OBJECTIVE AND PSYCHOPHYSICAL STUDIES OF INFANT VISUAL DEVELOPMENT

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SUMMARY

Distortion or deprivation of vision during an early 'critical' period of visual development can result in permanent visual impairment which indicates the need to identify and treat visually at-risk individuals early. A significant difficulty in this respect is that conventional, subjective methods of visual acuity determination are ineffective before approximately three years of age.

In laboratory studies, infant visual function has been quantified precisely, using objective methods based on visual evoked potentials (VEP), preferential looking (PL) and optokinetic nystagmus (OKN) but clinical assessment of infant vision has presented a particular difficulty. An initial aim of this study was to evaluate the relative clinical merits of the three techniques. Clinical derivatives were devised, the OKN method proved unsuitable but the PL and VEP methods were evaluated in a pilot study. Most infants participating in the study had known ocular and/or neurological abnormalities but a few normals were included for comparison. The study suggested that the PL method was more clinically appropriate for the objective assessment of infant acuity.

A study of normal visual development from birth to one year was subsequently conducted. Observations included cycloplegic refraction, ophthalmoscopy and preferential looking visual acuity assessment using horizontally and vertically oriented square wave gratings. The aims of the work were to investigate the efficiency and sensitivity of the technique and to study possible correlates of visual development.

The success rate of the PL method varied with age; 87% of newborns and 98% of infants attending follow-up successfully completed at least one acuity test. Below two months monocular acuities were difficult to secure; infants were most testable around six months. The results produced were similar to published data using the acuity card procedure and slightly lower than, but comparable with acuity data derived using extended PL methods.

Acuity development was not impaired in infants found to have retinal haemorrhages as newborns. A significant relationship was found between newborn binocular acuity and anisometropia but not with other refractive findings. No strong or consistent correlations between grating acuity and refraction were found for three, six or twelve month olds. Improvements in acuity (and decreases in levels of hyperopia) over the first week of life were suggestive of recovery from minor birth trauma.

The refractive data was analysed separately to investigate the natural history of refraction in normal infants. Most newborns (80%) were hyperopic, significant astigmatism was found in 86% and significant anisometropia in 22%. During the first week significant decreases in the levels of hyperopia were observed in the cross-sectional data. Although the range of refractions narrowed between the first week and three months no significant alteration in group averaged spherical equivalent refraction was noted, however subsequently hyperopia reduced significantly by six months and this trend continued until one year. Observations on the astigmatic component of the refractive error revealed a rather erratic series of changes which would be worthy of further investigation since a repeat refraction study suggested difficulties in obtaining stable measurements in newborns. Astigmatism tended to decrease between the first week and three months, increased significantly from three to six months and decreased significantly from six to twelve months. A constant decrease in the degree of anisometropia was evident throughout the first year. These findings have implications for the correction of infantile refractive error.

Key words:

Objective acuity techniques - preferential looking - visual development - visual acuity - infant refraction

This thesis is dedicated to

MY PARENTS

JOSIE and STUART THOMPSON

in appreciation of their efforts in bringing up myself and five more

AND

to the memory of my grandmother

LUCY MARGUERITE CUMMINGS

(26.3.11 - 29.1.87)

a wonderful example to
all that knew her

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1. HUMAN VISUAL DEVELOPMENT DURING INFANCY

1.1 Introduction

Why is early visual assessment important? Clinical experience has led to the understanding that remedial therapy is most successful the earlier that visual defects (such as strabismus and amblyopia) are identified and treated. This view has been reinforced by neurophysiological findings, in experimental animals, initially noted by Hubel and Wiesel (reviewed by Wiesel, 1982). The latter were able to demonstrate the remarkable plasticity of the visual system during early life and show the considerable influence of postnatal experience on the development of the visual cortex.

Although these findings have led to a renewed interest in the topic, the question of the extent to which human perception is innately (genetically) pre-determined has interested philosophers and scientists for many decades. Opinion was originally divided into two camps. The nativists believed that the ability to perceive was predominantly genetically determined and the empiricists that visual experience (i.e. environmental influence) was necessary for the development of form perception. Animal experiments provide some support for the empirist view by demonstrating the influence of the environment on visual development (Wiesel, 1982). On the other hand it seems likely that some capacities e.g. the perception of simple form characteristics are innate but that others such as the perception of configurations of sets of contours requires visual experience (Ganz, 1978). It appears that visual experience plays a constructive and sustaining role during normal development. The exact balance during development between innately determined and environmentally modifiable capacities is still not known. This point is not only of academic interest as it has implications for the clinical treatment of immature individuals having visual deficits.

Aslin (1985), recently proposed a rather nativistic model of human visual development. He suggested that the expression of particular sensory and perceptual abilities is dependent on the interaction of a fixed genetic filter and the "potential diversity of experiential inputs". The model assumes that most abilities are partially specified (genetically controlled) at birth and are susceptible to the effects of early visual experience (environmental factors). Early experience is deemed to play an attunement role in which rather severe constraints are placed on it for normal development to occur. A restricted range of ocular alignment and balanced inputs are required for binocular functions including fusion and stereopsis to develop; a relatively in focus retinal image without large degrees of astigmatism is needed to avoid meridional acuity deficits and the absence of large interocular refractive differences is necessary for the development of a sensory-motor linkage between accommmodation and convergence.

It appears that "critical periods" exist very early in life during which time the visual system is both susceptible to various forms of abnormal visual experience and more ameniable to treatment providing that the obstacle preventing normal development can be eliminated. Failure to initiate corrective

treatment during this sensitive period can lead to permanent impairment of visual function i.e. the clinical condition termed amblyopia. Certain infants may be more susceptible to the risk of amblyopia than others (see section 1.4). The sensitive period is not uniform but shows a peak (when the visual system is most susceptible to adverse experience) followed by a gradual decline. The peaks in sensitivity may vary for different visual functions but for all appear to occur within the first three years. These studies have provoked a wealth of research interest into investigation of many aspects of human visual development. Monitoring the natural history or effects of treatment of various clinical conditions should increase knowledge of the underlying pathology and offers the possible benefit of the development of more effective therapies.

A significant problem affecting the clinician is the difficulty in obtaining quantitative estimates of visual function during infancy as reliable methods are generally not currently available. Conventional subjective methods of visual acuity determination are ineffective before approximately three years of age. From this age symbol tests may be used successfully with co-operative children (Ffookes, 1965; Keith et al., 1972) but even these may not be reliably applied below four years (Fern and Manny, 1986). In infancy it is customary for gross visual function to be assessed clinically using rather limited methods that are dependent on observation.

A variety of objective methods for the quantitative assessment of human visual function, in particular visual acuity, have recently been developed. These techniques (reviewed in Chapter 2) can be classified into three main categories being dependent respectively on optokinetic responses (OKN), preferential looking (PL) and visual evoked potentials (VEPs). In general the methods have been applied in laboratory settings although the clinical potential of such methods has attracted more recent interest, including that of this study (section 2.6). The new methods have contributed greatly to our understanding of visual development in the pre-verbal child.

The present chapter summarises the current understanding regarding aspects of normal (sections 1.2 and 1.3) and abnormal (sections 1.4 and 1.5) human visual development. Particular emphasis is given to the first year. The overall findings give a clearer insight into the major postnatal developmental periods of the human visual system and thereby some impression of the duration of critical periods (section 1.6). Studies investigating the development of other visual functions not discussed here (e.g. colour vision, and critical flicker fusion) have been included in other reviews (Atkinson, 1984; Boothe et al., 1985a).

1.2 Studies of normal visual development

1.2.1 Visual acuity data

a) Binocular and monocular acuity norms

Comparison of a review of childhood acuity data published in the early 1960's [Weymouth, (1963) - data illustrated in Figure 1.1] with recent data [Teller et al., (1986) - data illustrated in Figures 1.2 and 1.3] reveals the vast increase in numbers of investigations of acuity development in the first three years. The data presented in Figures 1.2 and 1.3 are derived from studies based on preferential looking techniques. Studies based on optokinetic responses and pattern VEPs also show rapid increases in visual acuity in normal infants during the initial six postnatal months. Trends of acuity development using each method are summarised in Figure 1 of Appendix 8 reference 1. Details of individual studies may be derived from Dobson and Teller, (1978).

Figure 1.1 Acuities for children (birth to 20 years) plotted on the Snellen decimal scale (1.0 = 6/6 or 20/20 Snellen fraction; 1' M.A.R. or 30 c/deg. and 0.5 = 6/12 or 20/40 Snellen fraction; 2' M.A.R. or 15 c/deg. etc.)
Central line = median or average acuity; upper line = 90th percentile, lower line = 10th percentile (80% of cases would be expected to fall within the latter two lines. (After Weymouth, 1963).

Figure 1.2 Binocular visual acuity means of normal infants and children from birth to three years obtained with behavioural procedures utilising grating targets. Acuity card means are represented by filled symbols and PL or operant procedures are represented by open symbols (After Teller et al., 1986).

Acuity cards:

- ● McDonald et al., (1986a)
- ▲ McDonald et al., (1985)
- ▼ Yamamoto and Brown, (1985).
- ★ Mohn and Van Hof-van Duin, (1986)
- ■ McDonald et al., (1986b)
- ♦ Dobson et al., (1986)

PL or operant procedures:

- □ Allen, (1979)
- ▽ Gwiazda et al., (1978)
- ☆ Gwiazda et al., (1980)
- ⋈ Atkinson et al., (1982)
- ○ Mayer and Dobson (1982)
- ◊ Birch et al., (1983)
- △ Yamamoto et al., (1984)

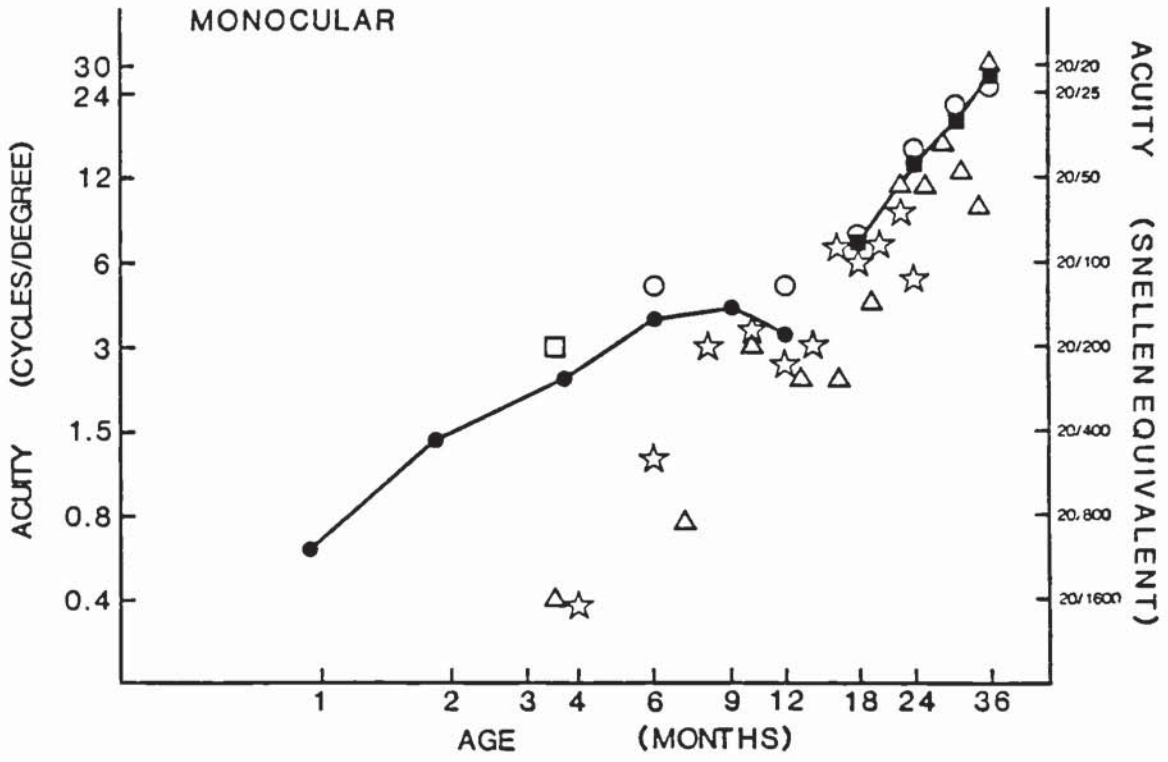


Figure 1.3 As Figure 1.2 for monocular visual acuity data.

Acuity cards:
- ● McDonald et al., (1986a)
- ■ McDonald et al., (1986b)

PL or operant procedures:
- □ Atkinson et al., (1982)
- ☆ Awaya et al., (1983)
- △ Yamamoto et al., (1984)
- ○ Maurer et al., (1985)

There is reasonable agreement about the acuity of three month olds using the different methods (around 3 cycles per degree or 10 minutes of arc) but estimates vary by as much as two octaves for one and six month olds (Atkinson, 1984). Higher levels of visual acuity are found when VEP rather than behavioural (OKN and PL) methods are applied. Discrepancies could be caused by differences in: stimuli, scoring criteria or motivation or may reflect differential maturation of the various neural pathways involved. At least part of the effect can be attributed to the higher criteria set for threshold measurements in behavioural techniques (Allen, 1979). Recent studies conclude that preferential looking acuity is temporally tuned but still poorer than VEP acuity at optimal stimulus reversal rates (Sokol et al., 1987) and that differences in scoring criteria and effects of motivation are the cause of disparities between acuity estimates using these methods (Allen et al., 1987). Since absolute differences exist between techniques it is important to use relevant acuity norms. Use of the terms "VEP acuity", "PL acuity" and "OKN acuity" has been advocated to distinguish between the values measured.

A criticism of the present author is the poor documentation of the acuity findings in much of the published literature. Acuity data has mainly been presented in graphical rather than tabulated form. The potential reviewer's compilation of norms from these graphs is complicated by the logarithmic scales generally employed although there are theoretical advantages of presenting the data in this manner (Westheimer, 1979; Boothe et al., 1985b). Information regarding the variability of data (i.e. standard deviations or errors) is seldom given. Many authors quote in their text acuity values of the youngest and oldest infants in their samples but do not comment on the absolute level of acuity found in intermediate groups. The most thorough study of infant visual development during the first six postnatal months has been provided by Allen (1979) using a forced choice preferential looking method. Mean data from this study is plotted in Figure 1.2 and numerical values are provided in Table 1.1. Estimates of mean newborn binocular PL acuity of around 35 minutes of arc (0.8 cycles per degree) are typical (Teller et al., 1986).

Table 1.1 Binocular preferential looking acuity norms derived by Allen (1979), using a laboratory (method of constant stimuli) technique. These values were computed from the original author's raw data.

Age (weeks)	Sample size	Grating visual acuity			
		Mins. of arc		Cycles/deg.	
		Mean	S.E.	Mean	S.E.
2	10	27.4	2.8	1.20	0.12
4	10	14.5	1.3	2.25	0.23
6	5	13.5	2.3	2.41	0.28
8	9	14.1	3.3	3.00	0.65
10	5	11.1	1.8	3.02	0.51
12	10	8.3	0.8	3.85	0.29
16	10	9.5	1.2	3.55	0.38
20	10	8.3	0.6	3.80	0.31
24	10	7.0	1.5	4.84	0.85

Monocular acuity was not assessed in Allen's study but in general a tendency is reported for these to be 0.75 octaves lower than binocular values. An improvement in binocular over monocular visual performance equalling a factor of $\sqrt{2}$ (i.e. one half octave) is predicted by probability summation. Improvements in performance which exceed $\sqrt{2}$ represent facilitative summation (Blake, 1982; Harwerth and Smith, 1985). Birch (1985), investigated monocular : binocular acuity ratios of normal human infants during development using a method of constant stimuli preferential looking technique. Binocular and monocular findings were not significantly different for age groups below six months. Binocular acuity was superior to monocular for infants between six and eleven months.

Spatial frequency sweep VEP methods suggest much higher acuity during the first year of life than is observed using behavioural techniques (Norcia and Tyler, 1985). Acuity levels increase from 4.5 cycles/degree during the first month to about 20 cycles/degree at 8 to 13 months using these methods. By eight months VEP grating resolution is not reliably different from adults examined using the same procedure. In comparison, PL acuity is almost adult-like by 36 months (see Figures 1.2 and 1.3).

Comparative studies of acuity development in fullterm and premature infants suggest the need to use post-term age rather than post-natal age to correct for any prematurity. This has been found to be true for both humans (Dobson et al., 1980; Dubowitz et al., 1980) and monkeys (Lee and Boothe, 1981).

b) Interocular acuity difference norms

Birch (1985), provided data on the inter-ocular acuity differences of normal human infants during the first year of life. A formal (method of constant stimuli) preferential looking technique was used. Interocular acuity differences were expressed in octaves, where an octave is a doubling or halving of spatial frequency. Mean differences were of 0.93 octaves for the 0 to 2 month group, 0.98 octaves for the 3 to 5 month group and 0.55 octaves from 9 to 11 months. The interocular differences were larger than the test retest differences (which were around 0.5 octaves throughout the first year). In a subgroup that were followed longitudinally superiority of individual eyes was not maintained for more than two months. These findings imply that unequal monocular acuities are common in normal infants during the first year and suggest that interpretation of the results of initial tests should be cautious. Yamamoto and co-workers (1984), using a staircase method (after Gwiazda et al., 1979), for clinical assesssment concluded that it seemed reasonable to assume that interocular differences of above one octave were reliable. In contrast to these findings, spatial frequency sweep VEP acuity measurements fail to demonstrate significant acuity differences between 2 and 42 weeks of age (Hamer et al., 1986).

Acuity levels are similar in adult monkeys and humans. This is also true of neonates providing that monkey age specified in weeks is compared with human age in months (Allen, 1979; Teller and Boothe, 1979). It is interesting to note that the range of PL interocular acuity differences encountered in normal monkeys fall within $\pm$ 1 octave and that amblyopia may therefore be defined as any value in excess of one octave in this species (Boothe et al., 1985b).

1.2.2 Contrast sensitivity data

Visual acuity represents the limits of resolution at maximum contrast. The contrast sensitivity function (CSF) provides an overall description of the visual function for stimuli differing in spatial frequency. The function is an inverted 'U" shape with a peak at intermediate spatial frequencies. An advantage of CSF testing rather than visual acuity measurement is that it provides information of the individuals sensitivity throughout a range of frequencies not just performance at high spatial frequency. It is therefore a more realistic measure of visual performance.

Contrast sensitivity in infancy has been studied using preferential looking (Atkinson et al., 1977a and 1977b; Harris et al., 1976; Banks and Salapatek, 1978) and pattern VEP (Atkinson et al., 1979; Harris et al., 1976, Pirchio et al., 1978) methods. Newborns and one month olds do not show low frequency attenuation and their overall sensitivity is greatly reduced. Under optimum conditions newborns respond to contrasts of about 10%, whereas two and three month olds will respond to contrasts of 5% to 8% (Boothe et al., 1985 a). A qualitative change in the shape of the function occurs at two months with the appearance of a marked low frequency cut. At two and three months the shape of the function is similar to that of adults except that it is shifted to lower spatial frequencies and lower sensitivities. Cut-off frequencies are consistent with grating acuity norms. Banks and Salapatek's data (1978) suggests that improvements in sensitivity are continuous and smooth but Atkinson and Braddick's data indicates greater rate of change between one and two months than before or after this age (Atkinson, 1984). VEP data suggests that infants' CSFs are nearly adult like at seven months.

According to the multiple channel theory of visual processing spatial frequency selective mechanisms with narrower bandwidths than the CSF are present in the human visual system (Campbell and Robson, 1968). These mechanisms may be investigated indirectly in humans using electrophysiological or psychophysical techniques. VEP methods provide evidence of spatial frequency selective mechanisms in infants of six to fifteen weeks (Fiorentini et al., 1983). At fifteen weeks infant channels are tuned at lower spatial frequencies than adults but appear similar to adult channels tuned to higher spatial frequencies (having sharper low-frequency attenuation than adult channels tuned at low spatial frequency). Behavioural (PL) studies provide evidence for spatial frequency selective mechanisms in infants of twelve weeks (Banks and Stephens, 1982).

1.2.3 Refractive error and accommodation

The most thorough review of this area has been provided by Banks (1980b). Infant refraction has been assessed directly using a variety of objective methods (ophthalmoscopy, retinoscopy, photorefraction) and occasionally has been estimated by mathematical calculation using ultrasonographic measurement of axial length combined with other biometric data. Each technique is objective in nature and therefore liable to various inaccuracies of measurement. A review of objective refractive methods is provided in section 2.5.

a) Spherical equivalent refraction

A wide range of S.E.R. findings are encountered in fullterm human newborns; myopia of up to 12 dioptres and hypermetropia of up to 12 dioptres has been reported in one sample of 500 infants (Cook and Glasscock, 1951). An earlier reviewer Steiger, (1913) combined the refractive data of four previous investigators although the data is sometimes erroneously credited to Wibaut, (1926). The combined sample comprised 2,398 newborn infants in which a range of refractive findings of between -1 and +8 dioptres were encountered. This data was biased towards the findings of Hermheiser (1892) who examined 1,920 infants and whose results have been regarded with suspicion (Hirsch, 1963) because he found a distribution of refractive findings quite unlike that of usual biological data and that have not been reported since. Despite this Steiger's review fostered the long held belief that myopia was an exceptional finding in the fullterm human newborn. Cook and Glasscock (1951) found an incidence of myopia of 25.1% in their sample and this result is in accordance with other modern studies. Most authors agree that the fullterm human tends to be hypermetropic at birth. Banks (1980b) concluded that the average S.E.R. was +2 dioptres with a standard deviation of +2 dioptres. The incidence of neonatal myopia, in studies that have excluded prematures vary from nought to 25%, with values of around 10% being typical. Only Mohindra and Held (1981) have recently noted a greater prevalence of myopia in very young infants but this may have been due to use of a new "near retinoscopy" method which does not rely on cycloplegia to control focussing (Mohindra, 1975, 1977b). In their study a mean spherical equivalent refraction of -0.6 dioptres was found in a sample of infants assessed during the first month of life.

There is still difference of opinion regarding whether hyperopia increases or decreases following birth. It was originally believed that hypermetropia decreased gradually during infancy but work done by Brown, (1936) and Slataper (1950) showed an increase of around 1.5 dioptres in average levels up to the age of seven years. This finding could have been caused by an artifact of the sampling method adopted in these studies. The populations examined were not a random cross section but patients that had presented themselves to private practice and many were squinters. As squint associated with hypermetropia tends to present itself later this could have biased the studies. Santonastaso (1930), noted an increase in hypermetropia immediately following birth followed by a gradual decline over the first year. Other later studies have reported decreases in mean levels of hypermetropia occurring between birth (Molnar, 1970) or three months (Akiba, 1969) and into the second year. There is clearly a lack of consensus on the

direction or time course of refractive change following birth. Studies on prematures suggest that mean refractions shift towards hypermetropia in the early months following premature birth (Gleiss and Pau, 1952; Grignolo and Rivara, 1968; Hosaka, 1970; Scharf et al., 1977).

b) Anisometropia

Few studies have investigated the incidence of anisometropia in newborns or investigated age related changes in infancy. It is not apparent from the details of some studies whether the examination was conducted on one or both eyes. Zonis and Miller (1974), reported an incidence of anisometropia (above 1 dioptre) in 17.4% of Israeli newborns. The incidence of levels between two and three dioptres was only 3.9% suggesting that marked anisometropia is rare at birth.

c) Astigmatism

Early investigations of newborn refraction tended to ignore measurement of astigmatism. Reported incidence of neonatal astigmatism varies from as little as 3.9% (Stampalija, 1981) to 73.5% (Gonzalez, 1968). Some discrepancies between studies could be caused by differences in the criteria for astigmatism as this information is omitted from several reports (where specified values of or above one dioptre are generally selected as the cut off point). Although the levels present at birth are not well defined, studies in older infants using a variety of methods (photorefraction, near retinoscopy and conventional retinoscopy), have consistently revealed that the incidence and magnitude of astigmatism is high during the first year or two of life (Mohindra et al., 1978, Howland et al., 1978, Atkinson et al., 1979, Fulton et al., 1980; Gwiazda et al., 1984). Atkinson and co-workers (1979), suggested that adult levels of astigmatism were attained at about 18 months.

A rather curious findings of widespread screening studies is large variations in the incidence of particular types of astigmatism in different populations (Atkinson and Braddick, 1983c). Most authors have reported that against the rule astigmatism (minus cylinder axis vertical) is more prevalent than with the rule (Fulton et al., 1980; Gwiazda et al., 1984; Dobson et al., 1984). Generally low incidence levels of oblique astigmatism have been noted, although Howland and Sayles (1984), found the ratio of against:oblique:with the rule was 15:9:1 in infants of up to two years. Dobson and co-workers (1984), observed a high prevalence of against the rule astigmatism (minus cylinder axis vertical) which disappeared by school age (when with the rule astigmatism was more prevalent). Refracting along the optic rather than visual axis has been suggested as a possible cause for the high levels of against-the rule astigmatism found in early infancy in some studies. Photokeratometric measurements suggest that an infant's astigmatism is highly correlated with the corneal curvature (Howland and Sayles, 1984).

d) Accommodation

A study conducted by Haynes and co-workers (1965), using dynamic retinoscopy, fostered the belief that accommodation was absent in newborns. The study suggested that newborn infants had a fixed focus of 19 cm. on average. Appropriate accommodation for the target distance was not found until around four months. Recent studies confirm that the young infant has greater control over focussing than this early study suggested (Braddick et al., 1979; Banks, 1980a). Newborns are capable of adjusting accommodation and do so more accurately for targets that are fairly close (≤75 cm.). Fairly accurate accommodation is obtained over a wide range of target distances by three to four months.

1.2.4 Binocularity

Three levels of binocularity may be investigated when quantifying an individual's binocular function. The presence or otherwise of bifoveal fixation, fusion and stereopsis are considered (Cashell and Durran, 1980). The three levels are hierarchically related. In normal adults bifoveal fixation is a necessary prerequisite for, though not a sufficient condition for functional fusion or stereopsis abilities. The infant's visual system may be investigated in the same manner to assess the development of binocular vision. Aslin and Dumais (1980) published an extensive review of these studies commenting that a basic misunderstanding of the different levels of binocular function had led several developmentalists to make inappropriate assumptions and inferences about infants' binocular vision.

a) Multiple-cue infant depth perception studies

Initial investigations of infant depth perception used stimuli containing multiple depth cues including monocular information e.g. differential reaching (Cruikshank, 1941) and early visual cliff studies (Walk and Gibson, 1961). Interpretation of the results of such studies is complicated by uncertainty about which particular cue provided the essential or sufficient condition for depth discrimination. Many later studies of infant depth perception have continued to confound monocular and binocular depth cues. All of the results found in these studies can be explained by the infant's processing of monocular depth cues or other methodological artifacts. No consistent conclusions on the development of binocular aspects of depth perception can be drawn (Aslin and Dumais, 1980). Yonas and Granrud (1985) have reviewed recent studies of infants' responsiveness to kinetic, binocular and pictorial depth cues. By six months infants respond to all three classes of depth information. Sensitivity to kinetic information appears first followed by detection of binocular disparity and subsequently sensitivity to pictorial depth information.

b) Bifoveal fixation studies

Several investigators have measured the binocular eye alignment of infants by attempting to specify the absolute locus in space to which the two visual axes are directed. Studies of binocular eye alignment have generally relied on determining the position of light reflexes from corneal photographs. Newborns' visual axes rarely appear coincident and generally give the impression of divergence (Wickelgren, 1967 and 1969; Rethy, 1969). This finding has been used to support the notion that binocular fixation is not present at birth. Slater and Findlay, (1972) have challenged this view arguing that the apparent divergence can be explained as an artifact of the large angle alpha found in the neonatal eye. In newborns the two eyes will appear optically divergent by 17° on average when fixing binocularly (Slater and Findlay, 1975a). In a related study the authors suggested that newborns do infact give evidence of binocular fixation showing co-ordinated eye movements when presented with an interesting visual stimulus providing correction for artifactual divergence is made (Slater and Findlay, 1975b).

Although non conjugate eye movements have often been noted in newborns (Blanton, 1917; Guernsey, 1929; Fonarev, 1959) conjugate eye movements occur with comparable frequency during visual stimulation (Wickelgren, 1969). EOG recordings during visual pursuit suggest that close conjugation of the eyes is common in the neonatal period (Dayton et al., 1964b). Aslin and Dumais (1980) consider that no currently available *objective* technique can measure binocular fixation with sufficient accuracy (i.e. within adult level Panum's fusional area - 15') to conclude that bifoveal fixation is present. The presence of bifoveal fixation in infants would satisfy one criterion for adult-like binocular vision but does not guarantee that fusion and stereopsis are present.

Although having insufficient accuracy to specify the absolute locus of the visual axes several techniques have sufficient resolution to detect small changes in binocular eye alignment. Measurement of relative eye alignment for targets presented at various distances provides an alternative method for determining whether infants fixate binocularly. Newborns show some degree of conjugation and convergence (Hershenson, 1964) and alter the relative positions of their eyes appropriately when presented with targets at 20 inch and 10 inch distances but not at 5 inches (Slater and Findlay, 1975b).

A further more direct approach is to study the actual binocular vergence eye movements as targets are moved towards and away from infants. Ling (1942) noted that appropriate vergence eye movement responses to moving stimuli did not appear until seven to eight weeks. Recent studies have suggested these can be elicited earlier. At one month infants will converge or diverge their eyes appropriately as a target is moved along the midline. Two and three month olds converge by amounts compatible with the presence of bifoveal fixation although it is still possible that they may be using an extraretinal locus to define the line of sight (Aslin, 1977).

Clinical reports suggest that the stability of eye co-ordination is not properly developed in the initial postnatal months. Full and constant co-ordination of the eyes cannot be expected before about four to six months (Brown, 1974). Transient strabismus is relatively common and its presence is of little practical significance prior to three months (Reinecke, 1984).

c) Fusion studies

Fusion can be studied in adults by observing eye movements induced by the introduction of a prism before each eye in turn. The prism shifts the image of the fixation target from the fovea causing diplopia until a compensatory saccadic refixation eye movement is made to realign the visual axes and reattain fusion. Aslin (1977) investigated the numbers of three, four and a half and six month old infants showing saccadic refixation movements following the introduction of 2.5° and 5° prisms. Refixation movements in response to the prisms were not present consistently until six months. A marked improvement in performance was found between four and a half and six months. The lack of fusional refixation movements in younger infants could be explained by measurement error, oculomotor immaturity and deficits in spatial resolution. This study does not provide conclusive data on the presence of fusion in infancy (Aslin, 1977; Aslin and Dumais, 1980) but the findings are compatible with those of later investigations (Birch et al., 1985; Shimojo et al., 1986). The latter studies have investigated infants' relative preferences for binocularly identical (fusable) or dissimilar stimuli (rivalrous patterns or orthogonal striped patterns) presented in a preferential looking paradigm. Age changes in the preferences for these stimuli allow inferences to be made regarding the presence of fusion.

The time course for the development of sensory fusion has been investigated by Birch and co-workers (1985). In this study fusable (identical) stimuli were presented to one eye and rivalrous (reverse contrast) stimuli to the other eye in a PL paradigm. None of the infants tested preferred reverse contrast stimuli at any age. All six month olds preferred the fusable stimuli. The proportion of infants showing differential fixation of the fusable stimuli increased steadily between two and six months. Findings for both checkerboard and random dot stimuli were comparable. Less than half of the two and three month olds preferred fusable stimuli compared with over 60% of four months olds. The mean age for the onset of fusion was 11.7 weeks.

Figure 1.4 Summary of frequency of infants aged one to six months demonstrating fusion or stereopsis. After Birch et al., 1985.

Shimojo and co-workers, (1986) in PL method presented young infants with a choice between binocularly identical (fusional) stimuli and non-identical (interocularly orthogonal) stimuli. Most infants younger than 3.5 months originally showed a preference for the dichoptic (interocularly orthogonal) stimuli. At an average age of 3.5 months (mean 14.2 ± 1.3 weeks) they showed a sudden shift in preference from this pattern to the interocularly identical (fusable) pattern. In a control condition interocularly identical grids were almost always preferred to interocularly identical stripes. The original preference for binocularly orthogonal patterns may be interpreted as a preference for a grid rather than grating. This finding was interpreted as suggesting that the pre-stereoptic visual system does not have the capability of interocular suppression and therefore non-selectively combines the information from the two eyes without regard to edge orientation. Binocular VEP summation data (see "additional binocularity and retrospective studies" below) suggests evidence in support of a lack of cortical inhibition during early infancy (Shea et al., 1987). Although inconclusive the findings provide indirect support for a physiological model of cortical development previously proposed by Held (1985). Held postulated that a switch in neural cortical control mechanisms (segregation of right and left eye inputs in cortical layer IV) occurring during the transition from pre to post stereoscopic visual systems, could account for the rapid onset and improvement in stereopsis that is found with age.

Odom and Harter, (1983), report on the basis of an electrophysiological study that pattern interocular suppression is of the same magnitude (≈ 30% decrease in VEP amplitude) in infants and adults but size specific interocular suppression is less marked in infants. The latter deficit was presumed to relate to the immaturity of the infants' spatial frequency or size channels. No firm conclusions can be made from this study as only three infants were tested and these were widely separated in age (mean 83 days; range 20 to 104 days). In normal adults suppression was greatest when the stimuli presented to either eye were patterns of identical spatial frequency. Further details of this study are provided in Appendix 1.

d) Stereopsis studies

Binocular disparity detection has been studied during infancy as it is a necessary prerequisite for stereoscopic depth discrimination. A variety of methods devised and used by several investigators produce comparable data. The data of several studies is summarised in Figure 1.5.

i) Spatially appropriate behaviours

The development of spatially appropriate behaviours (reaching or avoidance responses) to stereoscopically presented targets has been used to investigate infants' binocular depth perception (Aslin and Dumais, 1980 cite more than a dozen studies conducted between 1934 and 1979). These studies have typically employed shadow-casting devices to present disparate stimuli to the two eyes. The results are inconclusive since the frequency of reaching in neonates is low, older infants' reaching and avoidance responses lack a consistent relationship to object distance and the shadowcasting technique provides cues other than retinal disparity (Aslin and Dumais, 1980). Kinetic flow-field information for collision is present at 14 weeks (increased blink rate *and* defensive backward head movement for approaching rather than receding targets) and may be present as early as 4 weeks (slightly increased blink rate over many trials only), (Yonas and Granrud, 1985).

ii) Habituation-dishabituation procedures

Infant disparity detection has been investigated using habituation-dishabituation procedures. In these methods a decline in response (e.g. fixation, high amplitude sucking) is found with repeated presentation of a particular stimulus followed by an increase in response on presentation of a new stimulus providing that its novel features are identified. Early studies are inconclusive because of poor documentation of the procedures or failure to eliminate monocular stimulus cues (Bower, 1968; Appel and Campos, 1977).

Atkinson and Braddick (1976) examined disparity detection (26') of four two month olds using both a fixation preference and a high amplitude sucking habituation-dishabituation method. Results suggested that some two month olds could detect changes in disparity but the findings were not completely consistent across the two techniques.

Figure 1.5 Summary of the proportions of one to seven month olds meeting criterions for the presence of binocularity in various studies reported in the literature. Modified after Aslin (1985).

iii) Random-dot stereogram studies

Studies that have employed the random-dot stereogram (Julesz, 1986) have the advantage of excluding all monocular stimulus cues because random element displays are devoid of any coherent contours under monocular viewing conditions. Regions of elements in the two displays are moved to create binocular disparity. When viewed binocularly subjects with normal stereopsis obtain an impression of depth. Random-dot stimuli have been incorporated into both behavioural and electrophysiological studies of infant stereopsis. Bower (1968), reported different visual behaviour by infants presented with random-element displays both with or without form. Visual scanning was initiated in the absence of form but if present the infant appeared to orient to it. Few experimental details were given.

Atkinson and Braddick's early study (1976) discussed above incorporated random-dot stimuli presented in both a PL format and habituation-dishabituation protocol. The findings were rather inconclusive. Fox and co-workers, (1980) provided the first convincing evidence of disparity detection in young infants by observing their visual tracking behaviour when presented with a dynamic random-element display. Infants between two and a half and six months were tested. Performance improved with age. Infants of three and a half months and above responded above chance. Infants' performance exceeded chance only at moderate disparity levels (i.e. 45' and 134') at which adult observers report stimuli easily fusable and giving the impression of depth. Eight infants were tested longitudinally with 45' uncrossed disparity and both 45' and 134' crossed disparity stimuli. Group performance did not exceed chance for any stimuli at four and a half months but did so for all disparities at six months. Further details of this study are provided in Appendix 1.

VEPs can be elicited by dynamic random-dot correlograms and dynamic random-dot stereograms in adults with normal stereopsis (Lehmann et al., 1978; Julesz et al., 1980). As neither stimuli have monocular depth cues the VEPs are only obtained during binocular viewing. Presence of the former provides evidence of cortical binocularity and the latter of stereopsis. Further details of these methods are provided in Appendix 1.

Both types of binocular VEP have been recorded during infancy (Braddick et al., 1980; Petrig et al., 1981 and 1982; Braddick and Atkinson, 1983a and 1983b; Braddick et al., 1983). The studies conducted by Braddick and colleagues have used only correlogram stimuli but both stimuli have been applied in the investigations of Petrig and co-workers. No infants tested below 10 weeks show binocular VEPs but all infants tested above 19 weeks give positive results for both the correlogram and stereogram (40') stimuli (Petrig et al., 1981). Most infants show stereoscopically elicited VEPs by four to five months (Petrig et al., 1982). Braddick and co-workers (1983) in a longitudinal study noted that binocular VEPs could not be elicited in any newborns. The median age for the first positive recording of a binocular VEP was 13 weeks. There was a wide degree of individual variation some infants as young as eight weeks gave evidence of cortical binocularity but others still did not show this when tested at 15 weeks.

iv) PL line stereogram studies

Infants prefer to look at three dimensional objects rather than otherwise equivalent two-dimensional displays (Fantz, 1961). Stereoacuity development may be assessed using cross-polarised line stereograms presented in a conventional preferential looking display (Held et al., 1980; Birch et al., 1982; 1983; 1985). The two half fields of each stereogram (one for each eye) are superimposed on one screen and two zero disparity half fields are superimposed on the other. Infants wear goggles having cross-polarised filters. Control methods are used to ensure that preference behaviour is not the result of nonstereoscopic binocular or monocular differences between the stimuli (Held et al., 1980; Birch et al., 1982; 1983; 1985). Such controls are unnecessary in PL methods employing random-dot stimuli but despite this advantage the latter appear to have only been used in one study (Atkinson and Braddick, 1976). There is a limit to the disparity increments that can be provided in random dot stereograms. Each must be an integral multiple related to the width of individual dots the finest disparity possible being limited to the spatial frequency of the dot size used in the pattern.

In an early study employing line stereograms (Held et al., 1980) eight disparities (58, 46, 34, 23, 10, 6, 1 and 0 minutes of arc) were tested. Both uncrossed (behind the plane of fixation) and crossed (in front of the plane of fixation) disparities were used. Stereoacuity was taken as the smallest disparity at which the infant showed at least 80% preference for the disparate stimulus (75% preference criterion was adopted in later studies). Stereopsis developed earlier for crossed disparities (mean age 12 weeks) than for uncrossed disparities (mean age 17 weeks). The mean age at which stereoacuity of one minute of arc was first demonstrated was 15 weeks for crossed and 21 weeks for uncrossed disparities.

Birch and colleagues, (1982) confirmed the validity of these findings in a larger sample of infants. No evidence of stereopsis was found in 76% of infants before the fourth month. Crossed stereoacuity developed earlier (mean age 14.8 ± 4.4 weeks) but at approximately the same rate as uncrossed stereoacuity (mean age 16.8 ± 3.8 weeks). Stereoacuity of one minute of arc was obtained at mean ages of 17.8 ± 5.0 weeks for crossed and 21.0 ± 4.7 weeks for uncrossed disparities. A further study conducted by the same group demonstrated that development of accurate vergence was not the limiting factor in the development of stereopsis (Birch et al., 1983). Ensuring that stimuli were presented within 1.4° of the horopter did not significantly alter estimates of the age of onset of stereopsis (4.1 ± 1.2 months compared with 4.1 ± 0.9 months in the 1982 study). This finding suggests that neural development critical for the ability to make stereo discrimination must occur during the first three months postnatally.

Birch and associates (1985), determined the proportion of infants showing preferential fixation of 45' arc crossed disparity versus zero disparity stimuli. None of the infants preferred the zero disparity stimuli at any age. At three months 30 % discriminated the stimuli as did 82% of four month olds and all infants of six months. Mean age for the onset of stereopsis (12.3 weeks) was similar to the time course for the development of fusion (11.7 weeks) in nine infants tested longitudinally on both procedures.

The time course for the attainment of stereoacuity of one minute of arc is very short following the onset of stereopsis. An example for an individual infant is given in Figure 1.6 (after Birch et al., 1982). These findings give the impression that stereopsis is relatively mature at six months but improvements in stereoscopic thresholds occurring beyond the fifth year have been documented using subjective methods (Simons, 1981; Heron et al., 1985). It is not known to what extent practice or learning effects account for the apparent continued development of stereoacuity during childhood.

Figure 1.6 Time course for the development of stereopsis and improvement in stereoacuity, for an individual infant. After Birch et al., 1982.

e) Additional binocularity and retrospective studies

i) Binocular VEP summation

The essential feature of binocular summation is the integration of monocular inputs to produce binocular signals that are greater than either monocular component. In normal adults the amplitudes of pattern VEPs recorded during binocular viewing exceed those of the larger or the mean of individual monocular VEPs (especially when low contrasts are used to avoid saturation effects). It was originally considered that the observed enhancement could be explained by the involvement of binocular cortical neurones thereby providing an indirect index of functional binocularity. Stereodefective adults either do not show any binocular facilitation of the VEP (Amigo et al., 1978) or do not as a group show significant amounts (Shea et al., 1987). Binocular VEP summation (BVS) is the norm even in infants of two to three months (Amigo et al., 1978). Using a less conservative measure (comparison of the binocular amplitude with the mean rather than larger monocular amplitude), BVS is found to be considerably higher in two to five month old infants (≈145% greater) than in six to ten month olds (≈95%) or adults (Shea et al., 1987). The very high levels of BVS in young infants (occurring before the development of stereopsis) suggest that two independent pools of monocularly driven neurones are sufficient for significant levels of BVS. The binocular VEP signal may saturate at progressively lower levels in later infancy and adulthood as interocular cortical inhibition increases. These findings suggest that BVS provides a poor index of functional binocularity since it is uncorrelated with the presence or level of stereopsis.

ii) Binocular luminance summation

Under steady state conditions the pupil is smaller when both eyes are illuminated than when either eye is occluded. The age of onset of binocular luminance summation (BLS) of the pupillary response is highly correlated with the age of onset of stereopsis assessed by preferential looking (Birch and Held, 1983). These findings could be explained solely on the basis of developmental changes in the pupillary system (i.e. increasing sensitivity to luminance) rather than by factors intrinsic to binocular vision (Shea et al., 1985). Birch and Held (1983) noted no significant differences in pupil diameter under monocular and binocular viewing until the end of the fourth month whereas Shea and colleagues (1985) found significant levels of binocular luminance summation in two month olds. The latter findings imply that the pupillary measure of binocular luminance summation is not mediated by the same neural pathway that underlies stereopsis. Recent evidence suggests that BLS is valid only as a crude index for the simultaneous use of the two eyes rather than as a measure of binocular function (Sireteanu et al., 1987).

iii) Development of symmetrical monocular OKN

It has been noted that the time course for the development of monocularly symmetrical OKN (and OKAN) and stereopsis are comparable. This finding has led to the view that the neural pathways involved in OKN and binocularity share some common component(s). These points are discussed in section 1.2.5.

iv) Retrospective studies

Several retrospective studies have attempted to outline a critical period for the development of binocularity. Inferences are made from the binocular capacities of individuals having histories of disruption of normal binocular experience due to squint or other deprivation occurring at different stages early in life.

Bilateral eye patching is customarily performed whilst jaundiced neonates are undergoing phototherapy. This practice does not appear to increase the incidence of subsequent strabismus or stereoacuity deficits (Hoyt, 1980). A group of fifty five year olds treated (between the first to tenth postnatal day) had similar findings to an equivalent group that had not been treated.

Interocular transfer of the tilt after-effect (IOT) is a measure that may be used as an index of cortical binocularity (Banks et al., 1975). It should be noted that despite early opinion recent work fails to reveal any accurate quantitative correlation between stereothreshold and amount of transfer (Mohn and Van Hof Van Duin, 1983). After prolonged adaptation to a high contrast grating tilted slightly from the vertical, a vertical test grating appears to be rotated slightly in the opposite direction. If the adapted grating is viewed with one eye and the test grating with the other interocular transfer is defined as the amount of transfer of the after effect from the adapted to the unadapted eye. Banks and co-workers study involved 24 subjects having a history of concomitant esotropia at some period of life. All had a reasonably well defined age of squint onset and of surgical correction. Higher IOT values found among the congenital esotropes were associated with early surgery. Details of the method are given in Appendix 1. A mathematical model of the results was computed representing the relative sensitivity of the visual system to binocular deprivation occurring at different post-natal ages. The overall findings suggested that the sensitive period for the development of binocularity begins several months after birth and peaks between one and three years. A gradual reduction in deprivation sensitivity is evident beyond four years. On the basis of this study early surgery appears to be indicated for the development of cortical binocularity in congenital esotropes whereas immediate surgical correction is not necessary to maintain cortical binocularity when the esotropia is of late onset (i.e. above about four years).

A similar method was employed by Hohmann and Creutzfeldt (1975) although they referred to the IOT phenomenon as the transferred tilt after effect (TTA). Details of the method are given in Appendix 1. Nine of the sample tested had alternating convergent squints early in life that were operated on between

three and five years (mean 4.1 years) three others were normal controls. The congenital esotropes had simultaneous perception only, children with squint onset between six months and one year had fusion and those with squint onset at or beyond eighteen months had depth perception. The TTA was smallest (1 to 2°) in children with squints from birth and increased steadily the later the squint started. A child who had started to squint at 2.6 years showed no difference in TTA compared with subjects having normal vision. The findings suggested that the binocular functions of the visual cortex as assessed by the TTA are well enough developed by 2.6 months to be restored by correction of a squint. On the basis of these results about 2 to 2.6 years may be considered the end of the critical period for the development of human binocular vision.

Congenital esotropes adequately realigned (i.e. within 10 prism dioptres) after 24 months demonstrate a significantly lower percentage with evidence for binocularity when compared with children realigned at earlier ages (Ing, 1983). There was no significant difference between those realigned by 6 months versus 12 months versus 24 months. One hundred and fifty-four children were examined. Binocularity tests were Bagolini striated lenses, Worth four lights and the Polaroid Titmus vectographic stereotest. Fifty percent of infantile esotropes adequately aligned before one year show binocular eye movements (EOG recording technique) to a moving (47' disparity) random-dot stereogram within two weeks of surgery (Rogers et al., 1986). This response was not present in any of the twelve infants post-operatively.

Mitchell and co-workers (1983), documented improvements in stereoacuity thresholds in five to fourteen year old amblyopic children treated with a "minimal occlusion therapy" regimen. Modified Titmus Fly, Frisby and TNO random dot tests were applied. There is some question regarding the validity of the findings of the study which may be attributed to monocular cues in some tests or learning effects (Simons, 1984 ; Mitchell et al., 1984). Any conclusion that the study provides evidence for an extension of the sensitive period for the development of human binocular vision must therefore remain speculative. Assaf (1982) noted that the upper limit for the transfer of fixation following occlusion for strabismic amblyopia was about seven years.

Preferential looking acuity and stereopsis techniques have been applied to the investigation of infantile esotropes. These studies are discussed in section 1.5.2. Stager and Birch, (1986), noted that acuity findings were originally equal in the two eyes and that the acuity of non preferred eyes subsequently declined after five months. In the study approximately the same percentage of normal and esotropic infants (wearing prisms to correct the angle of deviation) aged three to four months demonstrated stereopsis whereas fewer esotropes than normal infants did so between five and fourteen months. Mohindra and co-workers (1985), noted that gross stereopsis was evident in treated esotropes (when tested with prism correction) up to at least two and a half years but not in a few untreated children of comparable age. Subjects older than six years with histories of infantile esotropia failed the test, but it is not entirely clear whether these infants were treated.

f) Summary

Objective techniques for the determination of fixation are not sufficiently accurate to conclude that bifoveal fixation is present (Aslin and Dumais, 1980). This would not in any case guarantee that fusion and stereopsis were present. The data on bifoveal fixation do, however, indicate that rudimentary binocular fixation (consistent line of sight in the two eyes) may be present at birth (Slater and Findlay, 1975b). Appropriate vergence eye movements are found in infants below two months but the facility to maintain constant binocular fixation particularly for moving targets and to alter convergence over large ranges improves with age (Ling, 1942, Aslin, 1977). By three months infants appear to be using a retinal area close to the fovea for fixation and the two foveal areas are in fairly close alignment (Aslin and Dumais, 1980).

Infants may respond to depth information in kinetic flow fields at four weeks (Yonas and Granrud, 1985) but presence of cortical binocularity or stereopsis is not evident in infants below two months (Petrig et al., 1981; Braddick et al., 1983). The only exception to this rule appears to be one infant in the sample of Birch and co-workers (1985) that showed stereopsis at one month of age.

Prior to the development of stereopsis it is possible that the visual system is incapable of interocular suppression (Shimojo et al., 1986). Comparable data on the time course for the development of stereopsis has been provided from electrophysiological and behavioural studies. The proportion of infants showing stereopsis increases steadily from two to six months. Most infants give evidence of stereopsis by four to five months and virtually all do so at six months (Fox et al., 1980; Held et al., 1980; Petrig et al., 1981 and 1982; Birch et al., 1982, 1983 and 1985; Birch and Held, 1983). Once stereopsis emerges in individual infants the time course for improvement in stereoacuity is very rapid. Stereoacuities of ≤ 1 minute of arc are achieved within five weeks of the onset of stereopsis (Birch et al., 1982). Stereopsis for crossed disparity stimuli develops approximately four to five weeks earlier than for uncrossed disparities (Held et al., 1980, Birch et al., 1982).

The development of stereopsis follows a time course comparable to that for the emergence of sensory fusion (Birch et al., 1985) and is not limited by the development of vergence (Birch and Held, 1983). Sensitivity to pictorial depth information does not develop until after six months (Yonas and Granrud, 1985).

Evidence from retrospective studies suggests that there is a relatively restricted sensitive period during which time anomalous binocular experience leads to a permanent loss of binocular functioning at the cortical level. Such studies indicate that the sensitive period for the development of binocular vision begins several months after birth (Banks et al., 1975; Hoyt, 1980). High sensitivity (and plasticity) is evident during the first two years (Banks et al., 1975; Hohmann and Creutzfeldt, 1975; Ing, 1983; Rogers et al., 1986). Sensitivity to the effects of deprivation gradually falls off after three or four years. Although some plasticity may be retained beyond ten years (Mitchell et al., 1983) this finding has been

the subject of some dispute (Simons, 1984; Mitchell et al., 1984). A more realistic estimate of the upper limit of the sensitive period for the development of binocular vision is around seven years (Assaf, 1982).

Detection of at risk individuals should be most beneficial between six months and two years when they are most ameniable to treatment because visual system plasticity is at its highest. Subjective methods are inapplicable for these age groups so objective techniques are required to monitor visual function during occlusion therapy.

1.2.5 Eye movements

This topic has been the subject of a recent review article (Fielder, 1985). Episodic foetal eye movements can be demonstrated from 16 weeks gestation using real time ultrasonography (Birnholz, 1981; Prechtl and Nijhuis, 1983). Initially these are merely slow changes in eye position which later become more rapid and are related to foetal behavioural state after 36 weeks. It is not clear whether non conjugate (Blanton, 1917; Guernsey, 1929; Fonarev, 1959) or conjugate eye movements (Dayton et al., 1964b) are most typical of the newborn period. Wickelgren (1969), found them occurring with comparable frequency during visual tasks. Part of the confusion may be explained by the large angle alpha in newborns eyes giving the appearance of divergence despite binocular fixation (Slater and Findlay, 1975a). Further discussion of this point is given in section 1.2.4 b).

a) Pursuit movements

Human neonates can perform smooth pursuit eye and head movements providing that target velocity is low (Kremenitzer et al., 1979; Roucoux et al., 1983). Responses are more easily elicited in the horizontal meridian (Brazelton et al., 1966). At higher stimulus velocities an afoveate type of tracking consisting of a series of successive hypometric saccades supervenes (Roucoux et al., 1983). The maximum velocity for smooth pursuit increases with age. Reliable smooth pursuit of faster moving targets is not seen until about 2 months of age (Dayton and Jones, 1964; Aslin, 1981).

Slow and fast phases of OKN can be elicited on the first day of life in newborns (Dayton et al., 1964a). This finding suggests that motor pathways involved in the slow pursuit mechanism are functional at birth although reliable following may not be demonstrated until about two months. Atkinson (1984) suggested that the apparent dissociation between OKN and smooth pursuit in young infants might be explained by the newborn being unable to follow a moving target when there are competing stationary contours in the rest of the visual field. This theory is compatible with Haith's idea (1978) that the newborn's attention mechanism locks onto whichever stimulus gives the most activation to the visual cortex (discussed in section 1.3.4 c).

b) Saccadic movements

With the exception of small corrective saccades adults alter their point of fixation using either a single saccadic eye movement or a single eye movement and single head movement in combination. Young infants rely on co-ordinated multiple component eye and head movements when shifting gaze. The dynamics of individual eye and head movement components are apparently adult-like at one month although the latency to initial saccade is still significantly longer than adults at five months (Regal et al., 1983). The ability to alter fixation to an eccentric target with one saccade develops by one year (Roucoux et al., 1983). Before this time two types of fixation movements are seen a succession of hypometric foveate-like saccades with a small head movement, or an afoveate-like co-ordinated eye-head movement which is often hypermetric (Roucoux et al., 1983).

c) Optokinetic nystagmus

Slow and fast phases of optokinetic nystagmus (OKN) can be elicited from the first day of life in fullterm newborns having both eyes open (McGinnis, 1930; Gorman et al., 1957) and in a proportion of premature infants (Kiff and Lepard, 1966). The response provides an objective method that has been used by several researchers to study pattern perception (see section 2.3). The slow-phase velocity of the response is more restricted in young infants than adults (Kremenitzer et al., 1979) and the form of the response to horizontal versus vertical movement is somewhat different (Boothe et al., 1985a).

Below three months of age an asymmetry in the elicitation of OKN is found during monocular viewing depending upon the direction of stimulus motion. Monocular OKN (M OKN) can be induced by temporal to nasalward field motion but not the reverse (Atkinson, 1979). In normal older infants and adults the response can be driven monocularly in either direction. A similar asymmetry in monocular optokinetic after nystagmus (OKAN) has been reported (Schor et al., 1983). Temporalward field motion does not evoke OKAN with a temporalward slow phase until four to five months.

Postnatally the gain of the M OKN response (slow phase) to temporalward motion increases steadily reaching equivalence to the gain for nasalward motion towards the end of the fourth month (Naegele and Held, 1982). The achievement of stereopsis occurs at an equivalent time to the equilization of these gains. In a sample having a close family history of strabismus symmetrical M OKN was observed on average about two weeks earlier than binocular (correlogram) VEPs (Braddick and Atkinson, 1983b). A substantial group of infants demonstrated symmetrical M OKN at 11 to 17 weeks but did not show binocular VEPs by 20 or even 25 weeks. Adult amblyopes including strabismics show the same directional asymmetries in M OKN (Schor, 1975; Schor and Levi, 1980) and M OKAN (Schor and Westall, 1984) as young infants. The deficit may be attributed to a combination of factors in strabismic amblyopes. The factors implicated are an asymmetrical central retinal OKN response (due to binocular central suppression) a selective involvement of the temporal hemiretinae and an extraretinal component (Westall and Schor, 1985). Collectively these findings have been taken to imply that the neural

substrate for symmetrical M OKN may have a cortical component related to binocularity.

Contradictory reports have been published on the relationship between binocular function and optokinetic asymmetries (Westall, 1986). This may be explained by normal binocular vision and symmetrical M OKN being dependent on the involvement of two sets of binocular neurones (Wolfe et al., 1981; Schor, 1983; Hine,1985). Cortical binocular neurones influence stereopsis with those of the NOT in the pretectum being responsible for symmetrical M OKN. There may infact be two classes of binocular cortical neurone, one involved in stereoscopic depth perception and the other more numerous variety not (Poggio and Fischer, 1977; Von der Heydt et al., 1978).

The exact pathways involved in the human OKN response are poorly understood since the anatomical data available is restricted to comparative studies in cat and monkey species (Braddick and Atkinson, 1983 a , 1983b; van Hof-van Duin and Mohn, 1983). There is good evidence that nasalward M OKN is largely subcortically mediated whereas a functioning cortex is necessary for the temporalward response. A route from the retina via the binocular visual cortex to the ipsilateral nucleus of optic tract (NOT) in the pretectum is believed to be the pathway responsible for generating temporalward monocular OKN. It is generally considered that this pathway is probably not functional in young infants thereby accounting for the initial nasalward directional bias (Schor et al., 1983). A direct route to the contralateral NOT is thought to be responsible for generating nasalward M OKN. Mehdorn (1983) investigated M OKN in patients having corpus collosum damage. Findings in these individuals suggested that there may be no direct pathway from retina to the contralateral NOT in humans. If this is so the pattern of asymmetry in young infants may be explained by a deficit in a callosal pathway and in the nasal half field of each eye without invoking binocularity (Atkinson, 1984).

Some evidence for a greater subcortical contribution to monocular temporalward OKN has been noted in humans suffering early brain damage (van Hof-van Duin and Mohn, 1983). A direct retinal projection to the ipsilateral NOT may occur as a functional adaptation to cortical pathway damage. Asymmetrical M OKN has been associated with latent nystagmus (Schor, 1983) and is frequently found in patients with dissociated vertical divergence who have a high incidence of latent nystagmus (Mein, 1983).

Schor (1983) proposed a plausible model in which asymmetrical M OKN in amblyopes and strabismics was explained by interference with the normal development of cortical control over the midbrain. Cortical projections to the pretectum mediating the control of temporal OKN for the ipsilateral eye become suppressed as a result of abnormal binocular stimulation by a subcortical projection to the pretectum mediating nasal OKN for the contralateral eye. The critical period for the development of human subcortical OKN pathways is not known. In adult cats cortical OKN pathways are highly plastic but connections to subcortical OKN pathways are determined early in development and are resistant to change (Malach et al., 1984; Strong et al., 1984). The maximum achievable symmetry of monocular OKN in humans could be determined in the first months being unaffected by later changes in cortical binocularity (Hine, 1985).

Monocular OKN in both aphakic and normal eyes of children treated for unilateral congenital cataract occurs significantly more often for nasally moving stripes than for stimuli moving in the reverse direction (Maurer et al., 1983; Lewis et al., 1986). No asymmetry is found in children incurring traumatic cataracts after three years. The marked directional asymmetry of M OKN responses in children having histories of congenital cataract occurs irrespective of a wide variation (2 to 28 months) in age of treatment (Lewis et al., 1986). These findings are compatible with Hine's (1985) estimate of the probable critical period for the development of symmetrical M OKN.

d) Vergence movements

Convergence to near targets is present by one month but cannot be consistently demonstrated until two months (Ling, 1942; Aslin, 1977). These studies are discussed in more detail in section 1.2.4 b). Vergence and accommodation are uncoupled in the dark (Aslin and Dobson, 1983) suggesting that the AC/A ratio develops rather than is innately determined.

e) Vestibulo-ocular reflexes (VOR)

The vestibulo-ocular reflexes ensure that the visual image remains stationary on the retina during head movements. The vestibular system is anatomically complete and functional at or before birth (Ornitz et al., 1979). In early infancy, before vision has developed sufficiently to suppress the response (or in comatose patients) the ocular-cephalic ("doll's head") manouevre results in a conjugate ocular deviation to the side opposite to the head rotation (Paine, 1963; Fielder, 1985). The response usually disappears at around 10 days (Thomas et al., 1960). At one month of age infants' compensatory (VOR) eye movements appear adequate to cancel out the effects of imposed head movements and maintain the point of fixation (Regal et al., 1983). The high quality of the infant's VOR in darkness indicates that a pure vestibular signal is sufficient to control this behaviour.

Caloric testing is generally considered clinically impractical in newborns because vernix in the semicircular canals interferes with irrigation (Paine, 1963). The fast phase of OKN induced by caloric stimulation is absent in young prematures.

Fielder (1985) describes the results of several studies that have applied rotational tests during infancy. The main findings are outlined here. Rotation of an infant about his own axis produces an ocular deviation with a slow phase opposite to the direction of rotation. Only the tonic slow phase is evident in very young prematures. The fast recovery phase (producing nystagmus) is found with increasing gestational age but may disappear during drowsiness (Paine, 1963). If an infant is held and rotated such that the axis of rotation is through the examiner the slow phase of the resulting ocular deviation is in the direction of movement. There is some dispute regarding the presence of fast phases in young prematures.

Premature infants exhibit large excursions (during rotational tests) which decrease with the development of fixation. An unusually large deviation in a three month old may therefore indicate reduced vision. Congenital esotropes consistently demonstrate abnormal responses whilst conversely esotropic infants with nystagmus have brisk responses (Hoyt,1982). Both slow and fast phases are seen in the VOR rotational test responses of most fullterm infants by one to two weeks of age (Hoyt et al., 1982). VOR responses to angular acceleration are well developed by one month but of a higher amplitude and velocity than found in later life (Ornitz et al., 1979).

The VOR is accurate at an early age although pursuit and OKN movements are immature. It therefore appears that the vestibular system plays a more important role in stabilising the retinal image (and visual world) during early infancy than in later life. There is some dispute regarding the maturity of eye movement control in preschool children (Kowler and Martins, 1983; Aslin and Cuiffreda, 1983; Dannemiller et al., 1983).

1.2.6 Visual fields

The infant visual field has been investigated primarily using techniques that are modifications of the preferential looking method although inferences have been made from EOG or photographic studies of infants' eye movements. Studies such as these have demonstrated that neonates are capable of detecting and making a saccade to fixate peripheral stimuli (Dayton and Jones, 1964; White et al., 1964; Harris and MacFarlane, 1974; MacFarlane et al., 1976; Lewis et al., 1978). Although the fovea is very immature at birth evidence suggests that neonates do not have a central scotoma (Lewis et al., 1978; Lewis and Maurer, 1980). Electrophysiological evidence indicates that at least by 10 weeks postnatally visual acuity is not uniform across the retina being highest in a small region (presumably the anatomical fovea) corresponding to a visual field of 2° (Spinelli et al., 1983). Both the central retina and the peripheral retina appear functional in the newborn.

The lateral visual field enlarges with age (Tronick, 1972; Harris and MacFarlane, 1974; MacFarlane et al., 1976) but the "effective" field is reduced in the presence of a central competing stimulus (Harris and MacFarlane, 1974; MacFarlane et al., 1976). The neonate will orient towards a stimulus 25° from the midline providing that no central stimulus is present, if such a stimulus is present the range of effective vision is narrowed to approximately 15° (Harris and MacFarlane, 1974). At seven weeks infants will orient towards stimuli located 35° from the midline but still only respond to peripheral targets at 15° eccentricity in the presence of a central stimulus. No study has yet systematically investigated the development of the visual field beyond the third month.

Detection is better in the temporal field than in the nasal before two months of age (Lewis et al., 1978 and 1985). Normal adults have better detection at 20° in the nasal field than at 30° in the temporal field (Frisen and Glansholm, 1975). The smallest lines detected by one month old infants at 20° in the nasal field are more that eight times wider than those detected at 30° in the temporal field. At two months old

smaller lines are detected at 20° in the nasal field than 30° in the temporal field (Lewis et al 1985). Detection in the temporal visual field did not alter significantly between 1 and 2 months but improved from 12.8° to 0.75° at 20° in the nasal field during this time. Lewis and co-workers (1985), considered that the improvements between one and two months were related to changes in the visual pathway beyond the retina since histological studies of young infants' retinae (Mann, 1964; Abramov et al., 1982) had not revealed obvious differences in the receptor density between the two hemiretinae. Provis and co-workers (1985), however, recently concluded that the ganglion cell layer of the temporal retina seemed relatively underdeveloped at birth in addition to the immature appearance of the fovea. A child that experienced deprivation from a unilateral congenital cataract until 4.5 months demonstrated greater threshold elevation in the nasal rather than temporal visual field of her aphakic eye (Maurer et al., 1983; Lewis et al., 1986). No asymmetry was found in infants that developed cataracts after six months. It was presumed that this finding suggests that early deprivation affects the development of cortical control over the superior colliculus.

