal stimulation and impulse or ramp acceleration (Michishita, 1967; Tibbling 1969; Kofanov, 1979; Kaga, Suusuki, Marsh and Tanaka, 1981). If the response was in marked decline fixation could fortuitously appear to be enhanced. But it has also been suggested that the child's ability to suppress vestibular information is actually increased (Herman, Maulucci and Stuyk, 1982). On the present evidence either or both explanations could be tenable and it is not possible to argue definitively in either direction. But, from the recordings made in this study, it was clear that the induced response was usually very vigorous in many instances just prior to the introduction of fixation and was not obviously about to fatigue (Figure 8. 2). Of course this is only a subjective impression, but the fact that nystagmus did not return when darkness supervened within a matter of seconds would also support the argument that enhanced vestibulo-ocular reflex suppression plays a part in this effect.

B. VISUAL-OCULAR CONTROL

i) the maturation and inter-dependence of pursuit,saccadic and optokinetic movements

The recordings of responses to tests of visual-ocular control showed little in the way of age related change. Certainly there were no obvious changes in nystagmus patterns in response to pursuit or optokinetic testing, and this was confirmed by regression analysis of the results obtained.

However previous studies have inferred subtle maturation effects in such movements for there is often saccadic intrusion to smooth pursuit when testing children (Herman, Maulucci and Stuyck, 1982; Larsby, Thell, Moller and Odkvist, 1988). Certainly saccadic intrusion to smooth pursuit was also apparent in the younger children tested in this study. When saccadic movements per se were tested in children some of the first excursions fell short of true target position and produced a small catch up movement (a hypometric saccade). But it later became clear that this was a learning phenomenon for it disappeared almost immediately and did not subsequently reappear

during further tests. In contrast, the most striking and consistent feature in many instances was hypermetria in response to saccadic tasks. This later finding was more apparent in measurements made to targets subtending larger angles from the midline. Both these findings seemed to be related to maturation since they became less obvious in the older children and were not apparent when testing normal adults. But not every subject displayed these features, and there was no obvious correlation between the two findings ie. saccadic pursuit did not invariably accompany hypermetric saccades and vice versa.

The presence of these apparent "abnormalities" could be explained by assuming that the younger children either did not fully understand the test or were liable to lapses of concentration. The importance of the latter factor was not insignificant for, as has been previously shown, children certainly required constant verbal encouragement and reinforcement of interest in the task in order to obtain satisfactory responses. But precisely because care was taken to ensure the subjects were fully alert it seems unlikely that these features were artefactual.

Previous work has shown that normal saccadic response exhibits a range effect and that a hypometric saccade is more apparent when target distance is increased: hypermetric responses are typically seen when ocular excursion is restricted to movements across small distances (Kapoula, 1985). Since the converse appeared true here (hypermetric responses which were more rather than less apparent with target distance), it seems probable that these findings represent a degree of cerebellar immaturity of ocular control. Certainly such findings reproduce to a lesser degree those seen in patients with proven cerebellar disease (Baloh, Konrad and Honrubia, 1975; Zee, Yee, Cogan, Robinson and Engle, 1976; Selhorst, Stark, Ochs and Hoyt 1976).

In this context it is also of interest to find that some recent work has supported the supposition that differing cerebellar centres have separate influences on eye movement. Thus abnormalities of the vestibulo-cerebellum (flocculus, paraflocculus,

nodulus and uvula) result in impaired pursuit (and abnormal visual modulation of the VOR), and abnormalities of the dorsal vermis and fastigial nuclei cause alteration in nystagmus amplitude, saccadic inaccuracy and dysmetria (Zee, 1984). It would therefore seem that the minor abnormalities of visual-ocular control demonstrated here in children infer that both these major cerebellar centres are immature.

Since the pursuit and saccadic systems are intimately involved in the genesis of the optokinetic response, it could be argued that the failure to find a maturation change in optokinetic testing is something of a surprise. Certainly the fast phase velocity of the optokinetic response is directly linked to that of voluntary saccades, and the two movements share the same neural mechanisms in the paramedian reticular formation (Keller, 1974; Henriksson, Hindfelt, Pyykko and Schalen, 1980). Thus gross lesions which interfere with fast saccadic movements commonly impair the fast phase of optokinetic nystagmus, and this explains the abnormal fast component initiation and ocular deviation in response to an optokinetic stimulus in congenital oculomotor apraxia, Huntington's chorea and progressive supranuclear palsy. In the same way the slow component of the optokinetic response and pursuit movements are centrally linked and fall prey to the same pathological processes (Jung and Kornuber, 1964; Baloh, Honrubia and Sills, 1977). With such interdependence it seems logical to assume that genuine immaturity in the brainstem neural mechanisms involved in the generation of pursuit or saccadic movements would be reflected in some maturational change in the results obtained with an optokinetic stimulus. Previous reports have been contradictory about this (Holm-Jensen, Skovgaard and Peitersen, 1981; Stefansson and Imoto, 1986), but there was certainly no obvious maturation effect when testing children in this study. It therefore seems likely that these brainstem pathways are mature, and this is also inferred by the results of testing optokinetic after-nystagmus (vide infra). But this still does not rule out minor immaturities of cerebellar control. Indeed it is often possible to find saccadic pursuit and hypo or hypermetric saccades in cerebellar disease in the absence of specific abnormalities in the optokinetic responses.

ii) optokinetic after-nystagmus

The conclusion that the major neural nets in the brainstem do not appear to show age related changes is confirmed by a lack of maturation of the interaction between the two systems seen by measurements of after-nystagmus. This measurement of the subcortical optokinetic response is of interest in the context of the present discussion for its genesis involves the brainstem and the vestibular nuclei. Since measurements of this parameter fail to show a maturation effect it seems reasonable to presume that the vestibular nuclei and the main brainstem pathways responsible for the vestibulo-ocular reflex do not display changing reactivity and are not the source of the observed differences in the vestibulo-ocular reflex.

C. THEORIES TO ACCOUNT FOR THE OBSERVED CHANGES

The observed changes seen in slow phase velocity, amplitude and frequency of the vestibulo-ocular reflex have been mooted before in a number of studies using rotational, ramp and caloric stimuli. The studies concerned are quoted in preceding sections. What is disputed is why these changes occur and what meaning they have in terms of maturation of either the vestibular apparatus or central pathways.

In this respect the previous literature is confusing and it is apparent that no consensus exists. What is clear is that higher slow component velocities in the youngest children are widely held to be consistent with an increase in vestibular responsiveness since, of course, measurements of slow phase velocity are usually held to be a direct measure of vestibular function. Thus Tibbling, amongst others, observed a higher velocity in young children and used this to argue in favour of a high peripheral element to a child's response.

The majority of dissent centres not around this finding, but around the observed changes in amplitude and frequency. Tibbling alleges that the amplitude of the slow component should be seen as a centrally induced parameter since its magnitude

depends on when it is interrupted by the fast phase (which is a centrally mediated saccade). However, she then has to assume that the low frequency of response in young children must be the result of changing amplitude, because it could not be obviously linked to slow phase velocity which was increased (Tibbling, 1969). In effect she is saying that the youngest children have the highest peripheral and lowest central components to their response. Other authors have produced directly contradictory conclusions. For example, measurement of the velocity of secondary nystagmus after ramp acceleration and comparison of this parameter (which is thought to be a centrally induced measure of vestibular adaption) to the primary response (which is again assumed to be of vestibular origin) has shown that the ratio of secondary to primary nystagmus is increased in children (Ornitz, Atwell, Walter, Hartmann and Kaplan, 1979). More recently the same group of workers have measured gain and time constants of the response to acceleration and movement at constant velocity, and have suggested that the increased time constants and reduced gain which are seen with increasing age are the direct result of altering activity in the brainstem reticular formation and vestibular nuclei respectively (Ornitz,Kaplan and Westlake,1985). So in effect they are arguing that there is an increased central and decreased peripheral influence in children which is due to a decrease in the activity of the vestibular nuclei and an increase in the activity of the brainstem reticular formation.