The effective visual fields of young infants are restricted to proximal distances. Below two months infants have difficulties in attending to distant objects (McKenzie and Day, 1976; De Schoenen et al., 1978). Accommodation for objects between 20 and 75 cm. is better than for more distant targets at this age (Braddick et al., 1979).

1.3 Physiological changes underlying normal visual acuity development

1.3.1 Foveal differentiation

The major anatomical development of retinal neurons and synapses occurs prenatally. Postnatal changes observed in the primate retina are primarily concerned with differentiation of the macular region. At birth the inner retinal layers still lie above a single layer of short thick immature foveal cones (Mann, 1964; Abramov et al., 1982, Hendrickson and Yuodelis, 1984). Foveolar cone diameter of 7.5μm has been reported at 5 days postnatal (Yuodelis and Hendrickson, 1986). It was originally concluded, on the basis of work done early in this century, that development of the foveal pit was virtually completed by four months (Mann, 1964). By this stage it was thought that the foveal cones had achieved their full length and that the inner nuclear and ganglion cell layers had moved to the side to form the adult foveal depression.

Recent work indicates that development of the human fovea extends beyond the third postnatal year. Hendrickson and Yuodelis (1984) concluded that the human fovea reached maturity at some stage between 15 and 45 post term months on the basis of five anatomical indicators (the shape of the foveal curvatures; the presence of the transient layer of Chievitz; the width of the rod-free zone in the central retina; the width and length of the individual foveal cones; and the number and thickness of layers of nuclei within the fovea). At 15 months; the transient layer of Chievitz is still present and cone outer segments are less than half the length of adults (Hendrickson and Yuodelis, 1984). Even at 45 months the cone outer segments remain shorter than those of adults. A more quantitative assessment of the same material reveals that although foveola width and cone diameter reach the adult levels (650-700μm, 2μm respectively) outer segment length and cone packing density are still only half the adult values at 45 months (Yuodelis and Hendrickson, 1986). Theoretical computations, based on cone density suggest that much of the post-natal improvement in spatial vision is a consequence of foveal cone maturation (Banks et al., 1987).

1.3.2 Visual pathway myelination

Myelination of the human optic nerve continues postnatally. Changes occur rapidly within the first four months then more slowly until adult levels are achieved at around two years (Friede and Hu, 1967; Magoon and Robb, 1981). Myelination of pathways subserving subcortical vision commences several months before birth and is apparently complete by three months (Yakovlev and Lecours, 1967). Retinocortical tract myelination commences around birth and proceeds rapidly during the first few months (Friede and Hu, 1967; Yakovlev and Lecours, 1967) adult levels being achieved in the optic tracts at around two years (Magoon and Robb, 1981). Myelination of extrastriate visual areas and intracortical interneurones occurs more slowly and continues into mid-childhood.

Increasing myelination should improve neural conduction rate and contribute to the reduction in visual evoked potential latency that is found during maturation. Such changes have been reported using both flash (Ellingson, 1960; Barnet et al., 1980; Blom et al., 1980; Fielder et al., 1983) and pattern reversal (Sokol and Jones, 1979; Moskowitz and Sokol, 1983) stimuli. These points are considered in section 1.3.4 b).

1.3.3 Synaptogenesis in the visual pathway

The number of cells in the visual system appears to be complete at birth but postnatally there is an increase in cell size, synapse numbers and interconnectivity especially during the first six months (Atkinson, 1984).

a) Lateral geniculate nucleus (LGN)

The volume of the human lateral geniculate nucleus (LGN) doubles between birth and six months then remains stable into adult life (Garey and DeCourten, 1983; Garey, 1984). The laminar pattern of the nucleus is laid down between 22 and 25 weeks of gestation (Hitchcock and Hickey, 1980). Most mature LGN neuronal types are identifiable before birth (DeCourten and Garey, 1982). Immature neurons differ from their adult form by the presence of numerous dendritic and somatic spines and hair-like processes. These are most abundant at about four months, declining to adult levels at around nine postnatal months (Garey and DeCourten, 1983; Garey, 1984).

All geniculate cells are on average 60% of their adult size at birth (Hickey, 1977). Postnatally cells in all laminae grow rapidly during the first six months, those of the parvocellular layers (3,4,5 and 6) reaching adult size near the end of the first year. Cells of the magnocellular layers (1 and 2) continue to show rapid growth during the first year approaching adult size around 24 months (Hickey, 1977). Parallel pathways have been described from the retina to cortex according to an X/Y classification (Stone et al., 1979; Lennie, 1980). Evidence from both the cat (Hoffmann et al., 1972) and monkey (Dreher et al., 1976; Sherman et al., 1976; Schiller and Malpeli, 1978) suggests that the magnocellular layers contain Y - like and the parvocellular layers X - like neurons. On this basis Hickey (1977) suggested that the human X and Y cell pathways appear to mature at different rates. The slower maturing Y pathway might be more susceptible to the effects of visual deprivation. Von Noorden and co-workers (1983), studied the LGNs of a human anisometropic amblyope, finding a decrease of cell sizes in parvocellular layers 3,4 and 5 innervated by the amblyopic eye. No significant difference was found between cells in parvocellular layer 6 or the magnocellular layers (1 and 2). This study does not support Hickey's view that the Y pathway is more susceptible than the X pathway to the effects of deprivation at least at the level of the LGN.

b) Visual cortex

Conel's studies (1936 - 1967) were until recently the most comprehensive accounts of the postnatal development of the visual cortex. This extensive work demonstrated that the visual cortex and other visual areas vary greatly in relative maturity at birth. Area 17, the striate cortex, is the most mature with relative maturity declining with more anterior position. The order of relative maturity remains areas 17, 18, 19, 21 and area 8 during the first year. Ablation studies in cat and monkey indicate that area 17 is the locus of fine pattern vision (Berkley and Sprague, 1979; Miller et al., 1980). Several recent studies have investigated the development of the human striate cortex.

The striate cortex increases four-fold in volume between 28 weeks gestation and birth and again quadruples to reach adult size by four months (Huttenlocher et al., 1982; Sauer et al., 1983). The complexity of the cortical convolutions increases considerably during this period (Garey, 1984). Some differentiation of neurones and growth of dendrites occurs in the human cortex during the first few postnatal months (Takashima et al., 1980). Conel's data (1939, 1947) showed a rapid change in visual cortex interconnectivity occurring between birth and three months.

Huttenlocher and co-workers (1982) conducted a detailed quantitative study of striate cortex development. Their findings indicate that synaptic density is low (particularly in layers I and IVb) at 28 weeks gestation, doubles by birth, increases most rapidly between two and four months and reaches a maximum at eight months postnatally. This phase of rapid growth is followed after one year by a period of stabilization of cortical volume and progressive loss of synapses, with the adult density (60% of the maximum density) being attained at around eleven years. Synaptic loss apparently occurs independently of neuronal loss, as the group found no evidence of the latter during the postnatal period or even late adulthood. The two developmental phases described are paralleled by those of pattern appearance VEP maturation (DeVries-Khoe and Spekreijse, 1982). From birth to about eight months there is a rapid increase in the spatial frequency of "threshold" and "optimum" pattern appearance VEP stimuli. This is followed by a slower improvement phase up to puberty, expressing itself by reduction in pattern threshold. (The authors suggested that this latter phase may represent maturation occurring at an extrastriate site since it was accompanied by an increasing prominence of the CII component thought to be of extrastriate origin). These points are discussed in more detail in section 1.3.4 b). Comparison of Huttenlocher's and associates (1982), figures for synaptic density and cortical volume suggests that the total number of synapses in the striate cortex is highest between eight months and two years. Between eight months and eleven years the calculated total number of synapses in the right area 17 declines from 3.5×10^{12} to 2.1×10^{12}, implying a loss of 1.4×10^{12} synaptic contacts.

Garey (1984) and co-workers conducted spine counts on apical dendrites of layer III pyramidal cells, finding that a maximum was reached at five months followed by a gradual decline to a stable level at the end of the second year. The developmental curve was similar to that of Huttenlocher and co-workers (1982) synaptic density data.

The functional significance of loss of visual cortical synapses is unclear. In the monkey afferent fibres from the two eyes are initially diffusely distributed in layer IV of the cortex before becoming segregated into ocular dominance columns at about six weeks (Hickey et al., 1977). Definition of these columns may occur through progressive loss of synaptic connections from one or other eye. A similar process of synapse loss may occur in humans since ocular dominance columns do exist in man (Hitchcock and Hickey, 1980). Overproduction of connections and subsequent synaptic elimination may impart plasticity to the developing visual system enabling the brain to adapt to malformations or perinatal damage. Recovery from injury or dysfunction should be greatest during the period when synapse numbers are high there being a subsequent progressive reduction in plasticity as the nervous system matures (Huttenlocher et al., 1982). The time course of synapse elimination in the striate visual cortex is compatible with sensitive periods in the human visual system. Clinically the upper limit of the sensitive period for the development of binocular vision is about seven years with the most critical time within the first two years (Assaf, 1982; Awaya et al., 1973).

Changes comparable to those of human studies have been reported in the maturing visual systems of animals including primates. Such animal studies have been extensively reviewed by Movshon and Van Sluyters, (1981) and Boothe and co-authors (1985a). In the monkey physiological changes are accompanied by improvements in the spatial resolution of foveal LGN cells which parallel the behaviourally assessed acuity development (Teller et al., 1978; Lee and Boothe, 1981).

1.3.4 Other factors

a) Ocular optics

The optical quality of the human eye as assessed by ophthalmoscopy is considered to be very good within days of birth (Kalina, 1979) but there is some debate regarding the clarity of the optic media. Boettner and Woltner (1962) reported that human newborns have clear ocular media. VEP studies of spectral sensitivity suggest the possibility that the optic media are clearer in infants than young adults though the infant's increased sensitivity for wavelengths below 550 nm. could be explained by other factors (Dobson, 1976; Moskowitz-Cook, 1979; Werner, 1982). Behavioural studies of spectral sensitivity do not support the view that the infant's optic media is more transparent (Peebles and Teller, 1978).

b) Electrophysiological maturation studies

i) Electroretinograms (ERGs)

Cumbersome contact lens electrodes were used in the initial electroretinography studies. Development of improved ERG electrodes (Dawson et al., 1979) and general advances in electrophysiological recording techniques have greatly facilitated the ease of data collection and analysis (Thompson D.A. and Drasdo, 1987). The recording of flash ERGs and possibly even pattern ERGs may now be considered clinically viable during early infancy.

Flash ERG

The first attempts to record the neonatal electroretinogram (ERG) were conducted by Zetterstrom (1951). This pioneering work suggested that the ERG was initially not present or negligible at birth. A b-wave of more rounded shape and longer latency than in the adult response developed during the first few days of life in fullterm infants or in accordance with the degree of maturity in prematurely born infants (Zetterstrom, 1951,1952). The a-wave was apparently absent from the neonatal response, which was therefore considered to be mainly of scotopic origin. Only a quarter of one year olds demonstrated an a-wave but the response was otherwise of mature appearance by this age (Zetterstrom, 1951). Early failures to record responses can be explained by the selection of stimuli of insufficient intensity. With proper recording conditions i.e. sufficiently bright stimuli and adequate dark adaptation both photopic (a-wave) and scotopic (b-wave) components are present in the responses of premature (Horsten and Winkelman, 1962) and fullterm infants (Horsten and Winkelman, 1962; Shipley and Anton, 1964; Algvere and Zetterstrom, 1967). An x-wave, related in adults to photopic vision is evident in the neonatal response induced by long wavelength (orange/red) light (Barnet et al., 1965; Lodge et al., 1969). Variations in recording conditions mean that direct comparison between studies is not possible. Barnet and co-workers (1965), were the first to record an averaged ERG from infants. If light of sufficient intensity is used there appears to be little difference between the appearance of the infant and adult ERGs. In newborns the components are of reduced amplitude (Heck and Zetterstrom, 1958; Horsten and Winkelman, 1962; Shipley and Anton, 1964; Barnet et al., 1965; Lodge et al., 1969) and slightly longer latency (Barnet et al., 1965; Algvere and Zetterstrom, 1967; Lodge et al., 1969).

Maturation is accompanied by an decrease in latency of the b-wave component (Zetterstrom, 1951; Francois and DeRouck, 1964) and an increase in its amplitude (Heck and Zetterstrom, 1958). Whether such changes are found for the a-wave is not certain. Heck and Zetterstrom, (1958) reported that photopic potentials reached adult amplitude at the end of the second month whilst the b-wave did not reach maturity until the end of the first year. Ricci and co-workers (1983) studied pre-term maturation of the flash ERG in premature infants from 29 weeks gestation. During this period the a-wave amplitude and latency remained virtually unchanged, whereas the b_2-wave increased in amplitude and decreased in latency with increasing age. The changes were most apparent in the infants of lower gestational ages. Flicker ERGs can be recorded soon after birth (Heck and Zetterstrom, 1958). The flicker fusion frequency

is initially low but increases to adult levels by the end of the second or third post-term month (Zetterstrom, 1955; Heck and Zetterstrom, 1958; Francois and DeRouck, 1964).

Fulton and Hansen (1985) studied scotopic retinal function using the flash ERG in full term infants of between two and twelve months. An increase in sensitivity was found with increasing age i.e. less intense stimuli were required to produce the ERG response as the infant matured. Sensitivity was equivalent to adults' by five to six months. By twelve months latencies had decreased to adult levels and the b-wave of the response approached adult amplitude values.

Pattern ERG

ERG responses can be elicited by pattern stimuli (gratings or checks) reversing in contrast or presented in an appearance disappearance mode without alteration in mean luminance. Steady state or transient pattern ERG responses (PERGs) may be recorded. Stimulation of at least two hertz (4 reversals per second) is used even when recording transient PERGs since a large number of responses must be averaged to obtain the small PERG signal. ERG acuity may be assessed objectively by determining response amplitudes to various pattern spatial frequencies and using an extrapolation technique comparable to that sometimes used to determine VEP acuity (see section 2.2.1 c)). ERG and VEP responses may be recorded concurrently and simultaneous measurements have been obtained in infants (Odom et al., 1983; Fiorentini et al., 1983 and 1984). Odom and co-workers (1983) concluded that retinal pattern processing matured earlier than cortical. Fiorentini and co-workers, (1984), found ERG and VEP acuity increased in parallel during the initial second to sixth postnatal month pointing out that inadequacy in data processing could account for the apparently contradictory findings of the earlier study.

ii) Visual evoked potentials (VEPs)

In addition to its application for the objective assessment of visual acuity (section 2.2.1) the visual evoked potential (VEP) can be used as an index of maturation as several of its features alter during development. VEPs may be induced by either a luminance change i.e. light flash (Harding, 1974) or temporal modulation of a patterned stimulus. The latter, usually checkerboards or square or sine wave gratings, are presented in a contrast reversing or appearance-disappearance mode without change of mean luminance (Spekreijse et al., 1973). A transient response with identifiable components is obtained with low stimulus repetition rates (Kinney, 1977). At faster repetition rates steady state responses of sine wave appearance are obtained (Regan, 1977b; 1981). Steady state and transient VEPs have both been used in VEP acuity studies which are dependent on response amplitude measurements. It is transient responses that are of interest in VEP maturation studies because information of individual components is sacrificed in favour of speed of recording with steady state stimulation. All types of evoked response may be recorded from early infancy. Differences in recording conditions complicate inter-study comparisons of latency and amplitude findings for particular age groups. Correct and consistent identification of particular components can be difficult even within individual studies due to the marked changes occurring in the initial postnatal months (Fielder et al., 1983). Although rigorous norms cannot

be established certain generalisations may be made.

Morphology

The complexity of the flash (Barnet et al., 1980; Blom et al., 1980; Fielder et al., 1983), pattern reversal (Moskowitz and Sokol, 1983) and pattern appearance (Spekreijse, 1978) VEP waveforms increases with age. In each case components become more numerous showing a sharpening of their peaks.

Flash VEP

The flash VEP in almost all subjects has a prominent positive component often labelled P_2 which occurs with a latency of around 100 to 120 msec in normal mature individuals (Ciganek, 1961; Dustman and Beck, 1969; Wright et al., 1985). As the flash VEP can be recorded through closed lids development of the response has been studied from prematurity. Hrbek and co-workers (1973) found the typical flash VEP of full-term newborns consisted of four peaks (positive, negative, positive, negative respectively). The response develops from an initial slow high amplitude negative wave (peak 2) which becomes preceded by an earlier positive (peak 1) sometime between weeks 32 and 35 of gestation (Umezaki and Morrell, 1970; Hrbek et al., 1973). In prematures the response is initially closely localised at the occiput but spreads outside of this area with increasing age (Umezaki and Morrell, 1970). Ellingson (1960) noted that the fullterm newborns' flash response was of more variable waveform and amplitude, of longer latency and fatigued more easily than adults. Up to eight different waveforms could be noted at birth (Ellingson 1960, 1970). Only the major positive P_2 component was consistently present and sufficiently stable in latency to be useful in quantifying the response (Ellingson 1970; 1973). Ferriss and co-workers, (1967) considered a negative component following P_2 to be more reliable, whilst Harden (1982) is of the opinion that a negative component preceding P_2 is more consistent, though of lower amplitude than the major positive component of the response. Attempts to relate variability of the response to the infant's sleep-wakefulness cycle have been largely unrewarding (Ferriss et al., 1967; Hrbek et al., 1969; Ellingson 1970; Watanabe et al., 1973). After birth there is a rapid increase in the complexity of the response with adult morphology being found by two to three months (Ferriss et al., 1967; Laget et al., 1977; Blom et al., 1980; Barnet et al., 1980; Fielder et al., 1983). Although more stable responses are obtained after two (Ferriss et al., 1967) or three months (Ellingson 1973) with the possibility of all adult components being present at three months the configuration is still variable from day to day and within recording sessions.

Pattern reversal VEP

The mature pattern reversal response consists of a fairly simple waveform with a predominant positive component occurring around 100 ms and often termed P_{100} due to its consistent latency. Moskowitz and Sokol, (1983) have conducted the most detailed study of pattern reversal VEP development examining subjects of between one month and five years. An early positive component occurring between 100 and 200 ms and corresponding to P_{100} was evident from the first month and consistently present at all ages for those checksizes which elicited a recognisable signal. Responses could be recorded at all ages using

pattern element sizes of 30 minutes or larger. When patterns of 15' element size were used responses were recordable from two months but could not be obtained before three months when using 7.5' elements. Later components of the response are initially less consistent than earlier ones. By one year the frequency of occurrence of late positive components is more adult-like for large (60') than for small (15') checks. Adult like waveforms for small checks are obtained by four years.

Pattern appearance VEP

The adult pattern appearance waveform, consisting of CI (positive ≈ 80 ms), CII (negative ≈ 120 ms) and CIII (positive ≈ 180 ms) is not present in infants (Spekreijse, 1978; De Vries-Khoe and Spekreijse, 1982). In the initial study, using checksizes giving optimal VEPs the pattern appearance response at two months consists of a single positive peak (190 ms). From about five months the response starts to resemble the adult form; the initial positive being followed by a negative (CII). When small (9') checks are used the incidence of CII increases continuously from 0% in the first five to ten months to about 20% at twenty months and to 100% at about eight years (De Vries-Khoe and Spekreijse, 1982). The initial absence of the CII component is thought to suggest that newborns lack a fully developed contrast mechanism since this component is absent or greatly reduced in amblyopic eyes (Spekreijse et al., 1972). CII reflects foveal stimulation with small sharply focused patterns in adults. In Wright and co-workers study (1985) a CII component was found in only two of ten teenagers, suggesting an even later development of the normal adult waveform. Psychophysical results indicated that spatial and temporal characteristics were fully developed in these individuals (Wright and Drasdo, 1985). The authors suggested that rather than being absent CII may be obscured by high amplitude signals from extrafoveal areas in these subjects.

Amplitude

VEP amplitude is a more variable measure than latency so it is difficult to generalize about developmental changes in this parameter (Sokol and Jones, 1979). Various amplitude measures can be used e.g. peak to trough amplitudes of individual components; amplitudes of individual components related to the baseline voltage of the trace; average amplitude of the total response or of components occurring within particular latency limits.

Flash VEP

Blom and co-workers (1980) found that the group mean amplitude of the flash VEP was small until two to four months, when it rose sharply then remained fairly constant before increasing suddenly after four years. Barnet and co-workers (1980), found flash VEP amplitude tended to increase during the first six months then gradually decrease up to three years. In contrast Dustman and Beck (1969) found group mean amplitudes of both early and late flash VEP components increased markedly from infancy to age five to six years, declined until about 12 years subsequently increasing around 13 to 14 years before reducing and stabilising at around 15 to 16 years. Fielder and co-workers (1983) commented that the amplitude of the total flash VEP trace increased significantly during the first year but amplitudes of individual components were too variable for such norms to be of practical use. Callaway and Halliday,

(1973), noted amplitude peaks at nine and fourteen years. Dustman and co-workers (1977), reported peaks at around eight and fourteen years and noted that flash VEP amplitude was consistently slightly higher from the right than from the left hemisphere. Responses were of higher amplitude in males than females during childhood but the reverse was true during adolescence and adulthood. Although the findings of the studies cited above are not directly comparable it is obvious that non monotonic alterations in amplitude are found during growth and development. There is reasonable agreement that responses are initially of low amplitude, increasing rapidly to a peak at some stage between the third to sixth postnatal month (Blom et al., 1980; Barnet et al., 1980). Response amplitude then tends to decline before showing a further increase after the fourth year (Blom et al., 1980; Dustman and Beck, 1969). This second peak occurs sometime between six to nine years being followed by a third peak around puberty (Dustman and Beck, 1969; Callaway and Halliday, 1973; Dustman et al., 1977). The later changes are considerably less marked than those occurring during the first year.

Pattern VEP

There is little available evidence of age related alterations in absolute measurements of pattern VEP amplitude during early life. This is understandable because pattern VEP amplitude is spatial frequency dependent a factor which obviously complicates developmental studies because the relationship does not remain constant. Pattern VEP amplitude versus spatial frequency plots reveal an inverted U - shaped function in adults (Rietveld et al., 1967; Harter and White, 1970; Parker and Salzen, 1977; Rentschler and Spinelli, 1978). Maximum amplitudes are normally obtained for pattern spatial frequencies of between 10 and 20 minutes of arc. Inferences about the subject's acuity may be made from VEP amplitude versus spatial frequency plots. Extrapolation of the function's high spatial frequency limb to zero amplitude or the average noise level of control trials has been claimed to coincide with subjective visual resolution. This objective visual acuity method is discussed in section 2.2.1 c). Karmel and co-workers (1974) noted that an inverted U - shaped function was present in infants and that the peak shifted to higher spatial frequencies with increasing age. DeVries-Khoe and Spekreijse, (1982) studied pattern appearance VEP amplitude versus checksize findings of a series of subjects ranging between two months and eighty years in age. The intersection point with the horizontal axis (pattern "threshold") and the check size giving the largest response ("optimal" pattern) were both analysed. From birth to about eight months there was a rapid increase in the spatial frequency of the "threshold" and "optimum" pattern. During this time the amplitude versus checksize function merely shifted along the horizontal axis to higher spatial frequencies without a change in shape. This period was followed by a slower improvement phase up to puberty, expressing itself by reduction in pattern threshold which gradually approached one minute of arc as the slope of the function altered. The authors suggested that the early phase could reflect foveal development and the latter maturation at an extrastriate site.

Latency

It is unanimously agreed that a reduction in visual evoked potential latency occurs during maturation. Such changes have been reported using both flash (Ellingson, 1960; Barnet et al., 1980; Blom et al., 1980; Fielder et al., 1983) and pattern reversal (Sokol and Jones, 1979; Moskowitz and Sokol, 1983) stimuli. No systematic study of latency changes of the pattern appearance response during the first year has been published. This is presumably due to the great variability of the waveform appearance found even in co-operative adult subjects (Wright et al., 1985) and the consequent difficulties in positively identifying specific components. The most dramatic postnatal changes in flash and pattern reversal VEP latency occur between birth and about three to four months.

Flash VEP

Peak latencies of flash VEP components decrease during prematurity (Umezaki and Morrell, 1970; Hrbek et al., 1973). The major positive component shows a linear reduction in latency from 230 to 180 msec between weeks 30 and 40 of gestation (Hrbek et al., 1973). In fullterm infants the latency of the flash VEP P_2 wave decreases rapidly from about 190 msec at term birth to about 100 msec by 10 to 13 weeks and is generally considered to reach adult levels by one to two years (Lodge et al., 1969; Ellingson et al., 1973; Barnet et al., 1980) although Blom et al., (1980) did not find adult-like latencies until four years. Fielder and co-workers (1983) found their early components (P_2 and a preceding negative) were of adult-like latency by six months. Ellingson (1960) initially found the developmental curve to be two-legged with the break occurring at four weeks but this was not the case when averaging methods were used (Ellingson, 1966). The latencies of the P_2 components at birth and six weeks are not significantly correlated with those at three, six and twelve months, whereas the latency at three months is significantly correlated with those at six and twelve months (Ellingson, 1966). By three months early components (those up to P_2) are fairly stable and have almost reached adult latency levels but longer latency components continue to show substantial reduction in latency to the end of the first year, presumably reflecting later maturation of secondary visual processing mechanisms (Barnet et al., 1980). Harden (1982) noted that the the major positive component could show a peak latency of up to 50 msec longer when the response was recorded in the sleeping state.

Pattern reversal VEP

Moskowitz and Sokol, (1983) labelled the major positive component of their pattern reversal responses "P_1". P_1 latency decreased significantly more rapidly for large (48' and 60') than for small (12' and 15') checks during the first year. At all ages the P_1 latency was longer for small checks than for large checks this finding being compatible with observations in adults (Parker and Salzen, 1977). Adult like latency was attained for large checks at about one year but adult levels for small checks were still not achieved by five years. The most dramatic improvements in P_1 latency for large checks occurred within the first four months. Infants of one to seven months showed significantly longer P_1 latency to small checks (7.5' and 15') than to equivalent stripes probably due to differences in the fundamental spatial frequencies

of these patterns (Kelly, 1976). No differences were found for patterns of, or above 30 minutes.

iii) Summary of electrophysiological studies

Electroretinograms and visual evoked potentials may both be recorded at birth even in premature infants, particularly if flash stimulation is used. Fiorentini's and co-workers combined pattern ERG and VEP study (1984) suggests that maturation at higher levels of the human visual system proceeds in parallel with development at the retinal level, at least between two and six months.

Postnatal changes in both flash and pattern VEPs can be summarised as an increasing of waveform complexity, decreasing of component latencies and a reduction in response variability. The most rapid postnatal decrease in the latency of the dominant pattern (reversal) and flash components occurs within the first three or four months. Latency then gradually approaches adult levels by eighteen months for flash, one year for large checks and five years for small checks. The configuration of the waveforms continue to develop probably reaching adult appearance consistently at the following times: around five years for the flash response; during the late teens for pattern appearance and at around four years for pattern reversal (with small checks). When assessing the normality of a patient's VEPs their age, stimulus type and element size (pattern stimuli) must all be considered. Patient's latency values must be compared with equivalent norms.

c) Neural models of early visual development

Several authors have proposed differential development of neural subsystems in attempts to explain infants early visual behaviour. In the various hypothetical models what develops is visual cortical function (Bronson, 1974), the cortical projection of Y-type neurones (Maurer and Lewis, 1979), or interactions between cortical and subcortical visual structures (Atkinson, 1984).

i) Theoretical models

Bronson (1974) postulated that the neonate is initially dependent on subcortical vision and that the cortex does not start to function at all until about two months. After this age the cortex begins to assume dominance. Maurer and Lewis, (1979), suggested that the infant at birth had a partially functioning cortex with an X cell input but no Y cell input, having a Y pathway to the superior colliculus only. At two months the human infant demonstrates for the first time behaviour for which the Y pathway to the cortex appears to be necessary. This theory is based mainly on the evidence from a few animal studies.

Atkinson (1984) doubted the likelihood of Bronson's view (since some cortical functioning appears to be present at birth) and also the wisdom of Maurer and Lewis's theory (1979). The latter model was rejected because of insufficient supporting evidence. The functional roles of the X and Y cell pathways are uncertain and the literature on their relative development and vulnerability to deprivation remains conflicting. Atkinson (1984) suggested a tentative alternative hypothesis. In the first two postnatal months infant visual responses are determined largely by subcortical pathways although some functional connections exist between the eye and cortex. After about two months the maturation of pathways between the cortex and subcortex allows the former to influence the responses of subcortical pathways. This integrated control enables the synchronous development of co-ordinated eye movements (see sections 1.2.4 and 1.2.5) and the 'tuning up' of cortical disparity detectors allowing the emergence of binocular vision (see section 1.2.4). A similar though less refined model was originally proposed by Karmel and Maisel (1975). The latter authors concluded that although an intact primary (geniculostriate) system was present from birth it was not sufficiently developed to control behaviour until after six weeks. Prior to six weeks visual attention was probably mediated by a nonprimary subcortical system that controls general arousal and saccadic eye movements. Specific maturation of an inhibitory pathway between area 18 and the superior colliculus was implicated in the subsequent development.

It is worthwhile recapitulating Bronson's theory since it has attracted considerable interest and the debate has recently resurfaced. The theory is based on the assumption of the existence in humans of two visual systems. Several other investigators have proposed the existence of dualistic visual processing systems in higher vertebrates (reviewed by Salapatek, 1975). The primary visual system comprising the lateral geniculate, striate cortex and other visual cortical areas is assumed to particularly subserve the fovea. Its main functions are to analyse, encode, recognise or identify pattern and to allow the voluntary regulation

of eye movements. The main components of the second visual system are the superior colliculus and the other motor nuclei of the midbrain. This system is assumed to supply information regarding the location of stimuli, to be equally or more responsive for peripheral than foveal targets and to interact with the primary visual system in the controlling of eye movements.

Bronson (1974) argued that the neonate's visual behaviour is guided mainly by stimuli falling outside the central area of the retina and is mediated primarily by components of the phylogenetically older subcortical "second visual system". An important feature of this initial system causes the neonate to merely automatically "lock on" to the most salient peripheral stimulus. From around two months development in the primary visual system (cortex) allows the infant to start encoding information in the stimulus. More active visual search patterns are then noted. Much of Bronson's conceptual model was based on studies of eye movement patterns in infants and in adults with cortical lesions.

Evidence of transfer from mainly reflexive to voluntary control mechanisms during development is provided by other sensory modalities. A variety of reflexes can be elicited in newborn infants (Thomas et al., 1960). The newborn grasp reflex is strongly present at four weeks, largely lost by eight weeks and disappears by twelve weeks (Illingworth, 1962). A primary standing response elicited in newborns decreases following birth and is very poor at or before two months (Thomas et al., 1960). Automatic or primary walking responses can easily be elicited from the first hours of life. These are generally considered to disappear within the first few postnatal weeks (Thomas et al., 1960; Illingworth, 1962) although they may still be evident, though difficult to demonstrate, between four and six months (Amiel-Tison, 1985). The precision of some neonatal response repertoires led early workers to attribute them to higher cortical functioning. This view was disregarded with the discovery of automatic walking and other complex integrative behaviours in premature (Saint Anne Dargassies, 1955) and anencephalic infants (Thomas and Autgaerden, 1966; Graham et al., 1978). Retention of aberrant infantile reflexes has been implicated in the causation of dyslexia (Blythe and McGlown, 1981).

ii) Continuous or discontinuous development?

If Bronson's switch-over theory is correct discontinuities in development would be anticipated as the reflexive secondary system is superceded by cortically controlled activity. Some authors have reported shifts in the basis of infants visual preference occurring around six weeks. It has been reported that infants prefer increasingly large elements before six weeks but after this age the number of elements rather than their size becomes more important (Fantz and Fagan, 1975). In contrast Pipp and Haith (1984), found no age trend in their data increases in the number of elements enhanced the number of fixations for newborn, four and eight week age groups. Studies of visual pursuit are compatible with a switch over from subcortical to cortical control (Volkmann and Dobson, 1976). Patterns of eye hand co-ordination in the first year suggest that the subcortical and cortical systems follow a parallel course of development so that development proceeds along a continuum (McDonnell, 1979).

Pattern VEP amplitude versus checksize functions tend to be bimodal in young infants (especially between 30 and 40 days), providing that a wide range of spatial frequencies are tested (Harter et al., 1977a, 1977b). The amplitude of the first mode, peaking at around 20 mins of arc, progressively decreases from 10 to 30 days and disappears by 40 days. The amplitude of the second mode, peaking at above 50 mins of arc, progressively increases from 10 to 30 days. These changes produce an unexpected increase in both the checksize giving the peak response and the checksize threshold from 10 to 45 days of age. Threshold estimates based on the first mode of the VEP amplitude function have good correlation with neonatal acuity estimates based on OKN (Dayton et al., 1964a; Gorman et al., 1957). Estimates based on the second mode of the function have reasonable correlation with acuity estimates determined by preferential looking techniques. The bimodal function could represent the activity of two aggregates of neurones tuned specifically to relatively high and low spatial frequencies. If the first and second modes respectively reflect the activity of subcortical and cortical neurones the apparent decrease in acuity in the second month could represent a point in development when the cortex becomes sufficiently mature to substitute for subcortical activity.

Little alteration occurs in pattern VEP spatial tuning functions during the initial postnatal month or in temporal tuning functions during the first two months (Porciatti, 1984). During this time pattern VEP latency decreased in an approximately linear fashion by about one msec. per day. This compares with a rate of around two msec/day between two and four months reported in another study (Moskowitz and Sokol, 1983).

Before approximately one to two months there is little evidence to suggest that infants' visual interest is influenced by the configuration of pattern elements or attracted by anything other than the maximum contour density (Salapatek, 1975). The ability for visual discrimination develops later and probably reflects the integrity of higher cerebral functions (Miranda et al., 1977) since it is not normal during the first few months in infants with future neurological handicap (Harmant et al., 1983). Infants below about two months suffer from an "externality effect" in which a surrounding contour interferes with the ability to discriminate internal detail (Milewski, 1976; Bushnell, 1979, 1982). Such interactions are suggestive of a visual system that transmits only degraded spatial phase information (Braddick, 1981) and may be comparable to the "crowding" effects of amblyopes (Braddick et al., 1986a).

iii) Neonatal cortical function?

State related EEG patterns are not present before 31 weeks and not clearly established until 36 weeks gestational age (Dreyfus-Brisac, 1979). State regulation is assumed to reflect higher cortical function implying that this is present at birth in the normal fullterm human infant. Haith, (1978), is of the opinion that the visual cortex is functional at birth and that specific scanning eye movement patterns of newborn and young infants can be explained by assuming they are initiated to maintain cortical firing rate at a high level.

Orientation and pattern discrimination are believed to be a function of the striate cortex and other cortical areas so they may be used to indicate whether visual behaviour in young infants is based on subcortical or cortical control (Braddick et al., 1986a, 1986b). Orientation specific pattern VEPs emerge only at six weeks (Braddick et al., 1986b). Two and three month olds can differentiate patterns that differ only in spatial phase but one month olds do not appear to make this discrimination despite being capable of resolving the pattern detail (Braddick et al., 1986a). Phase discrimination might depend on the development of some aspect of cortical processing.

Premature infants demonstrate reasonably normal visual behaviour up to 8 weeks post term even when there is gross destruction of the occipital cortex (Dubowitz et al., 1986). Symmetrical VEPs could be elicited initially in infants whose ultrasound scans revealed asymmetrical occipital lesions but these became asymmetrical at around two months. The authors concluded that both behavioural and electrophysiological visual responses are probably not cortically mediated in the neonate. Although there is fair agreement that the newborn's visual tracking performance may be mediated subcortically by the superior colliculus (Stanley et al., 1986; Stampalija, 1986) contrary evidence suggests that elecrophysiological responses are cortically based (Stanley et al., 1986). The scalp distribution of early (cortical) and late (possibly collicular) pattern VEP components alter in a manner that supports the notion that there is a shift from subcortical to cortical control of visual responsiveness occurring between six and ten weeks (Hoffmann, 1978).

Infants with delayed visual maturation (DVM) initially exhibit severely reduced visual interest and the onset of responsive smiling is often delayed. For infants without overt neurological damage the time of visual improvement is relatively constant at 9 to 19 weeks (Fielder et al., 1985). Several authors have suggested a cortical basis for DVM caused by a delay in dendrite and synapse formation (Mellor and Fielder, 1980; Hoyt et al., 1983; Cole et al., 1984) but a subcortical deficit may be implicated since the timing of improvement appears to coincide with the onset of increased cortical visual function (Fielder et al., 1985).

Monocular OKN asymmetries persist in both eyes of children treated for unilateral congenital cataract (between 2 and 28 months) but are not found in children incurring traumatic cataracts after three years (Maurer et al., 1983; Lewis et al., 1986). The same authors tested visual field thresholds of a child that experienced deprivation from a unilateral congenital cataract until 4.5 months. Greater threshold elevation was noted in the nasal rather than temporal visual field of the aphakic eye. No asymmetry was found in infants that developed cataracts after six months. A more elaborate dicussion of these findings is given elsewhere (sections 1.2.5c) and 1.5.2) but in simple terms they could be explained by interference with the normal development of cortical control over the midbrain occurring during the first few postnatal weeks.

The contribution (if any) of cortical control to neonatal behaviour is as yet unknown. Feedback from immature higher centres may possibly interfere with rather than modulate the functioning of lower

centres (Graham et al., 1978). Cardiac deceleration responses to acoustic stimuli were present at an earlier age (3 to 6 weeks) than normally expected in an anencephalic infant. An alternative view is that many obligatory (primary reflex) responses manifest from birth to two months may be linked to neck impotence (Grenier, 1980, 1981). Upper structures may already be functioning very early in life but this functioning may not be demonstrable unless head control is achieved. Normally head control is acquired at around six to eight weeks (Amiel-Tison, 1985). It is probable that as the higher brain centres become to assume control they may modify subcortical responses through partial inhibition or facilitation (Amiel-Tison, 1985).

iv) Overview

There is reasonable agreement that a major alteration in visual responsiveness occurs during the second postnatal month. Certain aspects of the cortex are apparently functional at birth (sufficient for example for the recording of VEPs - see section 1.3.4 b)), so it is unlikely that Bronson's (1974) suggestion of a totally unresponsive newborn visual cortex can be correct. Despite this cortical properties such as pattern orientation and phase discrimination appear absent or poorly developed before six to eight weeks (Braddick et al., 1986a, 1986b). It has been argued that behavioural and electrophysiological responses may not be cortically mediated before two months (Dubowitz et al., 1986). The validity of the latter point will probably remain a matter of conjecture until improved knowledge of the source origin of neonatal VEP components becomes available (Hoffmann, 1978; Stanley et al., 1986). It seems probable that visual behaviour is largely subcortically mediated during the initial postnatal weeks (Karmel and Maisel, 1975; Atkinson, 1984). The cortex may initially merely play a contributory role before beginning to assert dominance over the subcortical system as its properties mature. The bulk of evidence favouring a discontinuous pattern of development suggests an abrupt rather than gradual switch over may occur at around two months. Clinical evidence suggests that the first few weeks of life may be critical for the development of a normal balance between the visual cortex and subcortex (Maurer et al., 1983; Lewis et al., 1986; Fielder et al., 1985).

1.4 Discussion of factors associated with an increased risk of impaired visual development

Gardiner (1969) introduced the concept of identifying groups "at risk" for the development of visual disorders. It is particularly important to identify defective individuals within high risk groups at an early age as the chances of recovery in treatable conditions will presumably be at a maximum. Adequate screening of such groups allowing early corrective intervention (within the sensitive period) should have the benefit of decreasing the incidence of permanent visual impairment in the population. Woodruff (1973) discusses major categories that place children visually at risk. Specific risk factors outlined include maternal use of cigarettes, being born to mothers of ≤ 19 years, having rubella or mumps between birth and six years of age and being male (Woodruff, 1986). Maternal alcohol abuse during pregnancy is responsible for the foetal alcohol syndrome in which a high incidence (90%) of ocular abnormalities are found (Stromland, 1985). Ocular defects in this condition include ptosis, squint, hypoplasia of optic nerve head, tortuous retinal vessels and reduced visual acuity. Some of the risk factors mentioned obviously require the use of preventative rather than corrective medicine.

Congenital ocular abnormalities are rare affecting about 1% of the total newborn population and only 0.4% of fullterm newborns (Singh et al., 1980). Ellerbrock (1963) provides a review of developmental congenital and hereditary eye abnormalities. The classification includes some amblyogenic conditions (e.g. congenital cataracts) but most of the anomalies are structural malformations (e.g. aniridia, coloboma, microphthalmos) generally resulting in irreversible visual deficits which vary in severity but may be of a profound nature. Early visual assessment in untreatable conditions is still of value in determining the child's educational requirements. Genetic counselling may assist in reducing the incidence of inherited conditions. Screening methods should be particularly adapted to identify individuals having correctable conditions which will result in permanent visual impairment if left untreated throughout the critical period. The major causes of preventable visual impairment are discussed briefly in the following sections.

1.4.1 Incidence of visual problems in paediatric populations

Low acuity resulting from structural or pathological abnormalities of the eye is relatively rare. Friedmann and associates (1980), screened 3,375 children between the ages of six month and three years. In this sample 10.8% failed the screening; 5.4 % had abnormal refractive findings. Squint was detected in 3.9 %, 1.3 % had functional amblyopia and ocular abnormalities were noted in only 1.3%. MacLellan and Harker, (1979), screened 4,544 preschool children finding 11% needed referral for an ophthalmologist's assessment. Of those in whom visual defects were subsequently confirmed 40% had abnormal refraction only, 25% had squint only and 35% had both a squint and abnormal refractive error.

Schiava and Maccolini, (1982), reported the frequency of various visual disorders observed amongst children of under six years presenting to their ophthalmological clinic between 1958 and 1977. Children

having significant ametropia made up about 48% of the sample (38.7% had hypermetropia or hypermetropic astigmatism). The presence of squint (27%) was the second most frequent findings. Amblyopia (discussed below) was found in 12.7% of the population.

These representative studies confirm that squint and ametropia are the major causes of visual problems in paediatric populations. The conditions may be present in isolation but often appear in combination. It is therefore important to more accurately identify factors which predispose certain individuals to squint and amblyopia. Early screening of groups of individuals at risk for the development of squint and/or amblyopia should enable better management of defectives and hopefully improve the eventual outcome. Detection of amblyopia is of particular importance in straight eyed individuals.

1.4.2 Amblyopia

The literature on amblyopia is extensive and a complete review of the work is outside the scope of this report. Excellent reviews are provided elsewhere (e.g. Von Noorden, 1985).

Amblyopia may be defined as a decrease in visual acuity in one or both eyes which on physical examination appear normal and which, if treated early in life, is completely or partially reversible (Von Noorden, 1985). Table 1.2 summarises the clinical conditions known to cause amblyopia. These have in common an incongruity of visual information received by the two eyes, a decrease of visual input or a combination of both factors.

Table 1.2 Causes of Amblyopia (after Von Noorden, 1985).

The conditions can be separated into three main groups of strabismic, refractive and deprivation amblyopias. Visual deprivation amblyopia in this context refers to any condition in which there is a physical obstacle preventing formation of a clear retinal image during development. The term visual deprivation is often also used to encompass all conditions which result in amblyopia i.e. including strabismic and refractive causes.

The lack of agreement of acuity standards for amblyopia prevents accord in the figures for incidence. A level of about 2% is probably a fair estimate of the incidence of childhood amblyopia (Weymouth, 1963). Some of the discrepancies between studies could be caused by the inclusion of children with correctable ametropia or organic lesions. An incidence of 1.4% was reported in the Orinda study (Peters, 1961) although preliminary screening had suggested a level of 7.3% before the removal of such individuals.

a) Strabismic amblyopia

Strabismic amblyopia has been extensively studied as it is the most common form of amblyopia. Binocular vision is degraded or fails to develop in about 5 to 7 % of the population (Reinecke, 1984). Strabismus may be either the cause or result of the degraded binocular vision. It is useful to consider two distinct types of deficit in strabismus, these being losses in binocularity or acuity.

Clinically strabismus may be classified into several categories according to the type and constancy of the deviation. The deviation is described as either convergent or divergent depending on the position adopted by the non-fixing eye. Convergent deviations (esotropias) are more prevalent than divergent deviations (exotropias). Either of these squints may additionally be referred to as an alternating strabismus if fixation can be varied freely from right to left eye. In these cases acuities may be equal and normal in each eye but the patient does not possess binocular function since each eye is alternately suppressed in turn.

A concomitant strabismus is one that has a constant angle of deviation regardless of direction of gaze. An incomitant strabismus has a variable angle and is typically due to a paretic muscle. An intermittent strabismus is a deviation that can be controlled unless the patient is tired or otherwise debilitated or one which only occurs at a particular viewing distance (e.g control may be achieved for near tasks but break down for distance visual tasks or vica versa).

The terms "congenital esotropia" and "infantile esotropia" are used interchangeably in the current literature to describe infants that develop esotropia within the first six postnatal months. The latter term is more appropriate as the deviation is rarely unequivocally present at birth (Reinecke, 1984). The congenital esotrope typically alternates well at first before developing an eye preference at around six months. Refractive findings are about the same as in the normal population with only a tendency towards more hypermetropia. Poor abduction is often exhibited unless vestibular stimulation is used.

Monkeys provide good models of normal and abnormal human visual development (Harwerth, 1982; Odom, 1983). Studies have been performed in monkeys with the intention of modelling the mechanisms of normal human binocular development and of strabismus. In newborn rhesus monkey a proportion of cortical neurones have innate connections from the two eyes (Wiesel and Hubel, 1974). During normal development the subpopulation of binocular neurones increases in the early postnatal months and many individual neurones become precisely tuned to small retinal disparities of visual objects seen by the two eyes. If normal binocular visual experience is lacking (e.g. due to eye misalignment, poor image quality in or occlusion of one eye) binocular neurones rapidly disappear from the visual cortex and only monocular neurones serving one of the two eyes can be identified. Experimentally induced concomitant strabismus in monkeys produces an irreversible loss of striate cortex binocular neurones in direct proportion to the duration of prism wear (Crawford and Von Noorden, 1979; 1980). After brief periods of experimental strabismus monkeys show poor binocular summation (CSF data) and do not respond to random dot stereograms (Crawford et al., 1983).

There are many opinions on the treatment of infantile (and other forms of) strabismus. An alternate patching regimen is generally adopted before realignment surgery to assure alternation and reduce the chance of amblyopia developing (Reinecke, 1984). This therapy has the attendent risk of decreasing binocularity. Recent preferential looking (acuity and stereopsis studies) have provided quantitative data on visual development in stabismic infants (details are given in section 1.5.2).

There is some controversy regarding the optimum time for surgery in congenital esotropia. Ing's work (1983), suggests that there is better prognosis for the development of "gross" stereopsis if adequate surgical alignment (within 10°) can be achieved before two years. More details of this study are given in section 1.2.4 e). Other opinion (Lang, 1984) favours delaying surgery until the deviation is more stable so that fewer operations are required.

b) Ametropic amblyopia

Pattern deprivation can be caused by optical defocus although the effects of this are less marked than in strabismics. The main forms of ametropic amblyopia are caused by high levels of ametropia (particularly hypermetropic) and astigmatism or differences between the refractions of each eye (anisometropias). More details of subclassifications of these categories are provided by Von Noorden, (1985). Boothe and co-workers (1985a) have reviewed human and monkey studies of the effects of optical defocus on primate spatial vision. The main conclusions are summarised here.

Anisometropia causes moderate reduction in acuity and contrast sensitivity testing shows that deficits are primarily at high spatial frequency. Anatomically only the parvocellular central pathways appear to be affected. The deprived eye loses its ability to drive cortical cells tuned to high spatial frequencies but maintains its connections to low frequencies. Monocular optical defocus in monkeys leads to a disruption of binocular vision and there is a loss of most binocular cortical cells. Ocular dominance

shifts produced by optical defocus occur predominantly in cells tuned to high frequencies.

Although clinical judgement and traditional opinion suggest that acuity deficits are found in adults with bilateral high myopia or high hypermetropia, developmental studies are relatively sparse. Mohindra and associates (1983), found that acuity deficits in four young high hyperopes (aged 30 weeks to 3 years), were eliminated by the wearing of optical correction.

Adult human astigmats who are not optically corrected in early life show acuity (Mitchell and Wilkinson, 1974; Mitchell et al., 1973) and contrast sensitivity deficits for gratings whose orientation corresponds to the axis of astigmatism. These deficits have been termed meridional amblyopia. Equivalent losses are found in monkeys. Recent studies have suggested that grating acuities are equivalent in astigmats and non astigmats during early development (Gwiazda et al., 1985). Vernier acuity deficits are, however, found in infant astigmats (for stimuli orientated at axis of astigmatism).

Ingram and associates (working in Kettering) have conducted extensive studies in an effort to determine, from refractive data, infants at most risk for the development of amblyopia. The results of early studies suggested that one year olds having more than about 2.5 dioptres of hyperopia (in any one meridian of either eye) were at greatest risk (Ingram et al., 1979). A recent study (Ingram et al., 1986) found that amblyopia was highly likely (48% of children) if ≥ 3.5 dioptres of meridional hypermetropia was found at one year. Almost half of the children with this refraction also had a squint. No significant association was found between astigmatism and either squint or amblyopia. Attempts to reduce the eventual incidence of amblyopia by identification and refractive correction of these infants from one year were unsuccessful (Ingram et al., 1985). Preliminary results are still pessimistic even when refractive screening is conducted at six months (Ingram, personal communication, 1986).

c) Stimulus deprivation amblyopia

This category refers to conditions causing a deprivation of form vision during development. Deprivation may be either unilateral or bilateral. Clinical conditions included in this classification are summarised in Table 1.2. The most widely studied condition within this category is that of congenital cataract. Retrospective studies have indicated that acuity in unoperated incomplete congenital cataract patients is inversely related to cataract density but unrelated to size or morphologic type (Merin and Crawford, 1972). A number of recent studies using objective techniques to monitor acuity development in cataract patients are described in section 1.5.

Uncontrolled patching in patients with unilateral conditions can also lead to occlusion amblyopia of this type in the previously good eye. Whilst alternate occlusion therapy may keep the acuities equal it has the attendant danger of preventing normal binocular visual experience thereby disrupting fusion (Awaya et al., 1981). Some compromise is usually required to cope with this dilemma.

1.4.3 Importance of birth history

a) Birth trauma

Birth trauma has been implicated in the aetiology of amblyopia particularly strabismic (Kervick, 1986).

Two mechanisms for the development of squint have been proposed; direct trauma e.g. from forceps injury causing peripheral damage to the extra-ocular muscles (or their nerves) or central cerebral damage sustained during birth. Although isolated ocular birth injuries are reported sporadically in the literature severe trauma to the eye is very rare even with the use of forceps (Douglas, 1963; Kervick, 1986). Jain et al., (1980) found serious ocular injuries occurred in only 0.25% of live births. One child in their sample (n = 2,016) sustained forceps induced facial palsy but there were no cases of injury to the extraocular muscles. This contrasts with the relatively frequent occurrence of squint in the general population, estimates around 4% are typical. These findings suggest that if birth trauma is involved in the aetiology of squint the latter must occur either directly from damage to some central mechanism or secondary to other perinatal factors (unilateral ocular damage not affecting the extraocular muscles). Strabismus is very common amongst children having cerebral palsy of varying severity after suffering from brain damage caused by birth trauma (Friedman et al., 1980). This finding suggests the possibility that minimal (presumably subclinical) central cerebral damage sustained during birth could predispose certain individuals to the subsequent development of squint and be responsible for the relatively high incidence of squint observed in the general population. A variety of ocular injuries occurring with varying frequency and significance in the newborn are discussed below.

i) Retinal haemorrhages

Jaeger (1861) first reported observing retinal haemorrhages in newborn infants, eleven years after Helmholz's introduction of a practical ophthalmoscope. Numerous articles have since considered the incidence, aetiology and possible significance of neonatal retinal haemorrhage. Review papers include those of Giles (1960), and Critchley (1968). Reabsorption of retinal haemorrhages occurs within a few days in most cases (Baum and Bulpitt, 1970) so the incidence found is greatest when examination is conducted shortly after birth (Krebs and Jaeger, 1966; Sezen, 1971).

Reports of the incidence of neonatal retinal haemorrhages range from 2.6% (Chace et al., 1950) to 42% (McKeown, 1941). Most authors report between 20 and 30%. Haemorrhages may be unilateral but are bilateral in over half of the cases (Baum and Bulpitt, 1970; Bergen and Margolis, 1976). Haemorrhages may be scattered throughout the fundus but the common types tend to be located around the posterior pole or surrounding the main vessels around the disc (McKeown, 1941; Baum and Bulpitt, 1970). The incidence of macular haemorrhages is generally not mentioned but values of 1.8 to 11.6% have been reported (Von Noorden and Khodadoust, 1973; Lowes et al., 1976).

Many studies have attempted to correlate the incidence of retinal haemorrhages with details pertaining to the birth history. Efforts to identify a single causative factor have been largely inconclusive suggesting that a multifactorial mode of origin is probable (Baum and Bulpitt, 1970). Several authors report higher incidence amongst infants whose births have been assisted by vacuum extraction rather than following spontaneous deliveries (Krebs and Jaeger, 1966; Planten and Schaaf, 1971). The use of forceps may (Richman, 1936; McKeown, 1941; Krebs and Jaeger, 1966; Bergen and Margolis, 1976) or may not (Planten and Schaaf, 1971; Jain et al., 1980) be associated with increased prevalence of retinal haemorrhages. There is general agreement that the incidence of retinal haemorrhage amongst infants delivered via caesarian section is very low (Sezen, 1971; Bergen and Margolis, 1976; Besio et al., 1979) or even nil (McKeown, 1941; Jain et al., 1980). The latter findings are compatible with the belief that the main cause of neonatal retinal haemorrhages is birth trauma resulting from mechanical compression of the head (moulding) as the infant traverses the birth canal (Bergen and Margolis, 1976). It has been suggested that elevated intracranial (venous) pressure resulting from such compression is transmitted to the cavernous sinus causing ophthalmic vein engorgement which predisposes newborns to rupture of their retinal vessels (Richman, 1936). McKeown, (1941) considered that the newborn's retinal vessels are fragile but Planten and Schaaf, (1971) found no evidence to support this view. Asphyxia at the time of birth is also thought to be involved in the aetiology of neonatal retinal haemorrhages.

Amongst infants delivered normally increased incidence has been reported in certain groups that might be expected to sustain more severe head trauma e.g. primiparas (Richman, 1936; McKeown, 1941; Bergen and Margolis, 1976); large babies (Krebs and Jaeger, 1966) - not confirmed by Bergen and Margolis, (1976); those born after a long durations of labour (McKeown, 1941; Krebs and Jaeger, 1966) - not found by Richman, (1936); or with unusual birth presentation (McKeown, 1941) or low Apgar scores (Bergen and Margolis, 1976). Baum and Bulpitt, (1970) failed to identify any factor that was significantly associated with retinal haemorrhage although they considered many aspects including mode of delivery and birth asphyxia. Retinal haemorrhages were not found in any of their five cases of 'traumatic cyanosis' which suggests that raised venous pressure is not the main factor responsible for rupture of the retinal vessels. They concluded that blood viscosity may be an important factor. The aetiology of neonatal retinal haemorrhages thus remains somewhat obscure.

Presence of neonatal retinal haemorrhage particularly at the macula has been suggested as a cause of subsequent amblyopia or squint (Sachsenwager, 1965). It was postulated that an organic "receptor amblyopia" could arise from disorganization of the foveal receptors. Although many authors have discussed this point only four appear to have investigated the long term effect of neonatal retinal haemorrhage (Bonamour, 1949; Von Noorden and Khodadoust, 1973; Schenk and Stangler-Zuschrott, 1974; Lowes et al., 1976). These authors found no evidence of an increased incidence of squint or amblyopia amongst children that had suffered neonatal macular haemorrhages. Bonamour (1949) conducted a ten year follow up of 8 children with neonatal macular haemorrhages. Ophthalmoscopic findings, visual acuity and ocular motility were all normal. Von Noorden and Khodadoust (1973) found a

low (1.8%) incidence of neonatal macular haemorrhage in their original sample. Only 5 of 18 children were available for re-examination at five years, all had unilateral macular haemorrhage at birth but subsequently presented with normal fusion equal acuity and normal fundi. Schenk and Stangler-Zuschrott (1974) re-examined 23 of 42 children with neonatal macular haemorrhages between three and seven years. Ophthalmoscopy was normal in all cases; acuity was slightly reduced in three and fusion was reduced in four (strabismic) children. Although the incidence of squint was definitely higher than that normally encountered in general paediatric populations the small sample size and the overall findings of the study suggest that the sequelae of neonatal retinal haemorrhage should not be overestimated. Lowes et al., (1976) reported a surprisingly high proportion of infants with macular haemorrhage (11.6%) in their newborn sample but successfully followed up 38 of the original 48 children at five years. The incidence of squint and amblyopia was not significantly different from expected population norms. As yet there is no data available on the effect of neonatal retinal haemorrhage on neonatal visual acuity.

ii) Other ocular haemorrhages

Neonatal vitreous haemorrhages (McKeown, 1941; Braendstrup, 1969; Wiznia and Price, 1976) are much rarer consequences of birth trauma than retinal haemorrhages. Only a few cases are on record. This type of haemorrhage takes several months to reabsorb and may be followed by permanent visual impairment and anatomical sequelae (Braendstrup, 1969).

Anterior chamber haemorrhages in the newborn are extremely rare. Wu and Behrens (1982) found only five cases (amongst fullterm spontaneously delivered infants) reported in the earlier literature. Jain and co-workers, (1980) observed one case amongst 2,016 newborns (0.05%) believing it to result from direct eye trauma caused by forceps application. Reports suggest that such haemorrhages rapidly resolve without sequelae (Friedman and Neumann, 1973; Kinder and Cowett, 1976; Pohjanpelto et al., 1979; Wu and Behrens, 1982).

Subconjunctival haemorrhages are encountered much less frequently than retinal haemorrhages in the newborn (0.6% cf. 11.0%; Jain et al., 1980). Baum and Bulpitt, (1970) found similar incidences of conjunctival and retinal haemorrhages in their sample (13.3 and 15.5% respectively) but the two lesions seldom occurred in association (only two of 62 cases). Alterations in cephalic venous pressure could account for the conjunctival haemorrhages which were found in all cases of 'traumatic cyanosis' and more frequently amongst infants having relatively high birth weight, head circumference or gestational age. Such haemorrhages are considered of no significance (Pape and Wigglesworth, 1979).

iii) Corneal injury

Corneal birth trauma may result from direct forceps injury or other compressive mechanism during delivery (Hoffmann et al., 1981). This type of injury is rare, Jain et al., (1980) observed only 1 infant

having an oedematous cornea amongst 2016 newborns (0.05%). In cases of Descemet's membrane or endothelial ruptures the oedematous stage is succeeded by the appearance of Descemet's membrane striae (often vertical). Such permanent corneal injury is usually accompanied by high corneal astigmatism (along the axis of the break) and myopia which can lead to sequellae of amblyopia (astigmatic or anismetropic) or late endothelial decompensation in adult life (Angell et al., 1981; Hoffmann et al., 1981).

b) Prematurity

The normal human gestation period is on average 40 weeks (though a term baby is any infant born between the 37th week and the end of the 41st week). An infant born before the end of the 37th week of pregnancy is considered to be premature (Adams, 1983). Although all premature infants do not require neonatal intensive care with this facility infants as young as 24 weeks gestation are viable. The average birth weight of fullterm infants is about 3500g. Any infant of below 2500g. may be considered of low birth weight (LBW). Low birth weight infants can be subdivided into those of very low birth weight (VLBW) below 1500g. and those of extremely low birth weight (ELBW) below 1000g. Significant numbers (56%) of premature infants of below 1000g and many (42%) below 750g. survive if skilled intensive care is available (Orgill et al., 1982). The birth weight classifications described above are liable to decrease to accommodate improvements in medical care.

Premature infants represent a group at risk for the development of visual deficit particularly if they are of very low birth weight or gestation. Retrolental fibroplasia was first described by Terry (1942) and is the ocular defect most commonly associated with prematurity. The numbers of infants with retrolental fibroplasia originally decreased with the recognition that this condition could be alleviated by reducing the oxygen tensions in which premature babies were incubated (Campbell, 1951; Patz et al, 1952; Kinsey, 1956). The term retrolental fibroplasia (RLF) has been largely replaced by retinopathy of prematurity (ROP) which may be used to refer to the all phases of the acute retinal changes observed in premature infants (Flynn, 1985). Retinopathy of prematurity (ROP) may progress through a number of phases to retrolental fibroplasia with its possible final outcome of traction retinal detachment and subsequent blindness, but in most instances the disease resolves before this stage. The problem of retinopathy of prematurity has re-emerged since the early 1960s and is likely to remain because continual advances in medical and nursing care ensure a better survival rate of very low birth weight and correspondingly fragile premature infants. The condition is generally bilateral and usually affects infants of below 30 weeks gestation weighing under 1500g. (Spinelli and Cattaneo, 1982).

Significant ocular defects are more prevalent in premature infants; cicatricial changes, high refractive errors, strabismus and amblyopia have all been reported at increased incidence amongst children that have had ROP (Kushner, 1982). In contrast absence of any sequelae has been noted with complete ROP resolution (Schaffer et al., 1984). The actual incidence of visual abnormalities is largely unresolved. Studies are susceptible to sampling errors because it is generally not possible to follow up all of the

population of infants. Assumptions that those not attending for examination are free of significant visual problems may lead to inaccuracies. Keith and Kitchen, (1983) examined very low birth weight infants finding amongst the infants attending: squint 19%; RLF 11%; optic atrophy 2.7% and refractive error 17%. The authors suggested screening VLBW infants for refractive error and squint at two years. Hammer and co-workers, (1985) have a more optimistic view of the frequency of serious ophthalmic defects in VLBW infants e.g. squint 4.5%; RLF 4.5%; refractive errors 3.0%; blind 2.3%. These figures are based on the total numbers rather than the proportion attending. Keith and Kitchen, (1983) managed to trace 111 of 177 longterm VLBW survivors and had reliable ophthalmologists reports on three others whilst 172 were reviewed by developmental paediatricians at two years. Hammer and co-workers, (1985) examined only 33 of 131 infants assuming that the remainder were free of significant visual handicap on the basis of paediatricians' reports. When the percentages are restricted to the sample attending the findings are more similar to those of Keith and Kitchen; i.e. squint 18.2%; RLF 18.2%; refractive errors 12.1%; blind 9.1%.

The high incidence of myopia in prematures during early infancy is well documented (Gleiss and Pau, 1952; Fletcher and Brandon, 1955; Graham and Gray, 1963; Grignolo and Rivara, 1968; Scharf et al., 1975; Shapiro et al., 1980; Dobson et al., 1981). Higher incidences of anisometropia (Dobson et al., 1981) and hypermetropic astigmatism (Dobson et al., 1981; Keith and Kitchen, 1983) have also been reported in premature infants. Myopia is more prevalent in those premature infants found to have ROP (Nissenkorn et al., 1983; Keith and Kitchen, 1983). The degree of myopia tends to be greater in proportion to the severity of cicatricial ROP (Nissenkorn et al., 1983). Whether the tendency for myopia found amongst prematures persists beyond early infancy has yet to be resolved. A number of authors reported a higher incidence of myopia amongst children that were born prematurely than in fullterm children (Fledelius, 1976; Wagner, 1957; Gerhard et al., 1978). Other reports suggest that the myopia present in early infancy may not continue into childhood (Scharf et al., 1975). Some studies find that mean refractive errors amongst premature and fullterm infants of 6 months post-term age do not differ (Grignolo and Rivara, 1968; Shapiro et al., 1980). Linfield and Davies (1984), conducted repeat refractions in a sample of very low birth weight infants reporting that the amount of ametropia (generally myopia) found was inversely related to gestational age; the majority of infants regressed towards emmetropia by 47 weeks post-conceptional age. Bun and co-workers (1982), monitored refractive development in premature children between 2 weeks and 8 years, dividing their sample into a retinopathy and non retinopathy group. Rather surprisingly both groups were initially hypermetropic with the average hypermetropic error peaking at 3 months. The mean refraction of the non retinopathy group remained hypermetropic throughout this period whilst the retinopathy group developed progressively higher myopia.

Alberman et al., (1982) recorded distance visual acuity in a group of 7 to 9 year old children of up to 2000g. birth weight comparing the findings to those of fullterm age matched controls. The low birth weight group had significantly (slightly) poorer acuity suggesting that prematurity may be associated with an excess of mild as well as severely handicapping visual disorders.

1.4.4 Relevance of family history

Sarginuet-Badoche and Pinçon (1982) reported a 40% incidence of strabismus in children born of squinters. This compares with a frequency of around 4% in unselected populations.

Kramar (1973), working under the guidance of Robert Ingram, examined 20 families having at least two squinting members in an attempt to identify factors that may detect potential squinters. The conclusion of this initial study was that detection of hypermetropic or anisometropic refractive errors offered the best screening aid for predicting the later appearance of squint. This has been confirmed by wealth of subsequent studies. Ingram (1973) reported a significant relationship between the presence of squint and of a positive family history, equally he found a significant relationship between the presence of three or more dioptres of hypermetropia and other refractive errors and a positive history of squint. This latter finding encouraged him to pursue the idea of refractive screening for squint and amblyopia.

1.4.5 Summary

Research studies suggest that the majority of full-term infants at risk for the development of amblyopia are those with squint and or abnormal refractive error. Individuals at particular risk include those with high hypermetropia (above +3.50 dioptres in any one meridian), significant anisometropia or marked astigmatism. Astigmatism is known to be prevalent during infancy but knowledge regarding the levels which are acceptable in early life are not yet well defined. Individuals with histories of premature birth are more at risk for the development of squint and amblyopia than the remaining population.

1.5 Acuity development in infants with experience of visual deprivation

Recently developed objective techniques (reviewed in sections 2.2, 2.3 and 2.4) have been applied to the assessment of acuity in infants having various clinical conditions known to cause visual impairment. Preferential looking has generally been the method applied although OKN and VEP studies have also been conducted. The studies have to date been restricted to investigation of infants having visual deprivation caused by physical obstacles or strabismus (1.4.2a). The natural history of refractive amblyopias (1.4.2b) have not yet been adequately studied presumably because of the greater difficulty in identifying defective individuals in early life.

1.5.1 Bilateral conditions

Acuity development has been studied in infants having bilateral congenital or developmental cataracts. Infants having bilateral conditions are less frequently encountered than those experiencing unilateral conditions.

Two infants suffered bilateral toxic cataracts in their third year and then remained untreated for at least eight years. Acuity subsequently recovered to 6/12 (Singh and Schultz, 1984). This finding suggests that the ultimate success of treatment is not affected by deprivation beyond the sensitive period. After equivalent periods of deprivation from birth median Snellen acuity is higher in infants with history of bilateral cataracts compared with unilateral cataract (Brent et al., 1986).

Mohindra and co-workers (1983) using a formal preferential looking staircase method observed normal acuity development in bilateral cataract patients that were treated by two months. In cases where treatment was delayed until four to six months acuity was initially below average but subsequently recovered.

1.5.2 Unilateral conditions

It is a common practice to treat amblyopia by patching of the better eye. Studies have demonstrated that too rigorous patching of the "good" eye may result in a reversal of eye dominance the "good" eye is deprived and its acuity may fall below that of the fellow eye. This has been termed occlusion amblyopia and has been noted in both animals (Mitchell, Murphy and Kay, 1984) and humans (Awaya, Suguwara, Miayake et al., 1981; Jacobson, Mohindra and Held, 1981 and 1983). The finding indicates that patching therapy should be conservative (allowing binocular experience) and preferably conducted with adequate monitoring of relative acuities. A 'superacuity' (i.e. above normal level for age) has been reported in the non deprived eye of infants suffering from unilateral visual deprivation (Mohindra et al., 1983).

a) Esotropia

The acuity of freely alternating and preferred eyes of unilateral esotropes is not significantly different from the monocular acuity of aged matched normals between three and fourteen months (Birch and Stager, 1985). Jacobson and co-workers (1981) considered the earliest onset for the development of amblyopia in the non-fixing eye of untreated unilateral esotropes to be four months. Later estimates taking into account average interocular acuity differences in normal infants, suggest that acuity of non-preferred eyes is not significantly below normal between three and five months but is during months six to fourteen (Stager and Birch, 1986).

Acuity development has been monitored in monkeys having naturally occurring or experimentally-induced strabismus (Boothe et al., 1985b). Acuity in fixing eyes develops normally whilst acuity of non-fixing eyes often lags behind and in some cases never reaches adult levels. Some monkeys quickly develop amblyopia in their non-fixing eye whilst others fail to show significant interocular acuity differences or only do so several weeks or months following onset of the strabismus. One monkey was noted to display a significant interocular difference in contrast sensitivity but not in acuity.

b) Unilateral cataract

Childhood cataracts may be of three main types; congenital, developmental or traumatic. The median acuity achieved is influenced by the duration and timing of deprivation (Lewis et al., 1986). The worst acuities are shown by children having long periods of deprivation starting at birth. Good visual resolution may be achieved if the deprivation is short provided that the normal eye is patched regularly. Over 80% of children experiencing unilateral traumatic cataract after three years achieve at least 6/18 Snellen acuity. This figure compares with 15% of children with congenital cataracts. In individuals with unoperated incomplete congenital cataracts visual acuity is inversely related to cataract density, but unrelated by size or morphological type (Merin and Crawford, 1972). In bilateral cases where more than a 0.3 neutral density filter difference existed strabismic amblyopia always developed in the eye with the denser cataract.

A child that experienced deprivation from a unilateral congenital cataract until 4.5 months demonstrated greater threshold elevation in the nasal rather than temporal visual field of her aphakic eye (Maurer et al., 1983; Lewis et al., 1986). No asymmetry was found in infants that developed cataracts after six months. It was presumed that this finding suggests that early deprivation affects the development of cortical control over the superior colliculus.

Experiments in kittens have demonstrated that considerable recovery of visual acuity can occur if visual input is restored to the originally deprived eye sufficiently early, particularly if the non-deprived eye is occluded at the same time (Mitchell et al., 1984). Termination of this reverse occlusion (lid suture) is

followed by a rapid and reciprocal change in the acuity of both eyes. The acuity of the originally deprived eye quickly falls (to levels only marginally better than prior to reverse occlusion) and that of the initially non deprived eye improves but not always to pre-reverse occlusion levels. This reciprocal trade off in acuities has been reported in human studies (Jacobson et al., 1981; 1983). These findings draw attention to the risks of occlusion amblyopia when total occlusion therapy is applied during late stages of the sensitive period.

c) Other forms of unilateral deprivation.

Short term occlusion of approximately one week can cause stimulus deprivation amblyopia in children of up to 18 months with in some cases a poor or only fair subsequent recovery of vision (Awaya et al., 1979; 1981). The sample studied included individuals having histories of corneal or lenticular media opacities or experiencing post-operative occlusion following lid surgery.

Unilateral congenital ptosis is associated with a high incidence of amblyopia. The mechanism of amblyopia is unclear but anisometropia appears to be the main cause (Beneish et al., 1983). In patients with histories of congenital glaucoma the ultimate acuity achieved closely correlates with the degree of anisometropia (Clothier et al., 1981). Other important factors in the latter condition are corneal oedema in infancy and development of strabismus.

Unilateral stimulus deprivation in monkeys (lid suture) causes profound deficits in visual resolution (CS), rod saturation and the rate of change of sensitivity with light adaptation (Harwerth et al. 1981). Enucleation of the sound eye of mature monkeys raised with severe stimulus deprivation amblyopia does not result in a significant functional improvement of the deprived eye (Harwerth et al.,1984).

1.6 Overview and discussion of sensitive periods in the human visual system

Visual responsiveness is evident in the newborn infant but possibly mediated via subcortical pathways until about two months (1.3.4c). Different visual functions emerge at different ages and with varied rates of development. Atkinson (1987), has described recent attempts to summarise early visual development. Details of the proposed scheme (devised in a workshop session with other researchers) are given in Figure 1.7. It is clear from this figure and the discussions in section 1.2 (pages 25-51), that the visual system alters considerably in the initial weeks of life. By six months the basic visual functions which characterize the mature human visual system have emerged, although they may subsequently undergo longer periods of refinement. It has been suggested that the visual system is most sensitive (susceptible to visual experience) during phases of rapid development. It is evident that the first six months of life represents such a period and studies of visual development which encompass this time may therefore be most instructive in elaborating the mechanisms of normal and abnormal development.

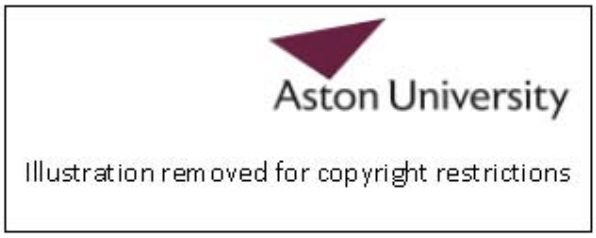


Figure 1.7 Developmental phases of the human visual system (summarised by Atkinson, 1987). S.F. = spatial frequency; M OKN = monocular optokinetic nystagmus.

Acuity and contrast sensitivity are examples of functions which undergo a long, slow development. Neonatal acuity appears to be limited mainly by neural rather than optical constraints. Postnatally resolving capacity improves dramatically (1.2) primarily reflecting differentiation of the fovea and cortical maturation (1.3). This improvement is particularly marked during the initial six postnatal months but continues at a reduced rate until at least three years. Morphoscopic acuity does not appear to reach adult levels until around eight years (Hohmann and Haase, 1982), although angular acuity is adult like at about three years (Atkinson and Braddick 1983c).

Binocular functions including fusion and stereopsis emerge between two and five postnatal months (1.2.4). The sensitive period for the development (or disruption) of binocular vision begins several months after birth, peaks at around two years and thereafter gradually declines reaching low levels of sensitivity around three or four years.

Refractive changes have been less clearly delineated during normal development (1.2.3) there still exists some confusion regarding the shifts occurring during the initial months of life. Part of the disparity in published findings can be attributed to the proportions of strabismic infants included in various studies. Accurate knowledge on the implication of early ametropia is lacking at present.

1.7 Scope of the present study

Three objective techniques for the measurement of infant visual acuity have been proposed in the literature. These depend upon visual evoked potentials, optokinetic responses and preferential looking. Reviews of previous studies using each method are provided in sections 2.2, 2.3 and 2.4 respectively. A pilot study was initiated to develop clinical variants of each method and determine the most clinically useful of these. The proposed variants of the methods are described in sections 2.2.3, 2.3.2 and 2.4.3. The comparative clinical usefulness of two of the techniques was then evaluated by examining a paediatric sample (the third method was abandoned due to technical difficulties). Subjects participating in this study were a sample having various ocular or neurological abnormalities (referred for immediate assessment) and a few normal infants. This study is described in section 2.6 (pages 143-162).

A normative study was subsequently conducted to evaluate more closely the clinical viability of the most promising method derived. Additional intentions of this study were to investigate the possible effects of birth history and refractive findings on visual development. The methodology of the study is described in Chapter 3 (pages 163-187).

One criterion for a robust clinical method is reasonable correlation with the results produced using lengthier testing methods. The normative study data was therefore compared with acuity norms reported in the literature (collected using extended laboratory testing procedures). The norms found for interocular acuity differences were compared to those of extended PL methods in order to determine the comparative sensitivity of the techniques to the detection of 'significant' differences between eyes. A

further consideration is the ability to segregate infants with known ocular pathology. The normative data was therefore compared with that of the clinical patients examined with our PL technique. These analyses indicated whether the test was sufficiently sensitive to be useful. The success rate of the method (i.e. the proportion of infants successfully tested) was determined as a function of age to evaluate its clinical viability. These findings are reported and discussed in Chapters 4 (pages 188-228) and 7 (pages 335-339 and 347-352) respectively.

A large proportion of newborns experience retinal haemorrhages the possible affect of these on acuity development was studied. Levels of ametropia are high in early life but little data is available to determine the influence on acuity development during the first year. Refractive and acuity data was assembled for a subgroup of infants at birth, three, six and twelve months. These findings are reported in Chapter 6 (pages 302-333) and discussed in Chapter 7 (pages 343-345 and 361-362).

The introduction of refractive assessment into the study additionally provided information on the natural history of refractive conditions. The development of refractive error from birth to one year was investigated since difference of opinion exists on the direction of refractive change in early infancy. The possibility of correlations existing between birth history and refractive findings was studied since there appears to be a higher incidence of hypermetropia and strabismus in infants experiencing significant birth trauma. These findings are reported in Chapter 5 (229-301) and discussed in Chapter 7 (pages 339-343 and 353-360).

2. OBJECTIVE ASSESSMENT OF INFANT VISION: REVIEW OF TECHNIQUES AND INITIAL PILOT STUDY

2.1 General introduction

Objective methods of obtaining visual acuity measurements in infants and young children can be classified into three main groups. These techniques depend upon visual evoked potentials (VEP), optokinetic responses - generally optokinetic nystagmus (OKN), and preferential looking (PL) respectively. Although absolute acuity differences may occur between techniques similar trends of acuity development in normal infants have been obtained by authors using the different methods (see section 1.2.1). Initial infant studies have mainly been conducted under laboratory conditions. Current research interest has been attracted to the evaluation of the various methods' clinical potential.

The preferential looking technique was developed specifically for evaluation of infant vision, though the basic method is applicable to neurologically impaired individuals of adult age (Duckman and Selenow, 1983). Reinforced (operant) conditioning techniques enable normal young children to be examined, from about six months (Mayer and Dobson, 1980; 1982; Birch et al., 1983). The OKN and VEP techniques are theoretically applicable to any age range. The following review (sections 2.2, 2.3 and 2.4) classifies variations of each method reported in infant visual acuity studies whilst referring to adult studies, from which they may be derived where appropriate. At the end of each section an overview is provided and a possible clinically appropriate variant is proposed (sections 2.2.2; 2.3.2 and 2.4.3). The PL and VEP techniques have been used to assess visual functions other than acuity in infancy, for example, contrast sensitivity and stereoacuity (Atkinson, 1984; Boothe et al., 1985a and sections 1.2.2 and 1.2.4 d) include recent reviews of such studies).

Several new methods have been developed for the refractive assessment of infants and young children. These and conventional methods are reviewed and selection of the most convenient technique (in the context of the present study) is discussed in section 2.5. Refractions were not performed on the sample of infants included in the pilot study (section 2.6) but most of the infants participating in the normative study (described in Chapter 3) had at least one refractive assessment.

2.2 Visual evoked potentials (VEPs)

The possibility of using electrophysiological techniques in the measurement of visual acuity was first envisaged following the results of a study undertaken by Campbell and Maffei (1970). They studied the relationship between steady state visual evoked potentials and threshold contrast sensitivity and found that, when the contrast of a sinewave grating was reduced logarithmically, the amplitude of the visual evoked potential (VEP) decreased linearly. Significantly, when this function was extrapolated to zero voltage, the contrast level indicated was very close to the subject's psychophysical contrast threshold. Spekreijse and Van der Tweel (1974), using transient evoked potentials and checkerboard stimuli, confirmed this finding but for a restricted range of contrasts and with a more variable correlation with psychophysics.

Kulikowski (1977) measured the amplitude of early (N90-P130) and late (N160-200) components of the transient evoked potential, to the appearance of square wave gratings as a function of contrast. In both cases the VEP amplitude was roughly proportional to the suprathreshold contrast. However, the late components were well correlated with the subjective threshold but the early components were not (i.e. the function did not extrapolate to the psychophysical threshold).

These and two other studies (Campbell and Kulikowski, 1972; Freeman and Thibos, 1973), demonstrate that the visual evoked response to form is well correlated with psychophysical threshold measurements. Several methods for estimating Snellen acuity from evoked potential recording have since been reported, using both pattern reversal and pattern appearance/disappearance evoked potentials. Stimuli used in the various methods include checks, sinewave gratings and square wave gratings.

2.2.1 Review of VEP acuity techniques

a) Direct location of threshold

Campbell and Maffei's result (1970) implies that a perceivable contrast produces a measureable VEP, therefore it could be assumed that the same would be true of a perceivable pattern. This hypothesis offers a method of estimating visual acuity since the smallest pattern element size which produces a detectable VEP in a pattern should represent the limit of that persons visual resolution (i.e. visual acuity). Grall and co-workers (1976) and Towle and Harter (1977) successfully demonstrated the validity of this hypothesis, using co-operative adult subjects, checkerboard stimuli and small stimulus fields.

Douthwaite and Jenkins (1982) comment that although this method may have much to offer clinically, in terms of speed, it is probably difficult to be sure of the endpoint. Approaching threshold, the responses deteriorate in quality due to reduced signal to noise ratio, therefore it may be difficult to assess at which point there is no signal to differentiate from noise. They suggest that increased precision may be possible by mathematically deciding on the "no signal" endpoint. McCormack and Tomlinson (1979)

considered that the method would not be speedy since many pattern sizes may be required when testing near threshold, in order to bracket the visual acuity value and, as the signal to noise level would be low, many responses would have to be averaged to assure validity.

Despite these criticisms, Marg and co-workers (1976) successfully applied the technique to a sample of infants ranging from one to seven months of age. Transient VEPs were recorded to the appearance of square wave gratings of various spatial frequencies. Visual acuity was taken as the highest spatial frequency which produced a visual evoked potential clearly different from the response to a defocused 30 cycle/degree grating (the control condition). The visual evoked potential acuities tended to match the highest values found by behavioural techniques.

b) Extrapolation from electrophysiologically determined contrast sensitivity functions

The contrast sensitivity function is a plot of contrast sensitivity (inverse of contrast threshold) versus spatial frequency. Visual acuity specifies only the finest details that the eye can resolve, whereas the contrast sensitivity function (CSF) provides a more comprehensive description of pattern detection. The peak of the contrast sensitivity curve represents the optimal spatial frequency for contrast detection and the final point signifies the finest pattern that the observer can detect at 100% contrast (i.e. visual acuity). In general, the CSF is plotted on logarithmic axes, however, if contrast sensitivity is plotted on a log axis as a function of spatial frequency on a linear axis, the high frequency part of the curve becomes a straight line. Extrapolation of this section of the function defines the highest detectable spatial frequency (visual acuity), from the cut-off point.

Campbell and Maffei's finding (1970) that the contrast thresholds of sinewave gratings can be accurately estimated from plots of EP amplitude versus log contrast, provides the basis of electrophysiological determination of the contrast sensitivity function and therefore visual acuity. In a study using adult subjects, Howe and co-workers (1981) compared Snellen acuity with "VEP" acuity. The method was a slight variation of Campbell and Maffei's technique. Transient evoked potentials were recorded rather than steady state. A pattern appearance mode of presentation was selected because it was found to be more sensitive to contrast and gave a better fit of the data to the amplitude/log contrast relationship. Checkerboard stimuli were used since they produce higher amplitude responses than gratings (Spekreijse et al., 1973). CI-CII amplitude was analysed as a function of contrast and contrast thresholds were obtained for a variety of check sizes. Contrast sensitivity functions were then plotted for twelve subjects. The method under-estimated Snellen acuity by about one line but this was due to the mean luminance of the T.V. screen being less than that of the Snellen chart.

Although technically accurate, this method is rather laborious since several experiments have to be performed with different contrasts and check sizes before a complete contrast sensitivity plot is obtained. As most patients cannot endure such lengthy experiments the method has not proved very popular. However, when used it has the advantage of providing more information about form vision than a visual

acuity score alone. Contrast sensitivity measurements may assist in clinical diagnosis, for example, the various forms of amblyopia show differing deficits on the C.S.F. (Hess and Howell, 1977).

Several groups have reported use of this technique in infant visual assessment. Each group was working in a laboratory setting. In the majority of these studies measurement of the whole function was given emphasis, rather than evaluation of visual acuity and steady state evoked potentials were used to restrict recording time.

Harris and co-workers (1976), plotted the C.S.F. of one six month old infant. They recorded steady state VEPs to the reversal of sinusoidal gratings of various spatial frequencies and also obtained behavioural data using forced choice preferential looking. Both techniques generated similar data. The high frequency cut-off was at 20 cycles/degree, a Snellen equivalent of $^{6}/_{9}$. In a later study, a sample of 97 neonates were assessed using the same technique (Atkinson et al., 1979). A group CSF was plotted by interpolating, for each spatial frequency, the contrast level at which 50% of the infants yielded a VEP. This indicated neonatal acuity of 0.85 cycles/degree and an optimal contrast threshold of 50%. VEPs were also recorded from two older infants at three and seven weeks. Individual CSFs could be plotted in these cases and similar results were obtained by one of these infants using forced choice preferential looking.

Pirchio and co-workers (1978; 1979) have reported use of this technique in evaluating early development of contrast sensitivity. Contrast sensitivity functions were plotted for three individual infants aged 2 $^{1}/_{2}$, 3 $^{1}/_{2}$ and 6 months. Estimations of the optimum spatial frequency and maximum contrast sensitivity (i.e. determination of the peak of the CSF) were also reported for twelve infants ranging from two to twelve months of age. Visual acuity was, however, evaluated using another method (based on extrapolation from the VEP amplitude versus spatial frequency function), which is outlined below. A later study by the same group (Fiorentini et al., 1980) used the method to evaluate scotopic contrast sensitivity of infants aged $2^{1}/_{2}$ to 7 months. They found that, whereas photopic contrast sensitivity does not reach adult levels before the sixth month after birth, the development of scotopic contrast sensitivity is practically accomplished at the age of 4 to 5 months.

Since the completion of the present pilot study Tyler's rapid stimulus sweep method (described below - Tyler et al., 1979 and 1981), has been modified to enable assessment of infant contrast sensitivity (Norcia et al., 1986). Steady state contrast reversing sine wave gratings were simultaneously swept in contrast (from 0.5 to 40% in 10 seconds). Response (second harmonic) amplitude and phase was derived by Fourier analysis. Contrast thresholds were estimated from a linear extrapolation to zero amplitude of the VEP amplitude versus log-contrast function. Six infants (4 to 10 months) participated in the study. At least three 10-s trials were attempted at each of three spatial frequencies but complete data was not obtained from all infants. This latter finding suggests a limitation of the method's clinical use even if recording duration can be minimised.

c) extrapolation from VEP amplitude versus pattern spatial frequency functions

A number of research groups have investigated the relationship between evoked potential amplitude and contour density (e.g. size of checks in black and white checkerboard stimulus patterns). They demonstrated a curvilinear function between these two variables; the greatest amplitude VEPs were evoked by checks subtending a visual angle between 15 and 30 minutes of arc, increases or decreases from these values resulted in a progressive reduction in VEP amplitude (Rietveld et al., 1967; Harter and White, 1970).

Parker and Saltzen (1977), using high contrast sinewave gratings presented in a pattern appearance mode, report that the N1-P1 complex produced VER amplitude functions which plateau'd for large bar sizes and dropped in amplitude for finer gratings. However, the N2-P2 complex generated functions with maximum amplitude at intermediate spatial frequencies. Rentschler and Spinelli (1978) also reported that the function of VEP amplitude versus log spatial frequency could be fitted by a triangular-shaped function with linearly sloping sides. Karmel and co-workers (1974), demonstrated that an inverted "U-shaped" function was present in infants (of 8 to 15 weeks), and that the peak shifted towards higher spatial frequencies with increasing age.

The interpretation often given is that inverted "U-shaped" functions between VEP amplitude and check size appear to reflect receptive field and spatial tuning characteristics of the neurones activated (Harter, 1970; 1971; Armington et al., 1971; Karmel et al., 1974; Karmel and Maisel; 1975). Generally, it has been assumed that extrapolating the high spatial frequency "limb" of the inverted "U-shaped" function to zero amplitude produces on intercept with the horizontal axis which coincides with subjective visual resolution. This is based on the results of Campbell and Maffei (1970), who showed that near threshold the VEP amplitude is proportional to log contrast, and of Campbell and Gubisch (1966), who showed that log contrast sensitivity is linearly proportional to spatial frequency near the acuity limit. The VEP amplitude should therefore fall off linearly with linear spatial frequency near threshold. Providing this assumption is valid, visual acuity measurements can be obtained by recording the evoked potentials to high contrast patterns of sequentially smaller check sizes, then extrapolating to zero amplitude (since control trials are often not completely flat, in many of the studies reported a regression line has been extrapolated to the mean noise level of the control rather than zero amplitude). Tyler and co-workers (1979), point out that an advantage of this method is that it is amplitude-insensitive, therefore restricting the number of extraneous factors influencing the result.

Although conventionally linear regression is assumed, Douthwaite and Jenkins (1982) noted that their data was better fitted with psychophysical results by a curvilinear function. Linear regression appears to be appropriate with logarithmic spatial frequency axes and curvilinear regression with linear spatial frequency axes - despite the theoretical expectations (Jenkins et al., 1985). Generally, EP amplitude is plotted on a linear scale and spatial frequency on a logarithmic scale. However, Chan and Odom (1983) report a study comparing the monocular acuities of nine normal adults assessed both by steady state

evoked potentials to checkerboard reversal, and using a standard Snellen chart. The data was analyzed in a variety of ways and VEP acuity was found to correlate most accurately with Snellen acuity when the threshold was extrapolated from a plot of log amplitude versus linear spatial frequency. Snellen acuity was over-estimated by less than 0.25 octaves. They stress that this result would not necessarily apply to other experimental conditions. The statistically significant differences in VEP acuity results from varying combinations of stimulus and response scales (Chan et al., 1986), indicate a need for caution in selecting scales for VEP estimates of acuity.

Regan (1978) advises that any developmental changes in the temporal tuning of pattern responses might distort the results of studies in which pattern EPs have been used as an index of visual acuity development. He recommends estimating visual acuity at more than one temporal frequency to check whether there is any effect. Additionally, he suggests use of EP amplitude per check versus check size functions, since, for a foveal field, this value grows progressively larger as check size in increased, whereas the amplitude versus check size function peaks at 10 to 20 minutes of arc (Regan, 1980).

However, Spekreijse (1978; 1980), documented several pitfalls in the general method. He illustrated two cases in which visual acuity could not be estimated from the slope of the EP amplitude versus check size plot, although use of direct threshold location or the plotting of a contrast sensitivity function adequately determined the VEP acuity. This might be expected since:

1) The retinal field contributing to the EP is a function of check size - smaller checks stimulating the foveal and larger checks, parafoveal retina. This alone is sufficient for waveform variations with check size and even polarity reversal is frequently observed. So, by extrapolating such a plot to zero amplitude, there is no guarantee that the intersection with the horizontal axis bears a relation to visual resolution.

2) The slopes of the curves relating EP amplitude to log contrast vary with bar width or check size (Campbell and Maffei, 1970), so that the slope of the curve relating EP amplitude to check size depends on the contrast used throughout the experiment. The use of high contrast (necessary for eliciting EP's to small checks) can produce saturation EPs for large checks - which will distort this curve.

Despite these criticisms, the technique has considerable advantages in terms of speed. This prompted De Vries Khoe and Spekreijse (1982), to temporarily ignore the inadequacies of the method in a study of 307 subjects. Both the intersection point with the horizontal axis ('pattern threshold') and the check size giving the largest response ('optimal pattern') were analysed for a series of subjects ranging in age from 2 months to 80 years. Results demonstrated two different development periods; a phase of rapid improvement in both threshold and optimal pattern - from birth to about eight months - indicating that the amplitude versus check size curve merely shifts along the horizontal axis, without a change in shape. This may reflect foveal development. There follows a slower improvement phase, up to puberty which

expresses itself solely in the slope of the amplitude versus check size curve. The intersection with the horizontal axis, i.e. the pattern threshold, gradually approaches one minute of arc. This phase can probably be attributed to maturation of the CII component, and would therefore appear to reflect development at an extrastriate cortical site. In those subjects above four years, the pattern EP threshold data was compared to checkerboard acuity measures. Since the correlation was good the study concluded that this EP criterion is a good substitute when conventional acuity tests are not applicable. However, since the optimal pattern criterion parallels the EP threshold criterion in the first year post term it is better to use the former, more easily established method for young infants.

Tyler and co-workers (1979), incorporated this method into a battery of tests designed for the rapid assessment of visual function. Sine wave and square wave gratings were counterphase modulated in contrast at a high temporal frequency and simultaneously swept in spatial frequency at a slow rate. A plotter displayed VEP amplitude as a function of spatial frequency of the alternating pattern. In the example given, the extrapolated VEP acuity (31 c/deg.) approximated the psychophysical acuity (32 c/deg.). For most conditions, the extrapolated acuity value falls within a factor of two from the psychophysical acuity corresponding to a maximum discrepancy of two lines on a Snellen chart (Tyler et al., 1981). Clinically it is claimed that swept evoked potential methods can discriminate Snellen acuity to within two lines while requiring only 20-s intervals of attentive observation from the patient (Wiener et al., 1985).

In a study by McCormack and Tomlinson (1979), square wave gratings of 80% contrast and various sizes were presented in a pattern appearance mode. Measurement of the amplitude of these transient VEPs was made from the largest trough to peak excursion occurring in the first 200 msec after the pattern onset (CII-CIII).The function of VEP amplitude versus bar size in a sample of co-operative adults was complex and variable. Visual acuity estimation by linear extrapolation was only valid for limited stimulus conditions (specific field size, bar size and contrast levels), for example, correlation between VEP acuity and Snellen acuity was greatest when 8 degree fields were used rather than 24 degree fields in their experimental procedure.

Conventionally stimulation in this method is provided by high contrast patterns. Stadler and Müller (1982) reported reasonable correlation between subjective and patttern VER acuity in 24 clinical patients when using checks of only 20% contrast. Steady state EPs were recorded at four spatial frequencies (4, 8.1, 16.2 and 36.4 minutes of arc) and acuity was derived by extrapolating amplitude versus log spatial frequency plots to the noise level on control trials.

A recent study found that extrapolation methods produced correlations between EP and subjective (Llandolt C) acuity that are no better than a method employing an amplitude measurement of a single 5.5 min arc check (Jenkins et al., 1985). High contrast checks of eight sizes (5.5 to 11 min arc) were presented reversing at 3 Hz. The subjects in the study were all adults with normal acuities. Computer modelling techniques predict that considerable variability and artifactual shifts towards elevated

extrapolated acuity determinations will occur for normal subjects having poor quality VEP data i.e. low signal to noise ratios (Fagan and Yolton, 1985).

A number of groups have reported use of this technique in samples of normal and visually impaired infants. Both transient and steady state evoked potentials have been used.

i) Laboratory studies

Harter and co-workers (1977) used flashed checkerboard patterns of various sizes. In the first month of life the VEP amplitude versus check size function was bimodal; during the second month the first mode disappeared, with a consequent decrease in the extrapolated visual acuity measurement. Harter suggested that the estimates of visual acuity based on the first mode of the function were reasonably consistent with data from OKN studies, whilst estimates based on the second mode were similar to data from PL studies.

Sokol (1978) recorded steady state evoked potentials to the pattern reversal of a checkerboard stimulus. Extrapolation of a regression line from the peak VEP check size to zero microvolts, demonstrated that VEP acuity improved from 20/150 at two months to 20/20 by six months. This data closely agrees with that of Marg and co-workers (1976), despite considerable variation in experimental design. Pirchio and co-workers (1978; 1979), plotted contrast sensitivity functions of infants between two and twelve months of age. However, visual acuity was evaluated by extrapolation from VEPs obtained with gratings of increasing spatial frequency at maximum contrast. The visual acuity data showed a rapid increase in the first months of life and a levelling off by the fifth - sixth month.

Odom and associates (1983), extended this technique to include pattern evoked retinal responses. Retinal and cortical responses, to the reversal of square wave gratings, were simultaneously recorded in three human infants of $3^{1}/2$ months average age and two adults of average age $28^{1}/2$ years. The relative power of retinal signals as a function of spatial frequency was very similar for both adults and infants and extrapolated to a threshold of about 30 c/deg (equivalent to Snellen acuity of $^{6}/6$). The relative power of the adult cortical signal also extrapolated to this value but the infants cortical signal was relatively more attenuated at higher spatial frequencies and extrapolated to a threshold of 8.5 c/deg ($^{6}/22$). This infers a greater relative maturity of retinal as compared to cortical neural function in $3^{1}/2$ month olds. Later work suggests that maturation at higher levels of the human visual system proceed in parallel with development at the retinal level (Fiorentini et al., 1984). Odom's groups findings could be explained by inadequate data collection (see section 1.3.4 b).

Since the completion of the present pilot study Tyler's rapid sweep VEP acuity method (Tyler et al., 1979; Tyler et al., 1981) has been successfully applied to the assessment of infants (Norcia and Tyler, 1985). Gratings were presented as a 10 second spatial frequency sweep spanning the acuity limit. Response (second harmonic) amplitude and phase was derived by Fourier analysis. VEP amplitude versus

spatial frequency plots showed narrowly tuned peaks at one or more frequencies. Acuity was estimated by linear extrapolation (to zero microvolts) of the highest spatial frequency peak in the functions. Acuity determinations were based on only 10 seconds of recording time but an hour is typically required to achieve the satisfactory period of recording (Westall, personal communication).

ii) Clinical studies (infants)

Odom and co-workers (1981; 1982), have used this technique to monitor the effects of eye patching on the "VEP" acuity of infants and young children having various ocular disorders. These included unilateral aphakia, from a congenital cataract, vitreous haemorrhage, polar cataract and esotropia. Visual acuity was estimated by extrapolating VEP amplitude as a function of the basic fundamental spatial frequency of the checkerboard stimuli to the baseline voltage or to the noise level of the control, which was obtained by presenting the smallest pattern out of focus. Gittinger and Sokol (1982) using this method were able to demonstrate that three infants initially believed to be blind by behavioural criteria, had normal visual acuities measured by VEPs.

d) Alternative methods based on the VEP

i) Harter and Suitt (1970) recorded an infants transient VEPs to flashed-on checkerboards of various check sizes. Acuity was estimated by comparing the responses of the infant to VEP data obtained from adults with differing degrees of optimally blurred vision. This data was published separately (Harter and White, 1970).

ii) Sokol and Dobson (1976), recording steady state VEPs to pattern reversing checkerboards, noted that the amplitude versus check size function generated by six-month-old infants was nearly identical to adults with $^{6}/_{6}$ Snellen acuity. On this basis they inferred that infant acuity probably reaches adult values by six months old.

iii) Mayles and Mulholland (1980), reported an attempt to produce a clinically useful method of assessing the visual acuity of very young or mentally handicapped children. They studied the visual evoked responses of 62 patients from an orthoptic clinic, having various degrees of amblyopia and also eight normal adult subjects. The stimulus was a check pattern or line grating with a reversal frequency of 4 Hz. The product of VEP amplitude and pattern size was plotted against log pattern size. A continuous, approximately linear, decrease was obtained. The intercept on the check size axis was plotted against visual acuity for the first eight subjects tested and this line was used to assess the acuity of the remaining subjects. The Snellen acuity of 70 out of 95 eyes was within one line of the acuity predicted in this way.

2.2.2 Overview and proposed clinical VEP acuity method

a) Overview

Three distinct objective methods for determining infant visual acuity using pattern VEPs produce comparable normative data (Dobson and Teller, 1978). The eye can be stimulated with high contrast patterns of successively finer line gratings to find the smallest which gives a recognisable pattern EP (Marg et al., 1976). A disadvantage of this "direct location of threshold" method is that the end point may be difficult to define because the EP signal to noise ratio is reduced approaching threshold. A greater number of responses can be averaged to compensate for this but test duration is then prolonged. A further problem is that infants may not find near threshold stimuli sufficiently compelling to attract their attention. Presentation of gratings against an interesting background (e.g. a movie cartoon) may help in this respect but decreases the signal to noise ratio and adds to the sophistication of the method.

Various groups (Harris et al., 1976; Pirchio et al., 1978; Atkinson et al., 1979) have estimated infants' contrast sensitivity at a number of spatial frequencies by applying an EP method reported by Campbell and Maffei (1970). In the original study EPs were recorded to the steady state reversal of sinusoidal gratings of various contrasts and the function of EP amplitude versus log contrast was extrapolated to zero voltage to indicate the subject's contrast threshold. Visual acuity was estimated by extrapolation of the high spatial frequency portion of the resulting contrast sensitivity function to the "cut-off point" (Bodis-Wollner, 1980). The method appears equally successful when stimulation is altered to transient pattern appearance of checkerboard patterns (Howe et al., 1981) but most studies have duplicated the original conditions. Theoretically this is the most accurate but unfortunately also the most lengthy method (several experiments are performed with different contrasts and pattern sizes), particularly if transient VEPs are recorded. Steady state recording decreases the testing duration particularly if combined with electronic sweep methods of stimulus presentation and Fourier analysis but even this does not ensure full data collection (Norcia et al., 1986). Important information about the VEP waveform is lost during steady state recording and response amplitude could be affected if the stimulus repetition rate coincides with the subjects alpha rhythm. The alpha frequency is reasonably consistent in adult subjects and so can be avoided. Infants and young children do not have well formed alpha rhythm in their EEGs. Both the proportion of alpha and its frequency increase during development (Petersen and Eeg-Olofsson, 1971; Benninger et al., 1984). Considerable individual variation occurs so it may be difficult to predict and avoid the alpha range for a particular child (unless high temporal frequencies are deliberately selected - which may not be optimum for the immature visual system).

A third method relies on the presence of an inverted "U-shaped" function between EP amplitude and pattern size both in adults (Rietveld et al., 1967; Harter and White, 1970) and infants (Karmel et al., 1974). EPs are recorded to high contrast patterns of sequentially finer detail. The amplitude of the evoked response is plotted as a function of the stimulus spatial frequency and visual acuity estimated by extrapolating the high spatial frequency "limb" to zero amplitude or the average noise level of control

trials. EP amplitude is affected by a number of factors in addition to spatial frequency (e.g. stimulus field size, intensity, contrast, subjects state of alertness, electrode position, variations in visual cortex anatomy amongst subjects). It would be expected that alteration of these variables could change the shape of the functions and therefore the acuity values obtained. A further problem is the lack of agreement on the most accurate combination of stimulation conditions and method of data analysis. Either linear or curvilinear regression may be assumed and either logarithmic or linear axes (or both) selected. Despite the theoretical inadequacies of the "amplitude versus spatial frequency plot" method (Spekreijse, 1978; 1980), advantages in terms of speed have enabled the technique to be used with normal infants (Harter et al., 1977; Sokol, 1978) and clinical samples (Odom et al., 1981, 1982).

Each of the three VEP techniques for the objective assessment of acuity (described above) has various advantages and limitations. As no method ideally fulfilled the requirements of a clinical technique preliminary investigations were directed at evaluating the clinical performance of each using co-operative adult subjects. Extensive studies were not undertaken because such investigations are outside the scope of the project and the findings in adults may not, in any case, be directly transferable to infants.

b) Preliminary findings (adults)

Relevant experimental details are provided in Appendix 2A.

i) Direct location of threshold

An attempt was made to determine the finest high contrast square-wave grating stimulus capable of producing clearly recognisable and repeatable transient pattern appearance VEPs. Satisfactory VEPs could not be obtained to stimulation with gratings, which were considerably above the psychophysical threshold of two co-operative visually normal adult emmetropic subjects. In both subjects only gratings of, or above 10 minutes of arc produced repeatable responses. This finding implies that suprathreshold high spatial frequency gratings cannot be relied upon to produce clearly recognisable repeatable evoked potentials. Douthwaite and Jenkins (1982), noted similar findings which suggest that acuity will be underestimated by the method. The technique could, however, still provide an accurate acuity estimate if a constant relationship exists between EP threshold and subjective acuity. Although it is possible that such a relationship could be defined in adults there is no guarantee that the findings would be applicable to infants.

Subsequent experimental work was restricted to recording of steady state evoked potentials because of the importance of minimising recording time when examining infants and young children.

ii) EP amplitude versus spatial frequency functions

Steady state EPs were recorded to the pattern reversal of a high contrast check generated on a television monitor. The three co-operative adult subjects were either emmetropic or wearing full optical correction. The mean EP amplitude was plotted versus stimulus spatial frequency (Figures 2.1 to 2.3). The shape of the function varied for the three observers but in each case failed to produce a high frequency portion which extrapolated to the psychophysical threshold (indicated by the arrow). Visual acuity would be grossly overestimated by these graphs.

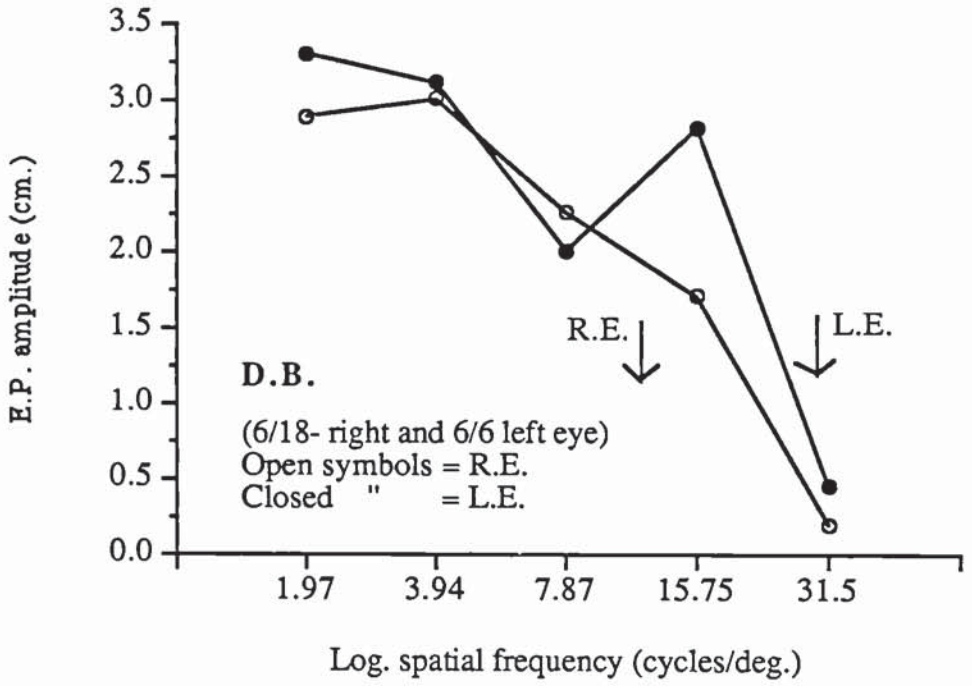


Figure 2.1 Evoked potential amplitude versus spatial frequency functions of subject D.B. The arrows represents an approximation of the subjective threshold of each eye (monocular viewing).

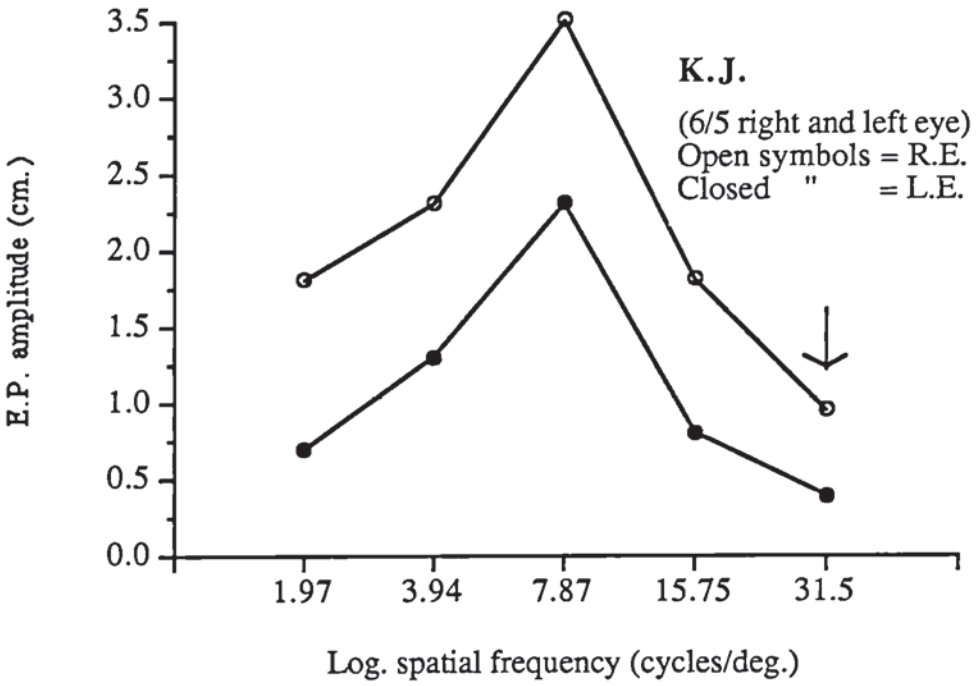


Figure 2.2 Evoked potential amplitude versus spatial frequency functions of subject K.J. The arrow represents an approximation of the subjective threshold. (monocular viewing)

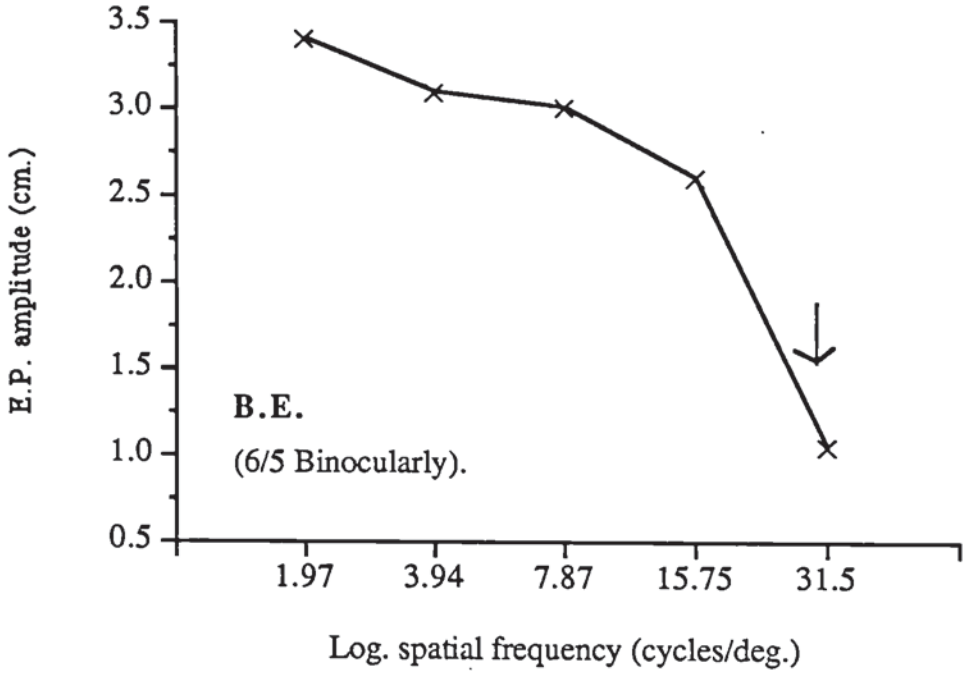


Figure 2.3 Evoked potential amplitude versus spatial frequency function of subject B.E. The arrow represents an approximation of the subjective threshold. (binocular viewing)

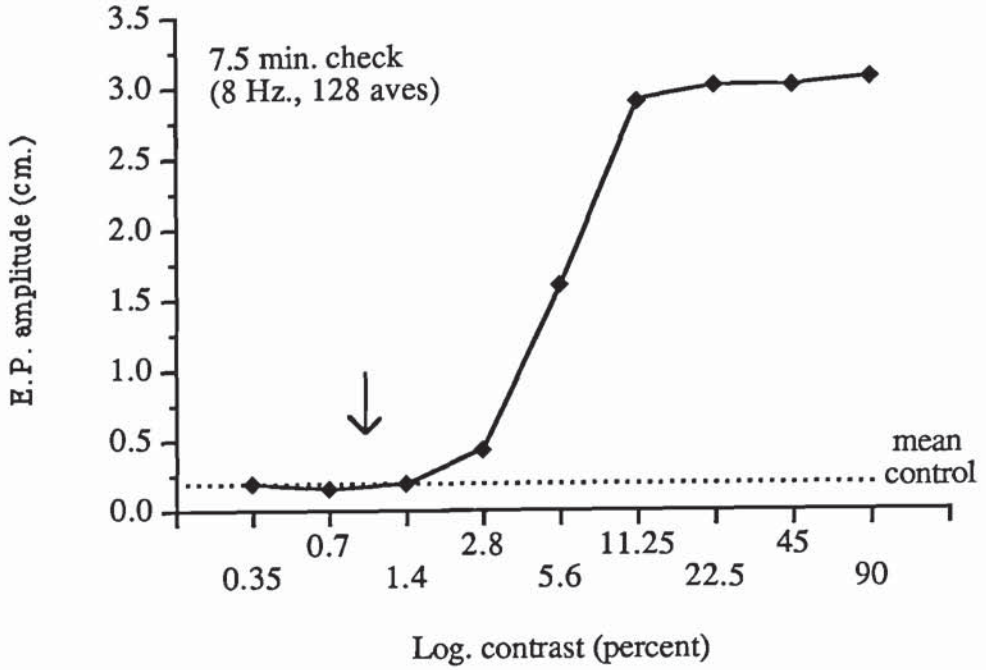
iii) Electrophysiological determination of contrast sensitivity

Steady state EPs were recorded to checkerboard stimuli reversing at frequencies of 4 or 7.5 Hz (i.e. 8 or 15 pattern reversals per second). The effect of pattern contrast and dioptric blur were investigated at two spatial frequencies - 7.5 minutes of arc (fundamental spatial frequency of 5.7 c/d) and 15 minutes of arc. One co-operative adult emmetropic subject, having monocular acuities of 6/5 in each eye was used throughout several recording sessions. In general EP amplitude was found to increase systematically with increasing contrast when amplitude was plotted versus log contrast (Figures 2.4 to 2.7). Amplitudes approximated to the mean noise level of control trials at contrast levels below the subjective threshold. The relationship between amplitude and log. contrast appears most consistent at intermediate contrast levels (presumably because of low signal to noise ratio at low contrasts and saturation effects at high contrast). The results were less variable for the 7.5 minute check size than the 15 minute check, (particularly when 15 Hz pattern reversal was used - compare Figure 2.5 a and b). More regular functions were obtained when 128 rather than 64 responses were averaged (compare Figures 2.6 and 2.7). Increasing the number of trials per contrast level appeared to increase precision (Figure 2.6 a) although smooth functions were sometimes obtained with only one trial (Figure 2.4). Subject fatigue may occur during the prolonged recording sessions but repetition of certain trials at the end of one session confirmed earlier results (Figure 2.7b). Providing the subjects gaze was directed towards the screen mean EP amplitude was identical whether central fixation was maintained or wandering eye movements occurred. This finding is encouraging in respect to the examination of infants.

The EP signal to noise ratio should theoretically approach unity near threshold so that values above 1.0 represent suprathreshold contrast levels. Plotting the ratio of EP amplitude during a stimulus trial and the mean amplitude of control trials immediately preceding and following the stimulus trial (defined as the signal to noise ratio) as a function of stimulus contrast does not appear to increase the precision of threshold determination (Figure 2.8). The amplitude of consecutive control trials varied considerably, on occasions, so it is probably inaccurate to assume that the noise level during a stimulus run will be around that of the preceding and following control trial.

The phase of the steady state EP was found to be considerably more sensitive to optical defocus (Figure 2.10) than its amplitude (Figure 2.9). An initial increase in EP amplitude noted may be explained by the improved visibility of the fundamental spatial frequency as the higher frequencies (responsible for edges) are blurred. The phase of the response altered in a monotonic fashion. The phase of control trials was noted to vary randomly whereas phase altered systematically as contrast was reduced. It is possible that incorporation of a combined amplitude and phase score could yield a more sensitive determination of threshold.

These findings confirm a close association between psychophysical and electrophysiological data using this method. However prolonged recording sessions are not appropriate when examining infants, whose attention is recognised to be labile.



2.4 a) above

2.4 b) below

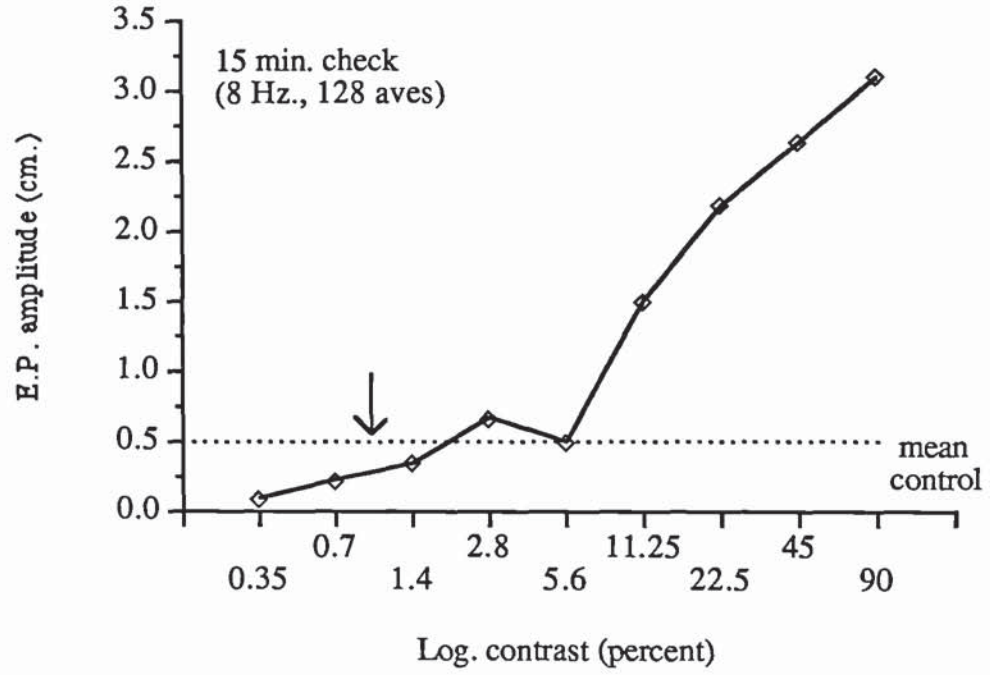
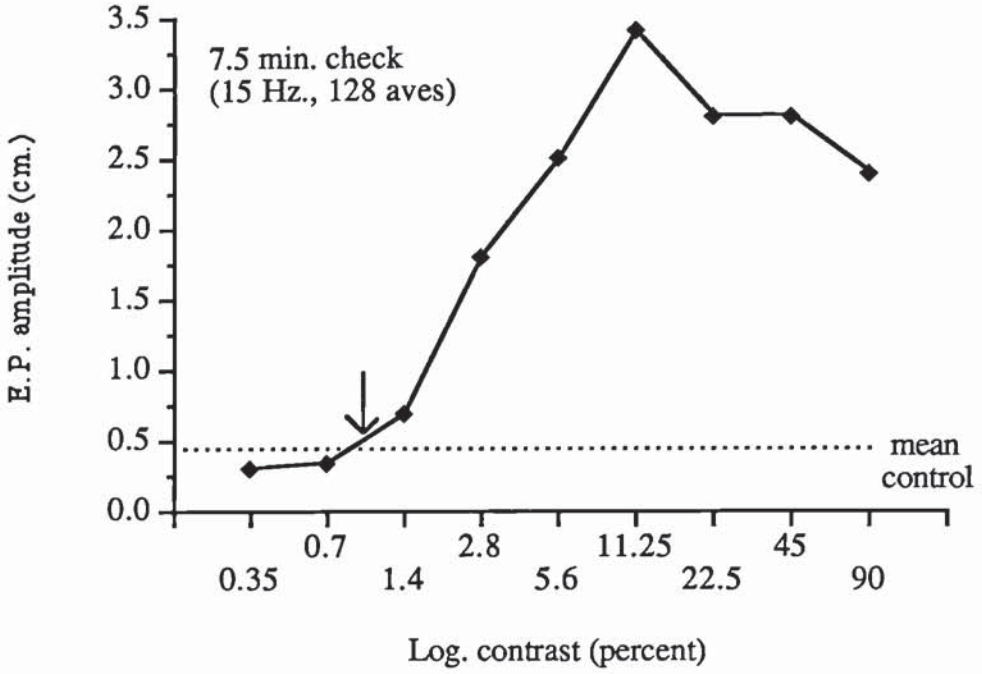


Figure 2.4 Evoked potential amplitude versus log contrast functions, 8 Hz 128 averages. a) 7.5 min checks b) 15 min checks. One trial per contrast level. The arrow represents an approximation of the subjective threshold. (binocular viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

a)



b)

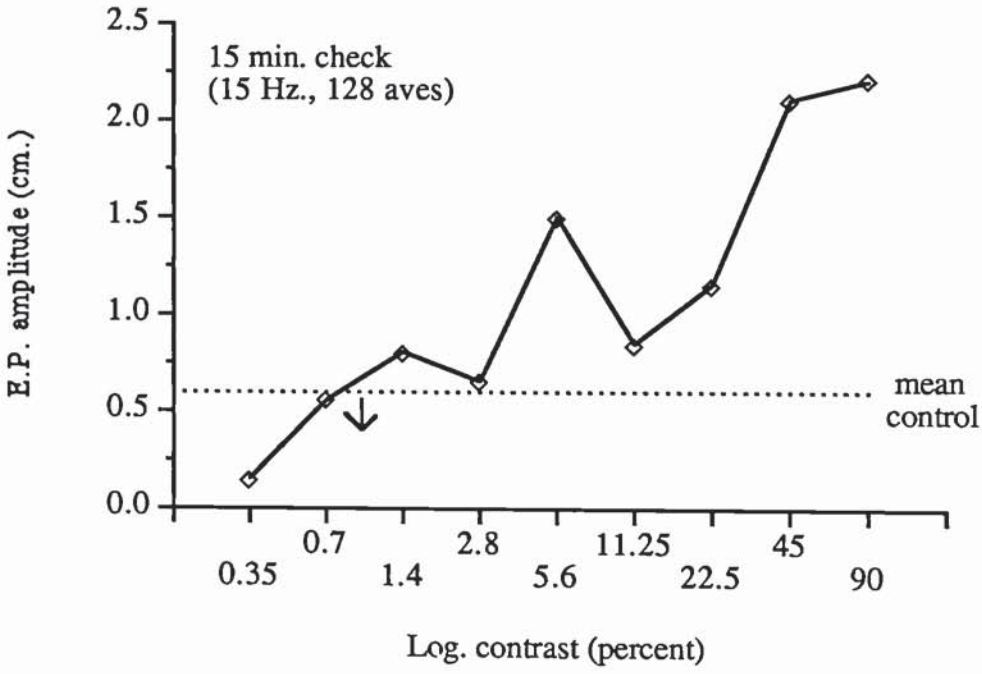
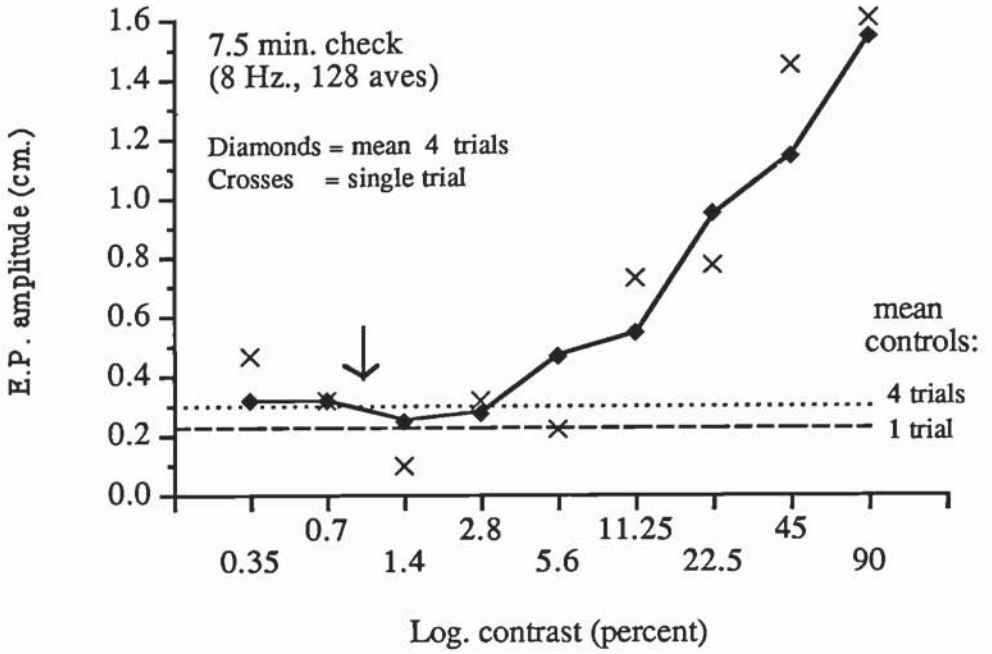


Figure 2.5 Evoked potential amplitude versus log contrast functions, 15 Hz 128 averages. a) 7.5 min checks b) 15 min checks. One trial per contrast level. The arrow represents an approximation of the subjective threshold. (binocular viewing, O2 - C4 derivation, filter 15 Hz., Q = 50).

a)



b)

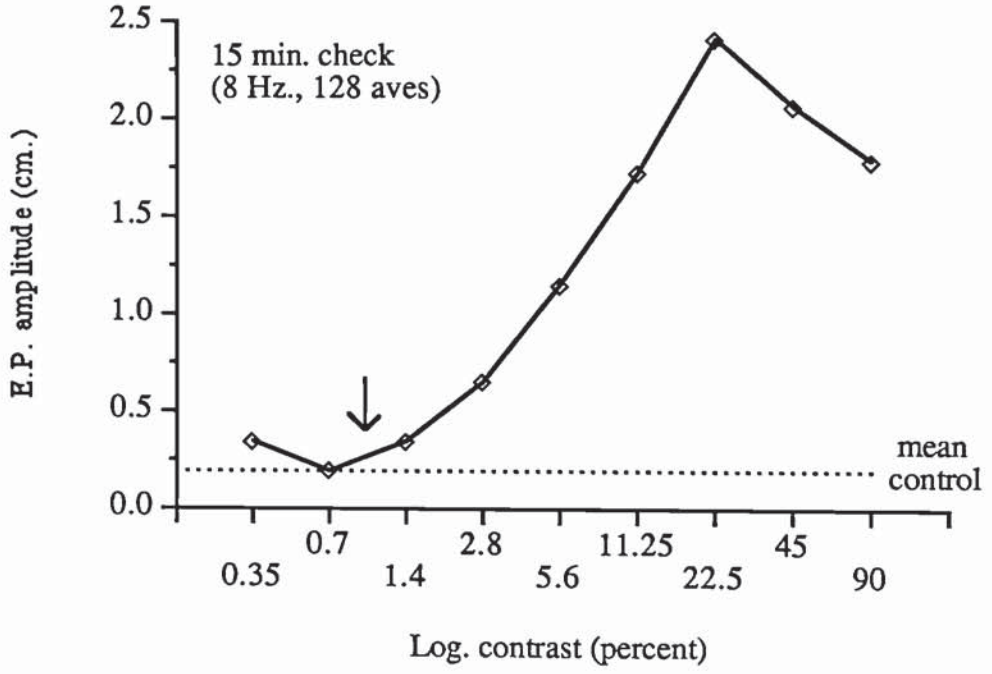
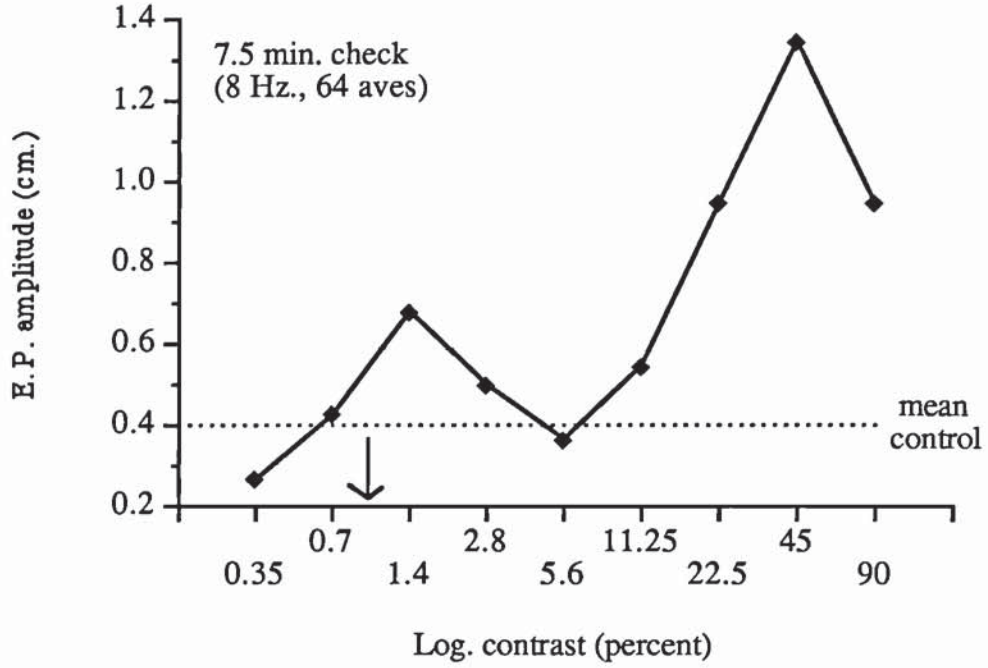