Such conclusions cannot be directly challenged but seem implausible. They also beg certain other important questions. For example why should brainstem pathways and closely related nuclei show a dissociation of maturation when, as the authors acknowledge, they normally show parallel changes in response to stimulation? They do point out, as have others (Blair and Gavin, 1979), that such a dissociation of effect can be reproduced with certain drugs, particularly Diazepam. But even if such an effect can be attained by pharmacological manipulation it seems unlikely that development would mimic this disconjugate effect. In addition such theories directly challenge the long held and soundly based beliefs that the vestibular nuclei are functionally mature in early infant life and that there is early anatomical maturation

of the vestibular apparatus and nerves (Langworthy, 1933; Humphrey, 1965; Rosenhall, 1972; Bergstrom, 1973; Dayal, Farkashidy and Kokshanian, 1973). Brainstem immaturity and immaturity of the vestibular nuclei are also made unlikely by the findings, presented here, of a lack of maturation change in optokinetic nystagmus and after-nystagmus, for such responses directly involve the brainstem pathways and vestibular nuclei.

Perhaps a more logical explanation lies in the observed dysrhythmia of the response. Dysrhythmia, or beat to beat variation in nystagmus amplitude, is certainly seen in measurements of the vestibulo-ocular reflex in children (Figure 8.1), and is also seen in cerebellar disease (Riesco-McLure and Stroud, 1960). Immature cerebellar control would therefore explain the dysrythmia and would, of course, also explain the observed changes in slow phase velocity. Pure cerebellar lesions produce apparent increases in the velocity of vestibular induced nystagmus which is thought to be due to a diminution of normal inhibitory influences on the vestibular nuclei (Baloh, Konrad and Honrubria, 1975). The centres involved are presumed to be the dorsal vermis and fastigial nuclei (Zee, 1984). Of course immaturity of cerebellar control has already been suggested to explain the minor changes observed in visual-ocular control. If such an explanation is extended to vestibular mechanisms then it is logical to assume that the increased slow phase velocity goes hand in glove with the dysrhythmia and is caused by the same physiological process.

However, even if this explanation is true it does not also immediately explain the apparently diminished duration of induced vestibular nystagmus in children which was seen in this study. This has been reported by a number of other investigators and the arguments for and against vestibular reactivity per se or enhanced or altered visual suppression as an explanation are advanced above. Diminished cerebellar influence through the vestibulo-cerebellum results in impaired rather than enhanced fixation suppression of the vestibulo-ocular reflex (Zee, 1984), so supposed abnormalities of cerebellar control cannot also be invoked to explain the apparent enhancement seen here. The only explanations which seem logical are to assume that

these findings represent either a true diminution of the vestibular response duration or an enhanced ability to suppress using visual clues as is seen in habituation of the vestibular response. Only tentative conclusions can be immediately drawn but, as has been suggested in previous discussions, it seemed most probable that enhanced fixation is responsible.

The observed changes are thus explained by assuming that a young child has some disparity in sensory input when compared to an adult and that, in children, visual input has dominance over the vestibular system. On this framework is superimposed immature cerebellar function. This theory would fit all the observed facts and would also accord with the commonly observed behaviour patterns. For example, it explains why neonates are relatively helpless and are unable to assume postural control (lack of cerebellar co-ordination), and explains why children, in stark contrast to normal adults, enjoy the vestibular challenges provided by a playground or fairground and suffer no vegetative sequelae (diminished vestibular responsiveness). If correct it also shows why young children are often afraid of the dark and find reassurance and comfort in going to sleep in well lit surroundings (dominance of visual input). Presumably total darkness reduces this dominant input for position sense and is liable, especially with a functionally immature cerebellum, to result in disorientation.

D. FUTURE STUDIES

Further studies are needed to investigate certain other aspects of the responses obtained in children.

i) vestibular function

When caloric tests are performed at normal room temperature it is usually found that warm water provides a larger stimulus gradient (Cawthorne and Cobb, 1954; Proctor and Glackin, 1985). Thus in most large series, in spite of large inter-individual variations in the results achieved, mean slow phase velocity measurements in

response to stimulation with water at 44 degrees usually exceed those at 30 degrees Centigrade (Sills, Baloh and Honrubia, 1977; Rudge, 1983; Proctor and Glackin, 1985). In this series this finding was reversed since the warm stimulus was apparently non-contributory in adding to the maturation effect. The reasons for this are not apparent and warrant further study perhaps by repetition using altered stimulus sequences.

In addition it is suggested in this study that optic fixation in children is enhanced, but it could equally be that this is an apparent effect and is secondary to a reduction in response duration. Although duration per se has been measured in varying conditions, no studies have been performed which have specifically measured the fixation suppression index (duration in light/duration in darkness) in children. Such experiments would allow further insight into the effect of optic fixation and this could also be augmented by examining the effect of fixation at the height of the response. This would clarify the supposition that children exhibit an advanced ability to use visual mechanisms to suppress the vestibular response as has been suggested here and in some previous reports (Herman,Maulucci and Stuyck,1982).

ii) visual-ocular control

With respect to tests of visual-ocular function it is clear that the experiments should be repeated with refinement of stimulation techniques. For instance the stimulus used for performance of tracking tasks was a fixed frequency and velocity pendulum. This obviously limited the information which could be collected in respect of gain. If cerebellar control of pursuit is reduced in children, then gain might be expected to be reduced in comparison to adults. This has been suggested in one previous study (Larsby,Thell,Moller and Odkvist,1988). Obviously this could only be tested if it were possible to alter the stimulus velocity used.

With large drum optokinetic testing the need for greater sophistication is also apparent. The tests should be repeated with a stimulus which rotates at a constant and unvarying speed in each direction. They should also be repeated with both a "stare"

and "look" response recorded and, in addition, since some reports have suggested that a higher stimulus velocity such as 90 to 120 degrees/second may reveal pathologies with greater ease (Jung and Kornhuber, 1964), it would be of interest to repeat the tests with a higher velocity of drum rotation.

CONCLUSIONS

1. The observed changes in vestibulo-ocular function fit a model which supposes immature cerebellar control in children.

2. The same immaturity would explain the abnormalities of pursuit and saccadic movements which are often observed in the youngest children.

3. Enhanced visual suppression of the vestibulo-ocular reflex in young children suggests that at this stage there is a relative dominance of this sensory input over the vestibular system and such a conclusion supports the observed behaviour patterns.

4. Arguments which have supposed alterations in the activity of the vestibular nuclei and brainstem reticular formation in children as an explanation of the changes in the vestibulo-ocular reflex are not supported by measurements of optokinetic nystagmus or after-nystagmus.

BIBLIOGRAPHY

Alpers BJ (1960) Vertiginous Epilepsy. Laryngoscope, 70; 631-637.

Andral G (1834) The Clinique Medicale:ou Choix d'Observations Medicale. Page 359. Paris. (Condensed and translated with observations by Spillan, D) London: Renshaw; 1836.

Aschan G, Bergstedt M, Stahle J (1956) Nystagmography: Recording of nystagmus in clinical neuro-otological examinations. Acta Otolaryngologica (Stockh). Supplement 129.

Aust G, Goebel P (1979) Vestibulookulare Gleichgewichtsreaktionen beim Saugling und Kleinkind. Laryngologie, Rhinologie,Otologie (Stuttgart), 58; 516-521.

Ayres AJ (1975) Southern California Post-rotatory Nystagmus Test. Western Psychological Services, Los Angeles, California.