Figure 2.6 Evoked potential amplitude versus log contrast functions, 8 Hz 128 averages.
a) 7.5 min checks (single trial and mean of four trials per contrast level)
b) 15 min checks (mean of three trials per contrast level)
The arrow represents an approximation of the subjective threshold.
(binocular viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

a)



b)

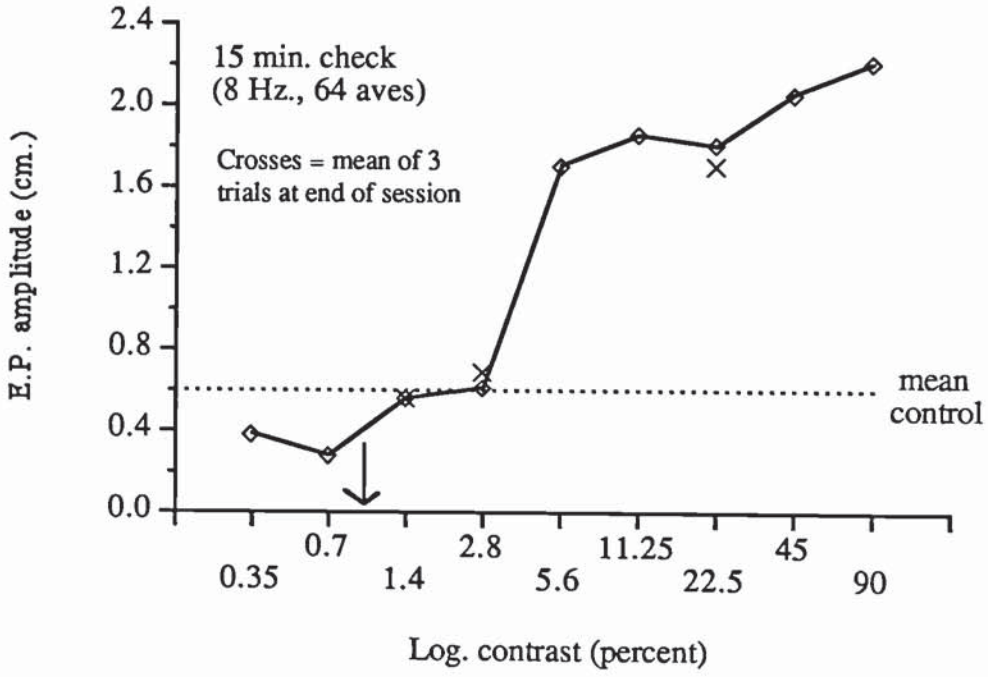


Figure 2.7 Evoked potential amplitude versus log contrast functions, 8 Hz 64 responses. a) 7.5 min checks b) 15 min checks. Four trials per contrast level. The arrow represents an approximation of the subjective threshold. (binocular viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

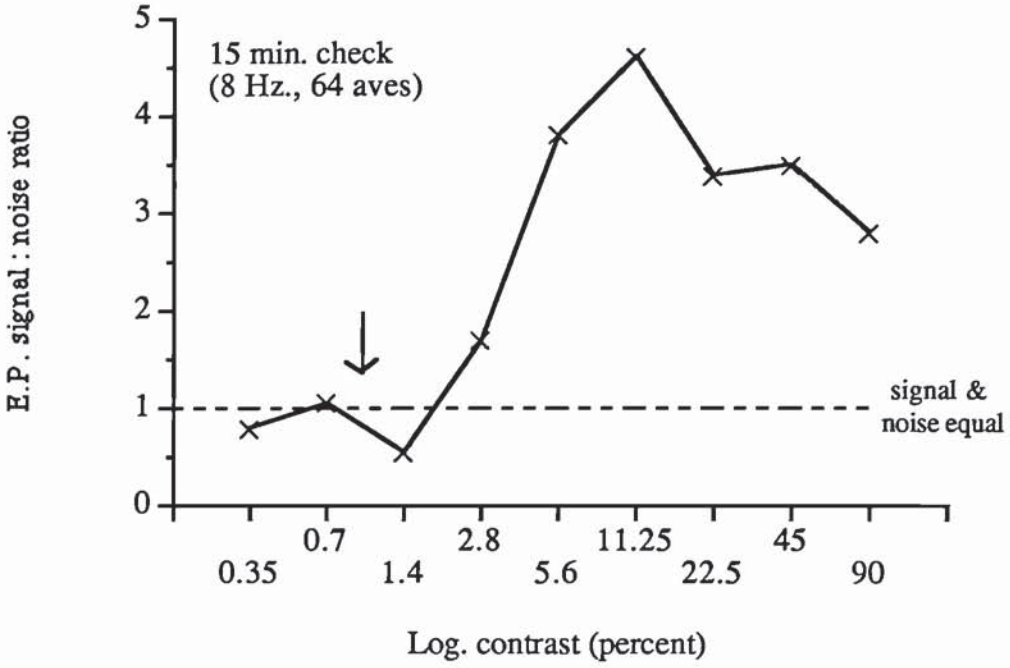
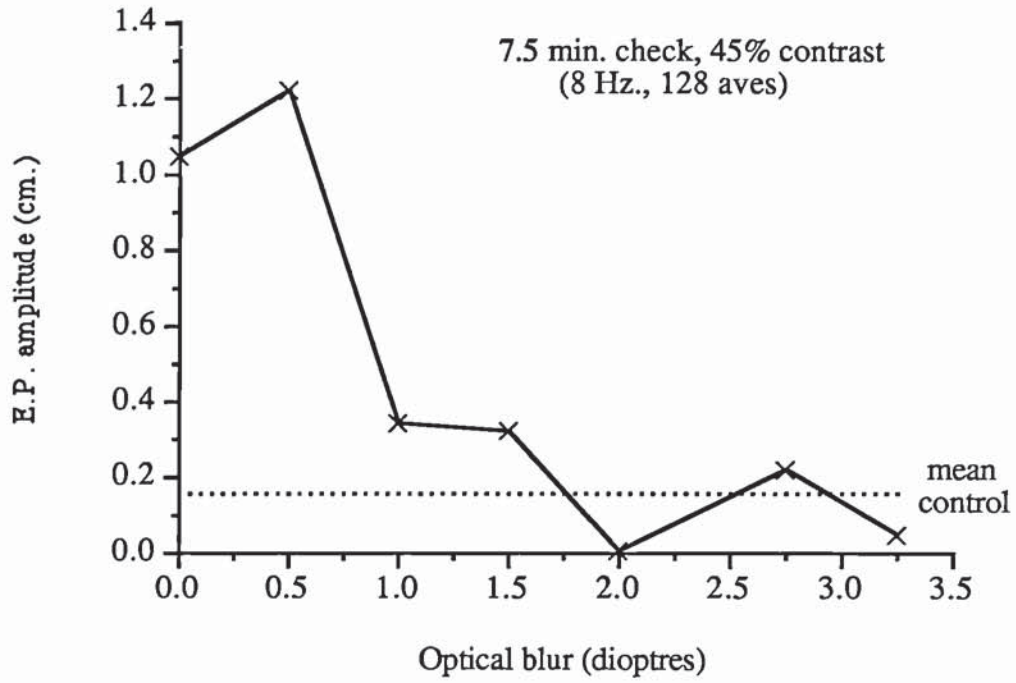


Figure 2.8 Signal to noise ratio of recorded pattern reversal evoked potentials versus stimulus contrast. Each point represents the mean of four trials. The arrow represents an approximation of the subjective threshold.
(15 min check, right eye viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

a)



b)

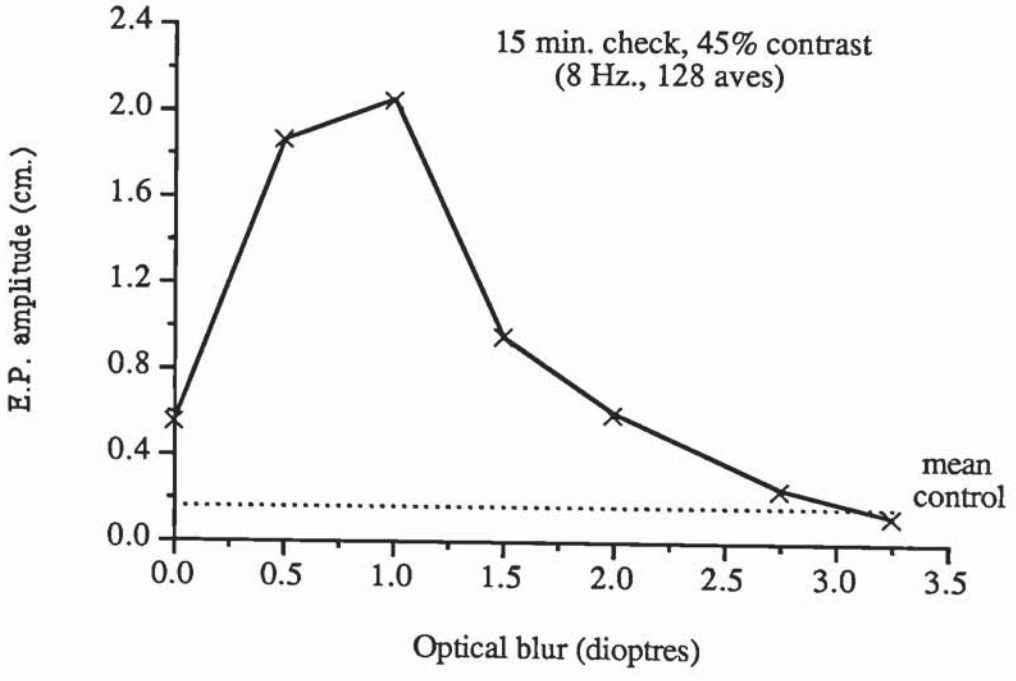
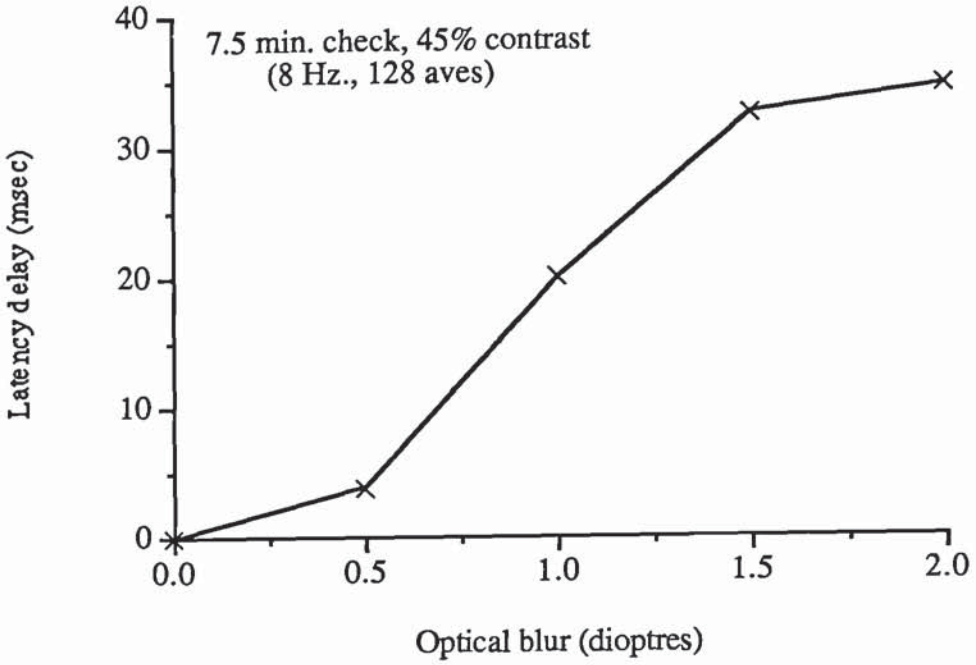


Figure 2.9 Evoked potential amplitude as a function of optical blur:
a) 7.5 min checks, 45 % contrast b) 15 min checks, 45 % contrast.
(binocular viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

a)



b)

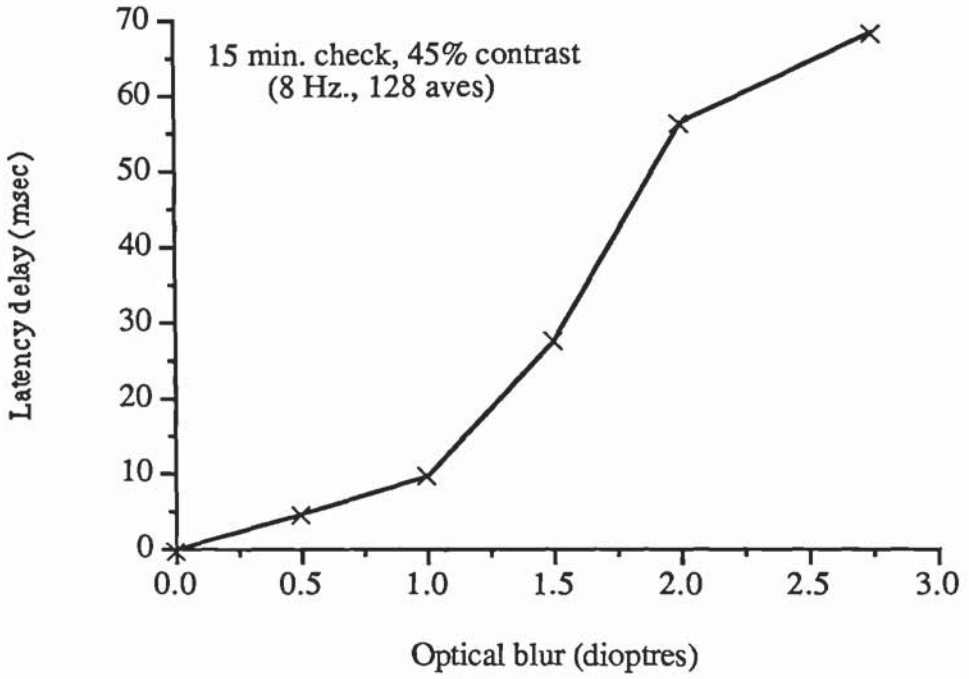


Figure 2.10 Latency delay of the first positive peak of the pattern reversal evoked potential with increasing optical blur:
a) 7.5 min checks, 45 % contrast b) 15 min checks, 45 % contrast.
(binocular viewing, O2 - C4 derivation, filter 8 Hz., Q = 50).

c) Conclusion

Three methods of visual acuity assessment using VEPs rely on either direct location of threshold, or electrophysiological determination of the contrast sensitivity function (CSF), or extrapolation from EP amplitude versus spatial frequency functions. No obvious clinically superior technique was suggested by the limited initial study conducted in adult subjects. The conclusions of this investigation were that:

i) The method of direct location of threshold may underestimate acuity.

ii) EP amplitude versus spatial frequency functions may not extrapolate to an individuals psychophysical threshold. Visual acuity would be grossly overestimated from the plots obtained. It may be possible to manipulate recording conditions to produce satisfactory functions (in adults) but time did not permit the extensive experimentation necessary to pursue this method.

iii) Reasonable estimates of contrast sensitivity can be obtained. However, prolonged experimentation was required to determine contrast sensitivity at two spatial frequencies in a co-operative adult subject. Testing time could be reduced if contrast level was selected according to a staircase rule and if a more automated system was available (allowing instant feedback of whether stimulus trials were significantly greater in amplitude than the average noise level). Methods employing Fourier analysis of the EEG spectrum offer the advantage of increased speed but should be considered with caution since very high noise levels are sometimes obtained during control trials. This latter observation inevitably leads one to question the validity of the steady state method particularly if trials are not repeated at each contrast level. (This experimentation was proceding concurrently with commencement of examination of a few infants referred for immediate assessment. Findings with these infants - described in section 2.6 - suggest that clinical objective determination of contrast sensitivity would be a very optimistic venture).

2.3 Optokinetic responses

Virtually all of the earliest methods developed for objective assessment of visual acuity depended upon optokinetic responses. As these techniques have declined in popularity, Pearson's reviews of studies published before 1973 (Pearson 1966, Pearson 1973), remain fairly comprehensive and the reader is referred to these sources for experimental details of individual studies. In this report, descriptions will be restricted to the basic principles of the main techniques and brief explanations of the original study and infant studies.

Pearson (1973) classifies the techniques according to the particular reflexes involved (fixation or following reflex or a combination of both), but, for simplicity they may be grouped thus:

1 Methods based on evoking oscillatory motion
2 Methods based on evoking optokinetic nystagmus
3 Methods based on the termination of optokinetic nystagmus
4 Methods based on arresting optokinetic nystagmus

Optokinetic responses can be assessed either by direct observation or by measuring the eye movements using electro-oculography in which case a permanent record is obtained.

2.3.1 Review of optokinetic acuity methods

a) Induction of oscillatory eye movements

By moving a large object, with a pendulous movement before the eye, a corresponding oscillatory movement of the eye itself can be evoked (Goldmann, 1943). Since the eye movement will not occur unless the object is perceived visual acuity may be estimated from the smallest stimulus which will induce the reflex oscillatory motion. Either successively smaller stimuli are used throughout the examination of the subject to stimulus is increased.

The method was originated by Goldmann (1943). The test figure was a checkerboard target composed of a central block of large squares surrounded by smaller squares. When the subject was unable to discern the large squares the target appeared as an even grey surface. The edges of the stimulus pattern were concealed behind an aperture therefore eye movements were only induced if the large squares were resolved. Visual acuity was estimated by measuring the maximum viewing distance at which the eye movements could be induced by the stimulus pattern. Luscher (1955) stated that the coefficient of correlation between subject and objective acuities was +0.91 with this method.

Schwarting (1954) reported a technique for use with infants, he evoked a pendular nystagus using steel wires of various sizes fitted on the swinging arm of a metronome. The wires moved across an

illuminated field and the smallest wire which evoked a synchronous movement of the eyes was considered an index of the visual acuity. Five wires were used at a testing distance of one metre to measure visual acuity ranging from finger counting to $^{20}/_{50}$ (equivalent to $^{6}/_{15}$). However, it was often impossible to test infants monocularly with this method.

Catford and Oliver (1971, 1973) designed a portable device in which a black disc on a white background was exposed through an aperture and moved by a small electric motor. The stimulus executed a slow phase across the field followed by a quick return. This apparatus subsequently became available commercially and has proved quite popular. However, Atkinson and co-workers (1981), commented on inaccurate results obtained in adult observers. Since the target measures minimum visible rather than minimum separable, the Catford drum overestimates visual acuity, unfortunately it does so by factors which vary from different visual disorders. They noted that the smallest spot on the drum would not distinguish $^{6}/_{6}$ from $^{6}/_{24}$ acuity, so this interocular difference would go undetected. They suggested a more appropriate target - a grating surrounded by an intermediate grey - so that when blurred the target would merge into its background.

b) Induction of optokinetic nystagmus

When a series of objects move in one direction across the visual field, an involuntary, conjugate, rhythmical movement of the eyes occurs consisting of a slow phase in pursuit of the moving stimuli and a fast recovery phase in the opposite direction. This pattern of eye movement is known as optokinetic nystagmus (Borries, 1923). This title is often abbreviated to OKN. Induction of optokinetic nystagmus indicates that a moving target is resolved by the patient and hence provides the basis of an objective method for determination of visual acuity. The smallest stimulus pattern which will evoke OKN provides an estimate of visual acuity.

Gunther (1948) first reported a method of measuring visual acuity objectively by evoking OKN. This has been described by Schumann (1961) and Pearson (1966). The apparatus consisted of a checkered ribbon having three different check sizes. The ribbon was viewed through an aperture as it moved over two rotating cylinders. The size of the checkerboard pattern and testing distance which evoked an eye movement were determined. Luscher (1955) stated that the coefficient of correlation between subjective and objective acuities was +0.66.

Freudenberg and co-workers (1960) compared Gunther's method with Goldmann's. With visual acuities between 0.01 and 0.25 (i.e. $^{6}/_{600}$ - $^{6}/_{24}$), Gunther's apparatus gave a closer approximation between the subjective and objective measurements. There was no significant difference between the methods for visual acuities between 0.30 and 1.25 ($^{6}/_{20}$ - $^{6}/_{5}$).

This general method, of eliciting optokinetic nystagmus, has been reported in a number of infant studies:

Gorman and co-workers (1957,1959) were the first to apply the method to an infant sample. Direct observation of OKN was used to assess visual resolution in 100 neonates. In order to occupy the whole visual field and therefore attract the infants attention, the stimulus - a roll of striped paper - was drawn over two plastic arcs from one spool to another. The infant was placed beneath this canopy of moving stripes. Visual acuity was estimated from the smallest stripe width which would elicit OKN. In the initial study, (Gorman et al., 1957), 93 infants exhibited OKN to 30' stripes but none showed a response to 10' stripes. A subsequent study, (Gorman et al., 1959), found that of 100 infants tested all showed OKN to 20' stripes and a "large percentage" responded to 15' stripes.

Dayton and co-workers (1964a) used an apparatus similar to Gorman's, in a detailed study of visual acuity of neonates. A paper target, on which were penned longitudinal black lines, was drawn across a plastic canopy that formed a 180 degree sector of 14.5 inch radius. The infants head was placed at the centre of this and the induced optokinetic nystagmus was recorded using electro-oculography. Of 30 infants tested, 18 yielded records which permitted analysis of the visual acuity level. Nine showed OKN to all three target widths, including the finest stripes (about 7'), five showed OKN to the 15' and 20' stimuli and four showed OKN only to the 20' stimulus. Kiff and Lepard (1966) used an apparatus of the same basic construction as Gorman and co-workers (1957, 1959). They reported that, although 55% of the infants responded to 40 minute stripes, 20 of a series of 44 premature infants showed no optokinetic response (as assessed by direct observation). Several reasons for these failures were offered - immature vitreous, immature retina and fovea, lack of sufficient fixation and following mechanism development, lack of subject awareness. Only two target sizes were used in their study, it is possible that additional, larger targets may have evoked a response.

Lewkonia (1969) developed a slightly different objective method of assessing visual acuity, based on determination of the minimum visible rather than minimum separable. Optokinetic nystagmus was induced using a white drum on which were marked six rows of twelve equally spaced black dots of graduated size, ranging from 0.50 to 7.50mm in diameter. The drum rotated on a turntable at 16 revs/minute and was viewed from a distance of one metre. The optokinetic response of subjects having known visual acuities, was observed so that an approximate visual acuity value could be assigned to each target size. Lewkonia stated that initial testing with young children, including infants, was very encouraging though modification of the scale for use at distances less than one metre would be needed to assess young children under 12 months of age. Despite this optimism no data has been reported on use of this technique on an infant population.

In a clinical study, Enoch and Rabinowicz (1976) monitored the OKN acuity in an infant with a unilateral cataract, before and after the removal of the cataract, using a hand held OKN drum at variable distances. The good eye was used as a control and showed acuity values comparable to those found by Fantz and co-workers (1962), for all ages except the youngest age tested.

c) Termination of optokinetic nystagmus

Adler (1950) suggested that optokinetic nystagmus could be induced, e.g. by rotating a striped drum, the width of stimulus elements (stripes) could then be decreased until the nystagmus ceased. At this point, visual acuity could be estimated from the visual angle subtended by one stripe. The test therefore consists of finding the smallest separation of stripes which still sustained optokinetic nystagmus. This approach has been adopted in only a few investigations.

In an adult study, Sibinskaja (1957) reported nearly 100% agreement between the objective and subjective measurements using this technique on a sample of emmetropes and ametropes. The apparatus consisted of a rotating drum with checkerboard patterns of nine different sizes. The smallest target size which resulted in a termination of the optokinetic response indicated the objective acuity. In a study evaluating preferential looking, Fantz and co-workers (1962) additionally obtained OKN acuity estimates for 46 infants between 4 days and 6 months of age. The apparatus was similar to that used by Gorman and co-workers (1957), though the stripes were photographic prints of machine-tooled stripes and could be hand cranked to produce either left to right or right to left movement at variable speeds. Presence or absence of O.K.N. was judged directly by an adult observer. The smallest stripe width to which at least 75% of infants responded at each age was taken to reflect visual acuity. The data showed closed agreement between the two techniques though the optokinetic test demonstrated lower values from one months to two months and preferential looking gave lower acuities from three to four months.

d) Arresting of optokinetic nystagmus

An optokinetic nystagmus is induced and stationary test objects are then superimposed on the patient's field of view. If these can be resolved, the nystagmus is suppressed. Visual acuity is estimated from the smallest test pattern which inhibits the O.K.N.

This method was originated by Ohm (1931) and described by Schumann (1952) and provided the first attempt to determine visual acuity objectively. In this method, optokinetic nystagmus was evoked by a rotating drum painted with black and white stripes. The arresting stimulus was the reflection of an electric bulb on a glass plate. The stimulus was arranged to appear directly in front of the drum when the light was turned on. The smallest target which arrested the nystagmus was noted and the visual acuity determined from its size and visual angle. Since the original technique measured the 'minimum visible' rather than the 'minimum separable' most studies found it was unsuitable for precise measurement of visual acuity. Voipio's (1961) use of horizontally-orientated black and white gratings as alternative arresting test stimuli considerably increased the accuracy of the method. A strong correlation ($r = +0.92$) was demonstrated between O.K.N. acuity and subjective acuity.

Despite the advantage of using stationary stimuli, as in conventional subjective methods - this technique has so far not been used to investigate infant acuity. A similar method was successfully applied in a

(rather poorly documented) study of infant contrast sensitivity in seven infants from birth to 38 weeks (Meijler and Van den Berg, 1982). Pursuit eye movements were induced by a horizontally sinusoidally moving coarse pattern and recorded by electro-oculography. Nine seconds after onset of the coarse pattern a stationary test pattern of a given spatial frequency and contrast was projected through the coarse pattern for nine seconds. In a series the grating alternately was and was not presented eight times. Suppression of the eye movements was determined using a statistical procedure and indicated that the grating was seen.

2.3.2 Overview and proposed clinical optokinetic acuity method

a) Overview

The principle of objective techniques which are dependent upon optokinetic responses is that contours moving across a subject's field of view will, if resolved, induce involuntary eye movements. Visual acuity is estimated either from the smallest moving stimulus (often a black and white striped field) which will induce or sustain reflex oscillatory eye movements or OKN or from the smallest stationary test object which, when superimposed on the moving test field, will consistently inhibit those eye movements. Eye movements may be observed directly or measured using electro-oculography (Shackel, 1960).

In the majority of laboratory studies reported, infant acuity has been assessed by placing an infant beneath a canopy of moving stripes (which can be varied in spatial frequency) and finding the narrowest stripe width which would induce or sustain OKN. Only three or four stripe widths are typically available and viewing distance cannot be varied greatly. These factors limit the sensitivity of acuity measurements for individual infants. For this reason, group acuity is usually specified by testing a large number of infants (of the same age) and finding by extrapolation the finest stripe width to which most (e.g. 75%) responded. Although this method has been applied to infants of up to six months (Fantz et al., 1962), it is more appropriate for very young infants. Older infants may be distressed by the claustrophobic effect of a canopy of moving stripes. The highest level of neonatal acuity (17') reported was found using this method (Dayton et al., 1964). However, it seems probable that the infants were reacting to lower spatial frequency components caused by the irregular spacing of the hand-penned lines used in the study (Banks and Salapatek, 1981).

Clinically infant acuity has been assessed using less cumbersome apparatus. Enoch and Rabinowicz (1976) managed to successfully monitor the acuity of an infant with a unilateral cataract clinically. Testing was conducted both before and after removal of the cataract, using a hand held OKN drum at variable distances. As only one infant was tested it is not possible to comment on the general viability of this method. It is probable that a carefully controlled environment would be necessary to elimimate room distractions. The only commercially available test which is in popular use is the Catford drum

(Catford and Oliver, 1971). This uses as targets moving black spots of various sizes. The relationship of the measurement to visual acuity is doubtful (Atkinson et al., 1981).

A major difficulty with methods based on eliciting optokinetic responses is that failure to do so may simply reflect poor co-operation with the test, rather than inability to perceive the moving stripes. Another limitation of these studies is that acuity is determined according to the responses elicited by moving stimuli. Some authors have questioned whether perception is in fact necessary to initiate reflexive optokinetic eye movements (Ruskell, 1967; Linksz, 1973). Acuity is known to be lower for kinetic stimuli than for stationary targets and the contrast sensitivity function varies for stationary and drifting gratings although most of the difference is found at low spatial frequencies. Both problems can be avoided by methods which depend on arresting of optokinetic responses. Continuous evaluation of the subjects responsiveness is provided by a permanently present coarse moving "OKN stimulus" onto which a stationary test pattern is momentarily superimposed. Providing that OKN is elicited by the coarse stimulus its attenuation indicates that the test pattern is resolved. Test stimuli should ideally rely on minimum separable rather than minimum visible acuity. Square-wave gratings (black and white stripes) fulfil this requirement and when orientated horizontally their visibility is not affected by blur due to horizontal eye movements. A method previously employed in adults satisfies these requirements and enabled accurate assessment of visual acuity (Voipio, 1961; Voipio and Lappi, 1969). It was proposed that this method should be adapted for use with infant subjects. The technique has not been used to investigate infant acuity although a similar method was applied in a (rather poorly documented) study of infant contrast sensitivity (Meijler and Van den Berg, 1982).

b) Proposed adaptation of Voipio's "arrestovisography" method

i) Voipio's method

In Voipio's method (Voipio, 1961; Voipio and Hyvarinen, 1966; Voipio and Lappi, 1969) nystagmus was elicited by a moving background saw-tooth stimulus (Figure 2.11) onto which a stationary test grating (Figure 2.12) was momentarily presented. The central grating figure could only be distinguished from its background when the individual lines were resolved, as the mean luminance of the grating was equivalent to its grey surround. The grating was initially out of focus and brought into focus manually by the examiner mechanically shifting the slide from D to C (Figure 2.13). This method of pattern appearance ensured that there was no associated change in luminance. Cessation or inhibition of the OKN indicated visibility of the stationary grating. The finest arresting grating was presented first, followed by successively coarser gratings until a definite cessation of OKN was observed. Eye movements were either viewed directly (Voipio, 1961) or recorded using electro-oculography (Voipio and Hyvarinen, 1966; Voipio and Lappi, 1969). Visual acuity was derived from the spatial frequency of the finest grating capable of arresting OKN at least twice. Eight spatial frequencies, arranged in logarithmic steps, were available but only five steps were used when examining 7 to 13 year old strabismic children (Voipio and Lappi, 1969).

The field of view subtended 15° horizontally and 10° vertically when viewed at 4.5 metres (Voipio, 1961). A viewing distance of 5 metres was used in subsequent studies (Voipio and Hyvarinen, 1966; Voipio and Lappi, 1969). The velocity of the saw-tooth pattern could be varied (and movement altered to the opposite direction) to enhance the OKN. In the original study speeds of 15 to 18 degrees per second were typical allowing 20 to 25 teeth to pass the centre of the screen every 10 seconds. The stimulus was sufficient to evoke OKN in all but 26 of 366 eyes tested (these eyes generally had very poor acuities or field defects). It was possible to arrest the OKN with the coarsest grating (1.3 c/d) in 245 of 254 eyes. Onset of OKN was generally below 1.0 second and the latency of arrest was usually between 0.4 and 1.0 second (Voipio and Hyvarinen, 1966). Testing of each eye was generally completed in about five minutes in alert emmetropic or corrected ametropic subjects, having relatively good vision. The spatial frequency of the finest arresting grating was consistently slightly coarser than the finest seen subjectively presumably due to rivalry between the moving and stationary stimuli during the conditions of the test. Despite this the correlation between the two measurements was very high ($r = +0.92$) suggesting that, for adult subjects at least, the technique provides an accurate and viable method for objective determination of acuity.

Figure 2.11 Saw-tooth O.K.N. stimulus (after Voipio, 1961).

Figure 2.12 Arresting stimulus (after Voipio, 1961).
The grating merged into its background in the original
the strong edge effect shown here is artifactual.

Figure 2.13 Projection system used by Voipio (After Voipio, 1966).
A = light source and condensing lenses
B = double saw-tooth pattern on a film loop
C and D = grating figure slides in sharp focus and out of focus
E = projecting lenses

ii) Proposed adaptation of Voipio's method

The main alteration from Voipio's technique was the incorporation of a sophisticated electronic system capable of controlling the entire sequence of presentation of the OKN stimulus and a series of test gratings. This would decrease the test duration and free the clinician to carry out other observations. A second projector was required since the test gratings (identical in design to those used by Voipio) needed to be arranged in sequence in a magazine. A diffusing shutter was used to facilitate rapid exposure of test gratings. To adapt the method for use with infants, a screen subtending a larger visual angle (30° x 20°) at a reduced viewing distance (50 cm.) was considered desirable. It was anticipated that this would be sufficient to compensate for room distractions when combined with testing in the dark.

The design provided for a triangular wave motion of the background stimulus in view of reports of an initial asymmetry of monocular OKN in infancy (Atkinson, 1979; Naegele and Held, 1982). The low ambient room illumination would probably necessitate indirect observation of eye movements using electro-oculography. The permanent records thus obtained could be studied for symmetry of monocular OKN. The development of symmetrical monocular OKN and cortical binocularity have been linked (see section 1.2.5c) so the method may help to identify infants with anomalies of binocular vision. Details of the apparatus constructed and of the electronically controlled automated sequence are provided in Appendix 2B.

iii) Summary of proposed test

The patient has one eye occluded and is seated 50 cm from the stimulus display in a dark room. A coarse "saw tooth" pattern appears on the screen and continually moves backward and forward during the test, inducing OKN in the unoccluded eye. Each of a series of ten horizontal stripe patterns are presented briefly in a predetermined sequence of spatial frequencies. The effect of each test grating on the OKN response is evaluated either by direct observation or by analysis of an EOG trace if this has been recorded. Visual acuity is assessed as equivalent to the spatial frequency of the finest grating which will arrest OKN more than once.

iv) Technical complications

An important feature of the test stimulus slides was the requirement that the central grating be of the same mean luminance as its background, so that it would merge into its surround if not resolved. Production of a perfect series of slides proved to be very difficult although many approaches were attempted these were finally abandoned without success.

Voipio (1961) maintains (without revealing the solution to the problem) that

> "the photographic-technical problem of copying the grey background and the grating figure together in such a manner that the grating melts into the background when the lines fuse together ..... is not prohibitively difficult".

Our experimentation involved photographing narrow strips of grating against several grey backgrounds of varying shades whilst systematically altering film exposure and additionally using a vertically orientated grating as background (this produced irregular fringes). A prototype of the latter design is illustrated in Figure 2.14. It is possible that satisfactory results could be obtained by photographing the strips of grating against the background of a specially adapted light box (which could be adjusted continuously in intensity by a rheostat). Even so laborious experimentation would probably be necessary to achieve the desired results.

The contrast of the black and white saw tooth was severely decreased by projecting the grey arresting stimulus pattern over it. The black stripes of the arresting stimuli were similarly affected by the central white area of the saw-tooth pattern. This effect could be reduced by using a saw tooth pattern composed of white teeth on a black background. The method would still be viable providing the respective stimuli are sufficient to evoke and arrest OKN, but trials with adults will be necessary to calibrate the low contrast test stimuli slides.

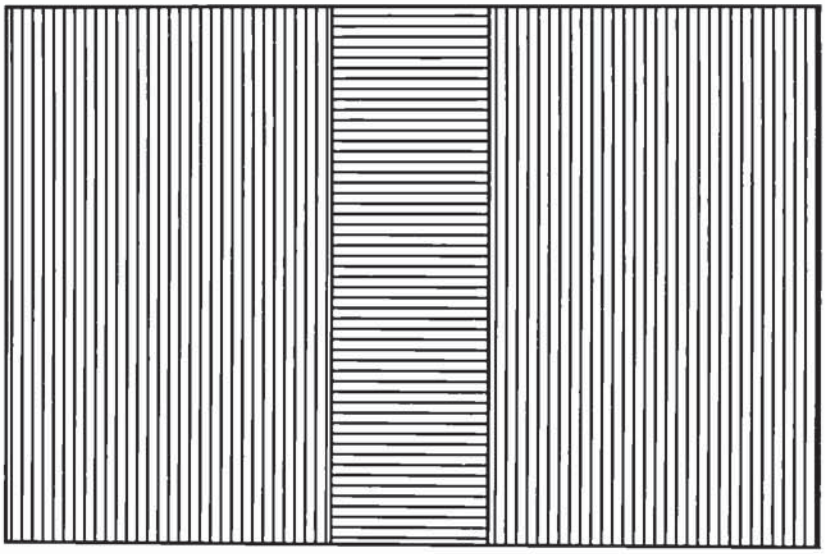


Figure 2.14 Prototype arresting stimulus.

c) Conclusion

Due to time constraints (and difficulty in constructing a sufficiently compact apparatus) further development work on the arresting of OKN method was not completed. If the technical problems described above could be successfully eliminated, the method may provide both a rapid objective method of assessing visual acuity and a screening test for anomalies of binocular vision. The test would be applicable in subjects of any age.

2.4 Preferential looking techniques

Several research groups are collecting data using variants of a psychophysical technique based on the observation that infants fixate patterned surfaces more than featureless surfaces (Berlyne, 1958, Fantz, 1958). This method has become known as preferential looking (P.L.) and depends on the assumption that the finest striped field which the infant will consistently fixate in preference to a homogeneous field provides a possible measure of grating acuity. The review presented here does not include details of the recently developed acuity card procedure, which has been reported in the literature since the completion of the pilot study described in this chapter (section 2.6). The acuity card procedure (McDonald et al., 1985), does not depend on formal psychophysical procedures. A range of formal preferential looking techniques, developed prior to the introduction of the acuity card method, are described:

i) Fantz's technique

This method (Fantz, 1958) provides the basis for the other techniques. In the procedure a black and white striped pattern and plain grey field of matched space average luminance are simultaneously exposed to the infant for 20 seconds. The test stimuli are then reversed in position and uncovered for a further 20 seconds. during each trial an observer, aware of the pattern stimulus position, watches the corneal reflection of the stimuli in the infants eyes and scores the number and duration of fixations of each stimulus using a timer and a counter.

Fantz designated an acuity level for a particular age group as being equivalent to the smallest stripe width used for which 75% or more of the infants show longer fixation of the striped pattern than of the grey field. Data collected from this laboratory, using the same technique over a period of 15 to 20 years (Fantz and co-workers, 1975), shows reasonable consistency with a small but systemic improvement with increasing stimulus luminance and/or increasing refinement of the technique. Miranda (1970) demonstrated that the technique could be successfully applied to test visual acuity in premature infants as well as full-term infants.

ii) Forced choice preferential looking (F.P.L.)

Teller and co-workers, (1974), introduced a modification to Fantz's original procedure by combining it with the two-alternative forced choice psychophysical method (Blackwell, 1953; Bush et al., 1963). They named their version forced-choice preferential looking (F.P.L.). Details of the logic and testing procedure are covered extensively by Teller (1979), a brief explanation will be given here.

During the procedure, the observer is both unaware of the position of the pattern stimulus and unable to see any corneal reflection in the infants eyes. The location of the test stimulus on each trial has therefore to be inferred from various cues given by the infants eye and head movement (e.g.

direction of first fixation, duration of fixations, facial expressions). On each trial the observer's response is scored as correct or incorrect. It is recommended that feedback of the grating location is given after each trial so that the observer can determine the most reliable stimulus position cues given by individual infants (Teller, 1979).

iii) Operant preferential looking (O.P.L.)

Preferential looking techniques are most effective between one and six months in normal infants, though testing in darkness may enable the upper range to be extended to about twelve months (Gwiazda et al., 1980). Neurologically-impaired individuals can be examined beyond this age using the standard procedure (Duckman and Selenow, 1983). Operant modifications can be used to extend the age range over which preferential looking testing may be conducted in normal children. Commencing at around six months reinforced conditioning methods (rewarding the child e.g. by the presentation of a squeaky toy following each correct response) may be successfully applied (Mayer and Dobson, 1980; 1982; Birch et al., 1983). Results of trials with the recently introduced acuity card procedure (which have been reported since the initiation of this pilot study) suggest that standard "restricted" PL methods are applicable throughout the preschool age (McDonald et al., 1985; 1986a; 1986b and Dobson et al., 1986). Whilst indicating that formal reinforced conditioning techniques are unnecessary it is likely that examiner coaxing and encouragement given between test trials acts as a form of conditioning.

2.4.1 Review of preferential looking acuity techniques

a) Extrapolation from group data

A group of infants of a particular age are each subjected to a few trials using a limited number of stimulus spatial frequencies (chosen to bracket their expected acuity range). Each trial is scored as pass or fail according to whether the infant shows preferential fixation of the grating. Acuity may then be defined for a particular age group as equivalent to the highest spatial frequency that 75% or more of the infants preferentially fixate (Fantz et al., 1962). Dobson and Teller (1978) reanalysed Fantz's groups data to find the interpolated 75% point between adjacent spatial frequencies, thus providing a more precise acuity estimate. An obvious limitation of this method is that it does not generate acuity data for individual infants.

b) Method of constant stimuli (M.C.S)

Repeated trials, at each of a number of preselected stimulus levels, are carried out. Typically data is plotted with the observer's percentage of correct responses in judging the stimulus location, as a function of the stimulus parameter being measures, e.g. stripe width of the test grating. Usually, the experimenter aims to select five or six stimulus levels which are equally spaced on this psychometric function and range in detectability from a chance performance (50%) to 100% correct. The reader is referred to Levitt, (1971), for an explanation of the mathematical properties of psychometric functions). Threshold, i.e. visual acuity, is defined as a particular point on the psychometric function, generally 75% correct by the observer. However, Atkinson and co-workers, (1974) set a lower criterion, 70% correct. The particular threshold level may be interpolated from the spatial frequencies tested towards the end of the staircase or calculated from the best fit cumulative normal distribution computed for the complete data (Allen, 1979).

The method has been used in a variety of laboratory studies examining the development of visual acuity (Teller et al., 1974; Leehey et al., 1975; Gwiazda et al., 1978; Dobson et al., 1978) stereoacuity (Held et al., 1980; Birch et al., 1982) colour vision (Teller et al., 1978; Pulos et al., 1980; Powers et al., 1981) critical fusion frequency (Regal, 1981) and contrast sensitivity (Banks and Stephens, 1982) in normal infants. Despite this the method has limited clinical applications. One of the main disadvantages of the method is that many stimuli are presented which are not near the area of interest - the threshold level. Assuming five stimulus levels are used, 100 presentations would be required in a 20 trial FPL procedure. Teller (1979) states that, on average, about 50 trials can be run per hour in their laboratory - indicating that the M.C.S. procedure is too lengthy for clinical assessment of visual function. An additional problem is that the efficiency of the method depends upon the ability of the experimenter to select five or six stimulus levels which will bracket the threshold. Although this is possible when studying goups of normal infants, whose visual acuities can be predicted in advance from established norms, this is not the case in infants having varied ocular conditions.

Use of the method of constant stimuli was reported by Baraldi and co-workers (1981) in a clinical study of full-term and premature infants. Each of five stimuli levels was presented in random order 20 times. No other clinical trials using this procedure have been reported.

i) Diagnostic Stripe Width (D.S.W.)

Dobson and co-workers (1978b) realised the disadvantages of a full psychophysical method of constant stimuli for clinical visual assessment of infants and suggested the possibility of screening infants at a single point on the psychometric function. In a preliminary laboratory study the minimum stripe width, to which infants with normal visual acuity would readily respond at a given age, was estimated from data obtained using a 40 trial F.P.L. procedure. This study indicated that the diagnostic stripe widths (DSWs) fell between 20' and 40' for four week old infants; between 20' and 27' for eight week old infants and between 10' and 20' for twelve and sixteen week old infants. By definition 95% of normal infants of a

particular age would be expected to detect stripes of the diagnostic width, i.e. perform significantly above chance in 20 trials or less with the F.P.L. procedure. Therefore success or failure on the D.S.W. could be used as an indication of whether the infant had normal acuity or not.

In the D.S.W. procedure each infant receives up to 40 trials - up to 20 trials with an acuity grating of large control stripes, each subtending 80' arc visual angle, intermixed with up to 20 trials of a finer acuity grating (of the D.S.W.). Testing continues until the infant either passes or fails on the finer stripe width. A passing score is indicated by correct response on 5 out of 5, 9 out of 10, 13 out of 15 or 15 out of 20 trials.

During initial clinical trials with the technique (Fulton et al., 1978; 1979), 40' stripes were used for infants less than 7 weeks, 27' stripes for 8-11 week infants and 20' stripes for 12-16 week old infants. Results obtained indicate that the test accurately identified babies with binocular vision problems. The procedure usually required less than 10 minutes and over 90% of the infants completed testing. Dobson and co-workers (1980), used the technique in a sample of premature infants. They concluded that visual acuity is more closely correlated with age from conception than age from birth and that visual acuity screening in prematures should be carried out with acuity gratings appropriate for the infants post-term rather than post-natal age.

In a report comparing a variety of methods, the diagnostic stripe test was stated as normally the most rapid and easily performed binocular PL procedure (Manning et al., 1982). The youngest group of a sample of high risk premature infants were tested using this technique (grosser D.S.W.s - 80' and 160' arc visual angle were assumed). Since half of the infants failed or were unable to complete the test at below two months post-term the authors did not advise PL screening of such patients at very early ages.

The D.S.W. technique has not proved very popular possibly due to two disadvantages; it can only be used as a screening method since a visual acuity value is not obtained, and (until recently) D.S.W.s had only been established for infants up to four months of age (Dobson et al., 1978). Appropriate D.S.W.s have now been successfully specified for infants of 6, 12, 24, 30 and 36 months but not for 18 month olds (Dobson et al., 1985).

c) Staircase procedures

Unlike the method of constant stimuli, staircase procedures are extremely efficient requiring the presentation of fewer stimuli than any other psychophysical method. After the first few stimuli, testing is concentrated near the threshold level, so less time is required to make a threshold measurement. Apart from the initial stimulus level, the stimulus to be presented is not predetermined but depends on the previous stimuli and the observers responses to the previous trials.

During a typical 'up-down' staircase procedure a stimulus having a high probability of producing a positive response is initially presented. If a positive response is obtained, the stimulus for the next trial is reduced in level (e.g. stripe width or contrast is decreased) by a predetermined amount - the step size. Each trial producing a positive response is followed by a trial with reduced stimulus level but if a negative response is obtained the stimulus level is increased on the next trial. In this way, during a sequence of trials the stimulus level will alternate between a descending and ascending series.

A recommended procedure is to continue testing until at least 6 or 8 reversals are obtained (Wetherill and Levitt, 1965) or to terminate the staircase after some pre-determined number of trials (Cornsweet, 1962). The threshold intensity can be determined in a variety of ways; the mean value of a given number of stimuli after the series has reached its final level; the stimulus level above which 50% of the responses are positive.

A variety of different staircase procedures have been used in conjunction with forced choice preferential looking.

i) Gwiazda's 'fast' P.L. technique

The procedure involves presenting a series of gratings in blocks of three (Gwiazda et al., 1979; 1980a; 1980b). The blocks are ordered by spatial frequency. Step size between blocks is one half octave (an octave is a doubling or halving of spatial frequency), except for the first three gratings which are arranged in one octave intervals - from 0.38 to 1.5 cycles per degree. The first spatial frequency presented is lower than the expected threshold value. Whenever the observer responds correctly the procedure advances to the next stimulus in the ordered set. If an incorrect response occurs the procedure reverses and the previous stimulus is presented. This procedure of advancing and reversing continues until a spatial frequency is reached at which the infant fixates the homogeneous field more often than the grating. The session is terminated at the first frequency at which there is an appropriate number of positive and negative responses to reject the hypothesis (at the 0.05 level of significance) that the infant was fixating the grating on 70% or more of the trials, e.g two positive and five negative responses at one spatial frequency would be sufficient to terminate the sequence. The 70% threshold value is taken to be the spatial frequency that is one half octave lower than the termination level.

Gwiazda and co-workers (1979) claim that they can obtain an accurate acuity in less than five minutes using their 'fast' procedure. The technique has, however, been criticised in two respects. Efficiency of the method is based on the assumption that near threshold infants prefer to fixate the blank screen rather than the acuity grating, i.e. the psychometric function is non-monotonic, having a negative dip. This finding was reported by Held and co-workers (1979). Other groups have failed to substantiate this type of function (Teller et al., 1982; Banks et al., 1982).

Additionally, Nachmias (1982) points out that this modified staircase method will work correctly only as a descending staircase. In reply to this criticism, the original authors agree that the fast technique only meets the criteria of an adequate psychophysical method if sessions are started at a spatial frequency that the infant preferentially fixates on more than 70% of the trials (Wolfe et al., 1982). They suggest starting all sessions at the lowest spatial frequency available. Banks and co-workers (1982) using computer simulations also concluded that an up-down staircase procedure is more efficient than the Gwiazda fast procedure. Gwiazda's group discussed the implications of non-monotonic psychometric functions in a recent article (Wolfe et al., 1983). Their own data was contrasted with that of other groups (Teller et al., 1982; Banks et al., 1982). Shallower functions, that did now show 'negative dips' were generated by these authors. In summary, they suggested that standard staircase procedures were more appropriate when the underlying psychometric function was known to be monotonic, their own method (Gwiazda et al., 1980a; 1980b) works well for non-monotonic functions and if doubt exists the method of constant stimuli is probably the safest option.

Gwiazda's technique was used in a laboratory study to demonstrate that PL acuity is decreased by induced optical blur (Boltz et al., 1983). As little as one to two dioptres of induced blur was sufficient to decrease the PL acuity in most infants tested. The technique has also been reported in numerous clinical studies monitoring the development of binocular or monocular visual acuity, throughout the first year of life, in samples of infants at-risk for the development of amblyopia. These groups include infants with bilateral congenital cataracts (Jacobson et al., 1981; 1982; Mohindra et al., 1983), unilateral congenital cataracts (Jacobson et al., 1981; 1982; 1983), strabismus (Mohindra et al., 1979; Thomas et al., 1979; Jacobson et al., 1980; 1983), astigmatism (Mohindra et al., 1979), unilateral eyelid closure (Jacobson et al., 1983), uncorrected high refractive errors (Mohindra et al., 1983) and ocular disease (Jacobson et al., 1982). The tests helped to confirm clinical evaluations, assisted in the selection of appropriate treatment and was particularly useful in assessing the results of occlusion therapy. The findings of some of these studies are outlined in section 1.5

ii) Mayer's staircase method

In contrast to Gwiazda's method, Mayer and co-workers (1982) reported use of a staircase method having relatively well defined statistical properties (Rose et al., 1970). The staircase rule used was a slight modification of the transformed up-down rule (Levitt, 1971). The initial suprathreshold spatial frequency presented in the staircase was derived from previously established acuity norms (2 to 3 octaves above

average threshold for age). After two correct responses spatial frequency was increased by an octave. An error on trial N was followed by a suprathreshold grating to maintain the infants attention and then by a one octave decrease in the spatial frequency below that used on trial N. Testing continued until three sequences of an error followed by two correct responses occurred. This resulted in staircases of 20 to 25 trials - excluding the added suprathreshold stimuli.

The geometric mean of all stimulus values presented, apart from the first three and suprathreshold gratings presented after errors, was calculated. This corresponds to the 70.7% correct point on the psychometric function (Levitt, 1971) and is taken to represent the visual acuity. The accuracy of the estimate should be to within 0.8 octave for young infants and 0.4 to 0.6 octave for older children.

The staircase provided estimates which agreed well with thresholds obtained by the lengthier M.S.C. (Allen, 1979; Mayer and Dobson, 1982) in infants and children with normal eyes. Eighty-five percent of 343 patients, having a variety of ocular conditions, successfully completed testing. The youngest infants tested were 11 weeks old but children up to 5 years were included due to an operant modification of the procedure (Mayer, 1980; Mayer and Dobson, 1982). The group report that testing should be completed in less than 20 minutes (10 minutes per eye) with alert co-operative patients.

In general, the results of the study indicated that the PL staircase procedure provided a useful measure of visual acuity in paediatric ocular disorders which could compliment clinical evaluation. In a clinical report assessing PL testing of high-risk prematurely born infants and children Mayer's staircase procedure was found applicable for monocular testing in the oldest group studied (average age 69 weeks post-term), whereas in an intermediate goup (average age 30 weeks post-term) only binocular testing was possible (Manning et al., 1982). The method has been applied to the clinical monitoring of acuity development in infants having various types of amblyopia (Mayer and Fulton, 1985).

iii) Atkinson's staircase method

Atkinson and co-workers (1982) reported successful use of a staircase technique to obtain monocular and binocular visual acuities of normal three and four month old human infants. In the procedure spatial frequencies were ordered in two-thirds octave (1.6x) steps. A 2 cycles/degree grating was presented on the initial five trials (significantly above the expected threshold level). Subsequently, the spatial frequency selected for each block of five trials was determined by a staircase rule (Cornsweet, 1962). Spatial frequency was increased by one step if the observer had made four or five correct choices on the previous block, the frequency was not changed if there were three correct responses and the next lowest spatial frequency was selected for the following block if two or less correct responses were made.

The staircase was terminated when at least 20 trials had been run at each of two adjacent frequencies with the proportion of correct responses bracketing or including the 70% value. Usually between 50 and 90

trials were required to reach this criterion. Acuity was taken as the 70% obtained by interpolation between these two frequencies. The authors suggest interleaving two staircases, e.g 25 trials on the first eye followed by 25 trials on the second eye then reverting to the initial eye and continuing the first staircase. This is to ensure that the infants state is comparable for each measurement.

iv) Manny's staircase procedure

Manny (1983) reports a system comprising a small microcomputer and a 12 inch black and white monitor. The microcomputer generates stimulus patterns and displays them on the monitor using an efficient staircase pocedure similar to that described by Pentland (1980). The computer determines the appropriate stimulus to be presented, records the observers responses, provides trial by trial feedback and terminates the testing after completing the specified number of trials. Hence, only a single operator is required. Although the system produces higher thresholds than those reported by other PL systems it demonstrates the rapid improvement of visual acuity which occurs during the first six months of life.

2.4.2 Factors influencing PL acuity estimates

Several studies have investigated the possible effect of various parameters on infant acuity estimates. The influence of stimulus type or mode of presentation and of optical factors have been the main areas of interest.

At least for a sample of two month infants tested, acuity for stationary stripes is very similar to acuity for phase alternated checks and for stationary checks (Dobson et al., 1978). Contrast sensitivity functions obtained using drifting or static grating stimuli are found to be similar in three month olds (Atkinson et al., 1977b). The results suggest that differential acuity values found between VEP and PL studies are not attributable to differences in the stimuli used (motivation and scoring criteria differences appear to be implicated - Allen et al., 1987). The acuity of two month old infants is relatively unaffected by variation of stimulus luminance above 1 log cd/m^2 (10 cd/m^2), but is reduced by approximately one octave at a luminance of -0.8 log cd/m^2 (Dobson et al., 1983). These findings are equivalent to those in adults. Below three months higher acuity estimates are obtained with larger screen sizes (19° vs 10° diameter) but screen separation (3° vs 10° eccentricity of inner edges from central line) has no significant effect (Atkinson et al., 1983). It is likely that acuity values would drop dramatically beyond 10° eccentricity so large, relatively high luminance displays should be used at relatively small eccentricities to optimize the performance of young infants.

Infants show strong preference for fixating a human face (Fantz, 1961) and it might be argued that such targets would provide more compelling and therefore sensitive stimuli for PL tests than acuity gratings. Atkinson and co-workers (1977c) developed a method which enabled a measure of infant's picture acuity to be derived. Infants (aged 4 to 14 weeks) were simultaneously presented with two pictures of the same face, one of which was defocussed by a set amount. Acuity was also measured conventionally using grating stimuli. There was a high correlation between the two estimates although grating acuity was better than "picture acuity" in most cases. This finding may suggest that face stimuli elicit a less sensitive visual performance than gratings but an alternative explanation could be that even a degraded face provides a highly attractive image. Harris and co-workers (1984) compared acuity findings in one, three and five month olds using schematic face and square-wave grating stimuli. Within each group, thresholds were not significantly different, but psychometric functions obtained with faces were 'gnificantly steeper than those obtained with gratings. This suggests that complex stimuli may yield more precise acuity estimates than gratings. Later workers have continued to use acuity gratings perhaps because these are easier to produce and more easily quantified.

Target distance has little effect on infant acuity over a three dioptre range (Salapatek et al., 1976; Atkinson et al., 1977). Acuity is degraded considerably less in six week old infants than in adults tested under identical conditions of optical defocus (Powers and Dobson, 1982). These finding can be explained by the larger depth of focus of the young infant's eye (Green et al., 1980) and the fact that the infant visual system is only sensitive to low spatial frequencies which are less affected by blur. In contrast one

to two dioptres of induced blur is sufficient to cause a significant decrease in visual acuity in some three to seven month old infants (Boltz et al., 1983). For convenience infant acuity estimates are usually obtained using gratings presented at near distances. Comparable normative data (for infants ≥ six weeks) is generated when using a viewing distance of 20 feet (Cornell and McDonnell, 1986). This finding confirms the validity of converting estimates of acuity obtained at close distances to Snellen notation.

2.4.3 Overview and proposed clinical preferential looking acuity method

a) Overview

The various preferential looking techniques reported in the literature produce broadly similar normative acuity data. The earliest studies used lengthy formal psychophysical procedures (Teller, 1979) which are accurate but not appropriate for clinical application.

Our specific aim was to develop a preferential looking system which could be used clinically by a single operator. Microprocessors are now relatively inexpensive and may be incorporated into such a system (Manny, 1983). Despite this, we preferred to devise a simple, manually operated system requiring little or no computation because this has the potential of wider clinical acceptance. In order to be clinically viable the procedure must depend upon a relatively low number of trials. In view of this, selection of a forced choice preferential looking procedure (Teller, 1979), was thought to be particularly important to reduce subjectivity. The method of constant stimuli is an accurate but inefficient procedure for acuity determination (McKee et al., 1985). With modification it can be adapted for screening purposes, but does not enable clinical determination of acuity level (Dobson et al., 1978b, 1985; Fulton et al, 1978). A number of staircase procedures have been devised in an effort to decrease the test duration whilst allowing acuity estimates to be derived. Some of these depend on relatively large numbers of trials (Atkinson et al., 1982) so that it is difficult to be convinced of their clinical suitability.

b) Proposed method

Stimulus spatial frequencies were selected according to a staircase rule in the present study. It was decided that the total number of trials should be minimized, by presenting only one stimulus of a particular spatial frequency before altering stimulus level. It was hoped that the advantages thus gained in terms of speed would not be offset by too drastic a fall off in the accuracy of acuity estimates - which theoretically decline in proportion to the number of trials. The exact staircase rule adopted is described below.

i) Apparatus

The apparatus was designed so that it could be used in the dark thereby extending the age range over which the test could be applied (Gwiazda et al., 1978). The basis of the equipment was an existing optical projection system previously developed as a stimulator for pattern appearance and reversal VERs. This apparatus was mounted on a trolley and therefore mobile. The stimulus display (Figure 2.15), featured two rectangular screens (each 10 x 20 cm.) which were selected to give the maximum solid angle in the smallest area of central vision. The angular subtense and eccentricity of each screen were sufficient to optimise the performance of young infants (Atkinson et al., 1983). The screens were separated by a narrow (4 cm) strip supporting several coloured fixation lights. Above them was an observation slot; this and the display were covered by a neutral filter which, in conjunction with a surrounding wooden shield, obscured the infant's view of the observer.

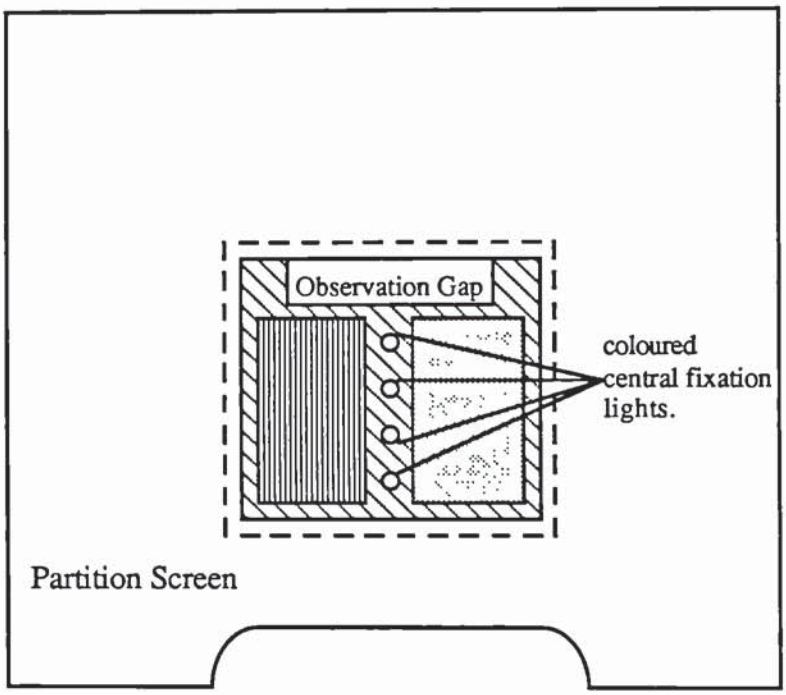


Figure 2.15 Diagram of front screen of the original preferential looking apparatus. The dotted line represents the extent of the tinted perspex sheet placed in front of the display. Each stimulus display measured 10 x 20 cm.

Stimulus slides, each consisting of a high contrast vertically-orientated square wave grating mounted with a 0.3 neutral density filter, were projected from the rear so that one screen contained a grating and the other a blank field of equivalent mean luminance. The spatial frequency of test gratings were arranged in ten approximately $\sqrt{2}$ steps (numerical values are given in Table 2.1). Grating location was arranged at random throughout the slide series.

Table 2.1 Spatial frequencies of original vertical series of preferential looking acuity gratings (one slide per spatial frequency).

Slide Number	Stripe Width (cm.)	Angular subtense (mins of arc) at the eye at different viewing distances 25 cm.	50 cm.
Vertical series			
1	1.73	238	119
2	1.18	164	81
3	0.85	117	58
4	0.59	81	41
5	0.43	59	30
6	0.30	41	21
7	0.21	29	14
8	0.16	21	11
9	0.11	15	8
10	0.07	10	5

ii) Procedure

The following is a description of the testing procedure proposed at the start of the study (later adaptations are described in section 2.6). The infant is held or seated either 25 or 50 centimetres from the stimulus screen. The room is darkened and the central fixation lights flashed to attract the infants attention to the display. A stimulus of low spatial frequency, about two octaves lower than the expected PL acuity for the infant's age (derived from available normative data - Table 2.2) is initially presented. This improves the efficiency of staircase procedures (Nachmias, 1982).

Table 2.2 Normative preferential looking acuity data (minutes of arc) used as a basis for selection of initial test grating. Values were derived from binocular M.A.R. data available in the literature. A one octave range bracketing the mean value was taken as representative of the normal range.

Age (weeks)	Mean acuity (mins of arc)	Normal range (mins of arc)
2	30	40 - 20
4	25	35 - 17.5
8	15	20 - 10
12	10	15 - 7.5
16	9	14 - 7
20	8	12.5 - 6.25
24	5	7.5 - 3.25

The observer, watching through the slit aperture, assesses which of the screens the infant prefers to fixate and checks whether this coincides with the position of the acuity grating. If the observer correctly identifies the location of the grating a finer stimulus is manually selected for the next trial. When an incorrect judgement is made, a coarse grating is subsequently presented. In the subsequent sequence, spatial frequency is altered by one octave (i.e. two steps) after each of the first three trials, then by one half octave after all later trials. A coarse grating can be presented occasionally within this sequence to help maintain the infants interest. The staircase is terminated following five changes in staircase direction (approximately 10 to 15 trials). PL acuity is specified as the spatial frequency of the coarser of the two gratings around which testing fluctuates towards the end of the sequence of trials. The procedure is repeated to obtain measurement of PL acuities from the right eye, left eye and binocularly. Orthoptic patches are used to occlude the unexamined eye.

2.5 Review of objective refractive techniques

It is beyond the scope of this review to discuss objective refraction techniques that are not applicable to the examination of young children. For this reason objective optometers, including automated versions have been excluded from mention. Optometers require accurate alignment of the subject's eye and are consequently impractical for examining the very young. The interested reader will find these instruments reviewed in recent texts (Henson, 1983b; Bennett and Rabbetts, 1984c). Objective refraction techniques based on VEPs have been proposed [reviewed by Regan (1977a)]. Briefly they involve finding the lens power that produces the largest visual evoked potentials, elicited by patterned stimuli of high spatial frequency. Only one author has applied the method in human infants, being rather unenthusiastic about the results (Harter et al., 1977a and 1977b). Since such methods have not proven popular or progressed beyond the initial experimental stages (extensive studies investigating accuracy have not been reported) they will be omitted from this review. A method proposed for the objective refraction of aphakic infants, relying on ultrasonographic axial length measurement coupled with corneal curvature determination by contact lens fitting (Belkin et al., 1973) is of limited accuracy and value and will not be discussed here.

2.5.1 Ophthalmoscopy

Ophthalmoscopy is a method routinely encountered in optometric practice that is principally applied to the examination of the media and posterior segment of the eye. Ophthalmoscopes may also be employed as a simple method for estimation of refractive error. Development of the first workable ophthalmoscope is credited to Helmholtz in 1851 (Emsley, 1953a). Ophthalmoscopic determination of ametropia was practised by ophthalmologists before retinoscopy became generally available.

a) Instrumentation

Ophthalmoscopes fall into two categories, direct and indirect models. The optical principles and clinical use of these instruments are described in various standard texts (e.g Emsley, 1953a; Bennett and Rabbetts, 1984a). The indirect version provides a real, inverted aerial image of the fundus of fairly low magnification (typically about x 2 to 3 but around x 5 in some models). Higher magnifications are possible but would be offset by a reduced field of view. The optical system of the indirect ophthalmoscope forms the basis of most types of objective optometer (Bennett and Rabbetts, 1984c) but the standard instrument is less satisfactory than the direct for refraction purposes (Emsley, 1953a). The direct ophthalmoscope forms a virtual, erect image of the fundus. Magnification approximates x 15 (Emsley, 1953a) but is higher for the myopic than hypermetropic eye. This instrument is more frequently used than the indirect version and has been applied to measurement of refractive error in infants.

The modern direct ophthalmoscope comprises an illumination system composed of tungsten bulb, condenser, lens and reflector (filters and aperture stops may be available). The viewing system has a sight hole and focusing system. The instrument is essentially a device that incorporates a beam splitter which allows a beam of light to enter the subject's eye and then return to the observer's eye by an identical or similar route following reflection at the fundus. Each of a series of positive and negative lenses (usually in 1 dioptre increments) may be placed behind the instrument's sight hole to allow successive focusing of any part of the media or fundus.

b) Theory and sources of error in refraction

An unaccommodated emmetropic or corrected observer will obtain the clearest view of a subject's fundus when the lens in the sight hole is of appropriate power to correct the spherical element of the patient's ametropia. An approximate estimate of the subject's mean refractive error can be obtained but the method is prone to a number of factors which introduce inaccuracies these are discussed by Emsley (1953a). Briefly the difficulties are as follows:

a) Accuracy of measurement requires complete relaxation of both subject and observer's accommodation.

b) The observation should be made at the macula (globe length may be different at the disc). The fundus is lacking in defined detail in this region and pupil constriction may lead to the corneal reflection impairing the field of view.

c) The sight hole lens is considerably more distant from the subject's eye than the spectacle plane (by about 20 mm). This leads to an overestimation of myopia and underestimation of hyperopia.

d) Astigmatism is very difficult to measure - especially the axis direction. This is the case even if able to focus successively on blood vessels travelling in one direction then those at right angles. The shape of the disc or foveal light reflex can be of some assistance in high errors (Borish, 1970b).

Graticuled ophthalmoscopes have been developed to overcome the problem of lack of focusable detail in the fundus (Sisson, 1951). A graticule is mounted on an axial slide between the elements of the condensing system this is moved until a well-defined image is obtained on the fundus. The amount of movement is proportional to change in axial length. The slide is calibrated to give a rough indication of the subject's ametropia (Bennett and Rabbetts, 1984a).

Borish (1970a) cites three studies that compared ophthalmoscopic refraction with subjective results. Conrad (1874) and Cohn (1867) concluded that a higher incidence of myopia was found with the ophthalmoscope. Agnew (1877) considered the results comparable with each method. Goldschmidt (1969) cites a study of infants refraction conducted by Ely (1880) that found a much higher incidence of myopia when the examiner did not atropinise his own eyes.

c) Infant studies

Between 1861 and 1901 at least ten German investigators studied newborn refraction using ophthalmoscopic observation. These studies have been reviewed by Goldschmidt (1969). The most comprehensive study, was conducted by Herrnheiser in 1892. Herrnheiser's data was atypical - the sample (variously quoted as including either 1,920 infants *or* eyes) contained only one myopic individual. This could have been caused by a sampling error, the method of measurement or a poorly calibrated ophthalmoscope (Hirsch, 1963). Despite this, Herrnheiser's data influenced the opinion regarding neonatal refraction for over 50 years.

Few studies have been reported since the turn of the century. Fletcher and Brandon (1955) examined premature infants finding large, variable myopic errors both with and without cycloplegia. The degree of myopia was higher when using an ophthalmoscope than with retinoscopy (this could have been an artifact of the distance of the sight hole lens from the spectacle plane). Some doubt has been raised regarding the method of measurement used in the study (Banks, 1980b). Andree (1964) used a visuscope (a modified ophthalmoscope with a graticule for the measurement of eccentric fixation) to study refraction between birth and five years. Atropine cycloplegia was used and the test figures of the instrument were projected onto the fundus.

2.5.2 Retinoscopy

Retinoscopy developed as an offshoot from ophthalmoscopy. The original technique was introduced by the French ophthalmologist Cuignet in 1873 (Borish, 1970c). Today retinoscopy is the standard method of objective refraction, being routinely employed by the refractionist. The method has been described using several other titles, most frequently "skiascopy". Retinoscopy is essentially a nulling method in which trial lenses are positioned before the subjects eye in order to neutralise movement of a reflex seen within the pupil.

a) Instrumentation

The optical system of a modern retinoscope comprises a light source (bulb), a single lens and a fenestrated or semi-reflecting mirror. The bulb may have a coiled filament thereby producing a circular (spot) image or a linear filament resulting in formation of a streak image. The two varieties of instrument are therefore termed spot or streak retinoscopes. In the streak retinoscope the bulb can be rotated so that the orientation of the line image can be adjusted about the axis of the instrument. Streak retinoscopy enables presence of low astigmatism to be detected and its axis direction determined more easily (Bennett and Rabbetts, 1984b). Spot retinoscopy is often considered easier to learn since at the end point the pupil floods with light whereas successive scanning to ensure neutrality in two meridians is necessary in streak retinoscopy. The results in either case depend upon experience, practice and familiarity with the techniques (Borish, 1970c).

The lens, in normal use, provides a divergent beam of light which therefore forms a virtual image (the immediate source) behind the instrument. In some retinoscopes the vergence of light may be adjusted by movement of the lens (conversion to a convergent beam is possible in streak retinoscopes). Detailed descriptions of the optical principles and clinical use of these instruments are discussed in various standard texts including Emsley (1953b), Borish (1970c), Bennett and Rabbetts (1984b).

b) Principles of retinoscopy

In use the retinoscope is moved so that a patch of light traverses the patients pupil. This results in an illuminated patch moving across the subjects fundus. When a divergent retinoscope is used (the normal case) the patch will move across the retina in the same direction as the mirror rotation. The *apparent* direction of movement of the light reflex within the pupil observed by the examiner, will however depend on whether the patient's retina is focused in front of, behind or at the sighthole plane of the instrument's mirror. The reflex moves in the opposite direction to instrument rotation, termed an "against" movement, if the far point plane of the eye is in front of the sighthole . If the far point is located behind the plane of the sighthole the converse a "with" movement is seen.

The retinoscopist's intention is to place correcting trial lenses in front of the patient's eye modifying the speed of movement of the reflex until a neutral point is reached (when the retina is conjugate with the plane of the sighthole). Plus power is added to neutralise "with" movement and negative power to neutralise "against" movement. The neutral point is also commonly known as the point of reversal; "with" movement being apparent as the retinoscope is moved closer to and "against" as the instrument is moved away from the eye under examination. As neutrality is approached the fundus image becomes brighter, speed of movement is faster and the image size smaller and sharper (Borish, 1970c). When neutrality is reached the reflex appears and disappears instantaneously as the retinoscope beam traverses the pupil. An exact neutral point is very difficult to attain so in practice the central value of a narrowly defined neutral zone may be taken as the appropriate point. In patients with astigmatism neutralisation must be obtained in the two orthogonal meridians coincident with the principal meridians of the eye.

At the point of neutrality the total lenses before the eye include the dioptric value of the working di tance (i.e. the patient to retinoscope distance). This value is algebraically added to the spherical component of the neutrality lens values when computing the distance refractive findings. The working distance used depends on personal factors (arm length being important), often either 50 or 67 cm. are chosen; resulting in correction factors of -2.00 and -1.50 DS respectively. Howland (1978) comments of the formation of anomalous "with" reflexes in myopic subjects which may occur if the pupil is not entirely filled with light from the retinoscope. As the working distance (or pupil size) is reduced the degree of myopia necessary to produce them increases. Due to the working distances commonly applied the clinician is unlikely to encounter problems except with young, uncorrected high myopes.

c) Theoretical sources of error

A number of factors can affect the accuracy of retinoscopy. These are discussed by Bennett and Rabbetts (1984b) and Henson (1983a) but will be mentioned here:

a) A split reflex is sometimes obtained in which the two halves of the reflex appear to move simultaneously in opposite directions. The neutral point may be obtained by bracketing this zone. The effect is due to irregularities in the media which will similarly affect the accuracy of alternative objective techniques.

b) Significant astigmatic errors will be induced if retinoscopy is conducted more than five degrees off-axis.

c) Determination of the sphere component may be affected by localised elevation or depression of the fundus. The cylinder component does not seem to be influenced to the same extent (Hodd, 1951).

d) Higher plus power may be revealed by retinoscopy than the subjective technique since the fogging method encourages relaxation of accommodative tonus. This is particularly true of hyperopes that do not habitually wear prescriptions.

e) Controversy exists regarding the origin of the reflex in retinoscopy. It has been argued that reflection at a surface other than the receptor layer should induce errors in the estimate of refraction (Glickstein and Millodot, 1970). Larger errors would be anticipated in smaller eyes such as those of newborn humans. Later evidence (Nuboer and Van Genderen-Takken, 1978) suggests that the artifact of retinoscopy is explained by chromatic aberration (see g below). Only a small error would be anticipated in humans due to the emmetropy of normal eyes for light of 580 nm.

f) Spherical aberration causes peripheral rays to be refracted to a greater extent than central rays. If the pupil is highly dilated, as when cycloplegia is used the examiner may note "with" movement of the centre and "against" movement of the periphery of the reflex. The centre of the reflex must be neutralised. A pinhole disc having a 3 mm aperture may be of assistance providing it is centred correctly with respect to the visual axis.

g) The retinal reflex is red so a more hyperopic result than the subjective findings may be expected due to chromatic aberration.

h) Working distance errors will obviously affect accuracy of the spherical component of the findings. Use of correct distance is more critical with shorter working distances. An error of about 100mm is required at 67 cm to induce 0.25 D error in refraction.

i) Subjective tests correspond more closely to the patient normal visual environment and may therefore give slightly different results to the retinoscope findings particularly with respect to the spherical findings (Freeman and Hodd, 1954; Copeland 1963).

Despite the numerous sources of potential inaccuracy in the technique experience makes retinoscopy findings a very valuable estimate of refraction. An accuracy of better than 0.50 D on the ametropia in

either principal meridian and within 15° on the astigmatic axis should easily be achieved, given a medium sized pupil and no irregularity of refraction (Bennett and Rabbetts, 1984b).

d) Controlling accommodation

i) Cycloplegic retinoscopy

In static retinoscopic techniques two procedures are usually followed to help relax the patient's accommodation. The patient is instructed to look at a large distant object (such as the green of the duochrome panel of the test chart) and sufficient plus power is added to the eye not under examination to produce an "against" movement. In infants and children too young to comply with these instructions accommodation may be relaxed by instillation of cycloplegic agents (which temporarily paralyse the ciliary muscle). Atropine used to be the preferred drug since it has pronounced cycloplegic effect (O'Connor Davies, 1976a) but shorter acting cycloplegics, having less local and systemic side-effects, are now considered satisfactory for routine use (O'Connor Davies, 1976b). Cyclopentolate hydrochloride, an anti-muscarinic is commonly employed. Since the cycloplegic effects of these drugs are accompanied by mydriasis (pupil dilation due to paralysis of the sphincter pupillae) spherical aberration may be observed and care must be taken to neutralise the centre of the reflex. Use of an artificial pupil may not be practical when examining infants because it is common for the trial lenses to be hand held in these cases.

"Cycloplegic" retinoscopy has been applied in numerous infant refraction studies. The most comprehensive review of the more extensive of the studies involving full term or premature infants of between birth and 12 months has been provided by Banks (1980b). Further large sample (> 50 infants) studies have investigated newborn refraction (Luyckx, 1966; Mathew and Sawney, 1970; Molnar, 1970; Chatterjee and Mukherji, 1979 and Yankov, 1982). Recent reports include studies of refractive findings in prematures (Shapiro et al., 1980; Dobson et al., 1981, Linfield and Davies, 1984) full-term infants and young children (Fulton et al., 1980) and individual eyes of unilateral amblyopes (Nastri et al., 1984) and studies of astigmatism during the first year (Friedburg and Sons, 1983) and in subjects of up to 9.5 years (Dobson et al., 1984). Ingram's continuing investigation of refractive screening for squint and amblyopia in pre-school children relies on "cycloplegic retinoscopy" (Ingram and Walker, 1979; Ingram et al., 1986).

Newborns have poor accommodation and use of a cycloplegic might therefore be expected to have little influence on the refractive findings. Several studies have investigated this effect, concluding that the incidence of myopia was significantly higher when cycloplegia was not used (Gonzalez, 1965; Khukhrina, 1968; Guseva, 1969; Yankov, 1982). These results imply that the newborn's accommodative mechanism is flexible but do not guarantee that the infant is capable of actively focusing to changes in target distance at this stage. Haynes et al. (1965), using a dynamic retinoscopy technique, considered that adult like focusing was not achieved until around four months and that the newborn had a fixed focus of on average 19 cm. This finding may have resulted from use of an inappropriate target (below the acuity

threshold of the younger subjects) as the stimulus. Recent work using various methods has shown that the infant is capable of adjusting accommodation in the first few months (Braddick et al., 1979; Banks, 1980a; Aslin et al. 1982; Brookman, 1983).

ii) Mohindra's near retinoscopy technique

Mohindra (1975, 1977b) introduced an apparently reliable method for determining the refraction of infants and young children without requiring cycloplegia. The technique completely avoids the risk of adverse local and systemic effects of cycloplegics. The method has become known as "near retinoscopy" to distinguish it from dynamic retinoscopy techniques. The latter are mainly intended to allow objective assessment of accommodation (infant studies include Haynes et al., 1965 and Brookman, 1983) and are of limited value in determining refraction (Borish 1970d). In dynamic retinoscopy the subject binocularly fixates a near target specifically selected to stimulate accommodation. "Near retinoscopy" is conducted in a totally darkened room with the patient's non-examined eye occluded and a distance of 50 cm. between patient and a low intensity retinoscope light (the only stimulus). The technique should be less prone to off-axis errors because examination is conducted along the visual axis.

The adult holding the child covers the non-examined eye with one hand and with the other holds a length of string attached to the retinoscope to the temporal orbital margin of the fixating eye to maintain the correct working distance. Each eye's refraction is assessed along its principal meridians in the usual manner, using a lens bar calibrated in 0.50 D steps for ease. The neutrality value is obtained by establishing reversal of the retinal reflex then deducting 0.25 D. The gross sphere - cylinder value for each eye is calculated from the meridional values and an adjustment factor of -1.25 D is algebraically added to the sphere component when computing the final results. This correction factor was arrived at empirically following a study comparing "near retinoscopy" and subjective findings in 27 adult patients which concluded that valid, reliable measurements of both sphere and cylinder were possible with "near retinoscopy" (Mohindra 1977a).

Owens and co-workers (1980) concluded that under the conditions of "near retinoscopy" adults' accommodation remains stable at an average of 0.70 D. This is probably due to a form of inadequate stimulus myopia rather than active accommodation. The tonus correction when incorporated with the dioptric equivalent of the 50 cm working distance (2.00 D) produces a 1.30 D adjustment factor which is close to the value obtained empirically by Mohindra (1977a). Since the appropriate correction factor varies to some extent between individuals this is a source of error in the method.

A further study investigated the accuracy of "near retinoscopy" in 31 children between 5 and 7 years (Mohindra and Molinari, 1979). Two optometrists (one experienced with both methods and the other only with conventional "cycloplegic" retinoscopy), performed "near" and "cycloplegic" retinoscopy on each patient. Cycloplegia was achieved by use of an antimuscarinic [1% tropicamide (O'Connor Davies, 1976b)] and sympathomimetic [10% phenylephrine (O'Connor Davies, 1976c)] combination. In

general a good match was found between the two techniques. Both examiners found good correlations between the techniques on sphere power (+0.83 and +0.75). The experienced examiner also found good correlation for cylinder power (+0.75) but the remaining examiner found very low correlation (+0.27). The orientation of the cylinder showed good correlation between the examiners. Inspection of the cylindrical findings obtained by the experienced examiner revealed 19 children to have more astigmatism by "near" retinoscopy, in 7 the findings were identical and the remaining 5 had more astigmatism by "cycloplegic" retinoscopy. This was not commented upon by the authors but suggests that estimates of astigmatism derived from "near" retinoscopy techniques are prone to be exaggurated and should perhaps be regarded with caution. The usefulness of near retinoscopy as a clinical technique has been questioned on the basis of inter observer differences in range and mean findings and the variability between and within observers (Kohl et al., 1987).

Borghi and Rouse (1985) conducted a similar study using a more commonly accepted cycloplegic agent [1% cyclopentolate (O'Connor Davies, 1976b)] and a sample including patients having greater amounts of hyperopia. Twenty one subjects between two and ten years completed the study. On average the "cycloplegic" retinoscopy revealed +0.50 to +0.75 D more plus than Mohindra's "near retinoscopy" technique. The results of the two methods were comparable when the authors introduced an adjustment factor to correct for the loss of normal accommodative tonus under cycloplegic conditions. O'Connor Davies (1976b) concludes that "in no instance of the use of cyclopentolate (or any other cycloplegic, with the exception of atropine) is a tonus allowance appropriate". A novelty of this study was the use of a cartoon projected at 10 feet as the fixation target during "cycloplegic" retinoscopy. It is doubtful that this would have significantly influenced the accommodative tonus due to the low residual accommodation found with cyclopentolate.

"Near retinoscopy" has been used to investigate aspects of infant refraction (Mohindra and Held, 1981) especially astigmatism (Mohindra et al., 1978, Gwiazda et al., 1984 and 1985).

2.5.3 Photorefraction

Photorefractive techniques assess refractive state by analysing flash photographs showing the distribution of light returning from the subject's retina. The size of the light patches on the film depends both on the defocus of each eye relative to the camera distance and on the pupil diameter. The original method, a form of orthogonal photorefraction,was developed by Howland and Howland (1974). Several methods - all based on modifications of standard single lens reflex cameras - have subsequently been reported in the literature. Video recording with a constant light source instead of a flash is feasible with any of the methods. Although given various titles these can be subdivided into three categories according to the type and arrangement of their optical components. The terms orthogonal, isotropic and eccentric photorefraction, suggested by Braddick and Atkinson (1984), identify distinctive features of each method. The reader is referred to the latter review for detailed discussion of the relative merits of each technique. The optics of photorefractive methods are outlined in Bennett and Rabbetts text (1984d).

a) Orthogonal photorefraction

Orthogonal photorefractors feature a point light source centred in a camera lens and surrounded by four cylindrical lens segments arranged in two pairs with their axes at right angles. The resultant photograph from which measurements are made, shows a star or cross image centred on each eye. The length of the star arms indicate the defocus in two orthogonal directions and increase with increasing defocus relative to the camera working distance. An additional photograph is taken without the cylindrical lens segments to allow measurement of pupil diameter. The photorefractive image is usually processed as a photographic slide (colour film is recommended) and then projected at magnification. Magnification levels of x 25 (Howland et al., 1978; Braddick et al., 1981) and x 29 (Aslin and Dobson, 1983) have been reported. The length of the star arms are measured and corresponding values for the dioptric defocus relative to the camera are determined according to a theoretical curve for the appropriate pupil size. The optics of orthogonal and isotropic photorefraction are discussed by Howland and co-workers (1983).

The method has been applied in several laboratory studies to investigate infant astigmatism (Howland et al., 1978; Atkinson et al., 1980) and accommodation (Braddick et al., 1979) and adult tonic accommodation (Braddick et al., 1981). It has been used in combination with isotropic photorefraction in some infant studies (Aslin and Dobson, 1983; Howland and Sayles, 1984 and 1985). The advantage of combining the techniques in this manner is that orthogonal photorefraction allows more accurate determination of magnitude of astigmatic error providing that the axis is known. Isotropic photorefraction provides information about the sign (myopic or hypermetropic) and axis of astigmatism which cannot be determined directly with the orthogonal or eccentric methods.

b) Isotropic photorefraction

The apparatus required for isotropic photorefraction is identical to that used for orthogonal photorefraction except that there are no cylindrical lens segments surrounding the central fibre optic probe on the camera lens. The blur circle of the fundus reflex does not have a star pattern. This adaptation of the original method was devised by Howland working in collaboration with Atkinson and Braddick's group based in Cambridge (Howland et al., 1979; Atkinson et al., 1981). Three photographs are taken while the subject looks in the direction of the camera. An initial photograph is taken with the lens focused in the plane of the pupil to determine pupil size. Additional photographs are taken with the camera defocused a fixed number of dioptres anteriorly and then an equal amount posteriorly. Values of 0.50 (Aslin and Dobson 1983) and 0.67 dioptres (Atkinson et al., 1984) defocus and camera to subject distances of between 75 and 150 cm. are typical.

The diameter of the blur circles obtained increase with the defocus of the eye relative to the camera distance. A blur ellipse is produced if astigmatism is present - the long and short axes being related to the eye's axes of maximum and minimum optical power. Defocusing the camera in front of and behind

the subject by equal amounts does not have an equal effect on the size of the blur image (Howland et al., 1983). If the subject's eye is myopically focused relative to the camera the blur circle is greater when the camera is focused behind rather than in front of the subject. The converse is true if the subjects eye is hypermetropic relative to the camera. For this reason the sign of the defocus (myopic or hypermetropic) can be determined by comparing the size of blur circle in the photographs taken at the two focal distances.

Isotropic photorefraction has been successfully applied to refractive screening of infants under cyclopentolate cycloplegia (Atkinson and Braddick, 1983a and 1983b). Photorefractive estimates of refractive error correspond well with retinoscopy findings providing that the photorefractor is calibrated against empirical values rather than the theoretical results predicted from computer ray tracing (Atkinson et al., 1984). This discrepancy is probably due to the visible blur image being smaller than the calculated value.

c) Eccentric photorefraction

The essential feature of eccentric photorefractors is the off-centre position of the flash source. The camera is adjusted to provide a clearly focused image of the pupil and red reflex as well as a sharply focused corneal reflex in the same photograph. Kaakinen (1979) introduced this form of photorefraction, referring to the method as photographic static skiascopy due to its analogy to retinoscopy. Refraction - the equivalent spherical power is measured only along the axis parallel to the flash axis. The orientation of the source has therefore to be adjusted to refract along other meridians. Kaakinen (1981b) adapted the original method by adding a second flash source perpendicular to the first so that refraction could be simultaneously conducted in two meridians. Both methods were well suited to the screening of infants and young children and easily taught to nursing sisters (Kaakinen 1981a; Kaakinen et al., 1986).

In orthogonal and isotropic photorefraction for typical values of working distance, lens aperture and pupil size the cone of rays returning to the camera fills the lens plane at about four dioptres of ametropia. Refractive errors beyond this vignetting limit cannot be measured and the technique of eccentric photorefraction is then more useful. In eccentric photorefraction no light will be visible in the pupil until the defocus of the eye exceeds a minimum amount which varies according to the eccentricity of the fla h source. When the threshold refractive error is exceeded a crescent will first become visible in the pupil. The crescent appears on the same side of the pupil as the source for myopic errors and on the opposite side if the error is hypermetropic. Above threshold crescent width increases as refractive error increases. This effect saturates about two dioptres above threshold so the method is most sensitive for refractive errors just greater than the threshold. In one version of the instrument eccentricity of the flash source is adjustable so the operator can vary the threshold refractive error (Braddick and Atkinson, 1984). Kaakinen's original method was unable to detect refractive errors of less than 2 to 3 dioptres. The sensitivity may be improved to enable detection of refractive errors above 0.75 dioptres by using a catadioptric lens and longer working distance (Norcia et al., 1986). In the improved system the essential

modification was a reduction in the angle between the flash source and the entrance pupil of the photorefractor.

The optics of eccentric photorefraction has been the subject of recent reports (Bobier and Braddick 1985; Howland 1985). The authors arrived at equivalent results via somewhat different routes. If cycloplegic agents are not used photorefractions must be conducted in a darkened room as the sensitivity of the method depends on pupil size (Howland 1980). Comparisons of photorefractions conducted both with and without cycloplegia and the findings of routine cycloplegic retinoscopy unanimously demonstrate the improved sensitivity for the detection of refractive errors with use of cycloplegia (Sjostrand et al., 1983; Day and Norcia, 1986; Kaakinen and Ranta-Kemppainen, 1986). Under-estimation of spherical hypermetropia must be accepted if cycloplegia is not used.

The corneal reflexes are clearly visible in the photograph obtained so the method may also be used to detect strabismus. Examination of the positions of these reflexes (Hirschberg test - see section 3.3.2) reliably identified individuals with strabismus of at least two degrees (Abrahamsson et al., 1986) or at least 5 prism dioptres (Griffin et al., 1986). These findings are in contrast to an earlier study which found the method less reliable when examining mentally retarded children and suggested use of photographic and conventional orthoptic screening in combination (Philipsen and Hobolth, 1985).

2.5.4 Overview and proposed method to be adopted in normative study

Although providing a simple technique ophthalmoscopy can only give an approximate indication of the refraction and is limited in its capacity to measure astigmatism. Borish (1970b) concluded that the method "is only a very approximate one for determining or even estimating the refractive state". Three distinct photorefractive techniques have been developed (orthogonal,isotropic and eccentric). Each has various advantages and limitations so that photorefraction is most effective if a combination of methods are used (Braddick and Atkinson, 1984). Urness and Roth (1986) claim to have developed a more versatile photorefractor, but details are not yet available. At the time the study was commenced no photorefractor was commercially available (Clement Clarke International in co-operation with Atkinson and Braddicks' group began marketing a video-based system group costing around £8,000 in 1987 - The Optician, September 25, 1987). Anyone wanting to construct their own instrument would need to conduct laborious initial studies using individuals having a range of refractive errors to empirically calibrate the photorefractor before use.

Isotropic photorefraction is the only method allowing direct assessment of the axis of astigmatism, but magnitude of this error is estimated more accurately using orthogonal photorefraction providing that its axis is known in advance. Isotropic and eccentric photorefraction enable the sign of the refractive error to be determined, the latter requiring only a single photograph rather than the three necessary in the isotropic technique. Eccentric photorefraction allows measurement of refractive errors beyond the

vignetting limit imposed by the finite size of the camera aperture in the orthogonal and isotropic methods (Bobier and Braddick 1985). This advantage is partly offset by the instrument having a corresponding "dead zone" in which refractive error cannot be measured. The location of this zone may be altered by adjusting the eccentricity of the source but it cannot be eliminated. The instrument enables measurement only to about two dioptres beyond its threshold.

Photorefractive techniques cannot compete with established methods of refraction such as retinoscopy. Even when used in combination they cannot provide measurement of absolute refractive error across the entire spectrum. In the context of the present study measurement limits provided by the methods would not encompass the range of refractions encountered in a newborn population. Despite these limitations isotropic photorefraction has proved valuable as a screening tool which could be applied by unskilled personnel (Atkinson and Braddick, 1983a and 1983b). A permanent record is obtained which may be helpful in identifying strabismus, anisometropia and astigmatism are recorded instaneously. It seems possible that the methods may in the future assist the retinoscopist in the examination of very young children particularly if economical electronic recording techniques are available to allow instant retrieval of photorefractive images (Braddick and Atkinson, 1984).

The conclusion from this review of available techniques is that retinoscopy offers the most appropriate method for study of infant's refractive error. In skilled hands it is more accurate than ophthalmoscopy and does not have the limitations of photorefraction. A streak (rather than spot) retinoscope was used in the normative study due to personal preference. The author has no experience of Mohindra's "near retinoscopy" technique (Mohindra, 1977b) which does not require use of cycloplegia. Review of the literature suggests that it is not widely used. Retinoscopy was therefore conducted under cycloplegia. Cyclopentolate hydrochloride (1%) was considered to be an adequate and suitable cycloplegic agent for the normative study (O'Connor Davies, 1976b). The associated mydriasis enabled ophthalmoscopic examinations to be conducted with greater ease.

2.6 Initial pilot study

2.6.1 Subject sources

Twenty three infants (16 male, 7 female) participated in the pilot study, which involved a total of 57 test sessions. Each infant attended on up to four occasions. The median post-term age at first attendance was 25.7 weeks (total age range examined 6.4 to 84.0 weeks). Twenty infants were clinical patients referred to the departmental clinics by a paediatric ophthalmologist or other medical practitioner for immediate assessment of their visual function. These infants were known to have various ocular and or neurological abnormalities. The most common clinical history was of bilateral aphakia, corrected by soft contact lenses, following removal of either congenital or developmental cataracts. The individual diagnoses are listed in Appendix 2C (Table A2.2). Sixteen infants had bilateral problems; two had unilateral problems and two asymmetric. Although most of the sample were resident in the West Midlands many had lengthy journeys to attend appointments. The three normal subjects were the children of University Staff who volunteered to have their infants included in the study.

2.6.2 Protocol

Slight modifications were made to the testing procedures during the period of the initial study. In general these adaptations were unavoidable (due to the experimental nature of the work) and restricted to refinements which allowed the tests to be more successfully applied. Throughout the study preferential looking testing was performed first to avoid undue disturbance of the subject by the application of electrodes. In some cases preferential looking was not performed e.g. if the patient was above 12 months or failed to respond to the test at an earlier visit. Initial experimentation in adult subjects failed to reveal a VEP acuity method which was both accurate and clinically suitable (see section 2.2.2). The direct location of threshold method was adopted as this should not overestimate an infants acuity. Transient VEPs were recorded. Flash VEPs were also recorded since these are more easily obtained. The proposed OKN method was eliminated from the study due to technical difficulties. A summary of the tests conducted during the 57 individual sessions is given in Figure 2.16. Preferential looking was attempted on 45; flash VEP recording on 35 and pattern VEP recording on 31 occasions. Figure 2.17 gives details of the numbers of infants participating in various electrophysiological tests. Three infants were not tested with preferential looking and two others were tested only with preferential looking.

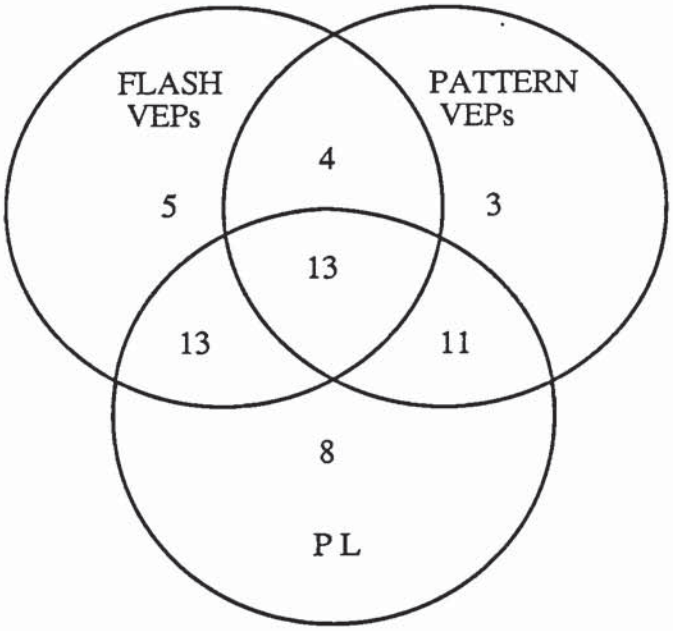


Figure 2.16 Summary of tests conducted on 57 sessions (sample comprised 23 infants including three normals).

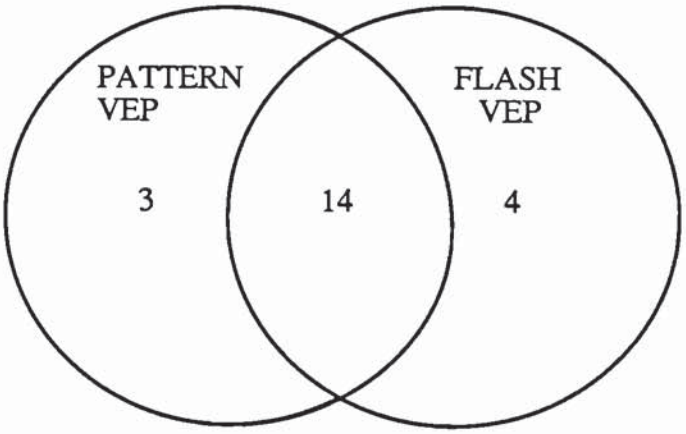


Figure 2.17 Numbers of infants participating in various electrophysiological tests. Two infants in the study participated in preferential looking only.

a) Preferential looking

All preferential looking tests were performed with room lights out. Room lights were extinguished in adjacent rooms to avoid light escape around door frames which were not completely "light tight". The original apparatus needed to be boxed in to eliminate stray light from the projector, which otherwise created distracting shadows. This modification also ensured that the observer could not view the projected gratings directly. The procedure described in section 2.4.3 was followed with the addition of improvements adopted during the duration of the study (outlined below).

Only one series of vertical gratings featuring one slide of each spatial frequency was available initially (Table 2.1). After completion of a few trials the examiner could not avoid remembering the location of previously tested gratings. This bias was eliminated by the introduction of a second grating of each spatial frequency (located on the opposite screen). A similar series of horizontally orientated gratings was produced at the same time. This allowed a total of six distinct acuity determinations to be attempted during each test session. A few test pattern slides were incorporated into these new slide series. Each featured a coarse multicoloured pattern paired with a blank field. These were used when there was doubt about an infant's general responsiveness to the test. During the staircase sequence coarse gratings or test patterns were occasionally presented to maintain interest in the test. As infants' looking behaviour tended to deteriorate near threshold, it was found that more useful information could be gained by showing two slides of a particular spatial frequency before obtaining feedback of grating location. The spatial frequencies of the new slide series are given in Table 2.3. The coarsest two slides from the original series were retained to allow testing of infants that failed to respond to finer gratings.

Table 2.3 Spatial frequencies of the horizontal and vertical series of preferential looking acuity gratings used later in the study (two slides per spatial frequency).

Slide Number	Stripe Width (cm.)	Angular subtense (mins of arc) at the eye at different viewing distances	
		25 cm.	50 cm.
1	0.96	132	66
2	0.69	95	47
3	0.49	67	34
4	0.36	48	24
5	0.24	34	17
6	0.18	24	12
7	0.13	17	8
8	0.09	12	6

b) Visual evoked potentials

VEPs elicited by diffuse flashes of light and high contrast checkerboard patterns reversing in contrast at a rate of one cycle per second were recorded where practicable. In each case an attempt was normally made to obtain responses recorded during monocular viewing (from each eye) and binocularly. All testing was conducted with room lights extinguished. Flash stimulation was delivered by a Grass PS22 photostimulator at intensity 2 which was hand held to allow compensation for the infant's head movements. The pattern stimulus display was provided by an optical projection system with a circular field subtending 30° diameter at 45 centimetres viewing distance. This was preferred to television systems which have a number of disadvantages when placed near the subject (direct electrostatic interference, flicker driving of the EEG, latency differences at the top and bottom of the screen, resolution limit imposed by the 625 line raster). A range of check sizes in approximately $\sqrt{2}$ steps from 2° to 11' was available (2°, 1° 20', 56', 43', 27', 19', 11') .

If the infant was sufficiently alert following application of electrodes an attempt was made to record pattern VEPs. Flash VEPs only were recorded (through closed lids) in a number of infants that fell asleep before pattern responses could be recorded. Apart from these cases efforts were made to record flash VEPs whilst the infant was alert. A large check size (minimum 56') was selected for use on the initial trial. For each pattern size testing was continued until certain that the responses obtained were repeatable. Testing was then continued using higher spatial frequencies, until consistent responses could no longer be obtained. Testing was terminated prematurely if the patient fell asleep or otherwise failed to co-operate sufficiently.

For practical reasons it was impossible to maintain continuity of averaging equipment during the study. This was due to the impracticality of conducting all examinations in the same departmental clinic and the replacement of averaging equipment during the period of the study. The four averagers used during the study were:- the Hewlett Packard PDP8; Research Machines Z80T microprocessor system; Nicolet Pathfinder II and the Cadwell 5200A. The Hewlett Packard PDP8 and Research Machines Z80T microprocessor system (both 6 channel) which were used most frequently were used in conjunction with a Nihon-Kohden EEG machine. The Cadwell (5200 A) is a portable system restricted to two channel recording. All other averagers were capable of processing at least six channels of data. The input signal w .s filtered using 1 to 30 Hz bandpass filters. A minimum of 50 samples of data were averaged. Averaging was extended on occasions to enhance the signal. Where possible the six channel hemianopic phase reversal electrode montage of Harding (1977), in which VEPs are recorded over each occiput, was used in conjunction with simultaneous monitoring of the background EEG activity. Electrode positions relevant to the examination were marked on the scalp using a non-toxic chinagraph pencil. Small areas of the scalp around these points were gently abraded to reduce skin resistance and silver-silver chloride disc electrodes, filled with electrode jelly were then attached using either non-allergic tape for the youngest babies or collodion for older infants. Artifact rejection and trigger interrupt facilities were available enabling elimination of abnormally high amplitude signals (e.g. due to movement artifact) and

prevention of averaging when the infant was not looking at the stimulus.

2.6.3 Preferential looking findings

a) Success rate

The numbers of right eye, left eye and binocular acuity estimates obtained during each of the 45 individual preferential looking sessions (20 infants) are listed in Table 2.4. A possible maximum of six acuities could be determined. A summary of the number (and percentage) of sessions in which particular numbers of acuity tests were completed is given in Table 2.5. This data is illustrated graphically in Figure 2.18 along with similar data for subgroups that additionally participated in pattern and flash VEP tests. Findings were very similar for the total sample and the subgroups suggesting that no bias was made in selecting infants for electrophysiological tests. At least one acuity estimate was obtained in about 95% of sessions, all six measurements being achieved in 13% of sessions. The numbers of sessions in which more than three acuities were determined must represent an underestimation because infants at the start of the study were only tested with vertical gratings.

The success rate data was re-evaluated to determine the numbers of sessions in which right eye, left eye and binocular tests were completed. In this analysis an infant completing tests using both grating orientations for a particular condition would be credited with one test. It was therefore possible for each individual to complete up to three tests. A summary of the number (and percentage) of sessions in which particular numbers of specific acuity tests were completed is given in Table 2.6. The data is illustrated graphically in Figure 2.19 along with similar data for the VEP subgroups. Over half of the infants tested completed at least two distinct tests and about one fifth completed all three tests.

b) General observations

The elimination of distractions from the test room was found to be essential. Poor co-operation with the test was obtained prior to "boxing in" the projection system to reduce stray light. This was particularly the case with older infants and the normal infants. Repainting the originally white partition screen a matt black helped to attract attention to the display screen.

At the start of the study attempts were made to apply a strict staircase method. This did not prove to be very useful. Fluctuations in the infants level of co-operation and interest during the test tended to produce erratic staircases even when fixations on initial trials had been convincing. More success was obtained by initially using a staircase procedure to provide an approximate estimate of the threshold then switching to a method of constant stimuli (MCS) to allow increased accuracy.

Table 2.4 List of numbers of acuity estimates obtained on each preferential looking test session during the pilot study.

PATIENT	GROUP	AGE (weeks)	PL DATA NO. OF VAs RIGHT	LEFT	BINOC	OTHER TESTS
M A	U(R)	26	2	0	2	F
M Ay.	B	36	0	0	1	F
		41	0	0	1	-
		47	1	1	1	-
		60	2	2	0	F,P
K B	B	26	0	0	0	F
P B	A(R>L)	33	2	0	2	F
		53	0	0	2	P
C C	B	36	0	0	1	-
		41	0	0	1	-
A F	B	12	2	2	2	F
		19	2	1	2	F,P
		30	2	2	2	P
		41	0	0	2	F,P
C F	B	45	0	0	2	F,P
LG	B	43	0	0	1	P
S H	A(L>R)	11	0	1	1	-
		12	0	1	1	P
		25	1	1	0	F
		37	2	1	0	F
M I	B	6	0	0	1	F,P
		11	0	0	1	F,P
		21	0	0	1	F,P
T K	U(R)	21	2	0	2	F
		24	2	0	2	F
		42	0	0	2	F,P
B L	N	13	0	0	1	-
		30	0	0	0	P
J M	B	10	2	2	2	F
		35	2	0	2	F,P
C R	N	12	2	2	2	P
		22	2	2	2	P
J R	B	7	1	0	2	F
		18	0	0	2	F,P
M S	B	32	2	2	2	F
J U	B	40	0	0	1	-
P W	B	23	1	0	2	F,P
		30	0	1	2	-
		31	1	2	2	P
T W	B	46	0	1	2	F
		68	0	0	2	F,P
		84	1	1	1	F,P
T Wi.	N	14	0	2	2	P
		19	2	0	2	P
		28	0	0	2	P

KEY

GROUPS (Deprivation)

- A Asymmetric
- B Bilateral
- N Normals
- U Unilateral

TESTS

- F = Flash VEP
- P = Pattern VEP

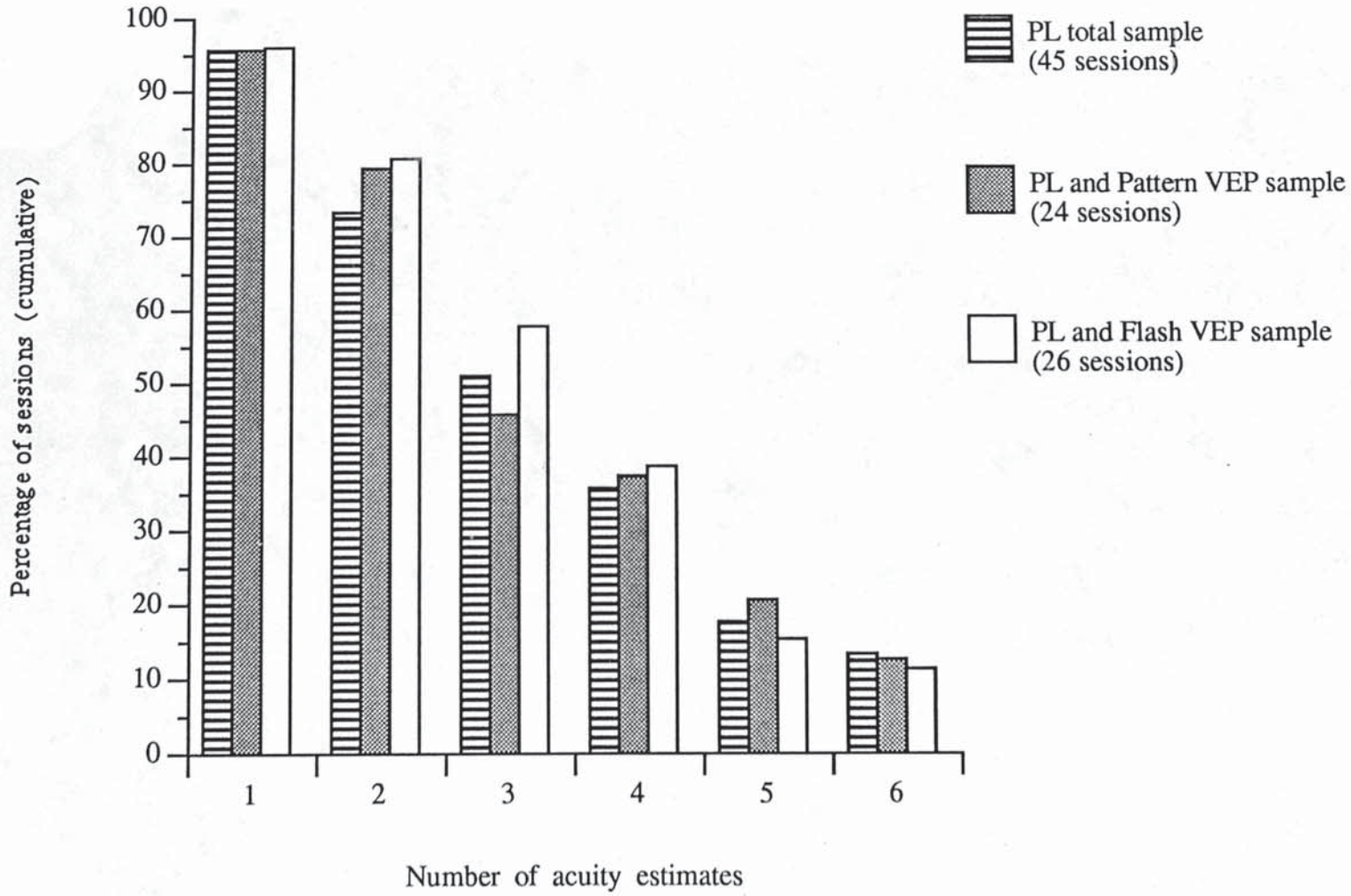


Figure 2.18 Overall success rates for preferential looking testing of the full clinical sample and of subgroups additionally participating in pattern and flash VEP tests. Findings were very similar for each group suggesting that there was no bias in selecting infants for electrophysiological tests. At least one acuity measurement was made in about 95 percent of sessions, all six estimates were obtained in about 13 percent of sessions. Numerical values are provided in Tables 2.5, A2.3 and A2.5.

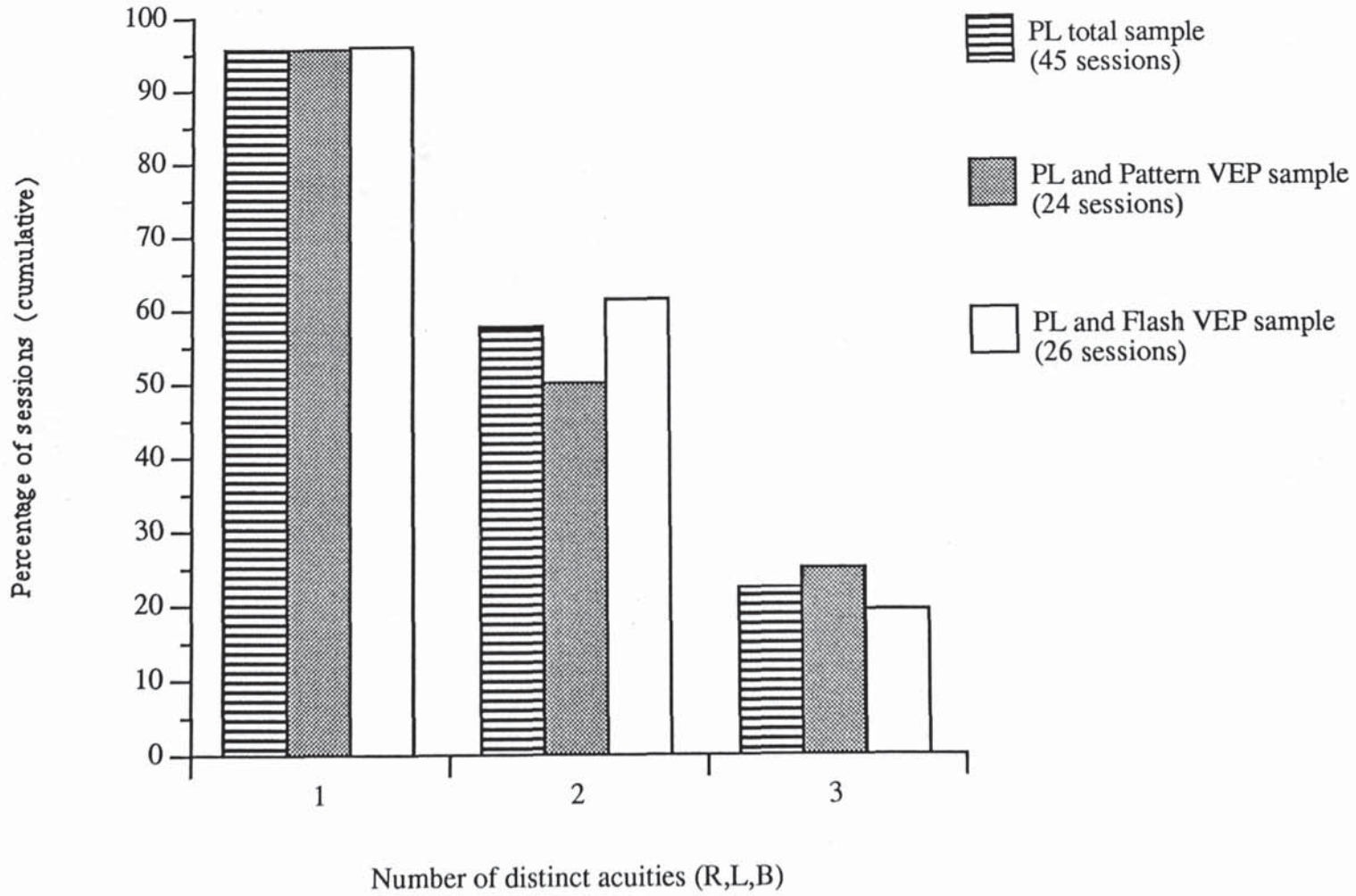


Figure 2.19 Percentages of sessions in which specific (right eye and/or left eye) and/or binocular preferential looking tests were completed. Infants completing tests using both vertical and horizontal grating orientations for a particular condition have only been credited with one test. Data is for the full clinical sample and the pattern and flash VEP subgroups. Slightly more than half of the sample completed two or more tests and about one fifth completed three tests.

The use of a forced choice testing procedure appeared to be very important in the examination of clinical patients whose looking behaviour could be difficult to interpret. Difficulty was experienced when examining patients having nystagmus (i.e. pendular horizontal nystagmus). Head position appeared to provide more useful cues than eye position and often several trials were required to correctly interpret the infants looking behaviour. It was thought that some of the difficulty could be alleviated by increasing the screen separation.

Table 2.5 Incidence of preferential looking test sessions in which particular numbers of acuity estimates were obtained. Values are based on 45 tests sessions.

Total number of acuity estimates	Numbers of sessions	Cumulative n	Cumulative %
0	2	45	100.0
1	10	43	95.6
2	10	33	73.3
3	7	23	51.1
4	8	16	35.6
5	2	8	17.8
6	6	6	13.3

Table 2.6 Incidence of successful (binocular, right eye and left eye) preferential looking test sessions (total number of PL sessions = 45).

Total number of successful tests (R.E./L.E./Binoc)	n	Cumulative n	Cumulative %
0	2	45	100.0
1	17	43	95.6
2	16	26	57.8
3	10	10	22.2

c) Acuity data

Binocular acuity data of binocularly deprived infants in the sample is plotted versus post-term age in Figure 2.20. Monocular acuity data of the clinical patients within the sample is plotted in Figure 2.21. In both figures acuity data has been converted to cycles per degree equivalent and the axes have been selected so that the values can be compared with normative data subsequently collected (and shown in Figure 7.1). Most of the data was lower than the normal ranges specified in Table 2.2 (values expressed in minutes of arc).

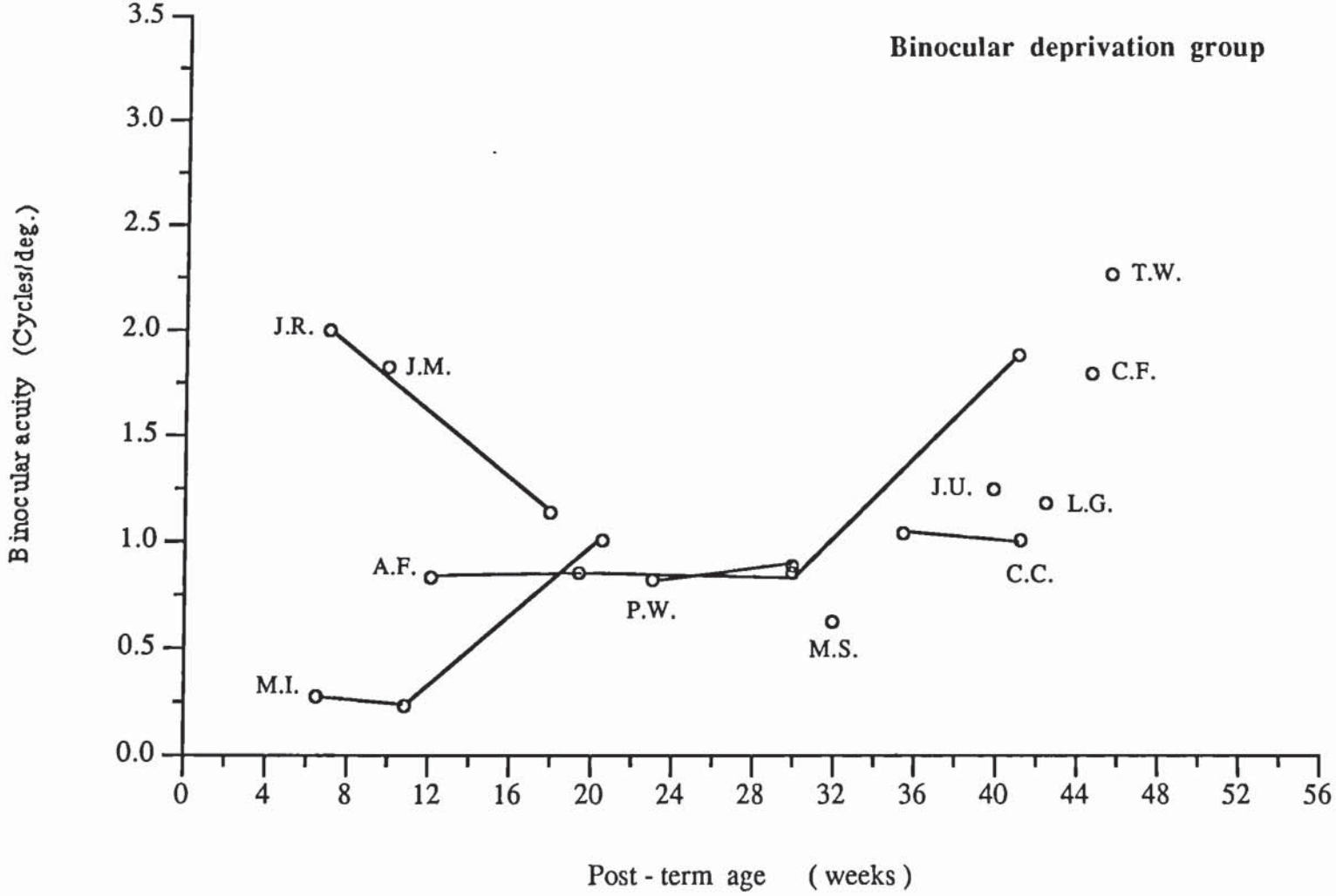


Figure 2.20 Binocular acuity findings of binocularly deprived infants participating in the pilot study. Data is either for horizontal or vertical gratings or the mean of the two estimates where both values were determined. Axes were selected to be comparable with normative data in Figure 7.1.

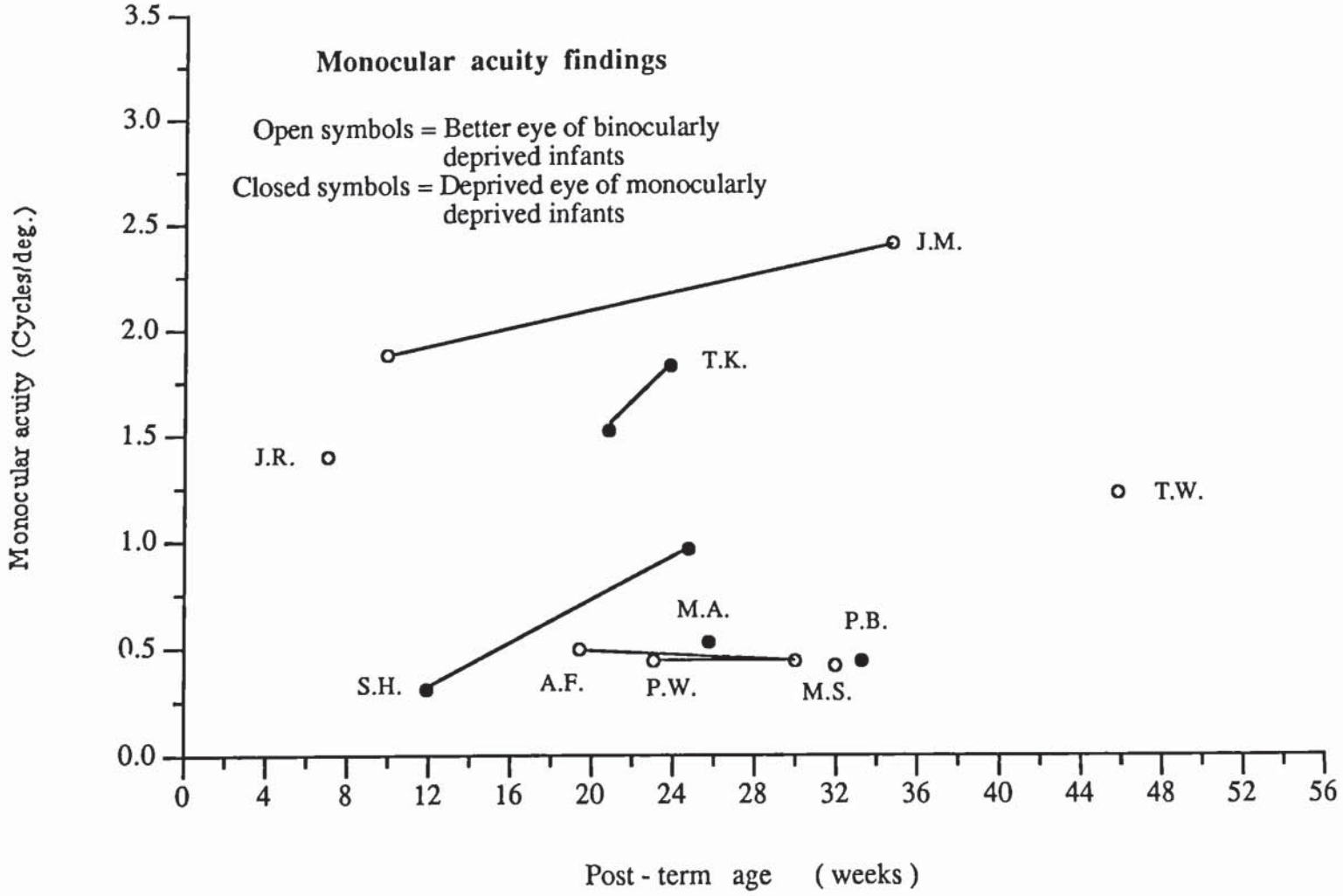


Figure 2.21 Monocular acuity findings of clinical patients participating in the pilot study. Data is either for horizontal or vertical gratings or the mean of the two estimates where both values were determined. Axes were selected to be comparable with normative data in Figure 7.1.

2.6.4 Visual evoked potential findings

a) Success rate

Pattern and flash VEPs were graded for repeatability and waveform quality. A summary of findings for individual patients is given in Tables 2.7 and 2.8. Examples of traces of two infants are included in Apppendix 8, publication 1. Sessions were classified as successful if VEPs fell into any of the categories included in Table 2.9. The first letter refers to the grading of waveform clarity and the second letter signifies the repeatability of the response. Pattern VEP sessions have been considered as successful if resulting in recording of *any* acceptable responses - there was no requirement to complete tests with different check sizes. At the start of the study the expectation was that this would normally be achieved.

A summary of the numbers of pattern VEP test sessions resulting in the recording of acceptable responses is given in Table 2.9. The number (and percentage) of sessions in which acceptable right eye, left eye and binocular pattern VEP responses were obtained is provided in Table 2.10. Equivalent data for flash VEP recording is available in Tables 2.11 and 2.12. A summary of the comparative success in recording of pattern and flash responses is given in Figure 2.22. Approximately a quarter of pattern and nearly 80% of flash VEP sessions resulted in the recording of at least one acceptable response.

b) General observations

Preparation time was excessive and often distressing for infant (and parent). This resulted in infants frequently falling asleep soon after the start of recording. In some cases recording of repeatable pattern VEPs was found to be impossible even though the EEG appeared satisfactory and the infant was very co-operative, quiet and eagerly watching the pattern reversal.

Table 2.7 List of findings on pattern VEP recording sessions during the pilot study.
Traces were scored for waveform quality and repeatability
(Infant state reported where particular observation was made).