Bala SP, Cohen B, Norris A, Gittleman R, Kates W (1981) Saccades of hyperactive and normal boys during ocular pursuit. Developmental Medicine and Child Neurology, 23; 323-336.

Baldwin RL, Schweitzer RS, Freind BD (1985) Meningitis and sensorineural hearing loss. Laryngoscope, 97(1); 802-805.

Baloh RW, Honrubia V, Konrad HR (1977) Ewald's second law re-evaluated. Acta Otolaryngologica (Stockh), 83; 475-479.

Baloh RW, Honrubia V, Sills A (1977) Eye tracking and optokinetic nystagmus. Results of quantitative testing in patients with well defined central nervous system lesions. Annals of Otology, Rhinology and Laryngology, 86(1); 108-114.

Baloh RW, Honrubia V (1979) Clinical Neurophysiology of the Vestibular System. Philadelphia: Davies.

Baloh RW, Konrad HR, Honrubia V (1975) Vestibulo-ocular function in patients with cerebellar atrophy. Neurology, 25; 160-168.

Baloh RW, Lyerly K, Yee RD (1984) Voluntary control of the vestibulo-ocular reflex. Acta Otolaryngologica (Stockh), 97; 1-6.

Barany R (1906) Untersuchungen uber den vom Vestibularapparat des Ohres reflektorisch ausgelosten rythmischen Nystagmus und Begleiterscheinungen. Monatsschrift fur Ohrenheilkunde, 40; 193-297.

Barany R (1922) Zur Klinik und Theorie des Eisenbahnnystagmus. Acta Otolaryngologica (Stockh), 3; 260-265.

Barber HO, Stockwell CW (1980) Manual of Electronystagmography. St Louis:Mosby.

Barnes GR, Benson AJ, Prior ARJ (1978) Visual-vestibular interaction in the control of eye movement. Aviation Space and EnviroNmental Medicine (Washington), 49; 557-564.

Barr CC, Schultheis LW, Robinson DA (1976) Voluntary, non visual control of the human vestibulo-ocular reflex. Acta Otolaryngologica (Stockh), 81; 365-375.

Bartels M (1911) (in discussion on Barany and Wittmaak); Funktionelle Prufung des vestibular Apparates. Bericht uber der Deutsch Otolaryngologischt Gesellsch, 20; 214.

Bartisch G (1583) Augendienst. Frankfurt am Main: Feyrabend.

Bechterew W (1882) Ergebnisse der Durchschneidung des N. acusticus, nebst Erorterung des Bedeutung der semicircularen Canale fur das Korpergaichgewicht. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 30; 312-347.

Behrman S, Wyke BD (1958) Vestibulogenic seizures. Brain, 81; 529-541.

Bekesy G von (1966) Pressure and shearing forces as stimuli of labyrinthine epithelium. Archives of Otolaryngology, 84; 122-130.

Bell C (1823) On the motions of the eye, in illustration of the uses of the muscles and nerves of the orbit. Philosophical Transactions of The Royal Society (London), Series B, 113; 166-186.

Bell C (1833) The Nervous System of the Human Body. Washington:Duff Green.

Bender MB (1980) Brain control of conjugate horizontal and vertical eye movements:a survey of the structural and functional correlates. Brain, 103; 23-69.

Bennett H, Savill T (1889) A case of permanent conjugate deviation of the eyes and head, the result of a lesion limited to the sixth nucleus:with remarks on associated lateral movements of the eyeballs, and rotation of the head and neck. Brain, 12; 102-116.

Bergenius J, Perols PO, Lonfqvist L (1988) Some considerations on caloric test results. Acta Otolaryngologica (Stockh), 455; 21-23.

Bergstrom B (1973) Morphology of the vestibular nerve. 11. The number of myelinated nerve fibres in man at various ages. Acta Otolaryngologica (Stockh), 76; 173-179.

Bergstrom L (1977) Osteogenesis imperfecta. Otologic and maxillofacial aspects. Laryngoscope (supp 6), 87; 1-42.

Blair SM, Gavin M (1979) Modifications of the vestibulo-ocular reflex induced by diazepam. Archives of Otolaryngology, 105; 698-701.

Borries GVT (1920) Studier over Vestibulaer Nystagmus. Copenhagen (Thesis)

Borries GVT (1922) Studies on normal caloric nystagmus. Acta Otolaryngologica (Stockh), 4; 8-20.

Borries GVT (1925) Theorie des kalorischen Nystagmus. Archive fur Klinische und Experimentsille Ohren-Nasen und Kehlkopfheilkunde, 113; 117-155.

Breuer J (1891) Ueber die Funktion der Bogengange des Otollithenapparate. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 48; 195-306.

Breuer J (1874) Uber die Funktion der Bogengange des Ohrlabyrinthes. Weiner Medizinische Jahrgang, 4; 72-73.

Brodal A (1974) The anatomy of the vestibular nuclei and their connections. In:Handbook of Sensory Physiology:The Vestibular System (ed. Kornhuber HH). V1(1). New York:Springer Verlag.

Brown-Sequard CE (1860) Thermal stimuli leading to vertigo In:A course of lectures on the Physiology and Pathology of the Central Nervous System. page 187. Philadelphia.

Brucher JM (1964) L'air oculogyre frontale du singe. Bruxelles:Arscia.

Buettner-Ennever JA, Henn V (1977) An autoradiographic study of the pathways from the pontine reticular formation involved in horizontal eye movements. Brain Research, 108; 155-164.

Busis SN (1983) Vertigo. In:Paediatric Otolaryngology (ed. Bluestone CD, Stool SE). pages 261-270. Philadelphia:Saunders.

Calseyde P van der, Ampe W, Depont M (1972) The nystagmic threshold in children during the damped sinusoidal stimulation. Acta Oto-Rhino-Laryngologica (Belgium), 26; 237-243.

Canegham D van (1946) Application du Romberg amplifie et de la reaction vestibulaire sonore au diagnostique differentiel entre la tmpanosklerose et l'otospongiose. Bulletin de la Societe Belge d'Otologie, de Laryngologie et de Rhinologie, 1&2; 88-95.

Cannon SC, Robinson DA (1986) The final common integrator is the prepositus and vestibular nuclei. In: Adaptive processes in Visual and Oculomotor Systems (ed. Keller EL, Zee DS). pages 307-311. Oxford: Pergamon.

Carpenter RHS (1977) Movement of the Eyes. London: Pion.

Cawthorne T (1945) Vestibular injuries. Proceedings of the Royal Society of Medicine (London), 39; 270-273.

Cawthorne T, Cobb WA (1954) Temperature changes in the perilymph space in response to caloric stimulation in man. Acta Otolaryngologica (Stockh), 44; 580-588.

Cawthorne T, Fitzgerald G, Hallpike CS (1942) Studies in human vestibular function:observations on directional preponderance of caloric nystagmus

(Nystagmusbereitschaft) resulting from unilateral labyrinthectomy. Brain, 65; 138-160.

Coates AC, Smith SY (1967) Body position and the intensity of caloric nystagmus. Acta Otolaryngologica (Stockh), 63; 515-532.

Cohen B, Suzuki JI, Bender MB (1964) Eye movements from semicircular canal nerve stimulation in the cat. Annals of Otology, Rhinology and Laryngology, 73; 153-169.

Collins WE (1974) Habituation of vestibular responses with and without visual stimulation. In:Handbook of Sensory Physiology. The Vestibular System. V1(2). (ed. Kornhuber HH). pages 369-388. New York: Springer Verlag.

Conraux C, Collard M (1970) L'ectronystagmographie chez l'enfant. Acta Oto-Rhino-Laryngologica (Belgium), 24; 363-369.

Crum-Brown A (1874) On the sense of rotation and the anatomy and physiology of the semicircular canals of the internal ear. Journal of Anatomy and Physiology, 8; 327-331.

Cyon E (1878) Recherches experimentales sur les fonctions des canaux semicirculares et sur leur role dans la formation de la notion de l'espace. These pour le doctorat en medicine. Paris.

Cyr DG (1980) Vestibular testing in children. Annals of Otology, Rhinology and Laryngology, 89; 63-69.

Darwin E (1794) Zoonomia; or, the laws of organic life. Vertigo, 1. pages 227-239. London: Johnson.

Dayal VS, Farkashidy J, Kokshanian A (1973) Embryology of the ear. Canadian Journal of Otolaryngology, 2; 136-142.

Dayton GO, Jones MH, Aiu P, Rawson RA, Steele B, Rose B (1964) Developmental study of co-ordinated eye movements in the human infant. Archives of Opthalmology, 71; 865-875.

de Kleijn A, Socin C, de Burlet HM (1915) Zur nahreren Kenntnis des Verlaufs der postganglionaren Sympathicusbahnen fur Pupillenerweiterung, Lidspaltenoffnung und Nickhautretraktion bei der Katze. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 160; 407-415.

de Kleijn A, Magnus R (1918) Sympathicuslahmung durch Abkuklung des Mittelhores beim Ausspritzen des Gehorganges der Kratze mit kaltem Wasser. Graefes Archiv fur Opthalmologie, 96; 368.

de Jesus CPV (1980) Neurological aspects of vertigo. Ear Nose and Throat Journal, 59; 336-376.

Dell'Osso LF, Abel LA, Daroff RB (1981) Absence of VOR suppression in the presence of intact pursuit. Investigative Opthalmology and Visual Science, 20; 57.

Demer JL, Robinson DA (1983) Different time constants for optokinetic and vestibular nystagmus with a single velocity-storage element. Brain Research, 276; 173-177.

de Vries H (1950) The mechanics of the labyrinthine otoliths. Acta Otolaryngologica (Stockh), 262-273.

Dichgans J, Reutern GM von, Rommelt U (1978) Impaired suppression of nystagmus by fixation in cerebellar and non-cerebellar patients. Archiv fur Psychiatrie und Nervkrankheiten, 226; 183-199.

Dix MR (1948) The effect of streptomycin on the eighth nerve system. Journal of Laryngology, 62; 735-745.

Dobson V, Teller DY (1978) Visual acuity in human infants:a review and comparison of behaviour and electrophysiological studies. Vision Research, 18; 1469-1483.

Dodge R (1903) Five types of eye movement in the horizontal meridian plane of the field of regard. American Journal of Physiology, 8; 307-329.

Dubowitz L, Dubowitz V, Goldberg C (1970) Clinical assessment of gestational age in the newborn. Journal of Paediatrics, 77; 1-10.

Duke-Elder S, Cook C (1963) Normal and Abnormal Development. In:System of Opthalmology, 3(1); 304. St. Louis:Mosby.

Estanol B, Romero R, Convera J (1979) Effects of cerebellectomy on eye movements in man. Archives of Neurology, 36; 281-284.

Eviatar L, Eviatar A, Naray I (1974) Maturation of neuro-vestibular responses in infants. Developmental Medicine and Child Neurology, 16; 434-446.

Eviatar L, Mirand S, Eviatar A, Freeman K, Bokowski M (1979) Development of nystagmus in response to vestibular stimulation in infants. Annals of Neurology, 5; 508-514.

Eviatar L, Eviatar A (1970) Vertigo in children:differential diagnosis and treatment. Paediatrics, 59; 833-838.

Eviatar L, Eviatar A (1980) Vertigo in adolescence and childhood. In:Paediatric Otolaryngology.A Review of Ear,Nose and Throat Problems in Children.(ed. Jazbi B) pages 29-39. New York:Appleton.

Eviatar L, Eviatar A (1981) Aminoglycoside ototoxicity in the neonatal period:possible aetiological factors in delayed postural control. Otolaryngology-Head and Neck Surgery, 89; 818-821.

Ewald J (1898) Ueber eine neue Hortheorie. Weiner Klinische Wochenschrift (Wein), 11; 721.

Ewald J (1892) Physiologische Untersuchungen uber des Endorgan des Nervus Octavus. Weisbaden:Bergmann.

Fernandez C, Goldberg JM (1971) Physiology of peripheral neurones innervating semicircular canals of the squirrel monkey. 11. Response to sinusoidal stimulation and dynamics of peripheral vestibular system. Journal of Neurophysiology, 34; 661-675.

Fernandez C, Goldberg JM (1976) Physiology of peripheral neurones innervating otolith organs of the squirrel monkey. 11. Directional selectivity. Journal of Neurophysiology, 39; 985-995.

Fernandez C, Goldberg JM (1976) Physiology of peripheral neurones innervating otolith organs of the squirrel monkey. 111. Response dynamics. Journal of Neurophysiology, 39; 996-1008.

Fischer JJ (1956) The Labyrinth. New York:Grune and Stratton.

Fitzgerald G, Hallpike CS (1942) Studies in human vestibular function. I. Observations on the directional preponderance of caloric nystagmus resulting from cerebral lesions. Brain, 65; 115-137.

Flock A, Jorgensen M, Russell I (1973) The physiology of individual hair cells and their synapses. In:Basic Mechanisms in Hearing (ed. Miller A). New York:Academic Press.

Flourens P (1842) Recherches experimentales sur les proprietes et les fonctions du systeme nerveux dans les animaux vertebres. Volume 203. Paris:Crevot.

Fluur E (1959) Influences of the semicircular canal ducts on extra-ocular muscles. Acta Otolaryngologica (Stockh), 149; 5-46.

Fluur E, Mendel L (1969) Relation between strength of acceleration and duration of post acceleratory nystagmus. Acta Otolaryngologica (Stockh) 68; 127-136.

Foville AL (1858) Paralysie de certain muscles de l'oeil et rapport avec l'anatomie et la physiologie de la protuberance cerebrale. Gazette Hebomadiare, 6; 146-150.

Fraser GR (1976) The Causes of Profound Deafness in Childhood. London:Balliere Tindall.

Gates GA (1980) Vertigo in children. Ear, Nose and Throat Journal, 59; 358-365.

Gacek RR, Lyon M (1974) Localisation of vestibular efferent neurones in the kitten with horseradish peroxidase. Acta Otolaryngologica (Stockh) 77; 92-101.

Galebsky A (1927) Vestibular nystagmus in new-born infants. Acta Otolaryngologica (Stockh) 11; 409-423.

Gilligan MB, Mayberry W, Stewart L, Kenyon P, Gaebler C (1981) Measurement of ocular pursuit in normal children. American Journal of Occupational Therapy, 35; 249-255.

Goebel P, Aust G (1978) Ein Vergleich der Entwicklung der Nystagmusfrequenz nach vestibularer Stimulation mit der motorischen Entwicklung in der denersten Lebensjahren. Archives of Otorhinolaryngology, 220; 265-276.

Goldberg JM, Fernandez C (1971) Physiology of peripheral neurones innervating semicircular canals of the squirrel monkey. 1. Resting discharge and response to constant angular accelerations. Journal of Neurophysiology, 34; 635-660.

Goltz Fr (1870) Uber die physiologische Beduntung der Bogengange des Ohrlabyrinthes. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 3; 172-192.

Gonshor A,Melvill Jones G (1976) Short term adaptive changes in the human vestibulo-ocular reflex. Journal of Physiology, 256; 361-379.

Gorman JJ, Cogan DG, Gellis SS (1957) An apparatus for grading the visual acuity of infants on the basis of optokinetic nystagmus. Paediatrics, 19; 1088-1092.

Graux G (1878) De la paralysie du moteur oculaire externe avec deviation conjugee. Paris (Thesis).

Greenwald MJ (1983) Visual development in infancy and childhood. Paediatric Clinics of North America, 30(6); 977-993.