PATIENT	GROUP	AGE (weeks)	NO. OF TRIALS		PATTERN VEP	WAVEFORM VEP DATA		VEP REPEATABILITY		INFANT STATE	OTHER TESTS
			RIGHT	LEFT	BINOC	RIGHT	LEFT	BINOC	RIGHT	LEFT	BINOC		
MAy	B	60	0	0	2	-	-	C	-	-	C	Cry++	F,PL
AB	B	71	3	3	0	C	C	-	C	C	-		F
KB	B	40	2	0	0	C	-	-	C	-	-		F
		72	0	0	3	-	-	B	-	-	C	Cry	-
		75	0	0	4	-	-	B	-	-	C	Cry	-
PB	A(R>L)	53	0	0	2	-	-	B	-	-	C	Quiet	PL
AF	B	19	0	0	5	-	-	C	-	-	C		F,PL
		30	2	2	3	C	C	C	C	C	C		PL
		41	0	0	4	-	-	B	-	-	C		F,PL
CF	B	45	1	2	4	C	C	B	-	C	B		F,PL
LG	B	43	0	0	3	-	-	C	-	-	C		PL
SH	A(L>R)	12	0	0	2	-	-	B	-	-	C		PL
MI	B	6	0	0	1	-	-	B	-	-	-		F,PL
		11	0	0	5	-	-	A	-	-	A		F,PL
		21	0	0	5	-	-	A	-	-	A		F,PL
TK	U(R)	42	0	0	3	-	-	C	-	-	C		F,PL
BL	N	30	0	0	1	-	-	B	-	-	-		PL
JM	B	25	0	0	4	-	-	B*	-	-	C		F
		35	4	1	0	B	B	-	C	-	-		F,PL
CR	N	12	0	0	3	-	-	C	-	-	N/A		PL
		14	1	1	3	A*	A*	A*	-	-	B		F
		22	0	0	7	-	-	B	-	-	B		PL
		30	0	0	3	-	-	C	-	-	C		-
JR	B	18	3	0	1	C	-	C	C	-	-		F,PL
PW	B	23	7	0	0	C	-	-	C	-	-	Variable	F,PL
		31	0	2	0	-	B	-	-	C	-	Drowsy	PL
TW	B	68	0	0	5	-	-	C	-	-	C		F,PL
		84	0	0	2	-	-	B	-	-	C		F,PL
TWi.	N	14	0	0	4	-	-	A	-	-	A	Variable	PL
		19	0	0	3	-	-	B	-	-	B		PL
		28	0	0	4	-	-	B*	-	-	B		PL

KEY

GROUPS (Deprivation)
- A Asymmetric
- B Bilateral
- N Normals
- U Unilateral

GRADES (Waveform clarity)
- A Clear components
- B Vague comps.
- C Unrecognisable c'n
- * Hemisph. asymm.

GRADES (Repeatability)
- A Consistent
- B Some variability
- C Inconsistent
- N/A Not applicable

TESTS
- F Flash VEP
- PL Preferential looking

Table 2.8 List of findings on flash VEP recording sessions during the pilot study.
Traces were scored for waveform quality and repeatability
(Infant state reported where particular observation was made).

PATIENT	GROUP	AGE (weeks)	NO. OF TRIALS		FLASH VEP		VEP WAVEFORM		DATA	VEP	REPEATABILITY		INFANT STATE	OTHER TESTS
			RIGHT	LEFT	BINOC	RIGHT	LEFT	BINOC		RIGHT	LEFT	BINOC		
M A	U(R)	26	3	2	4	B	B	B		B	B	B		PL
M Ay.	B	36	2	1	4	A	A	A		B	-	A	Cy ++	PL
		60	0	0	2	-	-	A		-	-	A		P,PL
A B	B	71	2	2	2	A	A(*)	A(*)		A	A	A		P
K B	B	26	4	4	4	A*#	A*#	A*#		A#	A#	A#	Variable	PL
		40	2	2	3	A	B*	B		A	B	B		P
P B	A(R>L)	33	2	3	2	A*	A*	A*		A	A	A		PL
A F	B	12	3	3	5	A	A	A		A	A	A	Variable	PL
		19	1	0	2	C	-	B*		-	-	B	Variable	P,PL
		41	0	0	2	-	-	A		-	-	A		P,PL
C F	B	41	2	2	1	B*	B*	A*		A	B	-		-
		45	1	1	2	B*	C*	B*		-	-	C		P,PL
		66	4	2	3	B(*)	C(*)	B(*)		A	A	A		-
S H	A(L>R)	25	2	2	3	A(*)	A(*)	A(*)		A	A	A		PL
		37	2	5	1	B	B	A		A	A	-		PL
M I	B	6	0	0	2	-	-	A		-	-	A	Asleep	P,PL
		11	0	0	1	-	-	B		-	-	-		P,PL
		21	0	0	2	-	-	B		-	-	B		P,PL
T K	U(R)	21	2	3	2	A*	A*	A*		A	A	A		PL
		24	2	1	2	A*	A*	A*		C	-	A		PL
		42	2	2	2	A	A	A		A	A	A		P,PL
J M	B	10	3	3	2	B	A	A		B	B	A	Asleep	PL
		25	2	2	2	A*	A*	A		A	A	A	Cry+	P
		35	2	2	1	A	A	A		B	A	-		P,PL
C O	B	12	4	4	5	B	B	B		C	C	C		-
		32	2	2	3	C	C	B		C	C	C	Drowsy	-
D P	B	34	3	2	2	B	A	B		A	A	A		-
C R	N	14	0	2	1	-	B	B		-	C	-	Asleep	P
J R	B	7	1	2	2	C	B	C		-	C	C	Asleep	PL
		18	0	0	2	-	-	B		-	-	A		P,PL
M S	B	32	1	1	2	C	C	C		-	-	C		PL
P W	B	23	3	2	2	B	B	B		B	B	A		P,PL
T W	B	46	2	3	5	C	C	B		N/A	N/A	B		PL
		68	0	0	3	-	-	C		-	-	C		P,PL
		84	0	0	3	-	-	D		-	-	B		P,PL

KEY

GROUPS (Deprivation)
- A Asymmetric
- B Bilateral
- N Normals
- U Unilateral

GRADES (Waveform clarity)
- A Clear components
- B Vague components
- C Unrecognisable o's
- * Hemisph. asymm.
- (*) Slight asymmetry
- # State affected

GRADES (Repeatability)
- A Consistent
- B Some variability
- C Inconsistent
- N/A Not applicable
- # State affected

TESTS
- P = Pattern VEP
- PL = Preferential looking

Table 2.9 Summary of numbers of pattern VEP test sessions resulting in the recording of acceptable responses.

Acceptable VEP grades:	Numbers of test sessions Binocular	Right Eye	Left Eye
A x A	3	0	0
A x B	1	0	0
A x -	0	1	1
B x A	0	0	0
B x B	4	0	0
Total (& %)	8 (25.8)	1 (3.2)	1 (3.2)

Table 2.10 Incidence of successful (binocular, right eye and left eye) pattern VEP test sessions (total number of pattern VEP sessions = 31).

Total number of successful tests (R.E./L.E./Binoc)	n	Cumulative n	Cumulative %
0	24	31	100.0
1	7	8	25.8
2	0	1	3.2
3	1	1	3.2

Table 2.11 Summary of numbers of flash VEP test sessions resulting in the recording of acceptable responses.

Acceptable VEP grades:	Numbers of test sessions Binocular	Right Eye	Left Eye
A x A	14	9	10
A x B	0	2	1
A x -	3	0	2
B x A	4	4	1
B x B	6	3	4
Total (& %)	27 (77.1)	18 (51.4)	18 (51.4)

Table 2.12 Incidence of successful (binocular, right eye and left eye) flash VEP test sessions (total number of flash VEP sessions = 35).

Total number of successful tests (R.E./L.E./Binoc)	n	Cumulative n	Cumulative %
0	8	35	100.0
1	9	27	77.1
2	2	18	51.4
3	16	16	45.7

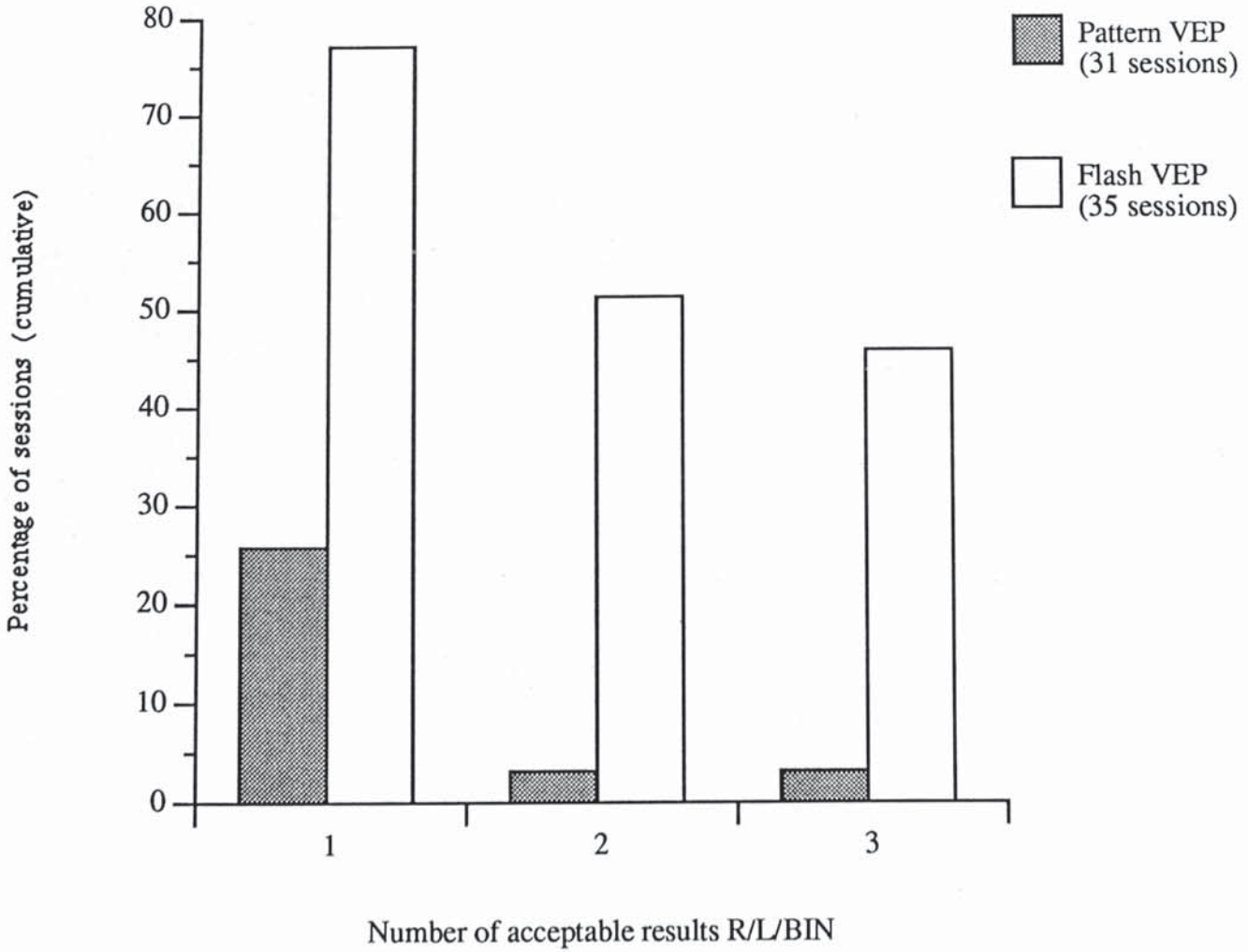


Figure 2.22 Percentages of pattern and flash VEP sessions in which specific (right eye and/or left eye) and/or binocular *acceptable* responses were obtained. About a quarter of pattern and almost 80 percent of flash VEP test sessions resulted in at least one acceptable response being recorded. Numerical values are provided in Tables 2.10 and 2.12.

2.6.5 Summary and conclusions regarding the most clinically appropriate method

An indication of the comparative success rates of preferential looking and pattern VEP tests is obtained by studying Figure 2.23 (numerical values are given in Table 2.13). The results provided by the pilot study strongly favour the use of preferential looking rather than pattern visual evoked potentials for clinical assessment of infant acuity. Estimates of binocular acuity were obtained in almost 90% of sessions and monocular acuities were determined in about half of the sessions. The pattern VEP results were very disappointing only a quarter of sessions resulted in the recording of *any* acceptable responses. The pattern VEP results were even poorer when sessions involving normal infants were removed from the data (Table 2.14). Only 13 percent of sessions involving clinical patients resulted in the recording of satisfactory pattern VEPs. Although it must be stated that the order of testing (PL before VEP) was likely to introduce a bias in favour of the preferential looking method those infants examined with VEP only produced equally unsuccessful results. Acceptable flash VEP results could be obtained during almost eighty percent of sessions - suggesting that the failure to obtain pattern results was not caused by technical problems.

Table 2.13 Incidence of successful binocular, right eye and left eye test sessions from the total numbers of preferential looking, flash and pattern VEP sessions. Total sample (31 pattern, 35 flash and 45 preferential looking sessions).

	Incidence of successful test sessions (%)		
	Preferential Looking	Flash VEPs	Pattern VEPs
Binocular	88.9	77.1	25.8
Right Eye	46.7	51.4	3.2
Left Eye	40.0	51.4	3.2

Table 2.14 Incidence of successful binocular, right eye and left eye test sessions from the total numbers of preferential looking, flash and pattern VEP sessions. Sample excluding normals (23 pattern, 34 flash and 38 preferential looking sessions).

	Incidence of successful test sessions (%)		
	Preferential Looking	Flash VEPs	Pattern VEPs
Binocular	89.5	70.6	13.0
Right Eye	47.3	52.9	0.0
Left Eye	39.5	47.0	0.0

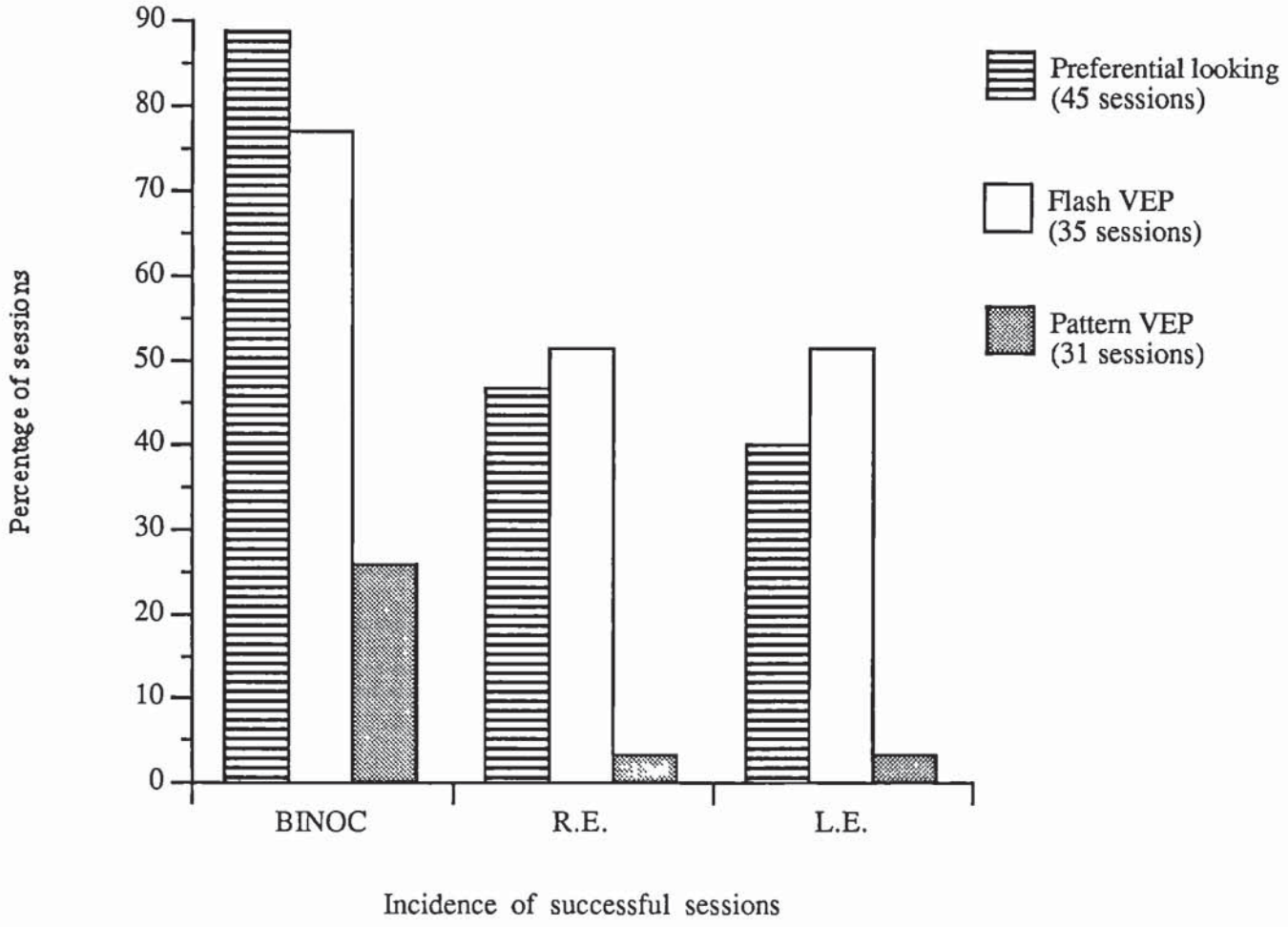


Figure 2.23 Incidence of successful binocular, right eye and left eye preferential looking, flash and pattern VEP test sessions. The values represent the proportion of sessions in which the particular tests were completed compared with the total numbers of sessions. Monocular tests were generally not conducted unless satisfactory binocular responses had been obtained. Numerical values are provided in Table 2.13.

An additionally advantage with preferential looking testing was that the test was often completed in less time than was necessary to prepare an infant for VEP recording. Parents were noticeably reluctant to volunteer their normal infants for VEP testing due to anxieties relating to the application of electrodes. The preferential looking method was generally more acceptable to the parents because it was seen to be less distressing for the child.

3. NORMATIVE STUDY - METHODOLOGY

3.1 Preferential looking test

Infants fixate patterned surfaces more than featureless surfaces (Berlyne 1958, Fantz 1958). This observation forms the basis of the preferential looking (PL) method. Preferential looking acuity techniques depend upon the assumption that the finest striped field that an infant will consistently fixate in preference to a homogeneous field provides a possible measure of grating acuity. Several preferential looking acuity methods have been reported in the literature - these are reviewed in section 2.4. The method adopted in the present normative study was derived following our experience examining clinical patients during an initial study (see section 2.6).

New equipment was designed and constructed by the author prior to commencement of the normative study. This was required in order to incorporate improvements suggested by the pilot study results. The equipment was installed in a maternity ward where testing of newborn infants was performed. A duplicate trolley was built to the same specifications, for use on follow-up sessions conducted at Aston. The natural ambient illumination in the hospital room allocated for performing examinations was too high for satisfactory preferential looking testing. Since the room was required for other purposes improvised blackout curtains were applied to the two external and one internal window (reducing the ambient illumination to a low mesopic level) prior to commencing a test session. The testing equipment was positioned so that an existing curtained partition formed a natural barrier, further eliminating room distractions from the infant's field of view. This environment proved satisfactory for the efficient examination of newborns, who have restricted "effective" visual fields (Tronick, 1972; Harris and MacFarlane, 1974). Provision of an ideal environment for follow up visits was simple as the departmental clinical rooms used were devoid of windows.

3.1.1 Equipment

An optical projection system was used for preferential looking (PL) testing. This equipment was housed on a moveable "trolley" constructed from dexion framework and clad with melamine covered chipboard. The internal walls were matt black to decrease reflections and improve the contrast of the projected image. The apparatus was additionally capable of providing stimulation for recording of both pattern reversal and appearance VEPs and pattern ERGs. Prior to the commencement of the preferential looking study the equipment was used in a study which applied a novel technique to extract a pattern specific response from the pattern ERG of adult subjects (described in Appendix 8, publication 3). Refinement of this method is still proceeding, so it was not able to be incorporated into the infant study. The features of the apparatus design pertinent to the application of preferential looking testing will be discussed here.

Slides

Two series of 35 mm stimulus slides were available in separate straight magazine slide trays. One series featured vertical and the other horizontal gratings. Each slide consisted of a high contrast (≥ 85%) square wave grating mounted with a Kodak 0.3 neutral density filter. The gratings were produced by photographing a range of commercially available "Letratone" papers (LT 213, 218 and 223), from various distances to produce the necessary spatial frequency increments. The slides were organised in approximately $\sqrt{2}$ (i.e. x 1.14) steps of spatial frequency and calibrated for use at 40 centimetres (Table 3.1). Slides in both series were numbered from 1 to 8. Two additional coarser spatial frequencies labelled -1 and 0 were available in the vertical series for the examination of infants that failed to respond to finer gratings. Attempts to produce satisfactory gratings of higher spatial frequency were unsuccessful. Two slides of each spatial frequency were available, one with the grating presented on the right and the other with the grating on the left screen. The right left position varied randomly throughout the series to avoid examiner bias. Two test pattern slides of a coarse multicoloured pattern paired with a blank field were also available in each series. The test pattern was presented on the right screen in one version and on the left screen in the other.

Table 3.1 Spatial frequencies of the preferential looking acuity gratings (minutes of arc) at the 40 centimetres viewing distance employed in the test.

Slide number	Stripe Width. (cm.)	Angular subtense at the eye at 40 cm. viewing distance (minutes of arc)
- 1	1.73	179
0	1.18	121
1	0.96	99
2	0.69	73
3	0.49	52
4	0.36	34
5	0.24	26
6	0.18	19
7	0.13	13
8	0.09	9

Stimulus display

The stimulus display consisted of two horizontally separated rectangular screens surrounded by a partition which obscured the infant's view of the examiner (Figure 3.1). The latter viewed the infant through a slit aperture above the display. The stimulus screens each subtended 18.5° horizontally and 33.4° vertically at the 40 centimetres viewing distance used. The inner edges of each screen were 5.7° eccentric from the midline. These values were selected because prior to three months higher acuity estimates are found when

large (19°) rather than small (10°) circular screens are viewed (Atkinson et al., 1983). Screen eccentricity (3° versus 10°) had no significant effect on acuity findings in the same study. However screen separation was increased in comparison to our pilot study because of difficulty experienced in the examination of infants having nystagmus.

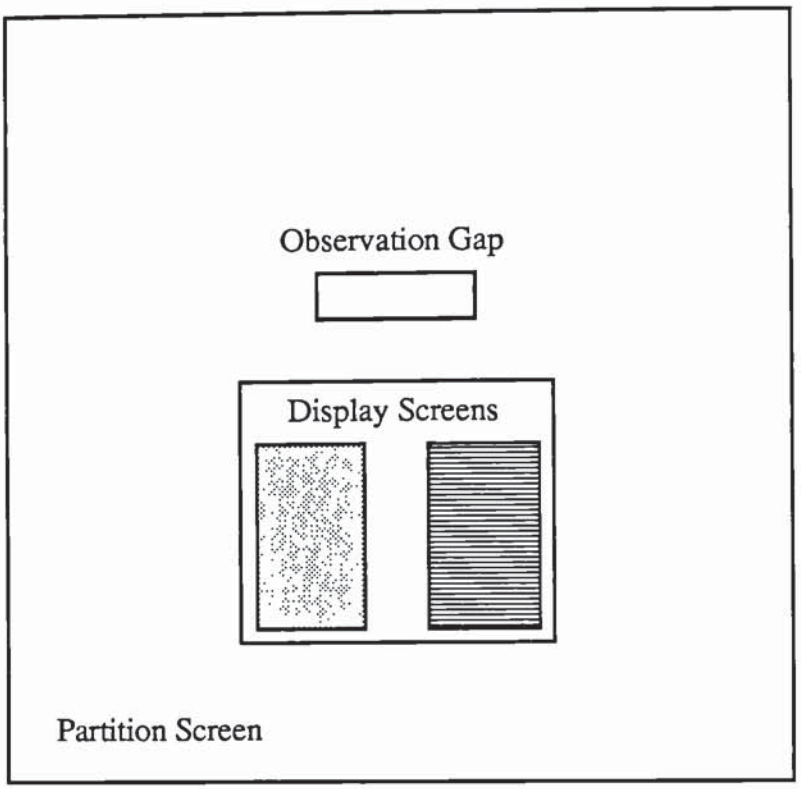


Figure 3.1 Schematic appearance of preferential looking apparatus front screen (drawn approximately one-tenth scale).

The display screen was constructed of 3 mm. thick clear perspex covered with 'Intavue' PVC rear projection screen material (available from Chiltern Photographic Company, 92 Stroud Green Road, London). A wooden black mask (for convenience cardboard was used in the duplicate trolley), separated the display into two screens. A sheet of neutrally tinted perspex placed in front of the screens protected them from damage by over enthusiastic infants and reduced possible distractions caused by the mask. The partition screen was constructed from 5 mm. thick hardboard and coated with matt black adhesive PVC.

Optical pathway

The trolley used for the testing of newborns was equipped with a Rollei projector (model P353) with a 85 mm. focal length lens. The trolley used on follow-up visits was equipped with an Agfa 'Reflecta' diamator 1500 projector with a Will-Maginon 1 : 2.8/85 mm. multicoated lens (having a halogen 24 volt, 150 watt bulb).

Images were projected onto the stimulus screen following reflection in a series of surface-silvered mirrors. Three reflections were necessary to allow a reasonably compact apparatus whilst maintaining an adequate pathlength to enable provision of large stimulus screens. The optical elements were positioned so that the total pathlength was 114 centimetres. Distances between successive elements were as follows; projector (nodal point) to M 1 = 7.5 cm., M 1 to M 2 = 22.5 cm., M 2 to M 3 = 31.0 cm., M 3 to screen = 53.0 cm.

Figures 3.2 and 3.3 clarify the arrangement of components. Mirror M 1 (measuring 3 x 4 cm) was positioned on a cross-shelf close to the projector lens and was mounted on a penmotor spindle and hence could be rotated around its vertical axis (a refinement required for pattern reversal stimulation). The projector protruded through the side of the trolley and was therefore conveniently placed for easy slide changes to be performed. The position of the examiner during the test is apparent from plate 3.1. Mirror M 2 was mounted vertically above M 3. Both mirrors measured 30 cm. square and were attached to round bars mounted through the side walls. They were adjustable about their horizontal axes.

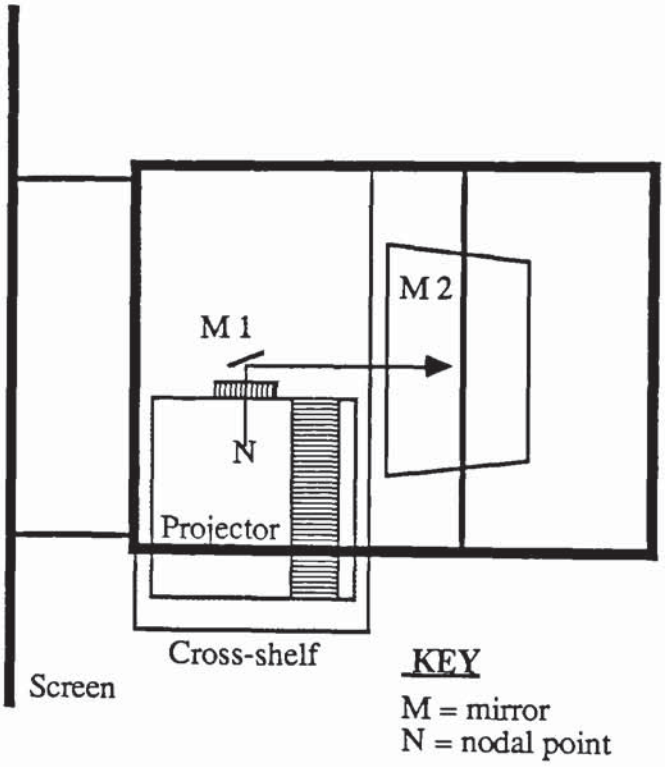


Figure 3.2 Plan of the preferential looking apparatus (drawn approximately one-tenth scale). Cover omitted for clarity.

The display screen and partition were mounted on dexion prongs that protruded from the main framework (Figure 3.3). The examiner was prevented from directly viewing the display screens by an opaque PVC mask. Following trials feedback of grating position was accomplished by raising a flap on the cover which formed a roof to the apparatus and observing the reflection in M 3.

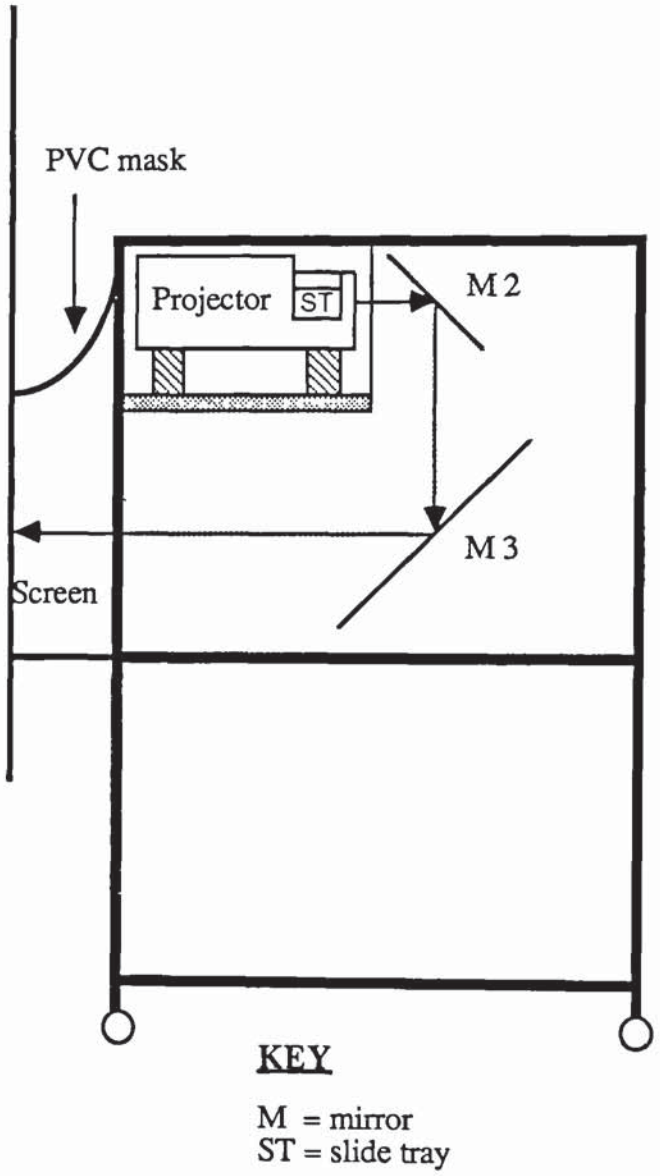


Figure 3.3 Side view of the preferential looking apparatus (drawn approximately one-tenth scale).

Plate 3.1

Preferential looking apparatus used in the present study
(designed and constructed by the author)
showing position of the observer during the test.

3.1.2 Testing procedure

The holder, a parent or assistant, was seated on a swivel chair with the infant on their lap, facing the screen. Where appropriate a brief explanation of the procedure was given. The holder was instructed to keep the infant facing the centre of the display screen unless given alternative instructions during the test. An orthoptic eye patch was applied before conducting monocular tests. The holder was asked to prevent the infant from removing this by restraining arm movements providing this could be accomplished without unduly upsetting the child. Infants were allowed to suck a dummy or bottle feed during the test. The distance between the screen and infant's eye was checked against a marker attached to the screen to ensure a 40 centimetre viewing distance was maintained. This distance is within the accommodative range of young infants (Banks, 1980a; Braddick et al., 1979).

After these preparations, the projector was switched on and the room lights extinguished. The examiner, standing behind the partition, initially presented a stimulus grating of low spatial frequency (subtending at least 99 minutes of arc for newborn and 73 minutes of arc for older infants). At the same time the infants eye and head movements were observed through the slit aperture above the screens. If the infant demonstrated a clear fixation preference for a particular screen a check was then made of whether this coincided with the position of the acuity grating. If the observer correctly identified the grating location by interpretation of the infant's looking behaviour a finer stimulus was selected manually for the next trial.

Whenever an incorrect judgement was made a coarser grating was subsequently presented. Spatial frequency was altered by one octave (i.e. two steps) after each of the initial three trials, then by one-half octave after later trials. Testing strategy was modified after two reversals of the staircase direction. Several repeated trials were then conducted using the spatial frequencies around which the staircase had been fluctuating. If possible testing was continued until a minimum of four trials had been conducted at each of three spatial frequencies which bracketed the designated acuity level (75 % correct by the observer). Two stimulus slides of each spatial frequency were available. In one the grating was projected onto the right screen in the other it was presented on the left screen. Testing was speeded up by successively presenting a pair of slides before obtaining feedback of the grating position.

In practice this testing strategy could not be rigidly applied, but was modified according to the quality of the infant's looking behaviour. This was sometimes difficult to interpret initially, or it deteriorated during the assessment due to declining interest with the test, general fussiness or sleepiness. Two test slides, consisting of a coarse multi-coloured pattern paired with a blank field, were available. These provided a method of checking the infant's responses. A test slide was presented when an infant failed to show preferential fixation of the coarsest grating available or if responses became erratic during the procedure. Use of test slides gave the examiner feedback of the infants co-operation and often encouraged renewed interest during the next few trials.

Occasionally younger subjects were found when tested monocularly to consistently gaze passively at the screen located in the temporal field. This tendency possibly relates to the known inferiority of the nasal field in early life (Lewis et al., 1978 and 1985). If this behaviour was noted *two* slides of a particular spatial frequency were then presented *before* obtaining feedback of grating position. If the infant continued to show a side preference the holder was instructed to slowly rotate from side to side. This resulted in the infant's gaze being directed at each screen in turn. The holder was asked to stop with the infants head level with the centre of the screen to avoid signalling the grating location to the examiner.

The examiner tapped on the back of the screen or called out the infant's name if visual attention strayed from the display. This assisted in attracting the subjects gaze to a central position before presenting the next slide. Testing was continued, where possible, until acuity estimates for both horizontal and vertical gratings had been obtained from each eye individually and binocularly. The maximum number of acuities determined was therefore six.

3.1.3 Determination of acuity

A written record of the sequence of trials was compiled during testing. This included details of slide number, screen preference demonstrated i.e. right (R) or left (L) and success of the trial. The latter was scored as correct (+) or incorrect (-) depending upon whether the side preference shown by the infant coincided with the grating location. This information enabled calculation of the infant's percentage of correct responses for each spatial frequency presented during the sequence.

Infants generally demonstrated strong preference (100 % correct responses) for the coarsest (suprathreshold) stimuli presented. Performance declined to chance level (50 % correct) for the finest grating(s) presented. At intermediate spatial frequencies performance usually decreased progressively with increasing spatial frequency although it may remain at the same level for adjacent frequencies. Acuity was defined as the finest spatial frequency (or interpolated spatial frequency) for which 75 % preference was shown. This is in agreement with many other studies (Dobson and Teller, 1978) although 70 % preference has been chosen as the acuity criterion by some research groups (Atkinson et al., 1974). If the infant did not respond at the designated 75 % correct level for any of the spatial frequencies tested this pc nt was found by interpolation (between two adjacent frequencies, A1 and A2, for which performance bracketed this level). The spatial frequency, A(75), which would be expected to elicit fixation on 75 % of trials was found by substitution into the following formula:

$$A(75) = A1 + (75 - P1)\ \frac{(A1 - A2)}{(P1 - P2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1).$$

Where A1 = acuity 1 (worse) mins of arc
A2 = acuity 2 (better) mins of arc
P1 = percentage correct for acuity 1 (i.e.>75%)
P2 = percentage correct for acuity 2 (i.e.<75%).

The performance of this calculation was made easier by the use of a programmable pocket calculator.

Some infants occasionally exhibited non-monotonic staircases which were consequently difficult to interpret. In these instances the infant performed below the designated 75 % correct (threshold) level at a particular spatial frequency then at or above threshold for higher frequencies. Random fluctuations in the infant's state of arousal would be expected to produce these artifacts as the method relies on relatively few trials per spatial frequency. Since the incidence of such tests was reasonably low i.e. 3.4 % (25/629) of tests conducted the results were included in data analysis. No strict ruling was applied to acuity estimation in these cases. A subjective decision of probable acuity was made after inspection of the percentage correct values and number of trials per SF (greater weighting being given to values dependent on more trials). Evaluation of infant's co-operation and the quality of their looking behaviour (i.e. convincing visual interest or passive gaze?) in response to various frequencies gave additional, very useful information on which to base this decision. In general acuity would be assumed to be better than the "dip" if an infant consistently showed good visual interest at higher spatial frequencies. A coarser spatial frequency than the dip may be selected if an infant barely responded above threshold at higher frequencies.

Some tests were abandoned, due to infant sleepiness or declining interest, prior to establishing a well-defined end point. Visual preference above the desigated 75 % 'threshold' level was found for one spatial frequency but no, or too few trials were completed at the adjacent higher frequency to determine response level. In these cases a conservative estimate of acuity was made, providing the examiner concluded testing had proceeded sufficiently for this to be justifiable. The higher spatial frequency was allocated a percentage correct value of 50 % (chance) if no trials or one correct trial had been performed and of 0 % if one incorrect trial had been conducted. Acuity was then estimated in the usual manner by substitution into equation (1) to find by interpolation the frequency corresponding to the 75 % correct value.

3.1.4 Treatment of data

Acuity results derived from the study are described in Chapter 4 (and summarized in Chapter 7 - section 7.2.1). The findings are based on preferential looking assessment of 174 newborns of which 86 were re-tested (collectively attending 147 sessions) in some cases up to the age of one year. Plate 3.2 shows a four month old participating in the test. In accordance with earlier work (Dobson et al., 1980; Dubowitz e al., 1980; van Hof-van Duin and Mohn, 1986) acuity data has been analysed versus the infant's post-term age. For convenience when computing group averages newborn data was considered as representive of nought weeks post-term age. Follow-up data was allocated to eight monthly age groups as indicated in Table 3.7. The one year old infants were assessed mainly in order to investigate their refractive development. The acuity data of this group, although presented in Chapter 4, have been excluded from some of the statistical tests (e g. Table 4.1). It was considered that this action was reasonable as the apparatus had been deliberately designed to be suitable for testing newborns - the large screen size limited the production of high spatial frequency gratings and the low eccentricity of stimulus displays was of no advantage in the assessment of older infants.

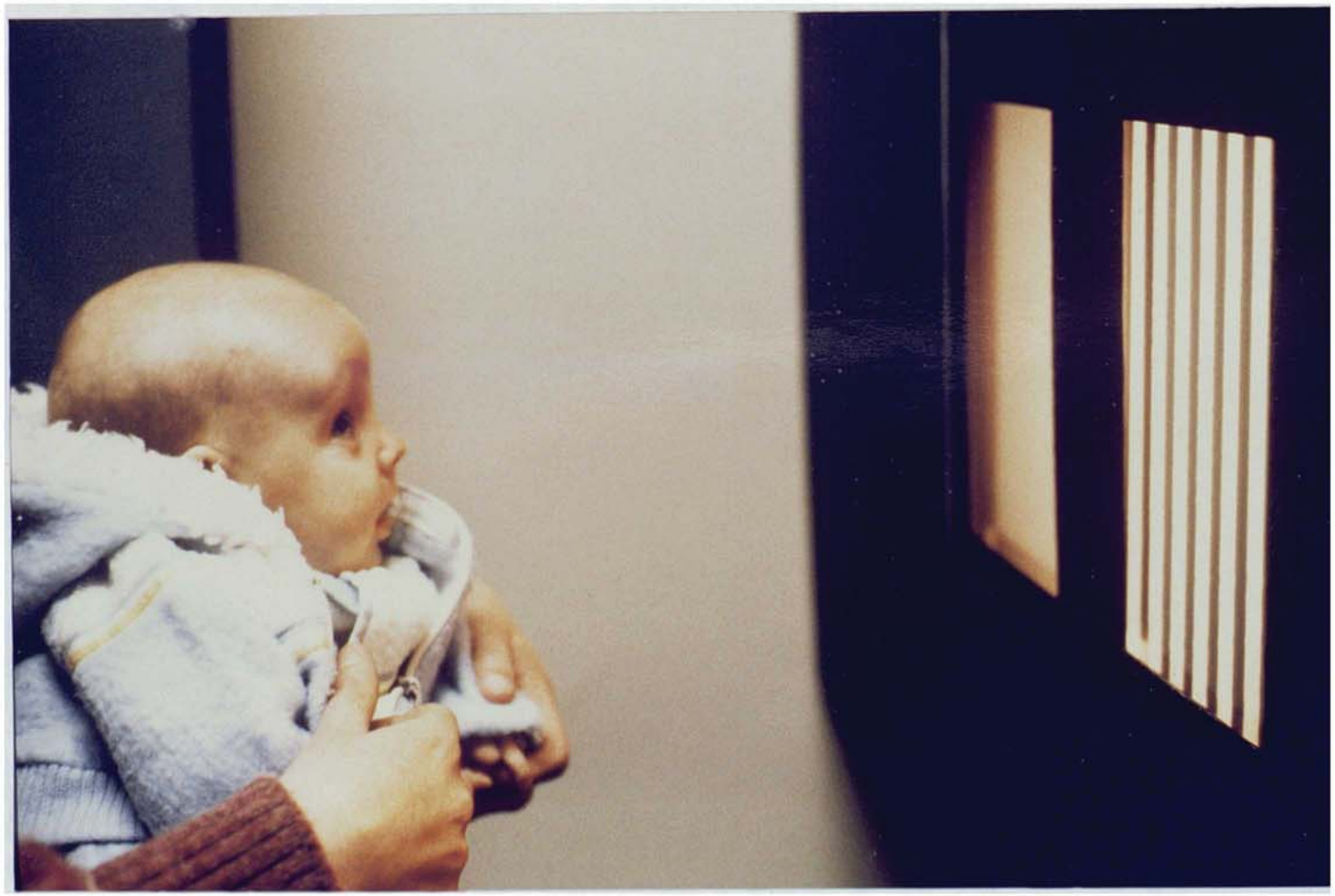


Plate 3.2

Four month old participating in preferential looking test.

When graphically plotting averaged data the mean post - term age of a particular age group was used. No infant appears in an age category on more than one occasion since consecutive visits of individual infants were arranged at intervals of at least four weeks.

Most of the newborn sample completed only one acuity test and no infant participated in more than three acuity tests. On follow-up visits an attempt was made to establish up to six distinct acuity estimates (horizontal or vertical gratings presented to the right eye, left eye and binocularly) during each test session. Full data sets (i.e. all six M.A.R. values) could not be determined for every infant. Data was therefore combined by computing the mean value whenever M.A.R. for both horizontal and vertical gratings had been established or taking either value if only one was available. Although not all data is based on the average of two measurements the terms "mean" right eye, "mean" left eye and "mean" binocular M.A.R. are used for convenience in the text. For each infant a representative "mean" monocular acuity score was derived by alternately selecting "mean" right eye or "mean" left eye data where both values were available or either value when only one had been established. This analysis ensured that each infant contributed no more than one acuity value in each age category.

3.2 **Retinoscopy**

3.2.1 Newborn sample

One drop of one percent Cyclopentolate hydrochloride solution was instilled into the conjunctival sac of each eye. Instillation was performed whilst the infant was reclining on its back in a cot, either besides the mother's bed, or in the testing room immediately after preferential looking if this test was conducted. Infants were returned to their cots, on the ward, to allow the cycloplegic agent to take effect.

All examinations were performed at least 30 minutes after instillation of the drug to allow for adequate cycloplegia (Vale and Cox, 1978). The average delay before retinoscopy was 91.1 minutes (S.E. 3.2) this was due to the difficulties of efficiently examining several infants during a session and reluctance to interfere with the nursing schedule. The average time of initial refraction was 67.9 (S.E. 3.0) minutes for the 35 infants participating in the repeat refraction study. The subsequent refraction was conducted, on average 141.6 (S.E 4.2) minutes after instillation of Cyclopentolate. The maximum delay experienced by any infant was 180 minutes. Although residual accommodation of, on average, 1.95 dioptres has been found (using an R.A.F. Rule and N5 print) after this time in adults (Ward and Charman, 1986) residual accommodation is unlikely to be a problem in newborns due to their poorly developed accommodation (Braddick et al., 1979) and lack of appropriate target during examination.

Examination was conducted with the infant lying in a cot in the darkened testing room. Streak retinoscopy was performed in two meridians. A working distance of 33 centimetres, sufficiently proximal to avoid difficulties with anomalous reflexes (Howland, 1978), was used. This distance was maintained by means of a length of string attached to the retinoscope head (plate 5.1). Full aperture

spherical trial case lenses held in front of the infant's eyes were used to neutralise the reflex. Where practicable pairs of lenses were simultaneously introduced with one lens in front of each eye. The findings were recorded in sphero-cylinder form before and after correction for working distance.

Newborn infants spend a large proportion of their time asleep. Many infants were refracted whilst in this state. In these instances the lids were manually retracted against the orbital rim by an assistant. Care was taken to avoid excess pressure on the globe with its risk of artifactually inducing astigmatism (Graham and Gray, 1963).

A further difficulty encountered with sleeping subjects was the tendency for the eyes to turn upwards and outwards on attempted eye closure - Bell's phenomenon, which interferes with refracting along the line of sight. This problem was overcome to some extent by adjusting the infant's position using supporting pillows (thus encouraging postural mechanisms to centre the eye). Alternatively the examiner relied upon the eye occasionally drifting down into a central position. A repeat refraction study was conducted in order to investigate the influences that such difficulties have on the accuracy of measurement. Alert babies were calmer and easier to test whilst sucking on a dummy.

3.2.2 Follow-up sample

Following completion of preliminary tests (e.g. preferential looking, Hirschberg, near cover test, pupil reactions) one drop of one percent Cyclopentolate hydrochloride solution was administered whilst the infant was lying, face upwards, across the parent's lap. Parent(s) and infant retired to the waiting room, for a minimum of 30 minutes (on average 38.6 ± 5.8 minutes) to allow adequate depth of cycloplegia to be achieved.

On returning to the test room, all room lights were extinguished. Some older infants were alarmed by this dark environment and in these cases the preferential looking apparatus screens were illuminated to provide low ambient background illumination. Streak retinoscopy was performed in two meridians, with the infant seated on the parent's lap. A working distance of 67 centimetres was employed - this does not produce difficulties with anomalous reflexes (Howland, 1978). Full aperture spherical trial lenses, held in front of the infant's eyes were used to neutralise the reflex. The findings were recorded in sphero-cylinder form before and after correction for working distance. All infants were awake so there was no necessity for lid contact during the examination.

Infants were allowed to bottle feed or suck on a dummy during retinoscopy. This generally had a calming influence enabling the test to be conducted with greater ease. The practice was terminated if encouraging eye closure. A small, squeaky toy, held close to the instrument was sometimes useful in attracting infants attention to the retinoscope light. This was generally only required in examination of infants above six months, who were more active and reluctant to sit still.

3.2.3 Treatment of refractive data

The spherical component of the refractive findings at neutrality was adjusted in accordance with the working distance used. This resulted in correction factors of - 3.00 dioptres and - 1.50 dioptres, for the newborn and follow-up examinations respectively. The spherical equivalent refractions (S.E.R.s) of astigmatic infants were calculated by adding one half of the cylindrical component to the spherical component. Anisometropia was calculated from the difference in the S.E.R.s of the right and left eye. Data from each eye has been analysed separately, since combining right and left eye data from individual subjects can lead to levels of significance being spuriously achieved (Ray and O'Day, 1985).

Refractive data was initially analysed into newborn and monthly age groupings for follow-up samples (from three to seven months and twelve month olds). Three and four month and six and seven month data was later combined to increase sample sizes (since statistical tests did not demonstrate significant differences between these groups - amplification of this point is given in sections 5.1.6, 5.2.3 and 5.3.3). The refractive data of five five month old infants was omitted to allow analysis for four main age groupings; newborns, "three", "six" and twelve month olds. The incidence of "significant" ametropia was calculated for each age category (section 5.5). The levels of refractive error selected as significant were defined in relation to levels encountered in mature populations. The following values were selected to represent significant refractive error; astigmatism $\geq$ 1.00 DC; anisometropia $\geq$ 1.00 DS; S.E.R.s outside the range 0.00 $\pm$ 0.99 DS.

The distribution of newborn refractive error was analysed. The percentage of infants falling into various refractive categories was determined. This was done for S.E.R. (5.1.1), anisometropia (5.2.1) and astigmatism (5.3.1). Class intervals of 1.00 dioptre for S.E.R. and of 0.50 dioptres for anisometropia and astigmatism were used. Follow-up data was not sufficient to justify similar analysis. Linear regression analyses were conducted to investigate possible relationships between neonatal refractive findings and maturity, physical size or other factors (sections 5.1.2, 5.1.3, 5.1.5, 5.2.2. and 5.3.2). The newborn data was divided into various subgroups for further analysis to elaborate possible explanations for the findings (sections 5.1.4, 5.1.5, 5.2.2. and 5.3.2).

Thirty-five newborn infants participated in a repeat refraction study (section 5.4) to investigate the accuracy of neonatal refraction. The subsequent refractive findings were, for each individual, subtracted from the initial refraction. This was done for both S.E.R. and astigmatic correction. The values of refractive difference, were either positive or negative so were additionally converted to their absolute equivalent where necessary. Evaluation of the mean of the unconverted values was conducted to determine whether there was any systematic alteration in refraction as a result of the time delay between tests. A value not significantly different from zero (student t - test) would indicate no systematic alteration. The mean of the corrected values represents the average difference between refractions. In the event of no systematic difference being found as a result of timing of the refractions this latter value indicates the accuracy of the measurement. These infants' initial refraction data was added to that of the remaining

newborn population refracted.

The means and standard errors of the means (S.E.) of certain refractive findings (S.E.R., anisometropia and astigmatism) were calculated for the four age categories. Individuals' follow up spherical equivalent refractions were compared with their earlier, mostly newborn, data (section 5.1.7). Alteration between successive refractions was determined by subtracting the later from earlier S.E.R.s. This resulted in positive values indicating myopic shifts and negative values representing hypermetropic shifts. The percentage of infants in each age group showing emmetropic shifts (relative to their newborn data) was calculated from this information. The approximate rate of refractive change (in dioptres per week) was calculated for each follow-up group by dividing the absolute refractive change by the time delay between examinations. This is recognised to be a simplification of the real situation as it assumes a linear relationship with age. However, analysis of the data in this manner allows some impression of the periods of most rapid alteration in refraction.

3.3 Supplementary ophthalmic examinations

Most newborn infants (209 of 227) participating in the study were screened for ocular pathology (3.3.1). Pupil reactions (3.3.4) of infants attending follow-up were checked but thorough ophthalmoscopic examination was often impossible without distressing the child. Infants of above two months attending follow-up were screened to exclude the presence of squint (3.3.2) and to ensure that their binocular status was appropriate for age (3.3.3). Descriptions of the latter tests can be found in standard texts (e.g Lyle and Wybar, 1967; Cashell and Durran, 1980 and Pickwell, 1984).

3.3.1 Indirect ophthalmoscopy

Assessment of the clarity of the ocular media and examination of the fundus was conducted for the majority (92 %) of newborn infants. Examination was necessary to check for the presence of retinal haemorrhage and to exclude serious pathology. Baum and Bulpitt (1970) described three types of neonatal retinal haemorrhage; superficial splinter, flame-shaped or geographic (lake) and deeper dense blot haemorrhages. Retinal haemorrhage was if present categorized into one of three grades, according to the degree of severity. Grade 1 = single or few small ; 2 = several small or single geographic ; 3 = multiple/many small or few geographic haemorrhages. This information was not used fully in the study reported here, although it proved useful in identifying infants with unilateral, bilateral or no retinal haemorrhage. The type of haemorrhage was not recorded.

Examination was performed using an American Optical monocular indirect ophthalmoscope (Henson, 1983a; Bennett and Rabbetts, 1984a). This instrument is shown in use in plate 6.1. It was chosen because in comparison to other indirect ophthalmoscopes it gives an erect image and has easy control of aperture size (iris diaphragm) and focussing (by lever). The American Optical monocular indirect

ophthalmoscope provides an angular field of view that can be extended to 20 degrees compared with about 10 degrees in direct instruments. The advantage of increased field of view was deemed to more than offset the lower magnification - approximately five times rather than the fifteen times, provided by the direct method.

Ophthalmoscopy was conducted in the dark, following retinoscopy. The pupils had been previously dilated using Cyclopentolate hydrochloride solution. Newborn infants were examined whilst lying on their backs in an infant cot. In many cases eyelids had to be gently retracted and supported against the orbital rim by an assistant during the examination. Infants were allowed to suck on a dummy whilst the test was conducted. Older infants were examined whilst seated on their parent's lap. Many were very unco-operative so that a thorough examination was only achieved in particularly co-operative children.

3.3.2 Hirschberg corneal reflection test and cover test

Infants of three or more post-term months were, at follow up, checked for correct eye alignment using a Hirschberg corneal reflection test and near cover test These tests were not applied to younger infants since eye co-ordination is not properly developed and full and constant co-ordination of the eyes cannot be expected before about 4 to 6 months (Brown, 1974). As transient strabismus is relatively common its presence is of little practical significance prior to three months (Reinecke, 1984).

The tests were conducted either without any room lighting or if the infant was disturbed by this with low background illumination derived from the preferential looking screens. Both tests were performed by holding a pentorch directly in front of the infants nose at a distance of between 30 and 40 centimetres.

Initially the reflections of the source were observed to ensure that they occupied the same relative corneal positions (Hirschberg test). Symmetrical corneal light reflexes imply the absence of strabismus. In cases of strabismus the reflection in the deviating eye appears displaced in accordance with the amount and direction of deviation. Each millimetre of deviation of the reflex indicates a deviation of roughly 8° according to Morgan (1963) or 11° according to Pickwell (1984). The validity of the results of the Hirschberg test were checked by performing a near cover test. The examiner's thumb was used to occlude each eye in turn whilst observing whether there was any movement of the uncovered fixing eye. Absence of eye movement implies absence of squint as a squinting eye will move to take up fixation when its fellow eye is covered. The cover test was repeated several times because the infants head movements and fluctuating interest in the pentorch invalidated the results in some cases.

3.3.3 Convergence

Infant's ability to make convergence eye movements was assessed. A small bright red sphere stimulus was gradually moved in along the midline towards the infant's nose from a distance of about 50 centimetres. The examiner checked whether both eyes turned in (visual axes convergent on the stimulus) as the target approached. The response was graded as not present, weakly, moderately or strongly demonstrated. Room lights were switched on during the test. This test was only conducted on infants included in the refraction follow up study. The proportion of infants demonstrating good convergence was calculated for each of the three age groups examined (three, six and twelve months). These findings are given in Appendix Table A3.1.

3.3.4 Pupil reactions

Infant's direct and consensual pupillary light reflexes (Pickwell, 1984) were checked to ensure efficacy of the afferent and efferent nerve pathways (Parsons, 1978). This test was most easily accomplished by attracting the infant's attention to a coloured penlight whilst directing a more intense light towards the eye to produce and observe the expected pupil constrictions. The test was conducted with low background room illumination to reduce distractions.

3.4 Data extracted from the clinical history

Most of the information obtained from the hospital records was required in order to investigate the effect of possible birth trauma on the clinical findings. All of the infants examined were born following relatively uneventful births with no requirement of surgical intervention. Certain details of the maternal labour history (3.4.1) and of the infant's condition at birth (3.4.2) were recorded. The reasons for including particular items are elaborated in the relevant results chapters, brief explanations are provided here *in italics* where appropriate.

3.4.1 Details taken from the maternal and labour history

The following information was, when available, extracted from the hospital records:

i) Maternal age, number of pregnancies (*first babies generally have more difficult births so the newborn sample has been divided into offspring of primiparous and of multiparous mothers*), and ethnic grouping (Asian, Caucasian, Negroid or "other" if of mixed parentage or Mongolian).

ii) Maternal medication administered during the labour. Drugs routinely administered were syntocinon, syntometrine, lignocaine, sparine and pethidine. Details relating to the obstretric uses of these drugs are summarised in Table 3.2 (modified from Adams, 1983). Further pharmacological information can be derived from Martindale (1977). *Of these pethidine, a narcotic analgesic, is known to enhance anti-muscarinic activity and is transferred across the placenta (Moya and Thorndike, 1962). Respiratory depression of the newborn infant may result when the drug is administered at an appropriate time before birth (Moya and Thorndike, 1963). Pethidine may also be expected to enhance the local anti-muscarinic activity of the cycloplegic drug administered and therefore affect the refractive findings and possibly in consequence impair performance on the preferential looking acuity tests. The newborn sample were divided into a pethidine and non-pethidine group to check for these effects.*

iii) Type of delivery (spontaneous, or assisted with forceps or ventouse). Birth presentation (normal cephalic i.e. with occiput towards the front of the pelvis or malposition e.g. occipitoposterior with occiput towards the sacrum or malpresentation e.g. breech) and presence of any complications such as cord knotted or coiled around the neck (which if tight could cause asphyxia). These obstretric terms are explained by Adams (1983). *All deliveries other than spontaneous occipitoanterior cephalic without complications are accompanied by increased risk to the infant which it was considered might be reflected in poorer performance on acuity tasks. The sample was subdivided into various low trauma and increased trauma subgroups to check for any effects.*

Table 3.2 Summary of pharmacological details and obstretric uses of the drugs administered to mothers.

Drug	Proprietary name	Dose	Mode of administration	Uses/Remarks
Local anaesthetic:				
Lignocaine hydrochloride	Xylocaine	0.5% or 1% 2%	Infiltration Epidural	10 ml 0.5% solution or 5 ml 1% may be used by midwives for infiltration prior to episiotomy and prior to pineal repair.
Analgesics:				
Pethidine hydrochloride		25 - 150 mg. 25 - 50 mg.	i.m. i.v.	Short-acting but effective. May cause depression of respiratory centre of baby.
Antiemetics:				
Promazine hydrochloride	Sparine	25 - 100 mg. q.d.s.	Oral	May be given in conjunction with pethidine in labour.
Myometrial stimulants:				
Ergometrine		0.5 mg.	i.v. i.m.	Acts in 45 seconds, so it is useful in prevention or treatment of post-partum haemorrhage. Acts in 7 minutes and gives sustained contraction of uterus.
Oxytocin	Syntocinon	1 i.u. in 1 litre solution at 15 drops/min = 1 milliunit/min	i.v. infusion	Induction of labour - stimulates contraction of uterine muscle.
Syntometrine		1 ml	i.m.	Consists of oxytocin 5 units and ergometrine maleate 0.5 mg., and so has rapid and sustained action. Active management of third stage of labour.

3.4.2 Information relating to the newborn infant

The following information was, when available, extracted from the hospital records:

> Time and date of birth, gestational age (either from post-menstrual age or ultrasound scan results). Gender, ethnic group (assumed to be that of the mother unless the father was known to be of another origin), birth weight, head circumference and length. Apgar scores at one and five minutes after birth. *The Apgar scoring (Apgar, 1953) rates the infants condition according to a three point scale on five different functions (heart rate, respiratory effort, muscle tone, reflex irritability and colour). The infant is given a score of 0, 1 or 2 for each of these categories so that the maximum value obtainable is ten.* Evidence of asphyxia if noted (or implied by the presence of meconium stained liquor) and treatment if required (oxygen mask).

3.5 Subject sources

All of the infants participating in the study, (n = 227), were full term, healthy newborns born at Dudley Road Hospital between February and December 1985. Gestational ages at birth varied between 36.0 and 42.1 weeks (mean 39.5, S.E. 0.1 weeks). A summary of average physical size at birth is included in Table 3.3. Each infant was initially examined in maternity ward R2 of the hospital during the first week of life. Subsequent follow-up examinations were conducted at Aston University, either in the Clinical Neurophysiology Unit or Ophthalmic Optics Clinic. Follow-up examinations were performed between March 1985 and June 1986.

Table 3.3 Summary of physical size and age details of newborn sample.

Variable	Mean	S.E.	Minimum	Maximum
Birth weight (kg.)	3.23	0.03	2.23	4.86
Head circumference (cm.)	34.2	0.08	31.5	37.5
Length (cm.)	50.6	0.17	43.0	57.5
Gestational age (wks).	39.5	0.10	36.0	42.1

On completion of the newborn investigations mothers were verbally instructed of the availability of follow-up assessments. An explanatory letter, map and appointment card were subsequently posted to the home address even if originally issued at this time. Examples of these are supplied in Appendices 3A and 3B. Eighty-seven of the total newborn sample of 227 infants attended a total of 151 follow up sessions. The information given to the mother after newborn tests was intentionally fairly vague to avoid biasing the sample returning for follow up.

3.6 Experimental procedure and sample construction - neonatal studies

Newborn infants were assessed using preferential looking (PL - section 3.1), streak retinoscopy (RET - section 3.2) and indirect ophthalmoscopy (I-O - section 3.3). Examination of all 227 newborns using each method was not feasible due to time constraints and reluctance to interfere with the nursing schedule. Infants that were refracted also underwent ophthalmoscopic examination. The Venn diagrams (Figure 3.4 a and b) summarises the numbers of infants participating in and completing the various tests. Table 3.4 indicates the order of testing (i.e. the tests conducted on successive visits to the test room) for the five subgroups which are, for convenience, labelled A to E. Groups A to C represent the 174 infants participating in preferential looking tests; B to E the 210 infants with retinoscopy and indirect ophthalmoscopy tests and the 35 infants in groups C and E provided repeat refraction data. The data of individual infants was collected during testing sessions performed within four hours on the same day. Infants were returned to their cots, adjacent to the mother's bed, between test sessions.

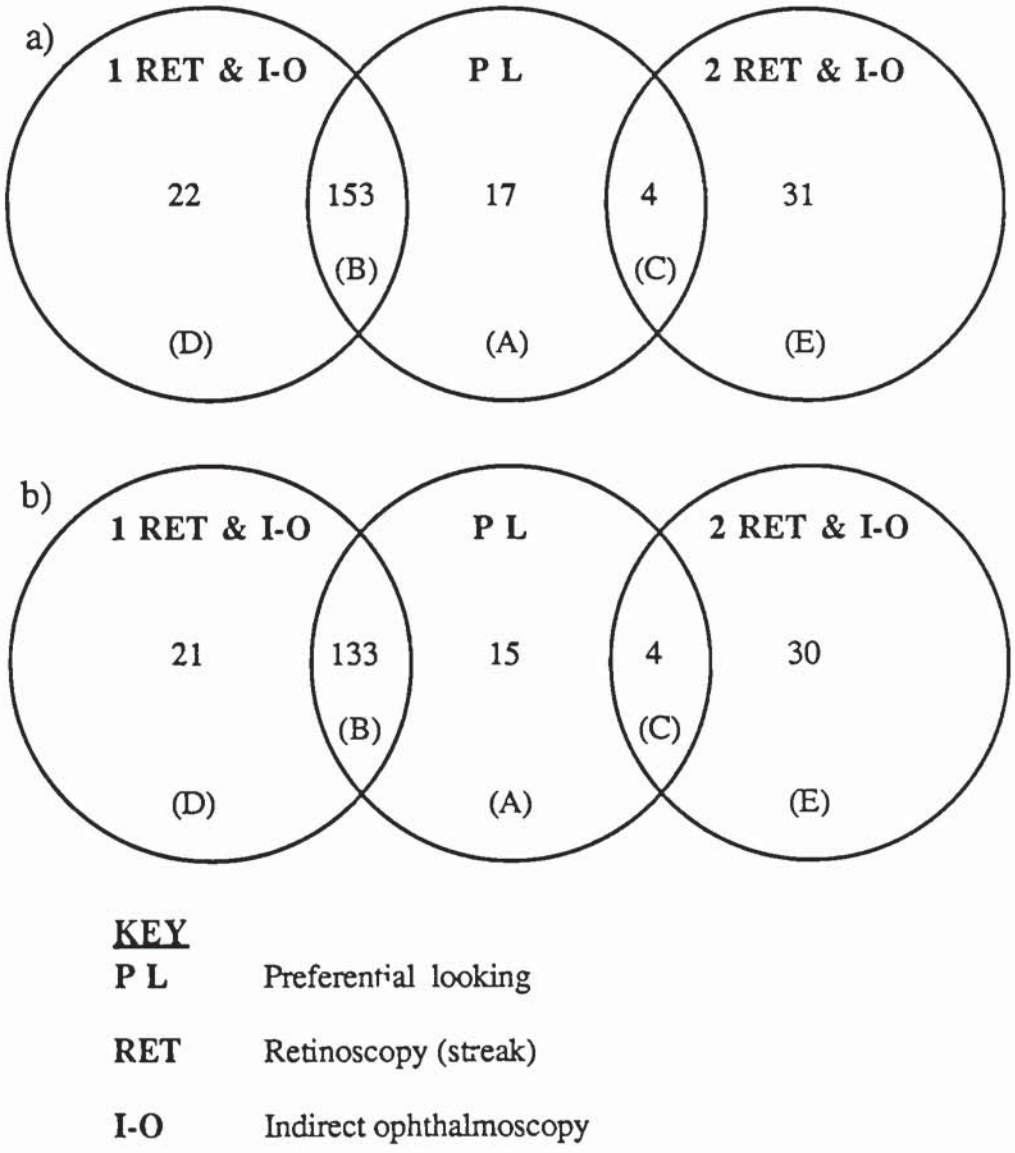


Figure 3.4 Venn diagrams showing a) numbers of newborn infants participating and b) numbers completing various attempted tests.