Gubler A (1859) Memoire sur les paralysies alternes en general, et particulierement sur l'hemiplegie alterne avec lesion de la protuberance annulaire. page 1. Paris: Masson.

Guedry FE Jr (1972) Theory of development of reactions to whole-body motion considered in relation to selection, assignment and training of flight personnel. In:AGARD Conference Proceedings, 98(1); 881-889.

Guedry FE Jr, Lentz JM, Jell RM (1979) Visual-vestibular interactions. 1. Influence of peripheral vision on suppression of the vestibulo-ocular reflex and visual acuity. Aviation Space and Environmental Medicine, 50; 205-211.

Guerrier Y, Dejean Y, Basseres F, Denise A (1970) Le seuil d'excitibilite vestibulaire de l'enfant normal. Revue de Laryngologie, Otologie et Rhinologie (Bordeaux), 91; 881-899.

Haid T (1979) Neuro-otological diagnosis of vestibular disorders in children. International Journal of Paediatric Otorhinolaryngology, 1; 87-92.

Hailine L, Turkel J, Abramov I (1984) Characteristics of saccades in human infants. Vision Research, 24; 1771-1780.

Hardy JB (1973) Foetal consequences of maternal viral infections in pregnancy. Archives of Otolaryngology, 98; 218-227.

Helmholtz H von (1866) In:Handbuch der Physiologischen Optik. Hamburg:Voss. (Edited and translated by Southall JPC. The Optical Society of America, 1924).

Henn V, Cohen B (1976) Coding of information about rapid eye movements in the pontine reticular formation of alert monkeys. Brain Research, 108; 307-325.

Henriksson NG, Pyykko I, Schalen L, Wennmo C (1980) Velocity patterns of rapid eye movements. Acta Otolaryngologica (Stockh), 89; 504-512.

Henriksson NG, Hindfelt B, Pyykko I, Schalen L (1980) Rapid eye movements reflecting neurological disorders. Acta Otolaryngologica (Stockh), 89(5-6); 504-512.

Hering E (1868) Die Lehre vom Binocularen Sehen. Leipzig:Engelmann.

Hering E (1879) Uber Muskelgerausche des Auges. Sitzungsberichte der Academie der Wein Mathematische-Naturwissenschaftliche Klasse, Abt 111, page 137.

Herman R, Maulucci R, Stuyck J (1982) Development and plasticity of visual and vestibular generated eye movements. Experimental Brain Research, 47; 69-78.

Hoegyes A (1881) Uber die Uraschen der Schwindelerscheinungen bei der Drucksteigerung in der Paukenhohle. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 26; 558-568.

Holm-Jensen S, Skovgaard LT, Peitersen E (1981) Synchronous optokinetic nystagmus. Acta Otolaryngologica (Stockh), 91; 255-266.

Hood JD (1968) Electro-nystagmography. Journal of Laryngology and Otology, 82; 167-183.

Hooker D (1952) The prenatal origin of behaviour. Lawrence. University of Kansas.

Hoyt CS, Nickel BL, Bilson FA (1982) Ophthalmological examination of the infant. Developmental aspects. Survey of Opthalmology, 26; 177-189.

Hoyt CS (1987) Nystagmus and other abnormal ocular movements in children. Paediatric Clinics of North America, 34(6); 1415-1423.

Humphrey T (1965) The embryological differentiation of the vestibular nuclei in man correlated with functional development. International Symposium on Vestibular and Oculomotor Problems. pages 51-56. Tokyo.

Igarishi M (1966) Dimensional study of the vestibular end organ apparatus. In:Second Symposium on the role of the Vestibular End Organs in Space Exploration. US Government Printing Office, Washington DC.

Jackson J Hughlings (1866) On lateral deviation of the eyes in hemiplegia and in certain epileptiform seizures. Lancet, 1; 311-312.

Javal (1878) Essai sur la Physiologie de la lecture. Annales d'Oculistique (Paris), 79; 197-224.

Jones GM, Milsum JH (1965) Spatial and dynamic aspects of visual fixation. IEEE Transactions on Biomedical Engineering, 12; 54-62.

Jones IH (1918) Equilibration and Vertigo. Philadelphia:Lippincott.

Jongkees LBW, Gasthuis W (1973) La fonction de l'organe vestibulaire du nouveau-ne et de l'enfant. Journal Francaise d'Oto-Rhino-Laryngologie, 22; 97-101.

Jongkees LBW, Philipszoon AJ (1964) Electronystagmography. Acta Otolaryngologica (Stockh). Supplement 189; 7-16

Jung R, Kornuber HH (1964) Results of electronystagmography in man:The value of optokinetic, vestibular and spontaneous nystagmus for neurological diagnosis and research. In:The Oculomotor System (ed. Bender MB), pages 428-482. New York:Harper Row.

Kaga K, Suusuki J-I, Marsh RR, Tanaka Y (1981) Influence of labyrinthine hypoactivity on gross motor development of infants. In:Vestibular and Oculomotor Physiology. International Meeting of the Barany Society (ed. Cohen B). Annals of the New York Academy of Sciences, 374; 412-420.

Kantner RM, Clark DL, Allen LC, Chase MF (1976) Effects of vestibular stimulation on nystagmus response and motor performance in the developmentally delayed infant. Physical Therapy, 56; 414-421.

Kapoula Z (1985) Evidence for a range effect in the saccadic system. Vision Research, 25(8); 1155-1157.

Keating NR (1979) A comparison of duration of nystagmus as measured by the Southern California Post-rotatory Nystagmus Test and Electronystagmography. American Journal of Occupational Therapy, 33; 92-97.

Keller EL (1974) Participation of median pontine reticular formation in eye movement generation in monkey. Journal of Neurophysiology 37; 316-332.

Kenyon GS, Levens L (1987) The impedance bridge and ENG controlled fistula test:results in children with unilateral deafness and comparison with normal controls. Clinical Otolaryngology, 12(2); 137-141.

King WM, Lisberger SG, Fuchs AF (1976) Responses of fibres in the medial longitudinal fasiculus (MLF) of alert monkeys during horizontal and vertical conjugate eye movements evoked by visual or vestibular stimuli. Journal of Neurophysiology, 39; 1135-1149.

King WM, Fuchs AF, Magnin M (1981) Vertical eye movement related responses of neurones in the midbrain near the interstitial nucleus of Cajal. Journal of Neurophysiology, 46; 549-562.

Kobrak F (1918) Beitrage zum experimentellen Nystagmus. Beitraege zur Anatomie, Physiologie, Pathologie und Therapie des Ohres, 10; 214-223.

Koenig E, Allum JHJ, Dichgans J (1978) The effect of visual-vestibular interaction upon nystagmus slow phase velocity in man. Acta Otolaryngologica (Stockh), 85; 397-410.

Kofanov RV (1979) Nystagmography in children. Vestnik Otorhinolaryngologii (Moscow), 6; 3-6.

Kravitz H, Boehm JJ (1971) Rhythmic habit patterns in infancy:their sequence, age of onset and frequency. Child Development, 42; 399-413.

Lamanski S (1869) Bestimmung der Winkelgeschwindigkeit der Blickbewung, respective Augenbewegung. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 2; 418-422.

Langworthy OR (1933) Development of behaviour patterns and myelinisation of the nervous system in the human foetus and infant. Contributions to Embryology, 24; 1-57.

Larsby B, Thell J, Moller C, Odkvist L (1988) The effect of stimulus predictability and age on human pursuit eye movements. Acta Otolaryngologica (Stockh), 105; 21-20.

Lau CGY, Honrubia V, Jenkins HA, Baloh RW, Yee RD (1978) Linear model for visual-vestibular interaction. Aviation Space and Environmental Medicine, 49; 880-885.

Lawrence MM, Fiend CR (1953) Vestibular responses to rotation in the newborn infant. Paediatrics, 12; 300-305.

Leider R, Bauer J (1911) Uber den Einfluss der Ausschaltung verschiedener Hirnabschritte auf die vestibularen Augenreflexe. Arbeite aus der neurologischen Institut an der Weiner Universitat, 19; 155.

Levens L (1988) Electronystagmography in normal children. British Journal of Audiology, 22; 51-56.

Levy DL, Proctor LR, Holzman PS (1977) Visual interference on vestibular response. Archives of Otolaryngology, 103; 287-291.

Lisberger GG, Fuchs AF (1977) Role of the primate flocculus in smooth pursuit eye movements and rapid behavioural modification of the vestibulo-ocular reflex. In: Control of Gaze by Brainstem Neurones (eds. Baker R, Berthoz A). pages 381-389. Amsterdam: North Holland/Elsevier.

Lorente de No R (1933) Anatomy of the eighth nerve. I. The central projection of the nerve endings of the internal ear. Laryngoscope, 43; 1-38.

Lorente de No R (1933) The vestibulo-ocular reflex arc. Archives of Neurology and Psychiatry, 30; 245-291.

Mach E (1875) Grundlinien der Lehre von den Bewegungsempfindun gen. Liepzig:Wilhelm Englemann.

Magendie F (1824) In:An Elementary Treatise on Human Physiology, (5th edition). New York:Harper.

Magnusson M, Pyykko I, Jantti V (1985) The effect of alertness and attention on optokinetic nystagmus in man. American Journal of Otolaryngology, 6; 419-425.

Magnusson M, Pyykko I, Norrving B (1986) The relationship of optokinetic nystagmus to pursuit eye movements, vestibular nystagmus and to saccades in humans. A clinical study. Acta Otolaryngologica (Stockh), 101; 361-370.

Magoon EH, Robb RM (1981) Development of myelin in human optic nerve and tract. A light and electron microscopic study. Archives of Otolaryngology, 99; 655-659.

Maier M, Lyon H (1921) Experimenteller Nachweis der Endolymphbewegung im Bogengangsapparat des Ohrlabyrinthes bei adaquater und kalorischer Reizung. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere, 187; 47-74.

Malcolm R, Melvill Jones G (1970) A quantitative study of vestibular adaption in humans. Acta Otolaryngologica (Stockh), 70; 126-135.

Markham CH, Yagi T, Curthoys IS (1977) The contribution of the contra-lateral labyrinth to second order vestibular neuronal activity in the cat. Brain Research, 138; 99-109.

Maulucci R, Herman R (1979) Non visual control of vestibulo-ocular suppression in man. Society of Neurosciences Abstracts, 5; 692.

Maunsell JH, Van Essen DC (1983) The connections of the middle temporal visual area (MT) and their relationship in a cortical hierarchy in the macaque monkey. Journal of Neurosciences, 3; 2563-2586.

May EF, McCrea RA (1985) Physiological characteristics of neurones in the medial vestibular nucleus and reticular formation of the squirrel monkey involved in foveal cancellation of the horizontal vestibulo-ocular reflex. Society of Neurosciences Abstracts, 11; 1039.

Mercier C (1877) Independent movements of the eyes in coma. British Medical Journal, 1; 292.

McGraw MB (1941) Development of rotatory-vestibular reactions of the human infant. Child Development, 12; 17-19.

McGinnis G (1930) Eye movement and optic nystagmus in early infancy. Genetic Psychology Monographs, 8; 374-402.

McLay K, Madigan MF, Omerod FC (1958) Electrical nystagmography and its use in the clinical investigation of vestibular function. Journal of Laryngology and Otology, 72; 48-55.

Meniere M P (1861) Maladie de l'oreille interne offrant les symptoms de la congestion cerebrale apoplectiforme. Gazette Medicale de Paris, 16; 597-601.

Mettler CC (1947) History of Medicine. Philadelphia:Blackiston.

Meurman Y (1924) Experimental investigations on conduction of warmth in the labyrinth of the ear and on the caloric nystagmus. Acta Otolaryngologica (Stockh), 6; 555-567.

Michishita K (1967) Studies of normal vestibular reactions in children. Journal of Otorhinological Society of Japan, 70; 37-60.

Mitchell T, Cambon K (1969) Vestibular responses in the neonate and infant. Archives of Otolaryngology, 90; 556-557.

Monakow C von (1895) Experimenttelle und Patholgische-anatomische Untersuchungen uber die Haubeuregion, den Sehhugel und die Regio subthalamica, nebst Beitragen zur Kenntnis fruh erworbeuer Gross-und Klinhirn-defecte. Archiv fur Psychiatrie und Nervenkraukheiten, 27(1); 386-478.

Money KE, Bonen L, Beatty JD (1971) Physical properties of fluids and structures of vestibular apparatus of the pigeon. American Journal of Physiology, 220; 140-147.

Mott FW, Schaefer EA (1890) On associated eye movement produced by cortical faradisation of the monkey brain. Brain, 13; 165-173.

Mueller J (1826) Zur vergleichenden Physiologie des Gesichtssinne, des Menschenund der thiere, nebat einen versuch Uber der Bewegungen der Augen und uber den menschlichen Blick. page 254. Leipzig:Cnobloch.

Muller-Deile J, Reker U, Zell E (1986) Uber die Bedeutung der Konvektions-Hypothese Baranys fur den thermischen Nystagmus. Laryngologie, Rhinologie, Otologie (Stuttgart), 65; 154-157.

Muller J (1834) Handbuch der Physiologie des Menschen fur Vorlesgungen. Berlin:Coblentz.

Ornitz EM, Brown MB, Mason A, Putnam NH (1974) The effect of visual input on post-rotatory nystagmus in normal children. Acta Otolaryngologica (Stockh), 77; 418-425.

Ornitz EM, Atwell CW, Walter DO, Hartmann EE, Kaplan AR (1979) The maturation of vestibular nystagmus in infancy and childhood. Acta Otolaryngologica (Stockh), 88; 244-256.

Ornitz EM, Kaplan AR, Westlake JR (1985) Development of the vestibulo-ocular reflex from infancy to adulthood. Acta Otolaryngologica (Stockh), 100; 180-193.

Paparella MM, Morizono T, Le CT, Mancini F, Sipilla P, Choo YB (1984) Sensorineural hearing loss in otitis media. Annals of Otology Rhinology and Laryngology, 93; 623-629.

Pappas D, Galanos A (1982) Prosper Meniere:beyond the controversial autopsy report. Southern Medical Journal, 75; 470-472.

Pappas D (1983) Hearing impairments and vestibular abnormalities among children with subclinical cytomegalovirus. Annals of Otology, Rhinology and Laryngology, 92; 552-557.

Parks MM (1982) Visual results in aphakic children. American Journal of Opthalmology, 94; 441-449.

Pendelton ME, Paine RS (1961) Vestibular nystagmus in newborn infants. Neurology, 11; 450-458.

Penfield WG, Jasper H (1954) Epilepsy and the functional anatomy of the human brain. London:Churchill.

Peron J-M, Courtin Ph, Aubert M-J,Dehesdin D,Andrieu-Guitrancourt J (1980) L'epreuve calorique par la stimulation a l'air chez l'enfant. Revue d'Oto-neuro-ophtalmologie, 52; 52-60.

Peterson BW (1970) Distribution of neural responses to tilting within vestibular nuclei of the cat. Journal of Neurophysiology, 33; 750-767.

Picart P, Conraux C, Grenier GF (1971) Response nystagmique et seuil chez le tout jeune infant. Revue d'Laryngologie, Otologie, Rhinologie (Bordeaux), 92; 258-261.

Pillsbury HC (1981) Metabolic causes of hearing loss and vertigo. Otolaryngologic Clinics of North America, 14; 347-354.