Table 3.4 Order of performance of the various newborn examinations for the five subgroups in the sample.

GROUP	TESTING SESSION		
	1	2	3
A	PL		
B	PL + DROPS	RET + I-O	
C	PL + DROPS	RET(1) + I-O	RET(2)
D	RET + I-O		
E	RET(1) + I-O	RET(2)	

KEY

PL Preferential looking

RET Retinoscopy (streak)

I-O Indirect ophthalmoscopy

Maternal consent was obtained prior to performing any tests. Mothers were approached on the ward and after a brief explanation of appropriate tests asked whether they would like their child examined. The maternity ward had 24 beds, over two-thirds of which were usually occupied. No particular selection procedure was adopted for the initial 88 infants participating in the preferential looking study but subsequently more alert infants were selected. Mothers were approached in turn, starting at bed one, and initially the child was deemed testable providing not deeply asleep. Later the infants were only selected if reasonably awake.

The selected infants formed two subgroups. Fifty-seven infants were investigated for the effects of binocular versus monocular viewing on acuity for vertical gratings. Either eye was selected at random for the first acuity attempt. The second attempt was conducted with the infant viewing binocularly. If the infant remained alert, determination of binocular acuity for horizontal gratings was attempted (this generally applied to cases where monocular testing had proven unsuccessful). Twenty-nine infants were investigated for the effect of grating orientation on binocular acuity. Grating orientation (horizontal or vertical) selected for the initial acuity attempt was varied according to an ABBA protocol.

Cyclopentolate hydrochloride (1%) eyedrops were instilled on the ward if the infant was not participating in the preferential looking study otherwise the cycloplegic was administered immediately after this test. Retinoscopy and indirect ophthalmoscopy were conducted after a minimum delay of 30 minutes. Infants (n=35) participating in the refractive accuracy study were refracted again during a final test session which was performed without reference to the previous findings. On completion of retinoscopy and indirect ophthalmoscopy tests reassurance was given to the mother that the eyes appeared healthy and of approximately equal focussing ability. The presence of retinal haemorrhage or marked ametropia was not reported since it was considered this may cause undue anxiety (which may prove to be unfounded) and could bias the sample attending follow up. The preferential looking results were explained but it was stressed that failure to respond to the patterns did not necessarily imply poor vision as the test depended upon level of alertness.

3.7 Experimental procedure and sample construction - follow-up studies

Mothers were offered follow up examinations at Aston University on completion of the newborn tests. If interested they were issued with an appointment card and map or informed that these would be posted to their home address. Although there was no effort to exclude any child from the follow-up study , mothers with other young children were more deterred by the prospects of travelling to Aston.

Initially a first appointment was arranged within six weeks of birth. Subsequent appointments were organised at approximately monthly intervals during the first six months. Preferential looking tests were conducted on the initial two follow-up visits with the addition of retinoscopy on one of the later sessions. The timing of refractive assessment was varied amongst individuals. This was necessary in order to assemble data from different age groups whilst avoiding repeatedly refracting infants. Despite expressing willingness to participate many mothers failed to attend though most were sent reminder cards prior to the appointment. Mothers that did not respond or declined the offer of additional follow up were not sent further appointments. Table 3.5 summarises the frequency of infants attending particular numbers of follow-up sessions. Thirty-six infants attended a total of 86 sessions. A total of 181 appointments were needed in order to generate this number of visits (an attendance rate of 47.5 %).

Table 3.5 Numbers of sessions completed by 36 infants offered appointments at monthly intervals during the first six months. The 86 sessions were generated from 181 arranged appointments.

SESSIONS ATTENDED	NUMBER OF INFANTS	NUMBER OF SESSIONS
1	11	11
2	12	24
3	3	9
4	8	32
5	2	10
TOTAL	36	86

Table 3.6 Numbers of sessions completed by 87 infants attending follow-up. These sessions were generated from 404 arranged appointments.

SESSIONS ATTENDED	NUMBER OF INFANTS	NUMBER OF SESSIONS
1	49	49
2	24	48
3	4	12
4	8	32
5	2	10
TOTAL	87	151

Inspection of the table reveals that approximately one-third of the sample attended only one session. One third attended two sessions and the remaining infants attended on at least three and mostly on four occasions. This level of attendance was insufficient to generate adequate data beyond the third month. Therefore subsequent appointments were arranged at specific ages, around three, six and twelve post-term months. The latter group was included mainly to evaluate refractive development but preferential looking tests were also conducted. Both tests were performed on most of the infants in the younger age groups. Six month follow ups were offered to infants for whom a three month appointment had been arranged regardless of whether they had attended this appointment. This resulted in a further 51 infants attending a total of 65 appointments. These visits were generated from 223 arranged appointments (an attendance rate of 29.1 %). On completion of the study 87 infants had attended a total of 151 follow up sessions. Table 3.6 summarises the frequency of infants attending particular numbers of follow-up sessions for the entire sample examined.

Infant's data was allocated to one of eight age categories according to the post-term age at the time of testing. Table 3.7 details the numbers of infants attending follow up sessions within these age groups. The frequency of infants with preferential looking tests, with retinoscopy assessments, and the numbers having retinoscopy and *successful* preferential looking testing are indicated in Table 3.8. Preferential looking could not be attempted on four infants because the equipment was disabled by an electrical fault.

Table 3.7 Details of monthly age categories and numbers of infants participating in follow-up visits.

Age Group (Months)	Allowed Age Range (Wks)	Sample Size	Actual Age Range (Wks)	Mean Age (Wks)
1	0 < 4	7	0.0 - 3.6	2.5
2	4 < 8	22	4.1 - 7.9	5.7
3	8 < 12	29	8.1 - 11.9	10.2
4	12 < 16	30	12.0 - 15.9	13.5
5	16 < 20	10	16.7 - 19.9	18.3
6	20 < 24	17	20.1 - 23.9	22.5
7	24 < 28	18	24.0 - 26.6	25.1
12	50 < 56	18	50.0 - 55.4	53.0

Table 3.8 Summary of numbers of infants within particular monthly age groups participating in preferential looking and refractive tests.

Age Group (months)	Sample Size	Numbers of infants tested PL	Refraction	No's tested successfully PL & Ref.
1	7	7	0	0
2	22	22	0	0
3	29	29	10	10
4	30	30	12	12
5	10	10	5	5
6	17	16	14	13
7	18	15	17	14
12	18	18	18	16
Totals (sessions)	151	147	76	70
(infants)	87	86	63	60

4. NORMATIVE STUDY - RESULTS I : VISUAL ACUITY FINDINGS

Although minimum angle of resolution (M.A.R.) is a measure of threshold and visual acuity is an index of sensitivity the terms have been, for convenience, considered as synonymous within this chapter. Where "combined" acuity data has been computed care has been taken to ensure that each infant contributes no more than one acuity value in each age category (more details are available in section 3.1.4).

4.1 Binocular visual acuity norms

4.1.1 Vertical and horizontal gratings

An attempt was made to measure two binocular acuities - using both vertical and horizontal gratings. The raw data obtained for binocular vertical and horizontal grating M.A.R. has been plotted versus post-term age in Figures 4.1 and 4.2. The newborn data has been omitted from these plots in order to improve clarity. Statistical analysis of the follow-up data (between one and seven months) shows that for both measures significant relationships exist between M.A.R. and post-term age. Details of regression curve equations and statistics, for the six testing conditions are given in Table 4.1. The binocular vertical and horizontal group mean data (including S.D. and S.E.) are presented in Table 4.2 and plotted in Figure 4.3.

Table 4.1 Details of regression curve equations and statistics (one month to seven month data), for the six testing conditions.
Format of regression equations y = reciprocal (m x + c)
where y = M.A.R. (mins of arc) and x = post-term age (weeks).

Acuity	Regression Coefficents			Statistics	
	m	c	r	d.f.	significance
B(V)	0.0034	0.025	0.65	1,91	$p < 0.001$
B(H)	0.0030	0.029	0.65	1,58	$p < 0.001$
R(V)	0.0023	0.022	0.49	1,71	$p < 0.001$
R(H)	0.0010	0.051	0.22	1,35	$p = 0.131$
L(V)	0.0019	0.026	0.39	1,73	$p = 0.001$
L(H)	0.0030	0.013	0.51	1,43	$p < 0.001$

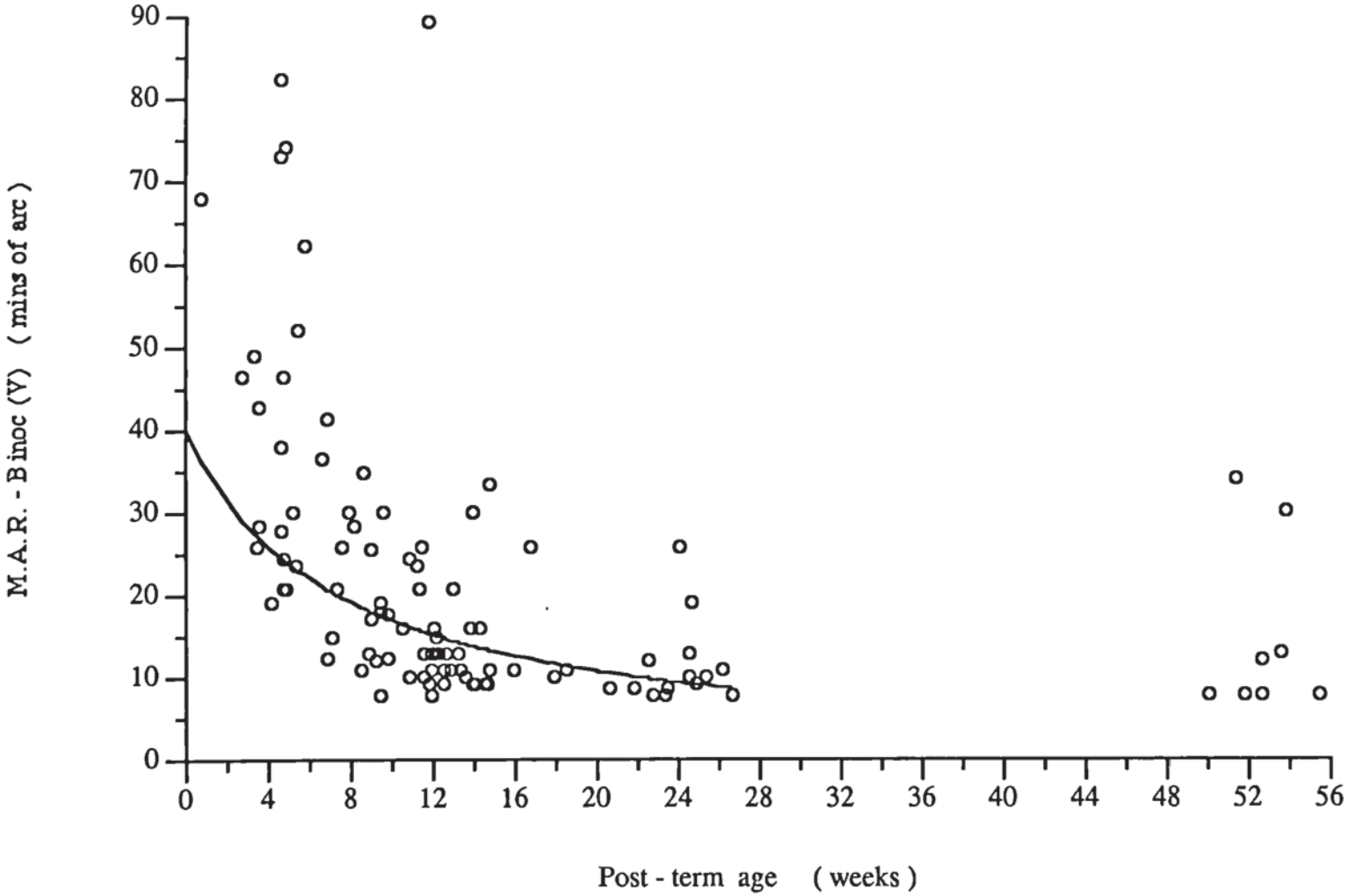


Figure 4.1 Scatterplot showing raw minimum angle of resolution (M.A.R.) data obtained for binocularly viewed vertical gratings plotted versus infants' post-term ages (weeks). All available follow-up data is included but newborn data has been omitted to improve clarity. Equation of regression curve (based on data excluding newborns and one year olds): y = reciprocal (0.0034 x + 0.025); r = 0.65; d.f. 1,91; p = < 0.001.

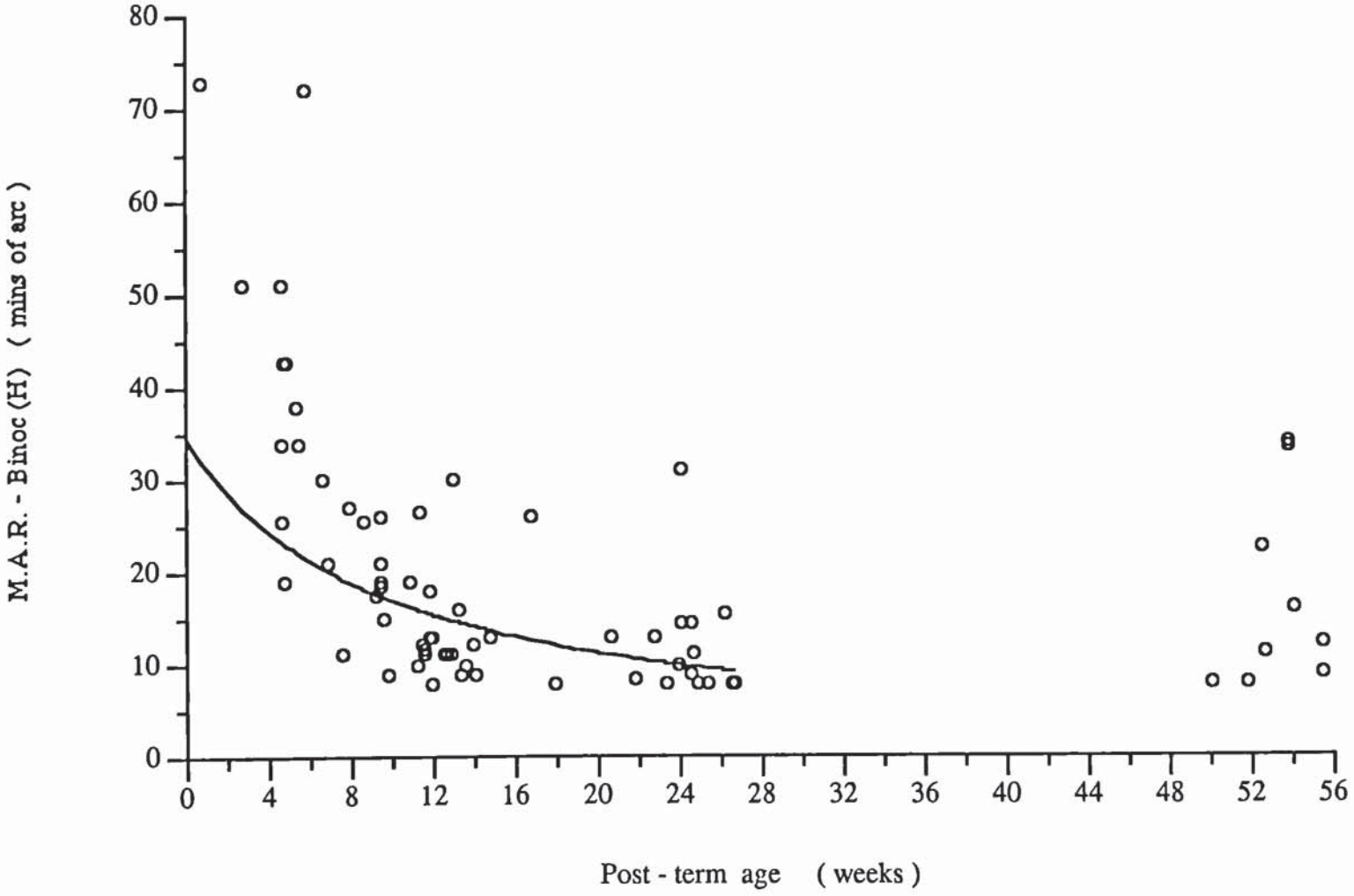


Figure 4.2 As Figure 4.1 for binocularly viewed horizontal gratings. Equation of regression curve: y = reciprocal (0.0030 x + 0.029); r = 0.65; d.f. 1,58; p = < 0.001.

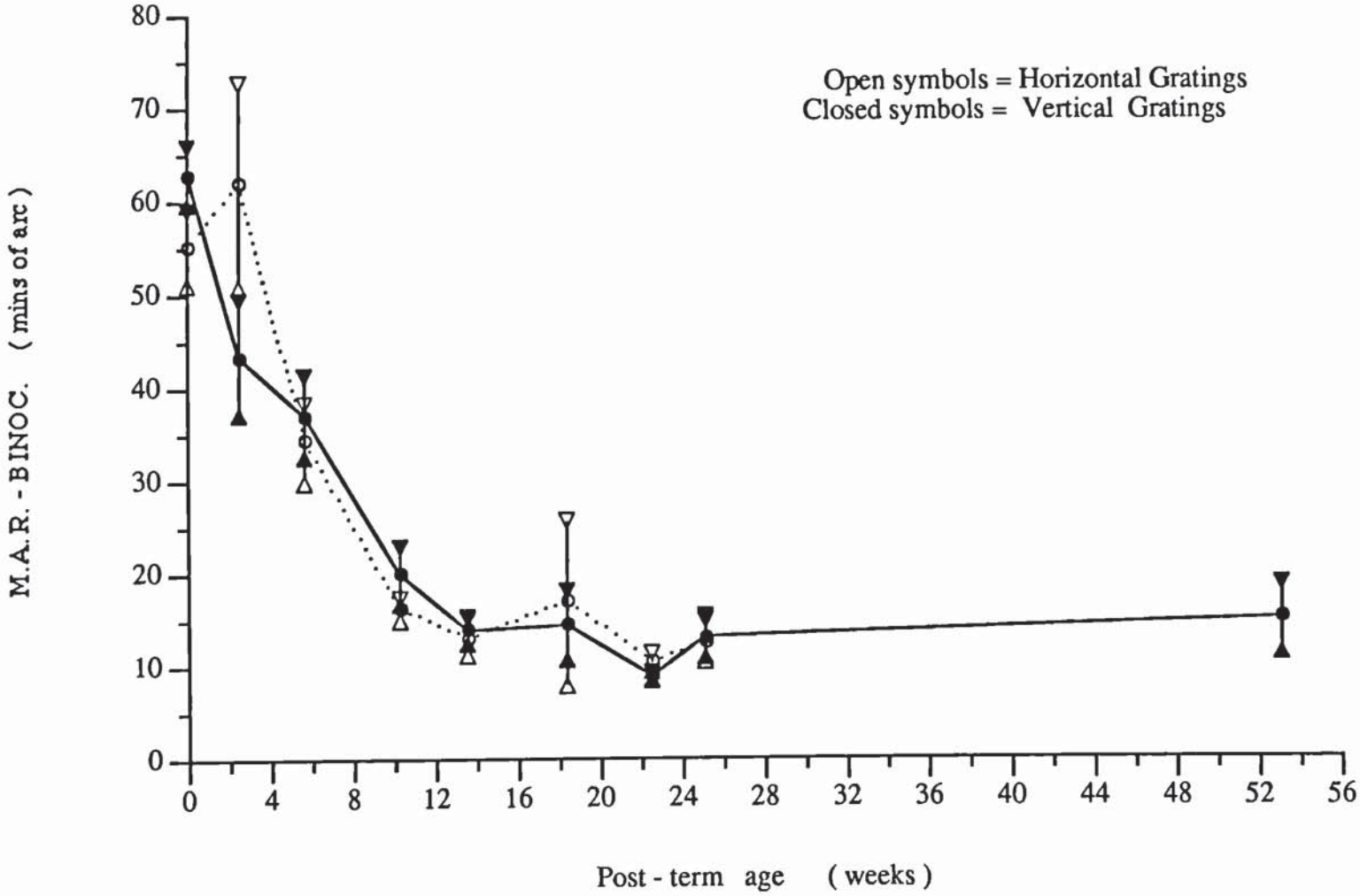


Figure 4.3 Group averaged binocular vertical and horizontal grating minimum angle of resolution (M.A.R.) age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.2.

Table 4.2 Binocular, vertical and horizontal grating M.A.R. means and group standard errors for each of nine age groups. Values are in minutes of arc.

Age Group (months)	Vertical Gratings Mean	(S.E.)	Horizontal Gratings Mean	(S.E.)
Newborn	62.9	(3.2)	55.2	(4.0)
1	43.5	(6.3)	62.0	(11.0)
2	37.1	(4.5)	34.4	(4.4)
3	20.1	(3.1)	16.3	(1.4)
4	14.1	(1.4)	13.2	(2.0)
5	14.5	(3.8)	17.0	(9.0)
6	8.9	(0.6)	10.5	(1.1)
7	13.3	(2.2)	12.8	(2.3)
12	15.1	(3.8)	17.1	(3.5)

The data of subjects completing both binocular tests (vertical and horizontal grating) has been analysed separately in order to test for significant differences in acuity development for the two grating orientations. The raw and group averaged data of the newborn sample is presented in Table 4.3. This data was collected from a subgroup of 29 newborns in whom the choice of grating orientation on the initial test was varied in ABBA fashion. Averaged data for follow-up age groups is shown in Table 4.4. Raw data for these groups is provided in Appendix 4B. There was no consistent trend for superiority of acuity for either grating orientation - findings for horizontal gratings were better for newborns and at two, three, five and seven months whereas acuity for vertical gratings were superior at one, four, six and twelve months. The differences between M.A.R. values for vertical and horizontal gratings did not reach statistical significance for the entire follow-up sample or any individual groups apart from at one month where only two infants contributed data. Statistical data is presented in Table 4.5.

Table 4.3 Paired binocular vertical and horizontal grating data of 21 newborn subjects completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Subject	M.A.R. (Mins of arc)	
	Vertical	Horizontal
1 (138)	34	52
2 (139)	26	13
3 (141)	48	52
4 (142)	73	99
5 (143)	34	30
6 (145)	52	52
7 (146)	91	52
8 (147)	29	34
9 (148)	34	52
10 (149)	71	73
11 (151)	39	34
12 (152)	52	99
13 (153)	34	34
14 (155)	99	59
15 (157)	34	34
16 (158)	43	26
17 (160)	70	46
18 (165)	121	90
19 (167)	34	52
20 (168)	43	73
21 (169)	52	19
Mean	53.0	51.2
S.D.	25.6	24.4
S.E.	5.7	5.4

Table 4.4 Averaged binocular vertical and horizontal data of follow-up subjects completing both tests. Means and standard errors are presented.

Age Group (Months)	n	M.A.R. (Mins of arc) Vertical	Horizontal
1	2	57.3 (15.2)	62.0 (15.6)
2	13	38.6 (5.9)	34.4 (4.5)
3	17	21.8 (4.8)	16.2 (1.5)
4	10	11.9 (1.2)	13.2 (2.1)
5	2	18.0 (11.3)	14.3 (12.7)
6	4	8.3 (0.2)	10.6 (1.6)
7	8	13.3 (2.3)	13.1 (3.0)
12	5	12.4 (4.9)	14.0 (5.6)
All Sample	61	22.0 (2.4)	20.2 (1.9)

Table 4.5 Statistical significances for group mean binocular vertical versus horizontal grating M.A.R. data. The differences between mean findings for each orientation did not reach significance for any age group apart from at one month.

Age Group	Comparison of Vertical and Horizontal M.A.R. Means		
	t - stat	d.f.	sig
Newborn	0.35	20	p = 0.727
1	-19.00	1	p = 0.033
2	0.83	12	p = 0.424
3	1.15	16	p = 0.266
4	-1.27	9	p = 0.235
5	1.00	1	p = 0.500
6	-1.73	3	p = 0.183
7	0.09	7	p = 0.934
12	-1.97	4	p = 0.120
Follow-up Sample	1.05	60	p = 0.298

4.1.2 Combined binocular ("mean") data

Due to the difficulties in obtaining full data sets the vertical and horizontal M.A.R. values were combined by calculating the mean if both data was available or either if only one value had been established. Treatment of the data in this way was justified because (as described above) no significant difference was evident in acuity development for each orientation. The group averaged data obtained in this manner is presented in Table 4.6 and plotted in Figure 4.4. The original data has also been reprocessed to provide an equivalent cycles per degree version of these acuity norms. The latter is presented in the summary section relating to this chapter (Table 7.1 and Figure 7.1).

Table 4.6 Combined (vertical and horizontal grating) "mean" binocular data; M.A.R. means, S.D. and group S.E. for each of nine age groups. Values are in minutes of arc.

Age Group (months)	Mean	S.D.	S.E.
Newborn	62.5	34.0	3.0
1	44.3	14.8	6.6
2	35.8	17.6	3.9
3	18.2	8.6	1.7
4	14.4	6.6	1.4
5	14.3	6.8	3.9
6	9.8	1.4	0.6
7	12.8	5.9	2.0
12	17.4	9.9	3.0

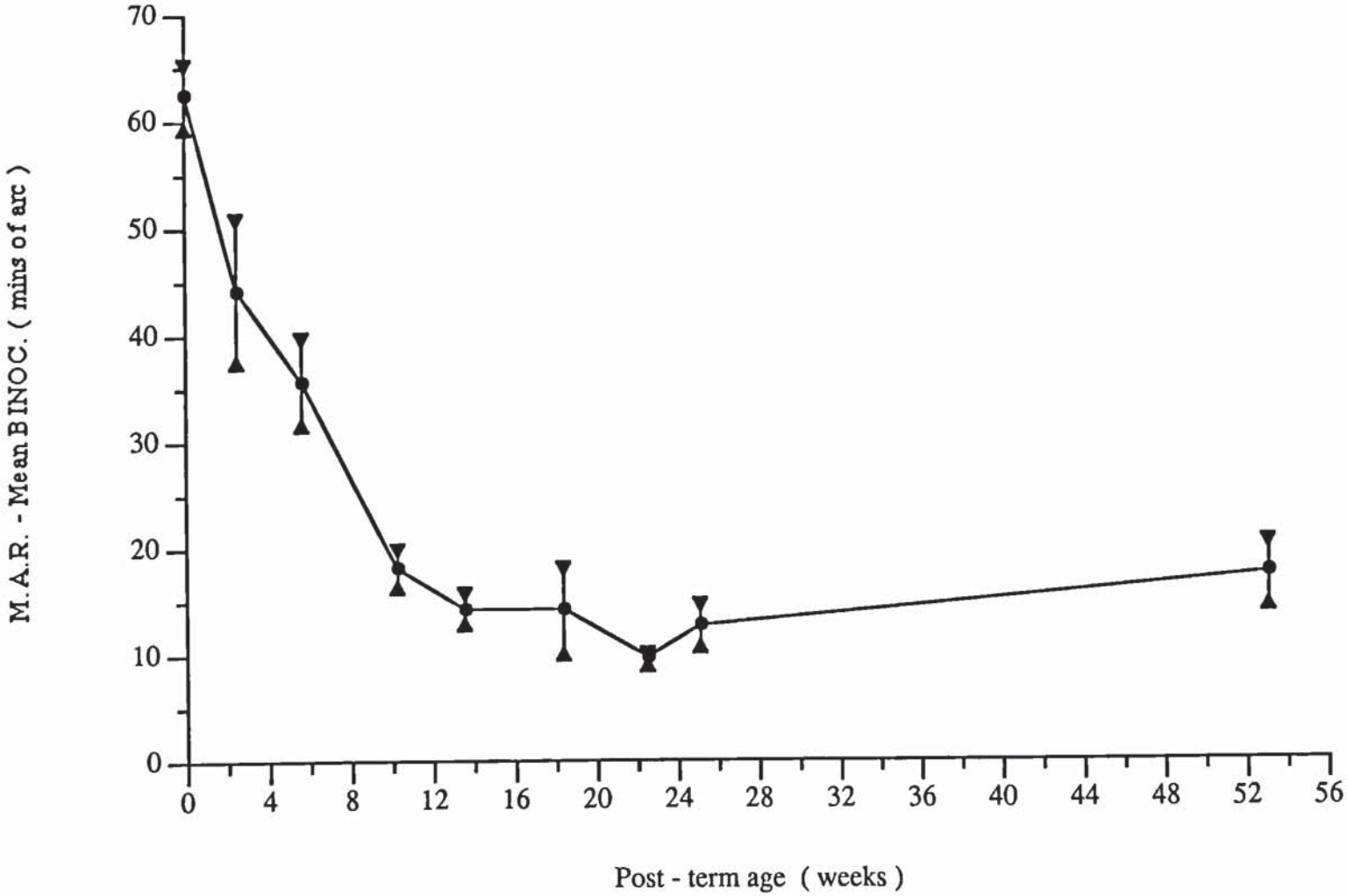


Figure 4.4 Group averaged "mean" binocular minimum angle of resolution (M.A.R.) age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.6.

4.2 Monocular visual acuity norms

4.2.1 Vertical and horizontal gratings

Attempts were made to measure up to four distinct monocular acuities (right eye - vertical and horizontal gratings; left eye - vertical and horizontal gratings). Scatterplots of the raw data can be found in Appendix 4A. Details of regression curve equations fitted to the one month to seven month data and statistics are provided in Table 4.1. A significant correlation was found between each acuity measure and post-term age except for horizontal gratings presented to the right eye (where the least data had been assembled). Group averaged data is presented in Tables 4.7 and 4.8. This data is also shown graphically in Figures 4.5 and 4.6.

Table 4.7 Right eye, vertical and horizontal grating M.A.R. means and group standard errors for each of eight age groups (no data was obtained at one month and only one infant contributed horizontal data at two months). Values are in minutes of arc.

Age Group (months)	Vertical Gratings Mean	(S.E.)	Horizontal Gratings Mean	(S.E.)
Newborn	61.3	(4.7)	58.7	(17.7)
1	-	-	-	-
2	26.9	(4.5)	82.5	-
3	36.2	(5.1)	16.9	(2.0)
4	22.1	(2.7)	18.6	(4.7)
5	14.8	(2.6)	9.7	(0.9)
6	17.2	(2.9)	23.0	(6.6)
7	17.6	(3.6)	14.5	(1.6)
12	12.5	(1.4)	13.5	(2.0)

Table 4.8 Left eye, vertical and horizontal grating M.A.R. means and group standard errors for each of eight age groups (no data was obtained at one month). Values are in minutes of arc.

Age Group (months)	Vertical Gratings Mean	(S.E.)	Horizontal Gratings Mean	(S.E.)
Newborn	61.6	(5.9)	68.0	(5.0)
1	-	-	-	-
2	43.9	(11.6)	46.8	(4.3)
3	28.0	(5.1)	39.6	(13.5)
4	24.1	(2.9)	21.4	(2.3)
5	17.7	(3.4)	11.1	(1.8)
6	15.6	(1.7)	15.5	(3.5)
7	23.5	(7.0)	15.8	(2.3)
12	15.2	(2.5)	15.7	(2.4)

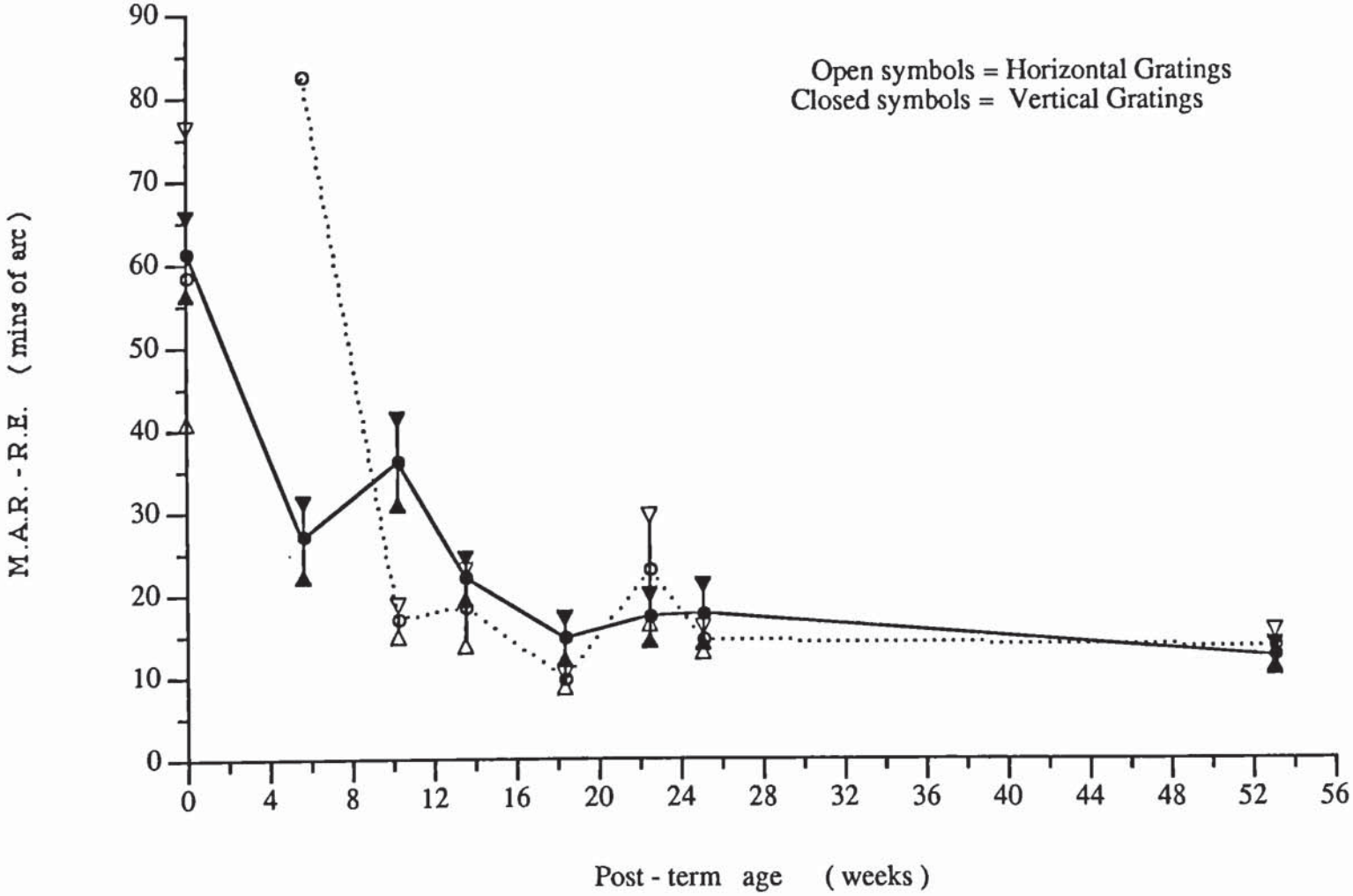


Figure 4.5 Group averaged right eye vertical and horizontal grating minimum angle of resolution (M.A.R.) age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.7.

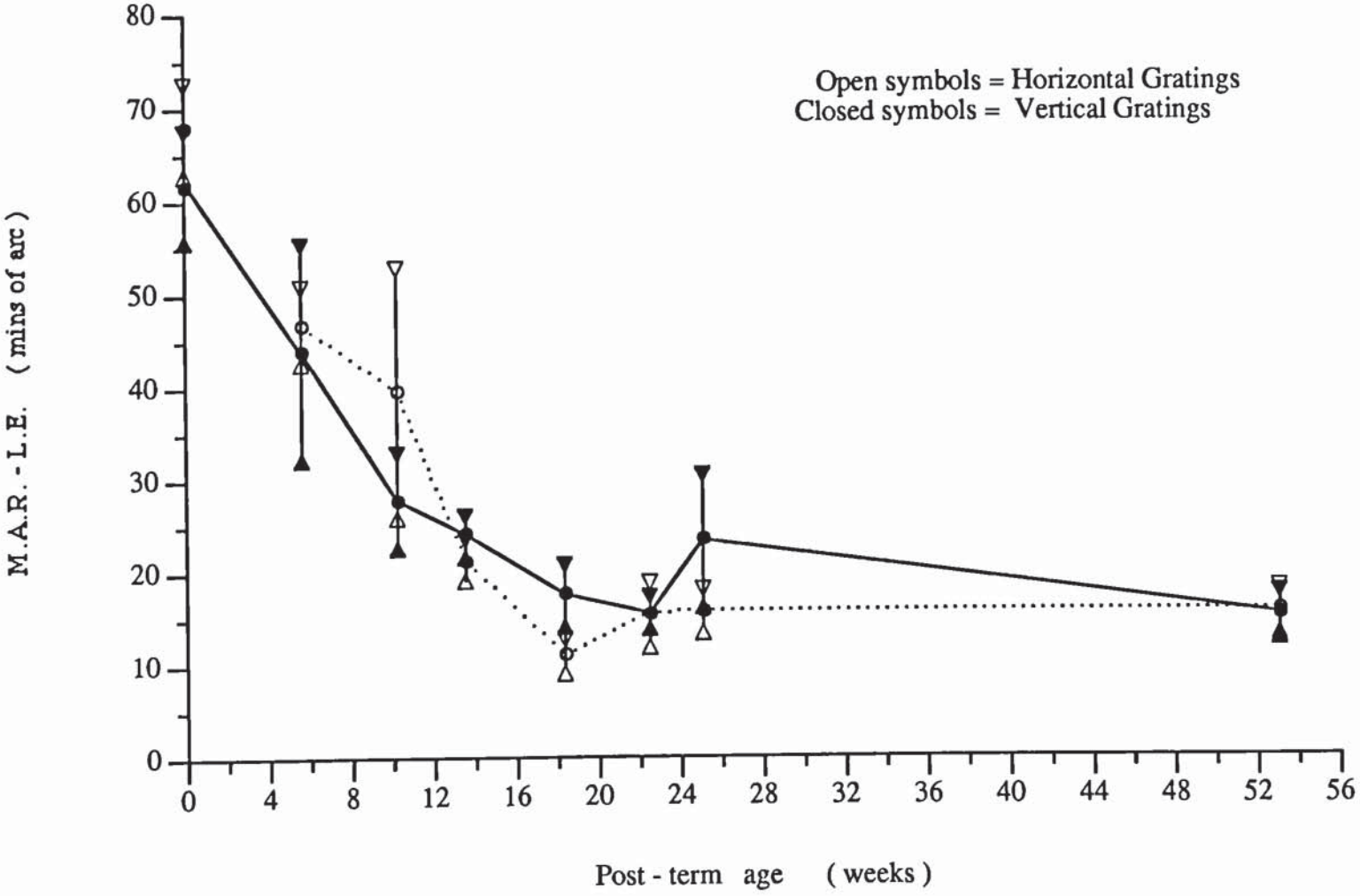


Figure 4.6 Group averaged left eye vertical and horizontal grating minimum angle of resolution (M.A.R.) age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.8.

4.2.2 Combined ("mean") right eye and left eye data

Analysis of paired data (Appendix 4B) revealed no significant variation in acuity development for vertical and horizontal gratings (apart from for one anaysis - the right eye data of the three month age group). For this reason "mean" right eye M.A.R. and "mean" left eye M.A.R. values were computed by combining vertical and horizontal data as previously described for the binocular results. Group averaged data thus obtained is presented in Table 4.9. This data is presented graphically in Figure 4.7.

Table 4.9 Combined (vertical and horizontal grating) "mean" right and left eye data; M.A.R. means and standard errors for each of eight age groups. No data was obtained at one month. Values are in minutes of arc.

Age Group (months)	Right Eye Mean	(S.E.)	Left Eye Mean	(S.E.)
Newborn	62.0	(4.8)	62.3	(5.5)
1	-	-	-	-
2	34.9	(8.8)	44.7	(8.1)
3	33.4	(5.1)	28.0	(4.9)
4	21.3	(2.5)	23.9	(2.2)
5	14.5	(2.6)	17.3	(3.5)
6	18.6	(3.6)	16.2	(2.0)
7	16.4	(1.9)	20.4	(4.4)
12	13.4	(1.3)	15.3	(1.8)

4.2.3 "Mean" monocular data

In accordance with expectations it is evident that acuity development trends for the right and left eye are similar. Monocular data has therefore been summarized by alternately selecting "mean" right eye or "mean" left eye data where both values were available or either value when only one had been established. The group averaged data derived from this computation is presented in Table 4.10 and is plotted in Figure 4.8. The original data has also been reprocessed to provide an equivalent cycles per degree version of these acuity norms which is presented in the summary relating to this chapter (Table 7.2 and Figure 7.2, section 7.2.1).

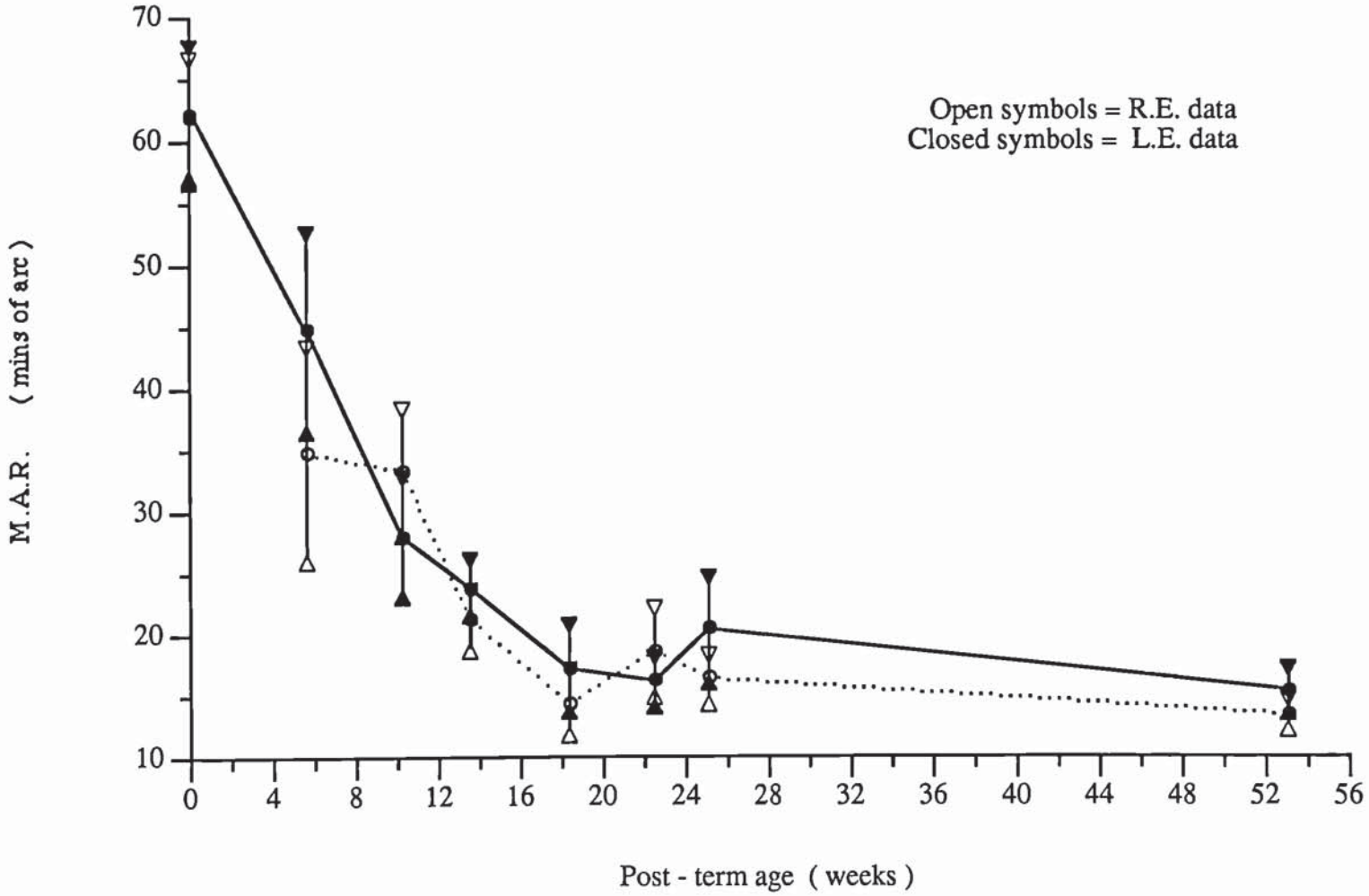


Figure 4.7 Group averaged "mean" right eye and "mean" left eye minimum angle of resolution age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.9.

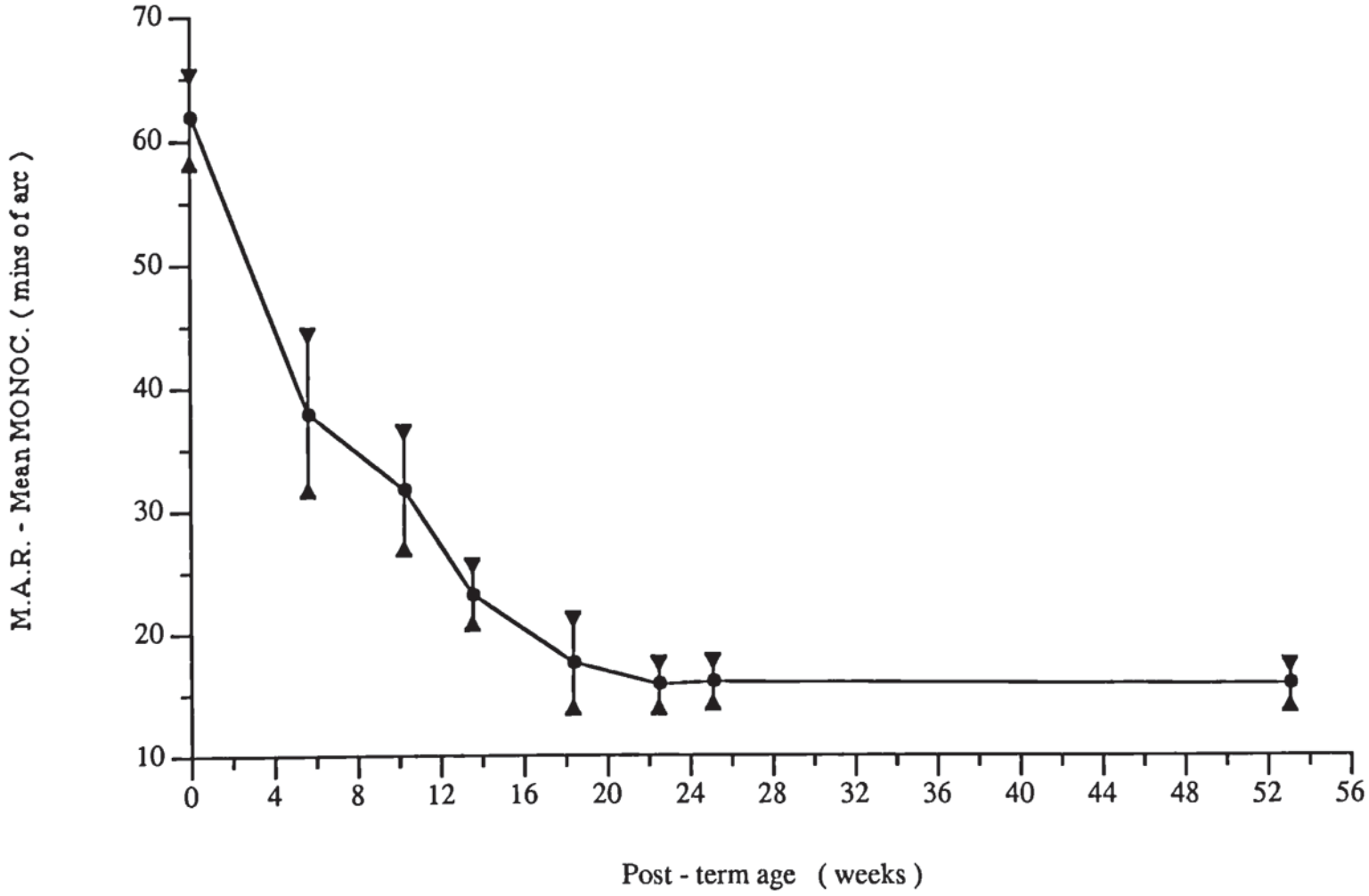


Figure 4.8 Group averaged "mean" monocular minimum angle of resolution age norms. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.10.

Table 4.10 Combined "mean" (right eye or left eye) monocular data; M.A.R. means, S.D. and group S.E. for each of eight age groups. No data was obtained at one month. Values are in minutes of arc.

Age Group (months)	Mean	S.D.	S.E.
Newborn	61.9	22.1	3.5
1	-	-	-
2	38.1	19.1	6.4
3	31.8	19.6	4.8
4	23.2	12.1	2.4
5	17.6	10.5	3.5
6	15.8	7.1	1.8
7	16.1	6.5	1.7
12	15.8	4.7	1.6

4.3 Interocular acuity differences

An interocular visual acuity ratio was calculated for all infants completing both right eye and left eye acuity tests. The acuity difference was expressed as a ratio (in octaves) to ensure that the measure was insensitive to absolute spatial frequency values (which vary with age). An octave is a doubling or halving of spatial frequency e.g. 5 to 10 cycles/degree. Individual "mean" right and "mean" left eye M.A.R. values were first converted to acuity values in cycles per degree by substitution in the formula:

$$\text{Acuity (Cycles/degree)} = 30/\ \text{M.A.R.(mins of arc)}.$$

The interocular acuity ratio of each infant was then found by substitution into:

$$\text{Acuity difference (Octaves)} = 1.44 \log_n \text{(R.E./L.E.Acuity Ratio)}$$

This computation produced a positive value whenever right eye acuity was better than left eye acuity and a negative value when the reverse was the case. All values were converted to their positive equivalent. This data is plotted versus post - term age in Figure 4.9. Acuity differences were generally not in excess of one octave. Excluding newborns 12.5 percent of infants (8 of 64), had differences of above one octave and only 3.1 percent (2 infants) had differences exceeding 1.5 octaves. Statistical analysis of all the available data (including newborn and one year olds) demonstrated a significant linear relationship between the two variables ($r = 0.25$; d.f. 1,64; $p = 0.05$). Group mean data is presented in Table 4.11 and plotted in Figure 4.10. This figure shows that the average interocular acuity difference score declined from 1.3 octaves at birth to around 0.5 octaves during months four to seven reaching about 0.4 octaves by 12 months.

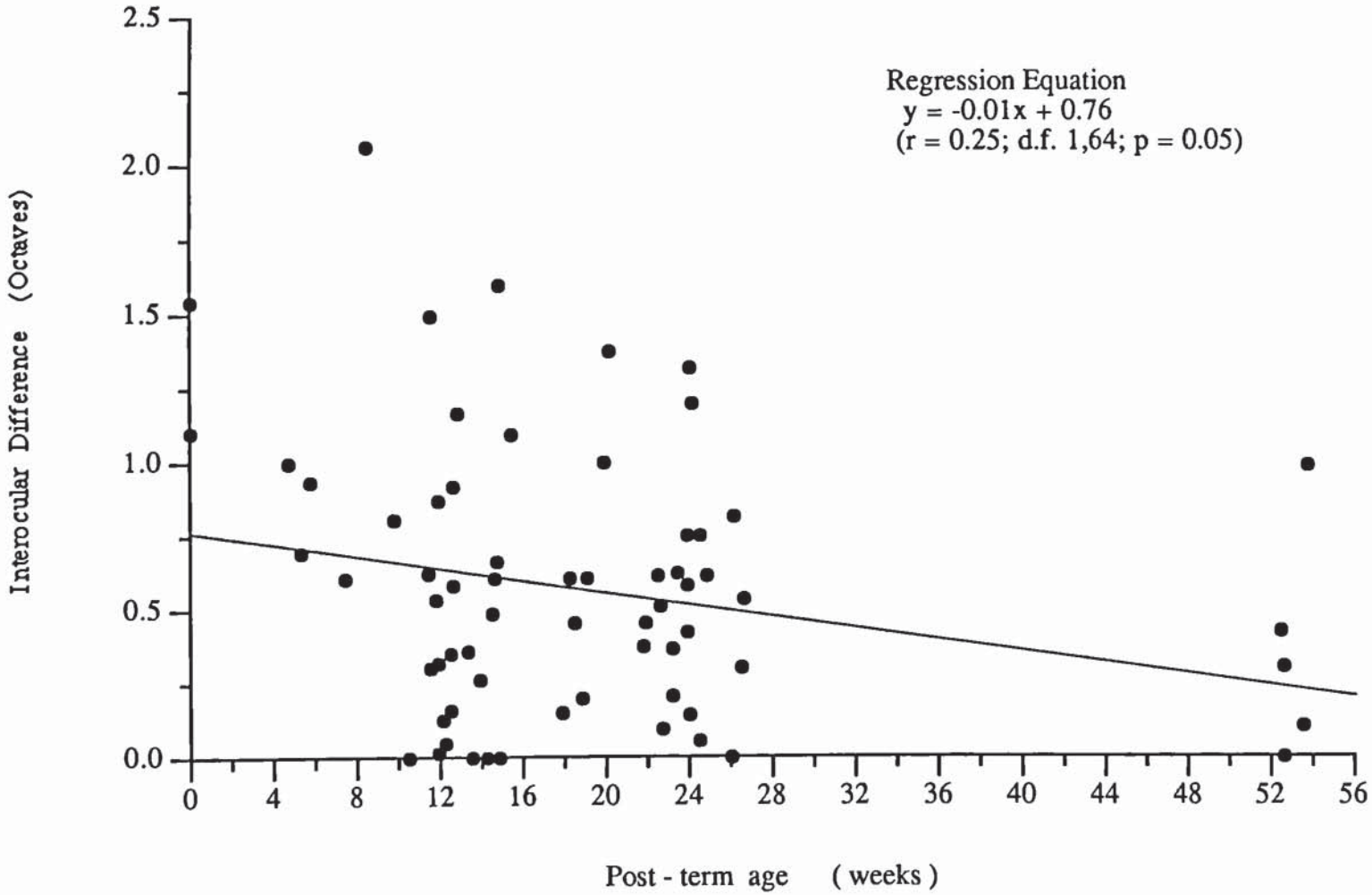


Figure 4.9 Scatterplot showing interocular acuity differences found in normal infants plotted versus their post-term ages (weeks). Difference values are expressed in octaves. All available newborn and follow up data is included (65 observations).

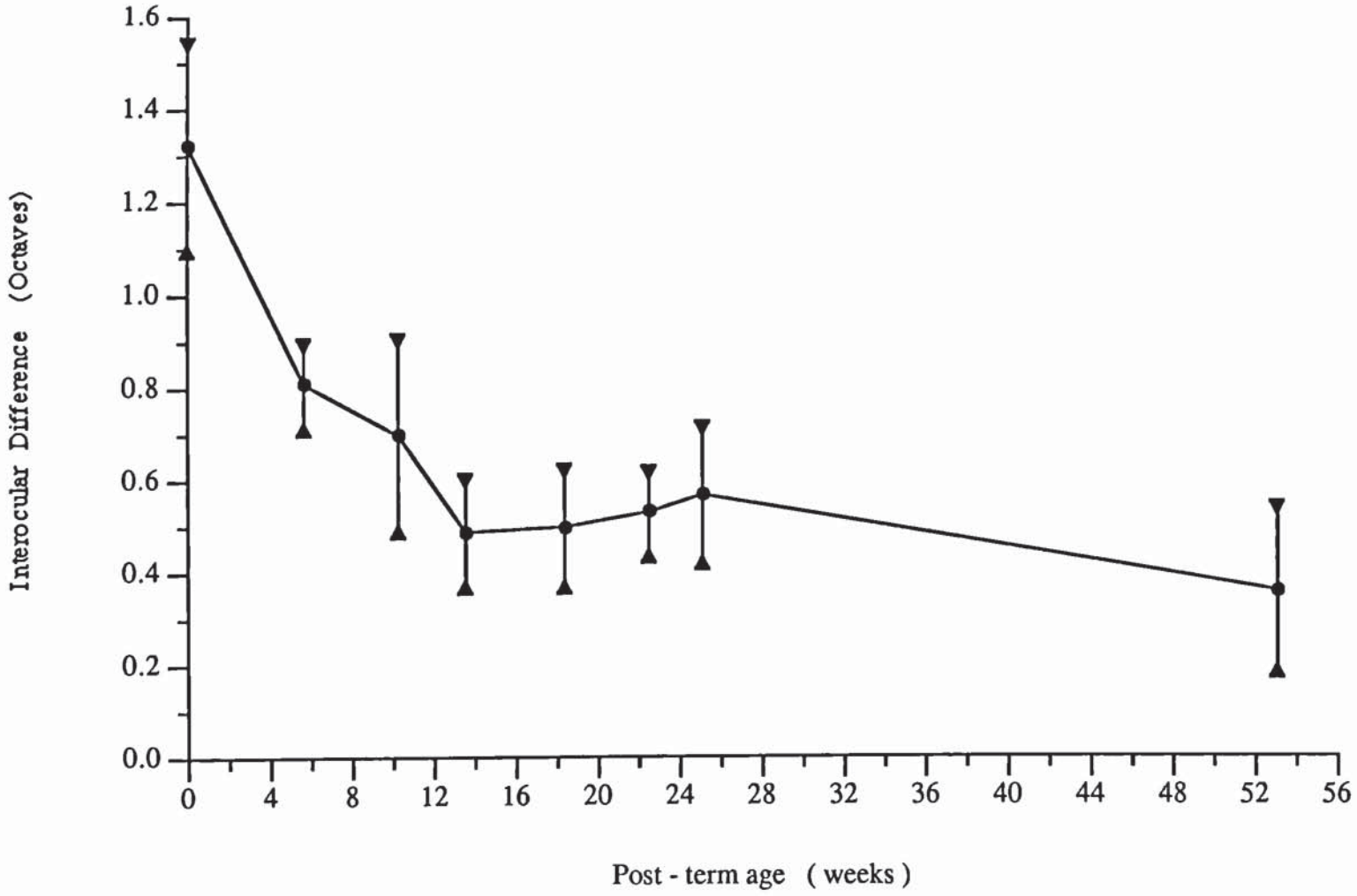


Figure 4.10 Group mean interocular acuity differences for the eight age categories at which data was obtained. Vertical bars indicate 2 SEM. Numerical values are provided in Table 4.11. The average interocular acuity difference score declined from 1.3 octaves at birth to about 0.4 octaves by one year.

Table 4.11 Interocular acuity difference (octaves) means, S.D. and group S.E. for each of eight age groups. No data was available at one month.

Age Group (months)	Sample Size	Mean	S.D.	S.E.
Newborn	2	1.32	0.22	0.22
1	0	-	-	-
2	4	0.81	0.16	0.09
3	10	0.70	0.62	0.21
4	17	0.49	0.46	0.11
5	6	0.50	0.28	0.13
6	12	0.53	0.31	0.09
7	10	0.57	0.44	0.15
12	5	0.36	0.35	0.17

4.4 Monocular : binocular acuity comparisons

Group averaged data for both binocular and monocular acuity versus post-term age is presented in Figure 4.11. It is clear from this initial comparison that there is a tendency for lower acuity values to be obtained monocularly than during binocular testing. This tendency has been investigated further by analysing paired binocular and monocular data from individual subjects i.e. from infants completing both tests. Two methods of data analysis have been used. Paired t-tests have been used to evaluate the significance of differences between "mean" monocular and "mean" binocular acuity. Twelve newborn infants (of 57 tested) completed binocular testing following successful monocular tests. The raw and group averaged data (mean values) of the newborn sample is presented in Table 4.12. Averaged data for follow-up age groups is shown in Table 4.13 (raw data is provided in Appendix 4C). Binocular findings were superior to monocular at all ages tested except 12 months. Table 4.14 summarises the statistical findings (student t-tests, paired samples). The finding of better binocular than monocular acuity reached significance for the newborn, three, four and seven month samples and for the overall follow-up sample. The finding of higher monocular acuity at twelve months may have been artifactual due to the order of testing (monoculars first) and did not reach significance.

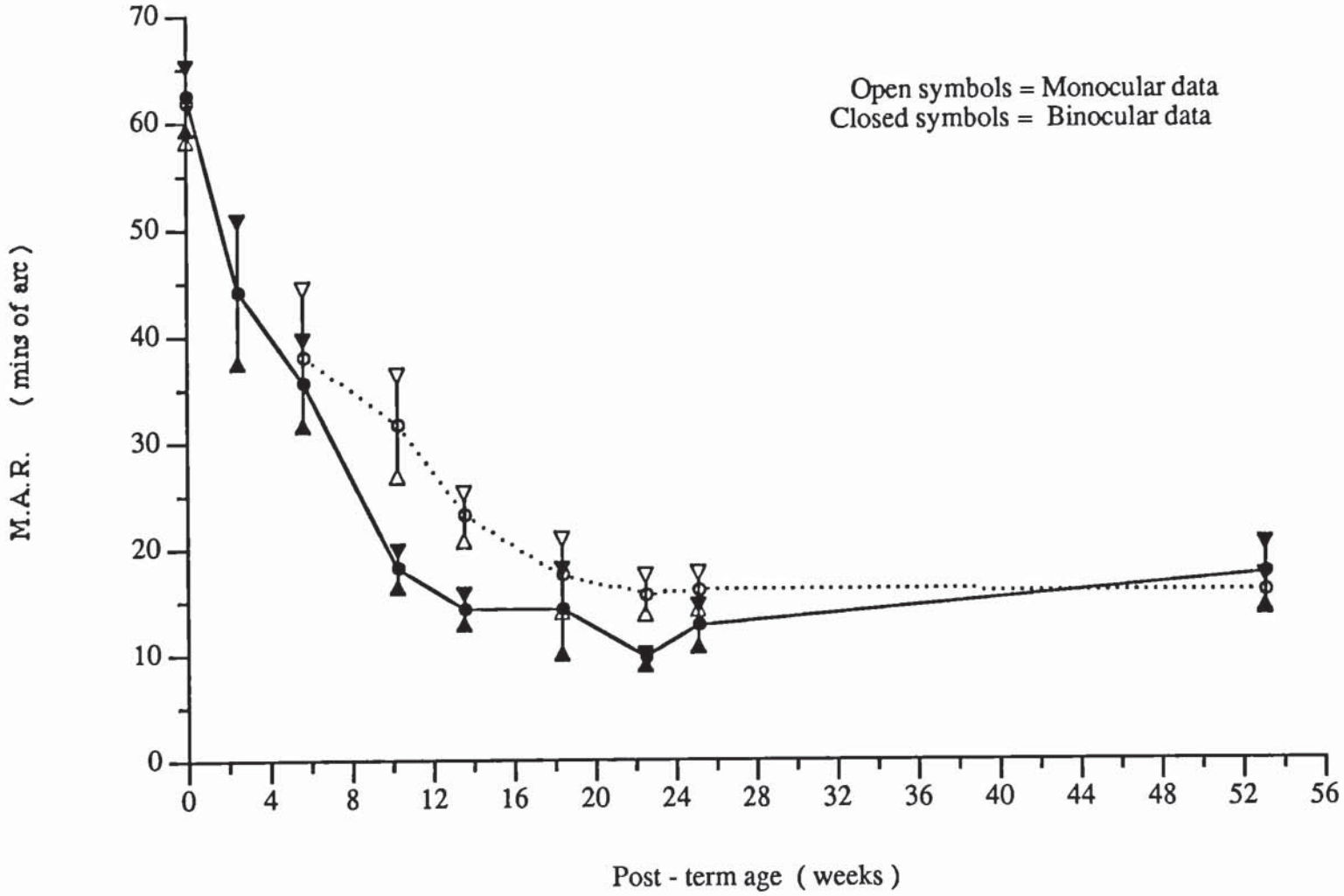


Figure 4.11 Group averaged binocular and monocular minimum angle of resolution age norms (from "mean" data). Vertical bars indicate 2 SEM. There is a tendency for lower acuity values to be obtained during monocular testing. This is most obvious at around three to four months post-term. (Numerical values are provided in Table 4.6 and 4.10).