Prevost JL (1868) De la deviation conjuguee des yeux et de la rotation de la tete dans certain cas h'emiplegie. Paris:Masson.

Proctor L,Glackin R (1985) Factors Contributing to Variability of Caloric Test Scores. Acta Otolaryngologica (Stockh), 100; 161-171.

Purkinje J (1819) Beobachtungen und Versuche zur Physiologie der Sinne, In:Beitrage zur Kentniss des Sehens in subjektiver Hinsicht, Vol 1, page 50. Prague:Calve.

Purkinje J (1820) Beytrage zur naheren Kenntnis des Schwindels aus heautognostischen Daten, page 79. Der Osterreichen Staates, V1, Band 11. Vienna:Stuck.

Raphan T, Cohen B (1978) Brainstem mechanisms for rapid and slow eye movements. Annual Review of Physiology, 40; 527-552.

Riesco-Mclure J, Stroud M (1960) Dysrythmia in the post-caloric nystagmus. Its clinical significance. Laryngoscope, 70; 697-721.

Robinson DA (1964) The mechanics of human saccadic eye movement. Journal of Physiology, 174; 245-264.

Robinson DA, Fuchs AF (1969) Eye movement evoked by stimulation of frontal eye fields. Journal of Neurophysiology, 32; 637-648.

Romberg MH (1846) Lehrbuch der Nerven Krankheiten des Menschen. Berlin:Dunker.

Ron S, Robinson DA, Skavenski AA (1972) Saccades and the quick phase of nystagmus. Vision Research, 12; 2015-2022.

Rosenhall U (1972) Vestibular macular mapping in man. Annals of Otology, Rhinology and Laryngology, 81; 339-351.

Rossi LN, Pignataro O, Nino LM, Gaini R, Sambataro G, Oldini C (1979) Maturation of vestibular responses:Preliminary report. Developmental Medicine and Child Neurology, 21; 217-224.

Royeen CG (1980) Factors affecting test-retest reliability of the Southern California Post-rotatory nystagmus Test. American Journal of Occupational Therapy, 34; 37-39.

Rudge P (1983) Clinical Neuro-otology. Edinburgh:Churchill-Livingstone.

Sakata E, Ohutsu K, Itoh A, Teramoto K (1986) Die Klassifizierung des optokinetischen Nachnysyagmus (optokinetic after-nystagmus, OKAN) und seine topisch-diagnostische Bedeutung beim Menschen. Auris Nasus Larynx (Tokyo), 13; 139-149.

Sallustro F, Atwell CW (1978) Body rocking, head banging and head rolling in normal children. Journal of Paediatrics, 93; 704-708.

Schalen L, Enbom H, Henriksson NG, Magnusson M, Pyykko I (1988) Clinical aspects of Eye Tracking Test. Acta Otolaryngologica (Stockh), 455; 28-32.

Scherer H, Clarke AH, Baetke F (1985) Uberlegungen zur Physiologie der kalorischen Gleichgewichtsreaktion Konsequenzen aus den Ergebnissen des Weltaumexperiments in Spacelab 1 vom December 1983. Laryngologie, Rhinologie, Otologie (Stuttgart) 64; 263-268.

Schmalz G (1931) The physical phenomena occurring in the semicircular canals during rotatory and thermic stimulation. Proceedings of the Royal Society of Medicine, 25; 359-381.

Schneider LW, Anderson DJ (1976) Transfer characteristics of first and second order lateral canal and vestibular neurones in the gerbil. Brain Research, 112; 61-76.

Schor RH (1974) Responses of the cat vestibular neurones to sinusoidal roll tilt. Experimental Brain Research, 20; 347-362.

Schuknecht HF (1974) Pathology of the ear. Cambridge:Harvard University Press.

Selhorst JB, Stark L, Ochs AL, Hoyt WF (1976) Disorders in cerebello-ocular control. 11. Macrosaccadic Oscillation:an oculographic, control system and clinico-anatomical analysis. Brain, 99; 509-522.

Shimazu M, Precht W (1966) Inhibition of central vestibular neurones from the contralateral labyrinth and its mediating pathways. Journal of Neurophysiology, 29; 467-492.

Sills AW, Baloh RW, Honrubia V (1977) Caloric Testing 2. Results in normal subjects. Annals of Otology, Rhinology and Laryngology, 86(3), Supp 43; 7-23.

Sills AW, Honrubia V, Baloh RW (1978) Is the adaptive model a valid description of the vestibulo-ocular reflex. Biological Cybernetics, 30; 209-220.

Silverstein H (1965) Induced rotational nystagmus in normal infants. Journal of Paediatrics, 67; 432-437.

Simons B, Buttner U (1985) The influence of age on optokinetic nystagmus. European Archives of Psychiatry and Neurological Sciences (Berlin), 234; 369-373.

Snashall S (1983) Vestibular function tests in children. Journal of the Royal Society of Medicine, 76; 555-559.

Spoendlin H (1964) Uber die Polarisation der Vestibularen Rezeptoren. Practica Otorhinolaryngologica, 26; 418-432.

Spiller WG (1924) Ophthalmoplegia internuclearis anterior:a case report with necropsy. Brain, 47; 345-357.

Steinberg M, Rendle-Short J (1977) Vestibular dysfunction in young children with minor neurological impairment. Developmental Medicine and Child Neurology, 19; 639-651.

Steinhausen W (1931) Uber den Nachweis der Bewegung der Cupula in der intakten Bogengansampulle des Labyrinthes bei der naturalichen rotatorischen und Calorischen Reizung. Pflugers Archiv fur gesamte Physiologie des Menschen und der Thiere. 228; 322-328.

Stefansson S,Imoto T (1986) Age-Related Changes in Optokinetic and Rotational Tests. American Journal of Otology, 7; 193-196.

Stratton GM (1902) In:Wundt's Philosophische Studien, XX Band, page 336. Leipzig:Engelman.

Suzuki DA,Keller EL (1984) Visual signals in the dorsolateral pontine nucleus of the alert monkey:Their relationship to smooth pursuit eye movements. Experimental Brain Research, 53; 473-478.

Szentagothai J (1950) The elementary vestibulo-ocular reflex arc. Journal of Neurophysiology, 13; 395-407.

Takemori S, Cohen B (1974) Loss of visual suppression of vestibular nystagmus after flocculus lesions. Brain Research, 72; 213-224.

Teller DY, Morse R, Borton R, Regal D (1974) Visual acuity for vertical and diagonal gratings in human infants. Vision Research, 14; 1433-1437.

Ter Braak JWG (1936) Untersuchungen ueber optokinetischen Nystagmus. Archives Neerl de Physiologie, 21; 309-376.

Ter Braak JWG, Van Vleit AGM (1963) Subcortical optokinetic nystagmus in the monkey. Psychiatria, Neurologia, Neurochirurgia, 66; 277-283.

Thornval A (1917) Funktionsundersogelser af Vestibulaerorganst og Cerebellum.Kobenhavn.

Thiringer K, Kankkunen A, Liden C, Niklasson A (1984) Perinatal risk factors in the aetiology of hearing loss in pre-school children. Developmental Medicine and Child Neurology, 26; 799-807.

Tibbling L (1969) The rotatory nystagmus response in children. Acta Otolaryngologica (Stockh), 68; 459-467.

Tjernstrom O (1973) Nystagmus inhibition as an effect of eye closure. Acta Otolaryngologica (Stockh), 75; 408-418.

Toglia JU, Rosenberg PE, Ronis ML (1970) Post-traumatic dizziness. Archives of Otolaryngology, 92; 485-492.

Tomlinson RD, Robinson DA (1981) Is the vestibulo-ocular reflex cancelled by smooth pursuit? In:Progress in Oculomotor Research (ed. Fuchs A, Becker W) pages 533-539. New York:Elsevier/North Holland.

Tomlinson RD, Robinson DA (1980) Responses of vestibular nuclei cells during vertical vestibular and pursuit eye movements. Society for Neuroscience Abstracts, 6; 477.

Torok N (1970) The effect of arousal upon vestibular nystagmus. Advances in Otorhinolaryngology, 17; 76-89.

Unterberger S (1938) Neue objectiv registrier bare Vestibularis-Korper drehreaktion erhalten durch Treten auf der Stelle:Der "Tretversuch". Archiv fur Ohren-Nasen und Kehlkopfheilkunde, 179; 273-282.

Veltri RW, Wilson WR, Sprinkle PM, Rodman SM, Kavesh DA (1981) The implication of virus in idiopathic sudden hearing loss:primary infection or reactivation of latent virus. Otolaryngology-Head and Neck Surgery, 89; 137-141.

Volkmann AW (1846) Sehen in Wagner Handworter-Buch der Physiologie. Page 265. Braunschweig:Vieweg und Sohn.

Vuori M, Lahikinen EA, Peltonen T (1962) Perceptive deafness in connection with mumps. Acta Otolaryngologica (Stockh) 35; 231-236.

Watson P, Steel JC (1974) Paroxysmal disequilibrium in the migraine syndrome of childhood. Archives of Otolaryngology, 99; 177-179.

Wendt GR (1951) Vestibular Function In:Handbook of Experimental Psychology (ed. Stevens SS), pages 1191-1223. New York:Wiley.

Westheimer G, Blair SM (1973) Oculomotor defects in cerebellectomised monkeys. Investigations in Opthalmological and Visual Sciences, 12; 618-621.

White OB, St Cyr J, Tomlinson RD, Sharpe JA (1989) Ocular motor defects in Parkinsons Disease:III. Co-ordination of eye and head movements. Brain, 3; 115-131.

Whittington DA,Lestienne F, Bizzi E (1984) Behaviour of preoculomotor burst neurones during eye-head coordination. Experimental Brain Research, 55; 215-222.

Worth CA (1903) Squint, its Causes, Pathology and Treatment. London.

Yagi T, Sekine S, Shimizu M (1983) Age dependent changes in the gains of the vestibulo-ocular reflex in humans. Advances in Oto-rhino-laryngology, 30; 9-12.

Yan-You N, Shu-Hua Y (1985) Improvement in hearing among otherwise normal schoolchildren in iodine-deficient areas of Guizhou, China, following use of iodised salt. The Lancet, 2; 518-520.

Yee RD, Baloh RW, Honrubia V, Jenkins HA (1982) Pathophysiology of optokinetic nystagmus. In:Nystagmus and Vertigo. Clinical approaches to the patient with Dizziness (ed. Honrubia V and Brazier M). Pages 251-296. New York:Academic Press.

Young LR, Oman CM (1969) Model for vestibular adaption to horizontal rotation. Aerospace Medicine, 40; 1076-1080.

Zasorin NL, Baloh RW, Yee RD, Honrubia V (1983) Influence of vestibulo-ocular reflex gain on human optokinetic nystagmus. Experimental Brain Research, 51; 271-274.

Zee DS, Yee RD, Cogan DG, Robinson DA, Engle WK (1976) Oculomotor abnormalities in hereditary cerebellar ataxia. Brain, 99; 207-234.

Zee DS (1984) New concepts of cerebellar control of eye movements. Otolaryngology-Head and Neck Surgery, 92(1); 59-62.

Zelenka J,Slaninova B (1966) Die Tatigkeit des Labyrinthes bei Kindern zwiischen 8 und 14 Jahren, die termingerecht oder nach verkurzter Schwangerschaftsdauer geboren sind. Zeitschrift fur Layngologie,Rhinologie und Otologie, 45; 808-813.

APPENDIX 1

The following schools kindly helped in the provision of subjects for study:

1. Park Barn School, Guildford.

2. Guildford County School, Farnham Road, Guildford.

3. Onslow County Infants School, Onslow Village, Guildford.

4. Guildford High School for Girls, London Road, Guildford.

5. Tormead School, Cranleigh Road, Guildford.

6. Stoughton County Middle School, Cranleigh, Surrey.

7. Stoughton First School, Cranleigh, Surrey.

APPENDIX 2

PROFORMA USED FOR HISTORY AND INVESTIGATION OF PATIENTS.

NAME dob Sex

General Practitioner

School

PAST HISTORY
Infectious Disease:
Measles
Mumps
V.Zoster
Rubella
Otitis Media
Meningitis
Other

Trauma

Drugs

Migraine

Kernicterus

Endocrine Disease

Seizures

BIRTH AND DEVELOPMENT

Sitting
Walking
Cycling

FAMILY HISTORY

PRESENT HISTORY

EXAMINATION
Tympanic Membranes

Tuning Forks

EYE MOVEMENTS AND ACUITY
Nystagmus

Pursuit

Saccades

Convergence

Strabismus

Acuity

GAIT

ROMBERG
UNTERBERGER

CEREBELLAR SIGNS

AUDIOLOGY
PTA
Tympanogram

APPENDIX 3

LIST OF FIGURES

4.9 Caloric Tanks.

4.10 Calibration lighting for caloric irrigation.

4.11 Irrigation cannula and disposable tip.

5.1 Histograms of the patients included in the study (all patients);

a) Raw Data

b) Logged Data.

6.0 Pendular Tracking: Regression comparing Gain of Movement to Left and Right.

6.1 Relationship between slow phase velocity of ocular movement and drum velocity.

i) normal subjects

ii) patients with central scotoma.

6.2 Pendular Tracking in a child.

i) saccadic intrusion.

ii) normal smooth pursuit.

6.3 Saccadic Movement in a child.

i) a mixed hypometric and hypermetric response in a child.

ii) normal response in an adult.

6.4 Large Drum Optokinetic responses.

Regressions of:

i) Slow phase velocity/Drum Speed.

ii) Amplitude/Drum Speed.

iii) Frequency/Drum Speed.

7.1 Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (unlogged).

i) Slow phase velocity

ii) Amplitude

iii) Frequency

7.2 Vestibulo-ocular reflex measurements.

Histograms of measurements obtained (logged).

i) Slow phase velocity.

ii) Amplitude

iii) Frequency

7.3 Regression of slow phase velocity/age ($\log_e$).

7.4 Regression of amplitude/age ($\log_e$).

7.5 Regression of frequency/age ($\log_e$).

7.6 Regressions of SPV/age for each thermal stimulus ($\log_e$). Warm water.

7.7 Regressions of SPV/age for each thermal stimulus ($\log_e$). Cold water.

7.8 Regressions of SPV/age for individual caloric irrigations. Warm water.

7.9 Regressions of SPV/age for individual caloric irrigations. Cold water.

8.1 Traces obtained in response to caloric irrigation

i) in a five year old male child.

ii) in a twenty-five year old male adult.

APPENDIX 4

LIST OF TABLES.

6.11 Optokinetic Testing; After-Nystagmus.

6.12 Optokinetic Testing: After-Nystagmus; Test/Retest (72°/sec).

6.13 Optokinetic Testing; Directional Preponderances.

7.1 Vestibulo-Ocular Function: Volume of water used in each caloric irrigation (mls).

7.2 Results of Caloric Irrigation; Unlogged.

7.3 Results of Caloric Irrigation; Logged (Log_e).

7.4 Coefficients for regression ($\log_e y = m\log_e x + c$).

7.5 Caloric Irrigation; Warm/Cold: SPV (°/sec).

7.6 Caloric Irrigation: Test/Retest (SPV °/sec).

7.7 Caloric Irrigation; Data by Sex of Subject.

7.8 Caloric Irrigation; Canal Paresis and Directional Preponderances.

7.9 Vestibulo-Ocular Function: Results of Optic Fixation at 90 seconds.