Table 4.12 Paired monocular and binocular data of 12 newborn subjects completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Subject	M.A.R. (Mins of arc)	
	Mean Monocular	Mean Binocular
1 (92)	43	33
2 (94)	68	34
3 (95)	99	58
4 (110)	57	34
5 (118)	41	52
6 (128)	52	26
7 (130)	34	52
8 (134)	73	52
9 (136)	34	63
10 (163)	114	66
11 (164)	73	23
12 (170)	34	34
Mean	60.2	43.9
S.D.	25.2	14.2
S.E.	7.6	4.3

Table 4.13 Averaged monocular and binocular data of follow-up subjects completing both tests. Means and standard errors are presented. Binocular findings were superior to monocular at all ages except 12 months.

Age Group	n	M.A.R. (Mins of arc)	
		Mean Monocular	Mean Binocular
2	9	39.1 (7.4)	30.7 (5.6)
3	16	33.3 (5.4)	18.5 (2.6)
4	19	24.9 (3.1)	13.0 (1.3)
5	4	23.8 (9.1)	14.3 (4.6)
6	7	12.1 (1.8)	9.8 (0.6)
7	10	18.0 (2.4)	12.8 (2.1)
12	6	16.2 (2.7)	20.4 (4.7)
All Sample	71	25.6 (2.0)	16.8 (1.3)

Table 4.14 Statistical significances for group mean monocular versus binocular M.A.R. data. The superiority of binocular over monocular findings was significant for the newborn, three, four and seven month samples and for the overall follow-up sample. The finding of higher monocular data at twelve months did not reach significance.

Age Group	Comparison of Mean Monoc and Mean Binoc M.A.R.		
	t - stat	d.f.	sig
Newborn	2.16	11	$p = 0.05$
2	1.35	8	not sig.
3	4.44	15	$p < 0.001$
4	4.00	18	$p = 0.001$
5	2.39	3	not sig.
6	1.37	6	not sig.
7	2.29	9	$p = 0.05$
12	-1.58	5	not sig.
Follow-up Sample	5.68	71	$p < 0.001$

Binocular : monocular acuity differences have additionally been expressed in octaves to investigate whether any disparity varies in magnitude during the first year of life. Right eye and left eye data has been assessed separately. Individual "mean" right , "mean" left eye and "mean" binocular M.A.R. values were first converted to acuity values in cycles per degree by substitution in the formula:

$$\text{Acuity (Cycles/degree)} = 30/\ \text{M.A.R.(mins of arc)}.$$

The binocular : monocular acuity ratio's of each infant were then found by substitution into the following equations:

$$\text{Acuity difference (Octaves)} = 1.44 \log_n \text{(Binoc/R.E.Acuity Ratio)}$$
$$\text{Acuity difference (Octaves)} = 1.44 \log_n \text{(Binoc/L.E.Acuity Ratio)}$$

These computations produce positive values whenever binocular acuity is better than monocular acuity and negative values when the reverse is the case. This data is plotted versus post-term age in Figure 4.12. Most of the data (with the exception of the twelve month sample) falls between 0.0 and +1.50 octaves. Group averaged data is presented in Tables 4.15 and 4.16 and illustrated graphically in Figure 4.13. The graph does not show any pronounced age related trends but suggests that the disparity between binocular and monocular acuity findings is highest during post-term months three, four and five (being of the order of 0.8 octaves during this time).

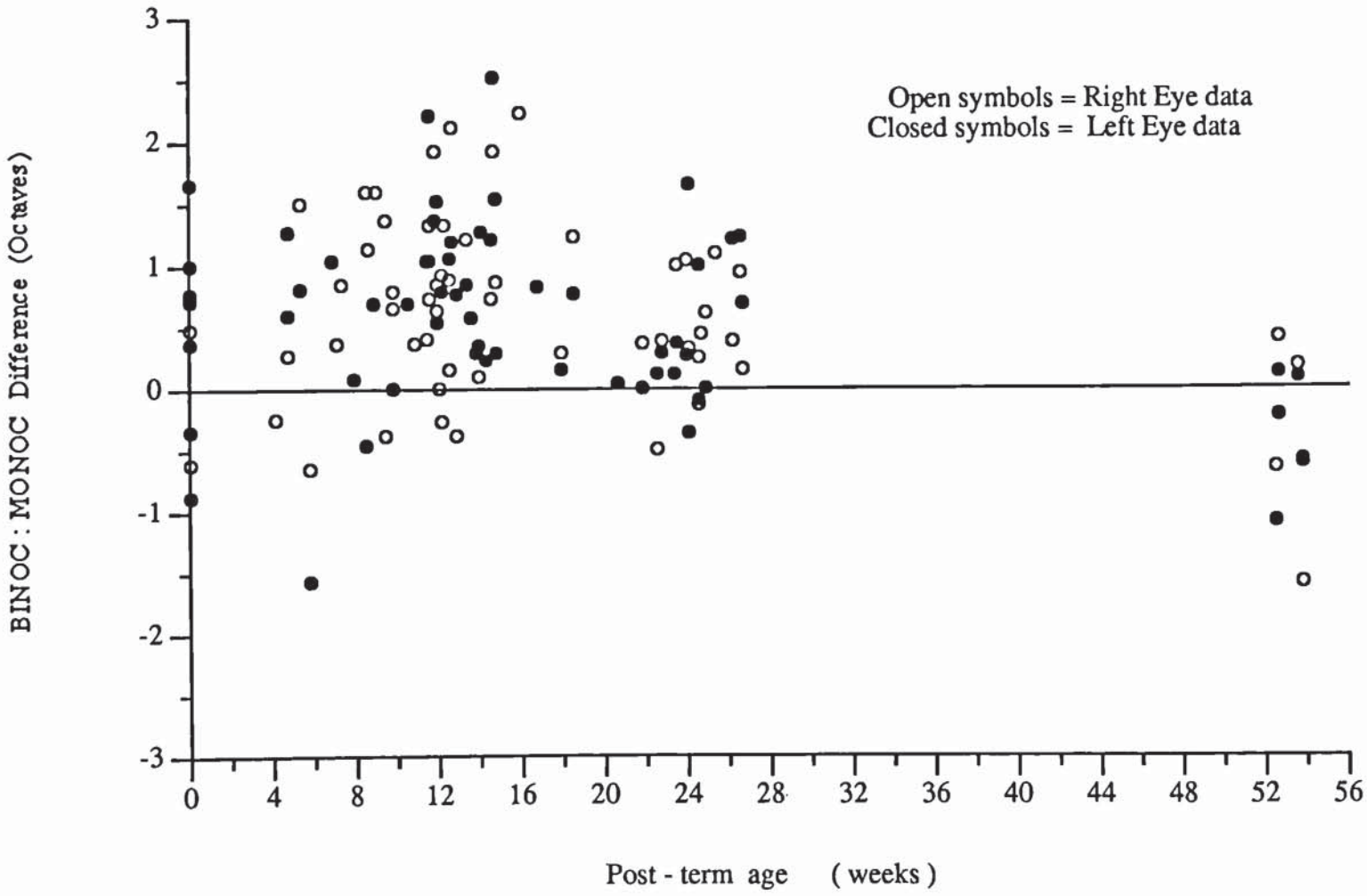


Figure 4.12 Scatterplot showing binocular : monocular acuity differences found in normal infants plotted versus their post-term ages (weeks). Right eye and left eye data is shown separately. Difference values are expressed in octaves. All available newborn and follow up data is included (65 right eye and 61 left eye observations). Positive values indicate better binocular than monocular acuity

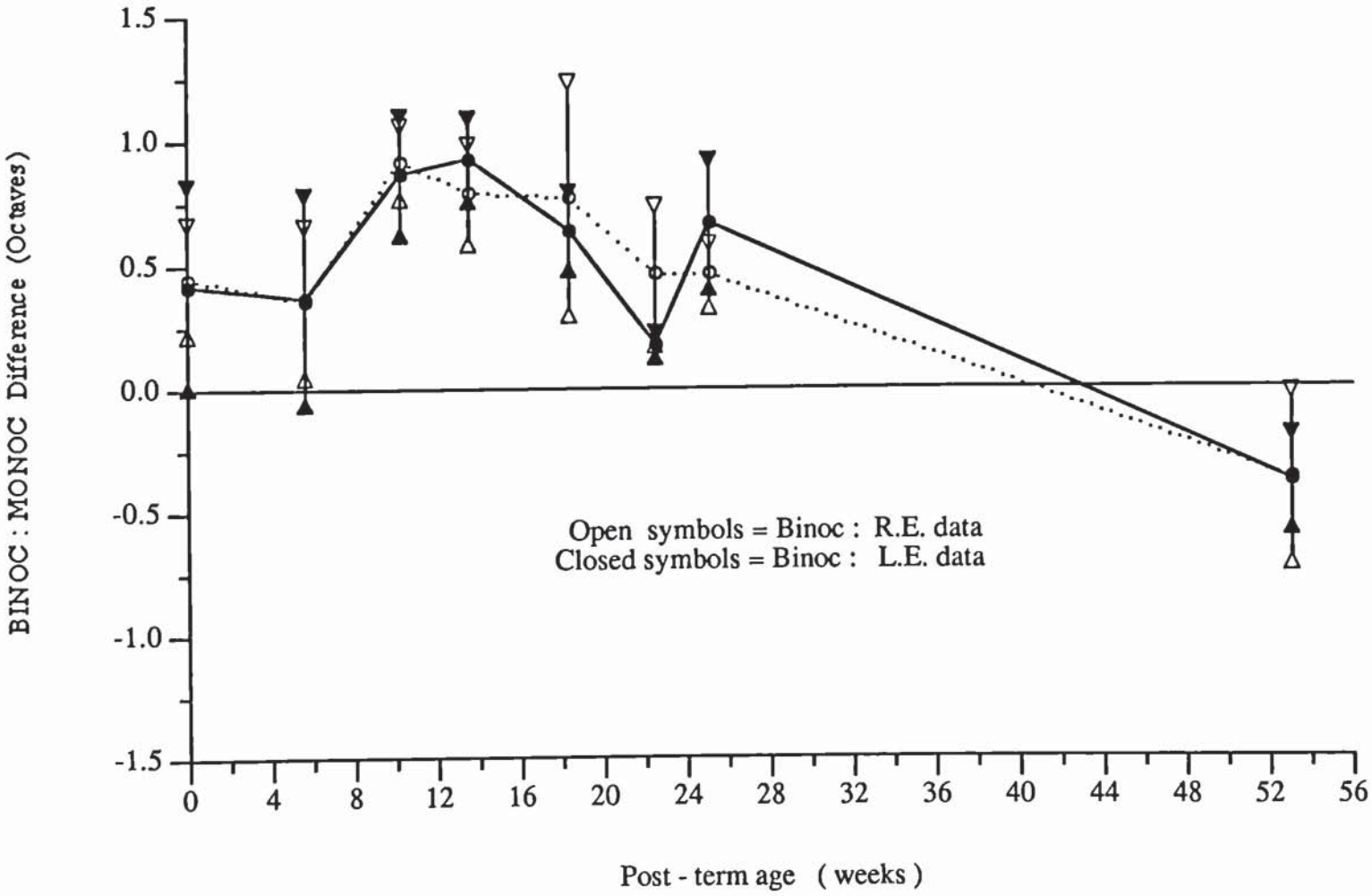


Figure 4.13 Group mean binocular : monocular acuity differences for the eight age categories at which data was obtained. Positive values represent better binocular than monocular acuity. Vertical bars indicate 2 SEM. Numerical values are provided in Tables 4.15 and 4.16. The data does not show any pronounced age related trends but suggests that the disparity between binocular and monocular acuity findings is highest (≈ 0.8 octaves) during post-term months three to five.

Table 4.15 Averaged binocular : right eye acuity differences (octaves) for each of eight age groups. No data was available at one month.

Age Group (months)	Sample Size	Mean	S.D.	S.E.
Newborn	7	0.45	0.57	0.23
1	0	-	-	-
2	6	0.36	0.70	0.31
3	15	0.92	0.57	0.15
4	16	0.79	0.79	0.20
5	2	0.77	0.47	0.47
6	5	0.46	0.56	0.28
7	9	0.46	0.36	0.13
12	5	-0.36	0.71	0.35

Table 4.16 As Table A4.15 for left eye data.

Age Group (months)	Sample Size	Mean	S.D.	S.E.
Newborn	6	0.42	0.92	0.41
1	0	-	-	-
2	6	0.37	0.95	0.42
3	10	0.87	0.72	0.24
4	14	0.93	0.60	0.17
5	4	0.64	0.28	0.16
6	7	0.18	0.13	0.05
7	8	0.67	0.69	0.26
12	6	-0.38	0.43	0.19

4.5 Longitudinal data

A disadvantage associated with the presentation of group averaged acuity data is that it inevitably masks changes occurring in individual subjects. Information regarding acuity development in longitudinally-assessed normal infants is of practical importance in relation to the monitoring of acuity in clinical patients e.g. those undergoing occlusion therapy. For this reason the acuity data obtained from nine individual infants that were assessed on five or more occasions was studied. The "mean" binocular, right eye and left eye M.A.R. values of these infants are presented in Table 4.17. An asterisk has been used to denote occasions upon which an apparent decrease in acuity performance was found. Only one of the nine infants (no. 9) did not suffer any acuity set-back. Apparent set-backs in binocular acuity were noted for six infants; four infants demonstrated set-backs in development of right eye acuity and one infant did so for the left eye. It is likely that further set-backs in acuity development would have been noted if more complete data was available. Apart from subject number five no set-back in acuity was noted for any infant until after 13 weeks post-term.

Table 4.17 Acuity development in nine infants assessed on five or more occasions. P - T = post-term age, number in brackets = true subject number (more details are provided in the text).

SUBJECT	P-T AGE (Weeks)	MEAN BINOC	M.A.R. (mins of arc) RIGHT	LEFT
1 (18)	Newborn	-	-	-
	0	-	-	-
	7.43	-	19	29
	12.43	9	10	-
	18.43	11 *	-	19
	23.43	8.5	17 *	11
2 (20)	Newborn	99	-	-
	4.86	58.25	-	-
	9.43	19.5	-	-
	13.86	30 *	-	-
	26.43	8	16	19
3 (28)	Newborn	73	-	-
	5.29	30.75	82.5	51
	11.29	23.75	-	-
	14.86	-	12.5	38
	19.86	-	17.5 *	8.75
4 (34)	Newborn	50	-	-
	4.57	44.5	-	-
	9.43	18.5	19	-
	14.43	9	15	21
	18.43	11 *	26 *	19
	24.43	13.75 *	13.5	13.5
5 (46)	Newborn	24	-	-
	4.71	31.75 *	-	42.5
	9.71	10.75	16.5	-
	13.71	16 *	-	21
	21.71	8.5	11	8.5
6 (50)	Newborn	44	-	-
	6.86	16.75	-	-
	10.86	10	-	-
	15.86	11 *	52	-
	21.86	-	19	26
7 (111)	Newborn	99	-	-
	8.43	11	33.5	8
	14.29	16 *	19	19 *
	18.29	-	8	12.25
	23.29	8	-	8.75
8 (113)	Newborn	30	-	-
	3.43	26	-	-
	10.43	16	26	26
	15.43	-	11	23.5
	18.86	-	11.5 *	13
9 (123)	Newborn	46	-	-
	5.43	43	-	-
	9.43	22.5	57.5	-
	15.43	-	14.5	-
	18.43	-	-	19

4.6 Success rate of preferential looking test

Newborn and follow-up data has been separately processed, since newborns (who outnumber the remaining sample) were clearly considerably more difficult to test than older infants. Most of the newborn sample completed only one acuity test and no infant participated in more than three acuity tests. On follow-up visits an attempt was made to establish up to six distinct acuity estimates (horizontal or vertical gratings presented to the right eye, left eye and binocularly) during each test session. The numbers of infants within each age category completing various tests are summarised in Table 4.18. Table 4.19 summarises the numbers of infants contributing particular data after the results had been combined to provide "mean" right eye, "mean" left eye, "mean" binocular and representative "mean" monocular acuity scores.

Table 4.18 Numbers of infants within each age category providing M.A.R. data under six distinct testing conditions.

Age Group	Sample	Numbers of infants completing various PL tests					
(months)	Size	B(V)	B(H)	R(V)	R(H)	L(V)	L(H)
Newborn	174	124	38	22	3	18	2
1	7	6	2	0	0	0	0
2	22	21	13	6	1	5	2
3	29	26	18	15	7	12	4
4	30	22	10	21	7	20	13
5	10	4	2	6	3	10	4
6	16	6	5	12	8	16	12
7	15	8	10	13	11	12	10
12	18	8	9	6	4	9	6

Table 4.19 Numbers of infants in each age group providing "mean" right eye (R.E.), "mean" left eye (L.E.), "mean" monocular and "mean" binocular M.A.R. data.

Age Group (months)	Numbers of infants contributing specific acuity data			
	Mean R.E.	Mean L.E.	Mean Monoc.	Mean Binoc.
Newborn	22	20	40	127
1	0	0	0	6
2	7	7	10	21
3	16	12	18	27
4	23	21	27	22
5	6	10	10	4
6	12	16	16	7
7	13	12	15	10
12	6	9	10	12

4.6.1 Newborn infants

Newborn infants were subdivided into two groups - the initial 88 infants who were deemed testable provided not deeply asleep and a selected group of 86 infants that appeared reasonably awake when approached on the ward. No infant completed more than three acuity tests. Table 4.20 summarises the numbers and percentages of infants that completed one, two or three acuity estimates for the unselected, selected and overall newborn population tested. Appreciably more infants in the selected rather than unselected sample completed more than one test. Plate 4.1 shows a newborn infant participating in preferential looking testing.

Table 4.20 Testability of newborn infants - selected and unselected samples. Numbers (and percentages) providing M.A.R. values.

Sample	Sample Size	No. (&%) contributing specific acuity data		
		1 estimate	2 estimates	3 estimates
Unselected	88	60 (68.2)	10 (11.4)	1 (1.1)
Selected	86	40 (46.5)	39 (45.3)	2 (2.3)
Total	174	100 (57.5)	49 (28.2)	3 (1.7)

Plate 4.1

Newborn participating in preferential looking test
(grating is mostly obscured by photographic flash).

Cumulative figures have been calculated from the data in Table 4.20. These values are provided in Table 4.21 and the data is illustrated in Figures 4.14 and 4.15. Within the unselected sample 80.7% of infants were testable but only 12.5% successfully completed more than one test. In the selected sample 94.2% completed at least one test and 47.7% of these provided two or more successful tests. Considering the newborn population as a whole 87.4% were testable; 29.9% completed two or more tests but only 1.7% satisfactorily completed three tests.

Table 4.21 Testability of newborn infants - selected and unselected samples. Numbers (and percentages) providing M.A.R. values. Cumulative values.

Sample	Sample Size	No. (&%) contributing specific acuity data		
		≥ 1 estimate	≥ 2 estimates	3 estimates
Unselected	88	71 (80.7)	11 (12.5)	1 (1.1)
Selected	86	81 (94.2)	41 (47.7)	2 (2.3)
Total	174	152 (87.4)	52 (29.9)	3 (1.7)

4.6.2 Follow - up sample

Infants within follow-up samples completed up to six acuity tests per session. Table 4.22 summarises the numbers of infants within each age group completing particular numbers of acuity tests. Table 4.23 shows the same data expressed as a percentage of the total number of infants in each age category. Cumulative percentage figures are given for the total follow-up sample. The percentage success data for the monthly age groups is illustrated in Figures 4.16 and 4.17. These figures demonstrate that the testability of the sample varied with age. During the first post-term month most infants completed only one test and no infant completed more than two. Most two month olds completed two tests and no infant finished more than four. From three months onwards at least some infants completed all six tests. Three and four month olds generally completed two tests, five month olds usually completed three, six month olds most often finished four and seven month olds most commonly completed either four or five tests. By twelve months infant interest and co-operation with testing had declined noticeably and this is reflected in the reduced success; most one year olds failed to complete more than two tests. The overall cumulative percentage success rate irrespective of age is illustrated in Figure 4.18. Ninety-eight percent of infants were testable and 50% completed at least three tests.

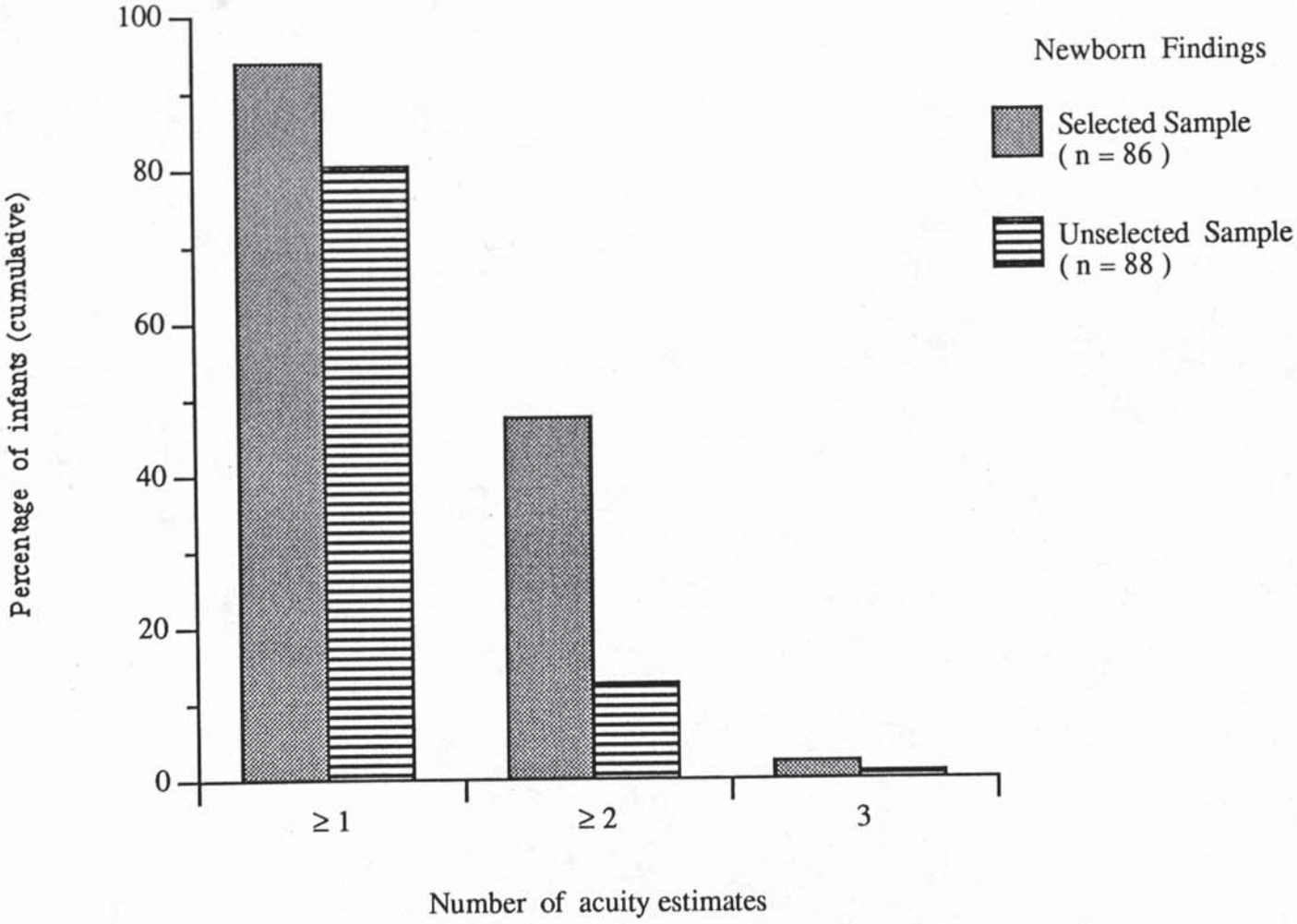


Figure 4.14 Test success rates shown by the selected and unselected newborn samples (86 and 88 infants respectively). Up to three acuity tests were performed. Improved performance was found for the selected sample; 94.2% cf. 80.7% were testable (i.e. ≥ 1 test) and this difference was emphasised in the proportion completing supplementary tests (47.7% cf. 12.5%). Full numerical values are provided in Table 4.21.

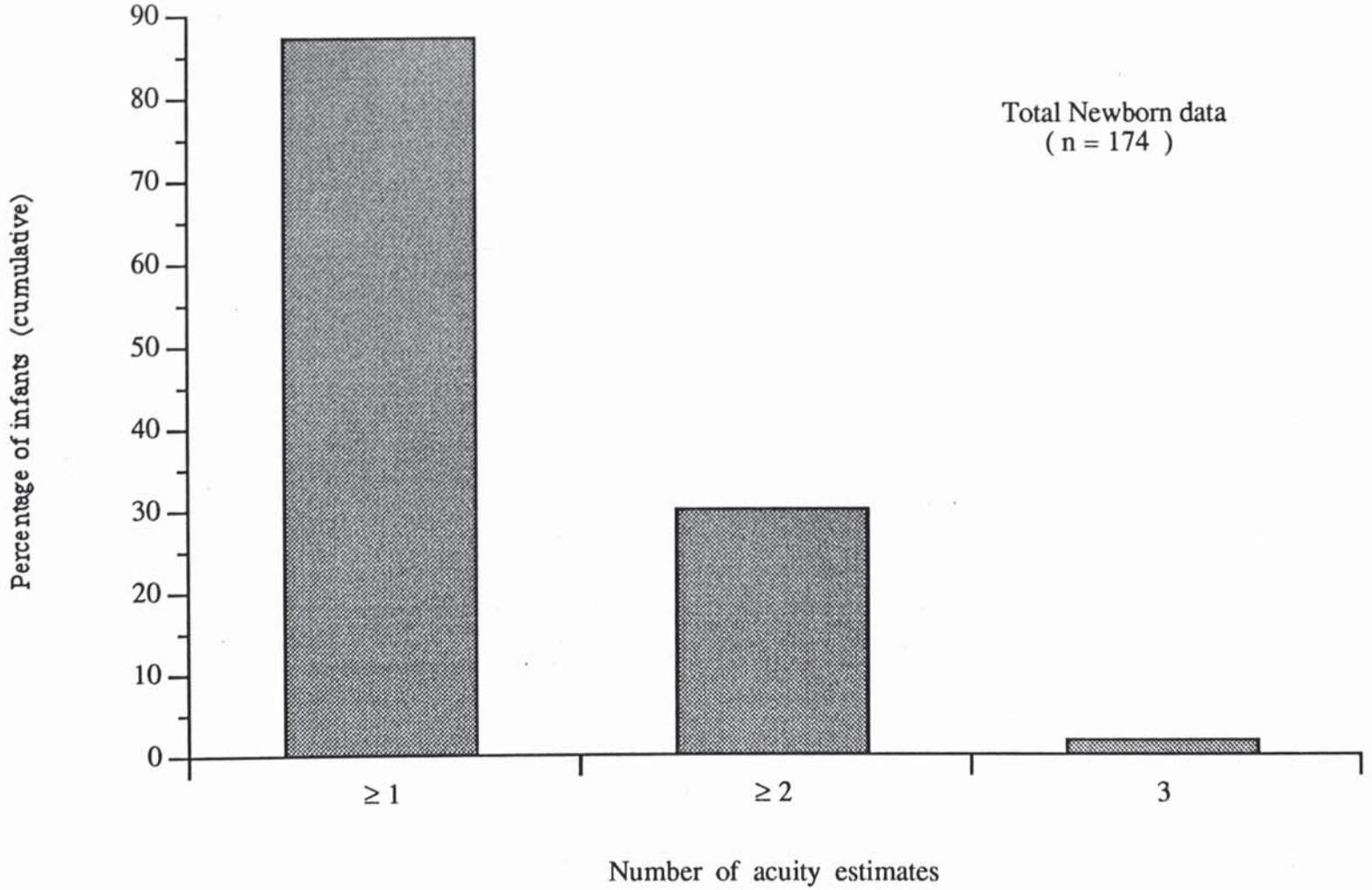


Figure 4.15 Overall success rate shown by the newborn sample (174 infants). Up to three acuity tests were performed. Infants were testable (at least one successful test) during 87.4% of test sessions but only 1.7% of sessions resulted in three completed tests. Full numerical values are provided in Table 4.21.

Table 4.22 Numbers of infants in each age group providing specific M.A.R. values (est. = estimate).

Age Group (months)	Sample Size	No. of infants contributing specific acuity data					
		1 est.	2 est.	3 est.	4 est.	5 est.	6 est.
1	7	4	2	0	0	0	0
2	22	4	13	2	3	0	0
3	29	4	10	8	3	2	2
4	30	2	11	8	3	3	3
5	10	1	3	4	1	0	1
6	16	1	2	3	6	3	1
7	15	0	2	2	4	4	3
12	18	5	6	1	0	2	2
Total	147	21	49	28	20	14	12
Cum. figs.		144	123	74	46	26	12

Table 4.23 Testability of infants in each age group (percentage).

Age Group (months)	Sample Size	Percentage of infants contributing specific acuity data					
		1 est.	2 est.	3 est.	4 est.	5 est.	6 est.
1	7	57.1	28.6	0.0	0.0	0.0	0.0
2	22	18.2	59.1	9.1	13.6	0.0	0.0
3	29	13.8	34.5	27.6	10.3	6.9	6.9
4	30	6.7	36.7	26.7	10.0	10.0	10.0
5	10	10.0	30.0	40.0	10.0	0.0	10.0
6	16	6.2	12.5	18.8	37.5	18.8	6.2
7	15	0.0	13.3	13.3	26.7	26.7	20.0
12	18	27.8	33.3	5.6	0.0	11.1	11.1
Total	147	14.3	33.3	19.0	13.6	9.5	8.2
Cum. figs.		98.0	83.7	50.3	31.3	17.7	8.2

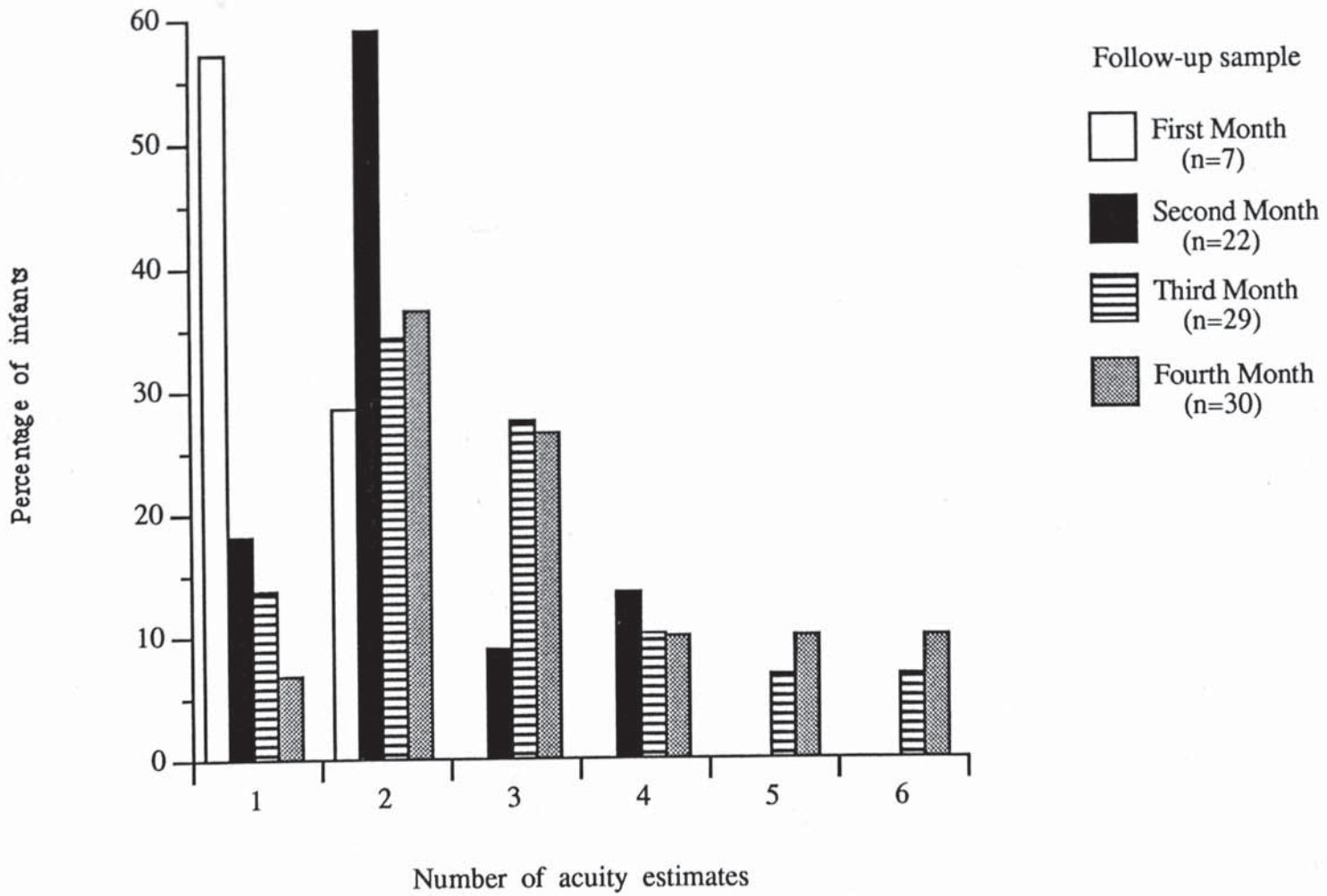


Figure 4.16 Percentages of infants within the one, two, three and four month age groups completing particular numbers of tests. Up to six tests were performed. Modal performance increased from one completed test at one month, to two tests between months two and four. Below three months no infant completed more than four tests. Numerical values are provided in Table 4.23.

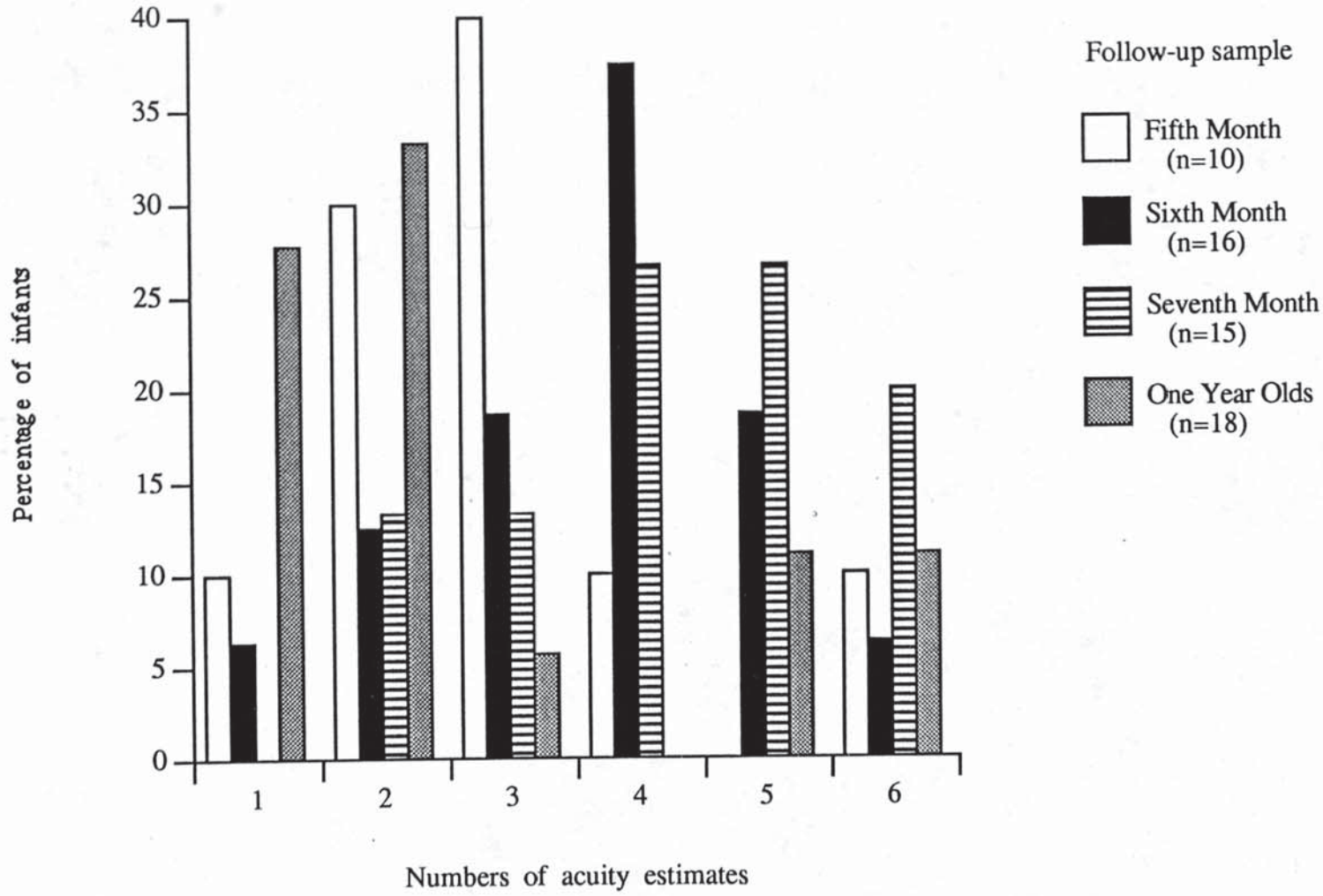


Figure 4.17 As Figure 4.16 for the five, six, seven and twelve month old age groups. Modal performance increased to three tests in month five, four tests in month six, four or five tests in month seven but dropped to two tests at one year. The two figures illustrate the consistent improvement in performance on the test occurring between one and seven months and the relative difficulty in testing one year olds. Numerical values are provided in Table 4.23.

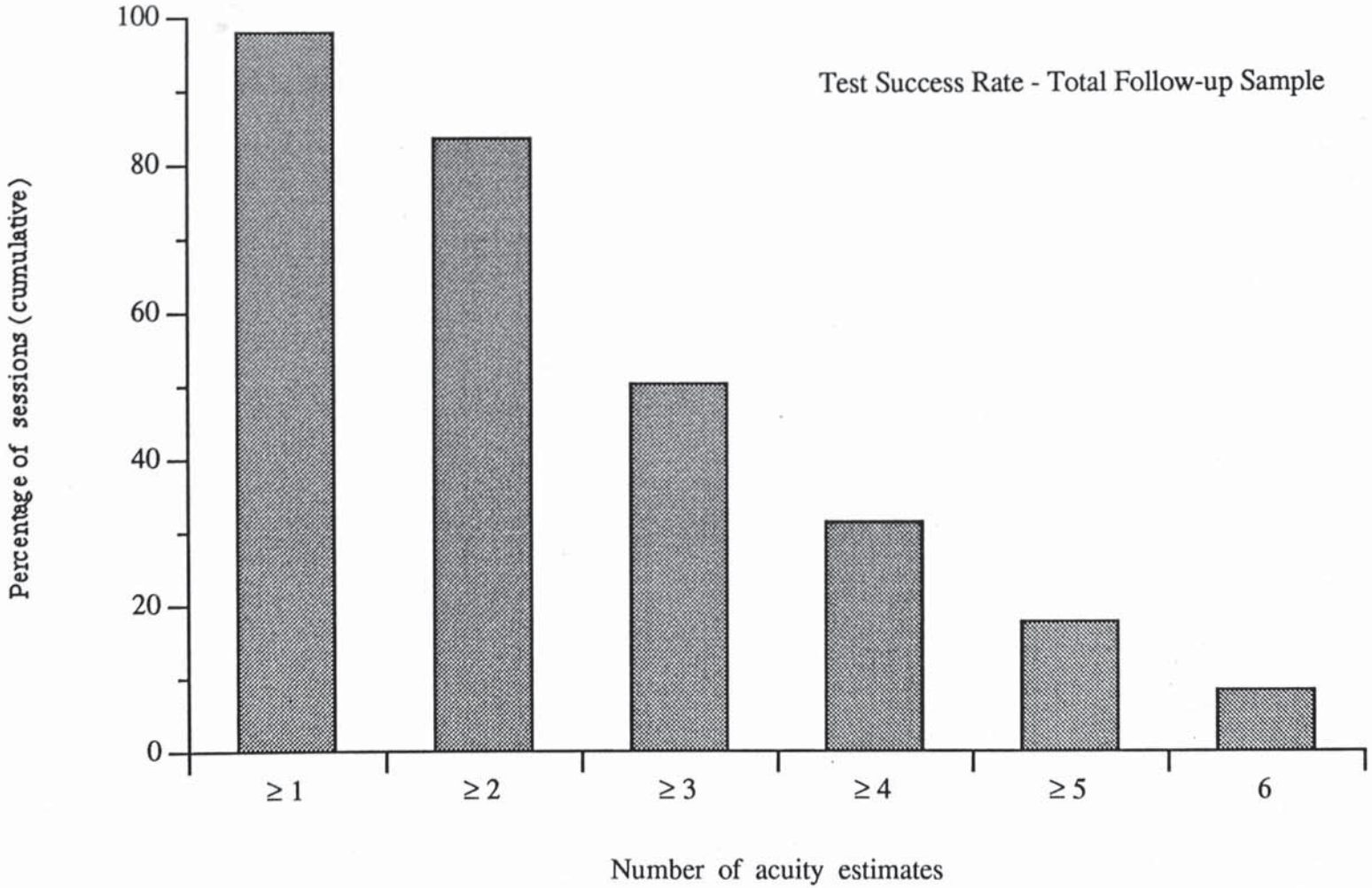


Figure 4.18 Overall success rate shown by the total follow-up sample (147 sessions, 87 infants). Up to six acuity tests were performed. Infants were testable during 98% of test sessions and 50% of sessions resulted in at least three completed tests. Full numerical values are provided in Table 4.23.

One difficulty produced by the use of two grating orientations in this study is that it cannot be inferred that an infant that completed three acuity tests would necessarily satisfactorily finish right eye, left eye and binocular tests if only one orientation was used. The success rate data was therefore re-evaluated to determine the numbers of infants completing right eye, left eye and binocular tests. In this analysis an infant completing tests using both grating orientations for a particular condition would only be credited with one test. It was therefore possible for each infant to complete up to three such acuity estimates. Table 4.24 summarises the number (and percentages) of infants within each age category completing one, two or three tests. The cumulative figures derived from this table are presented in Table 4.25. Figure 4.19 illustrates the cumulative data of the newborn sample and of the overall follow-up sample. Only 9.8% of newborns provided two distinct acuities whereas 63.3% of older infants contributed two or more such estimates and 28.6% completed all three. Figures 4.20 and 4.21 illustrate the cumulative findings within each monthly age group. Apart from the one month and twelve month age all infants completed at least one test. The percentage of infants completing two or more tests steadily increased from the second to seventh post-term month. In the latter age group 86.7% of the tested sample finished two or more tests and almost half (46.7%) completed three. Only a third of one year olds satisfactorily completed two or more tests.

Table 4.24 Numbers (and percentage) of infants in each age group providing distinct (right eye/left eye/binocular) M.A.R. values.

Age Group (months)	Sample Size	No. (&%) contributing specific acuity data		
		1 estimate	2 estimates	3 estimates
Newborn	174	135 (77.6)	17 (9.8)	0 (0)
1	7	6 (85.7)	0 (0)	0 (0)
2	22	12 (54.5)	7 (31.8)	3 (13.6)
3	29	12 (41.4)	8 (27.6)	9 (31.0)
4	30	5 (16.7)	14 (46.7)	11 (36.7)
5	10	2 (20.0)	6 (60.0)	2 (20.0)
6	16	2 (12.5)	9 (56.3)	5 (31.2)
7	15	2 (13.3)	6 (40.0)	7 (46.7)
12	18	10 (55.6)	1 (5.6)	5 (27.8)
Follow-up Sample	147	51 (34.7)	51 (34.7)	42 (28.6)

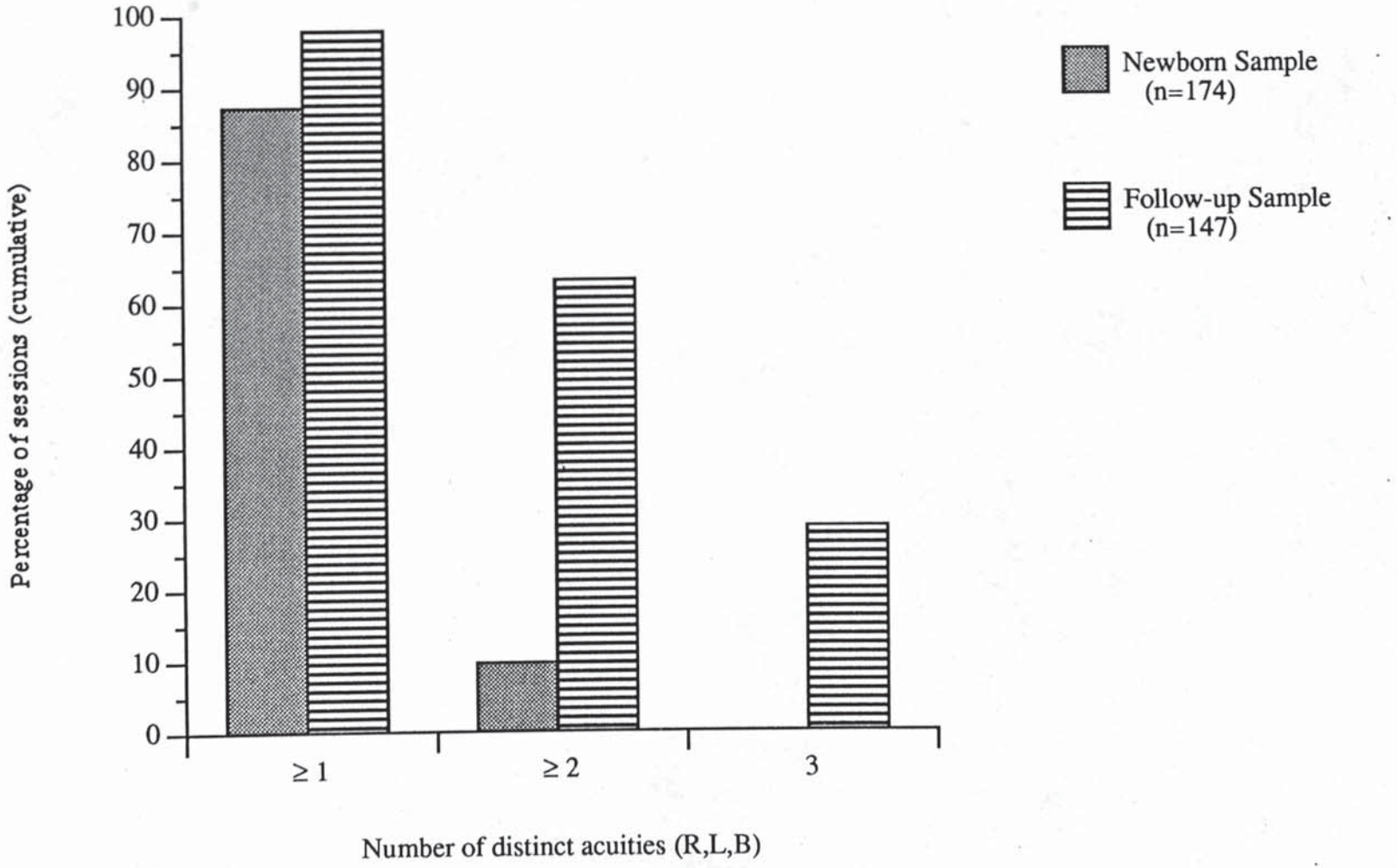


Figure 4.19 Percentages of sessions involving the newborn and total follow-up samples in which specific monocular (R.E. and/or L.E.) and/or binocular tests were completed. Infants completing tests using both vertical and horizontal grating orientations for a particular condition have only been credited with one test. This figure emphasises the difficulty in completing more than one test on newborns. Numerical values are provided in Table 4.25.

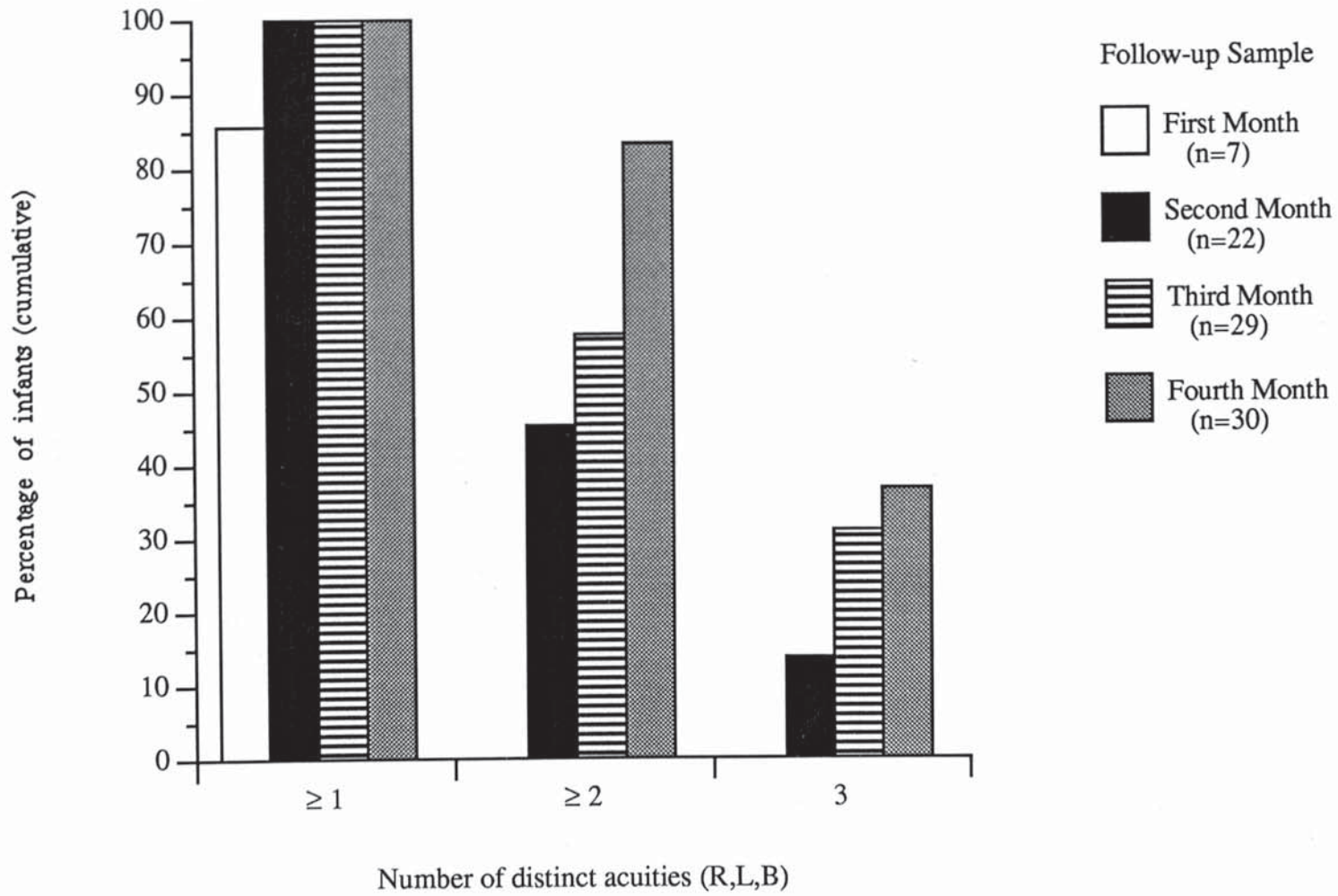


Figure 4.20 Percentages of infants within one, two, three and four month age groups completing specific monocular (R.E. and/or L.E.) and/or binocular tests. Infants completing tests using both vertical and horizontal grating orientations for a particular condition have only been credited with one test. Numerical values are provided in Table 4.25.

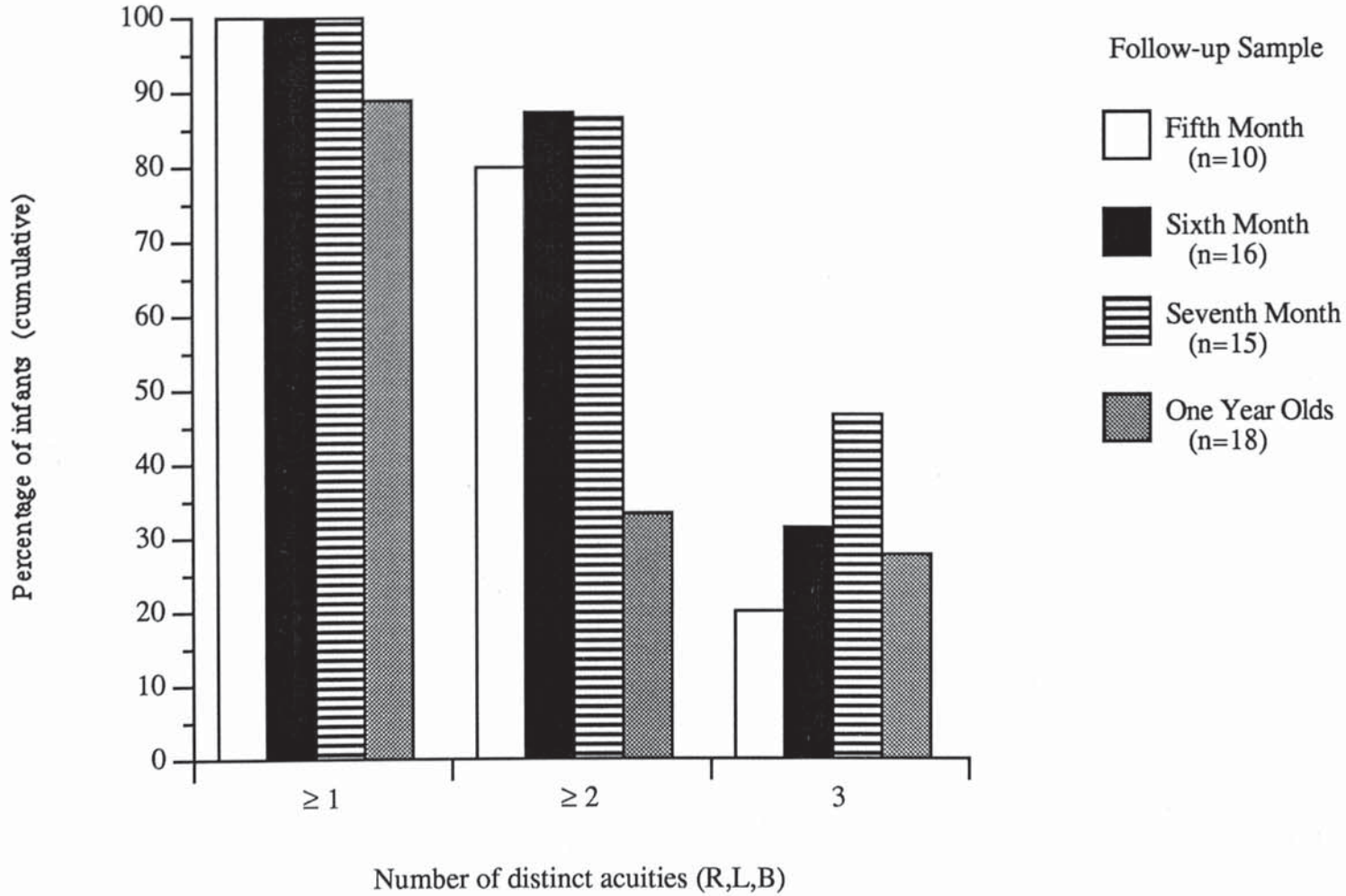


Figure 4.21 As Figure 4.20 for the five, six, seven and twelve month age groups. Comparison of the two figures shows that apart from the one month and twelve month groups all infants completed at least one test. Performance was not uniform but improved steadily with age reaching a maximum at seven months when almost half the sample completed all three tests. Numerical values are provided in Table 4.25.

Table 4.25 Numbers (and percentage) of infants in each age group providing distinct (right eye/left eye/binocular) M.A.R. values. Cumulative values.

Age Group (months)	Sample Size	No. (&%) contributing specific acuity data		
		≥ 1 estimate	≥ 2 estimates	3 estimates
Newborn	174	152 (87.4)	17 (9.8)	0 (0)
1	7	6 (85.7)	0 (0)	0 (0)
2	22	22 (100.0)	10 (45.4)	3 (13.6)
3	29	29 (100.0)	17 (58.6)	9 (31.0)
4	30	30 (100.0)	25 (83.4)	11 (36.7)
5	10	10 (100.0)	8 (80.0)	2 (20.0)
6	16	16 (100.0)	14 (87.5)	5 (31.2)
7	15	15 (100.0)	13 (86.7)	7 (46.7)
12	18	16 (88.9)	6 (33.3)	5 (27.8)
Follow-up Sample	147	144 (98.0)	93 (63.3)	42 (28.6)

4.6.3 General observations

The greatest difficulty in testing (regardless of age) was experienced in completing monocular tests. In the youngest infants poor performance on monocular tests could be attributed to restriction of the visual field (sensitivity in the nasal field being reduced), although selection of a low screen eccentricity and rotation of the infant between each display during trials should have minimized this effect. In older infants physical disturbance caused by the wearing of an eyepatch is likely to be responsible for failure on monocular tests.

The test success rate data discussed in section 4.6.1 and 4.6.2 does not distinguish between success rates on monocular and binocular tests because the tests were not applied in the same order and failure to complete a particular test may have been caused by general tiredness or boredom. With this reservation in mind, Tables 4.18 and 4.19 do allow an impression of the relative ease with which monocular and binocular acuity estimates could be obtained. Newborn infants were very difficult to test monocularly, often becoming sleepy when an eyepatch was applied. It was common on removal of the eyepatch after unsuccessful monocular testing for infants to co-operate sufficiently to complete a binocular test. Few infants below eight weeks of age complied with monocular testing (it was usual for binocular testing to be attempted first with these age groups). Infants of four months and above completed more monocular than binocular tests (monocular tests were usually performed first - before boredom set in!). Infants below six months of age rarely possessed the manual dexterity to remove the eyepatch which was worn during monocular testing, but some became very disturbed and unco-operative when it was worn. Older infants could sometimes be persuaded to wear the patch if the examiner initially "modelled" it. Despite this non-tolerance of eye patching was the most frequent reason for failure to obtain monocular acuities in older infants.

A summary and discussion of the findings described in this chapter can be found in Chapter 7.

5. NORMATIVE STUDY - RESULTS II : REFRACTIVE DEVELOPMENT

Attempts were made to determine the refractions of 210 of the 227 newborns participating in this study. The method used was streak retinoscopy. Data is only available from 209 right eyes as one patient would not co-operate sufficiently to complete the test. Full data was collected from left eyes. Thirty five newborns participated in a study to investigate the accuracy of neonatal refraction (section 5.4). In this study two refractions were performed on each infant. The initial of these infants two refractions has been included in group averaged data.

Refractive development was studied in 63 infants who were refracted between the ages of three and seven months or at one year. Thirteen infants were refracted during two follow-up sessions, the remaining sample were refracted only once. Initially data was analysed according to the monthly age categories defined in Table 3.7. In subsequent analysis three and four month data has been combined as has the six and seven month data to increase the sample sizes.

Where statistical tests have been performed the trends noted for the right eye data are in almost all cases supported by the left eye findings. To prevent some repetition of similar figures left eye data is mainly confined to tabular presentation whereas right eye data has generally been presented in both tabular and graphical form. All refractive power values are positive (representing hypermetropia) unless otherwise indicated.

5.1 Spherical equivalent refraction (S.E.R.)

5.1.1 Neonatal distribution and mean data

The range of spherical equivalent refractive findings encountered in the newborn sample varied between - 4.25 and + 9.12 DS in the right eye and between - 4.50 and + 9.75 DS in the left eye. The distributions of neonatal S.E.R. findings are summarised as frequency histograms (in dioptre intervals) in Figures 5.1 and 5.2. These figures are based on the data provided in Table 5.1. Group averaged data is presented in Table 5.2. Mean S.E.R. findings were 2.78 and 2.70 DS for right and left eyes, respectively. The high standard deviations (≈ 2.6 DS) reflect the wide spread observed in the data.

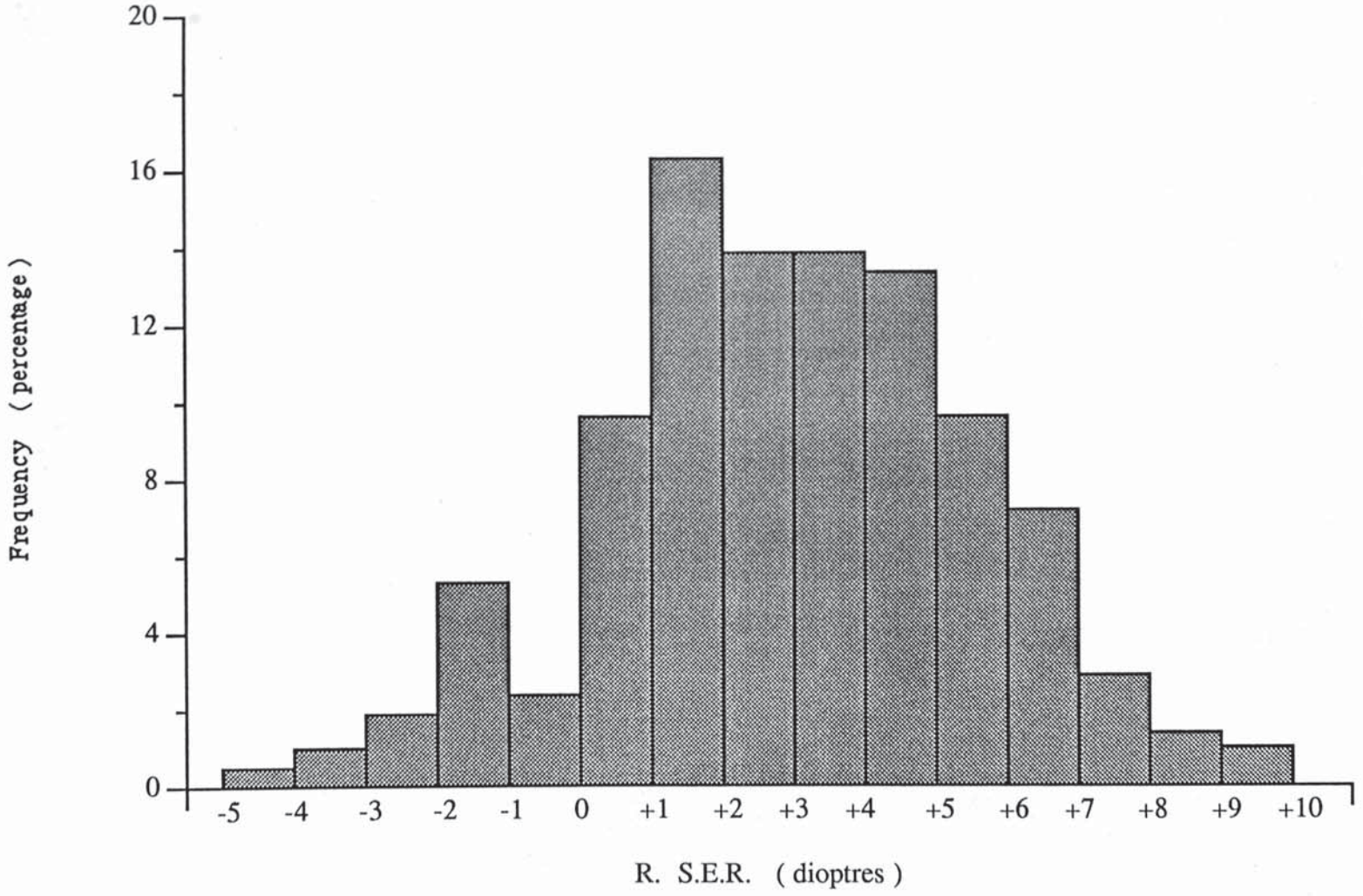


Figure 5.1 Frequency histogram illustrating the distribution of spherical equivalent refractive error findings amongst 209 newborns' right eyes. Numerical values are provided in Table 5.1.

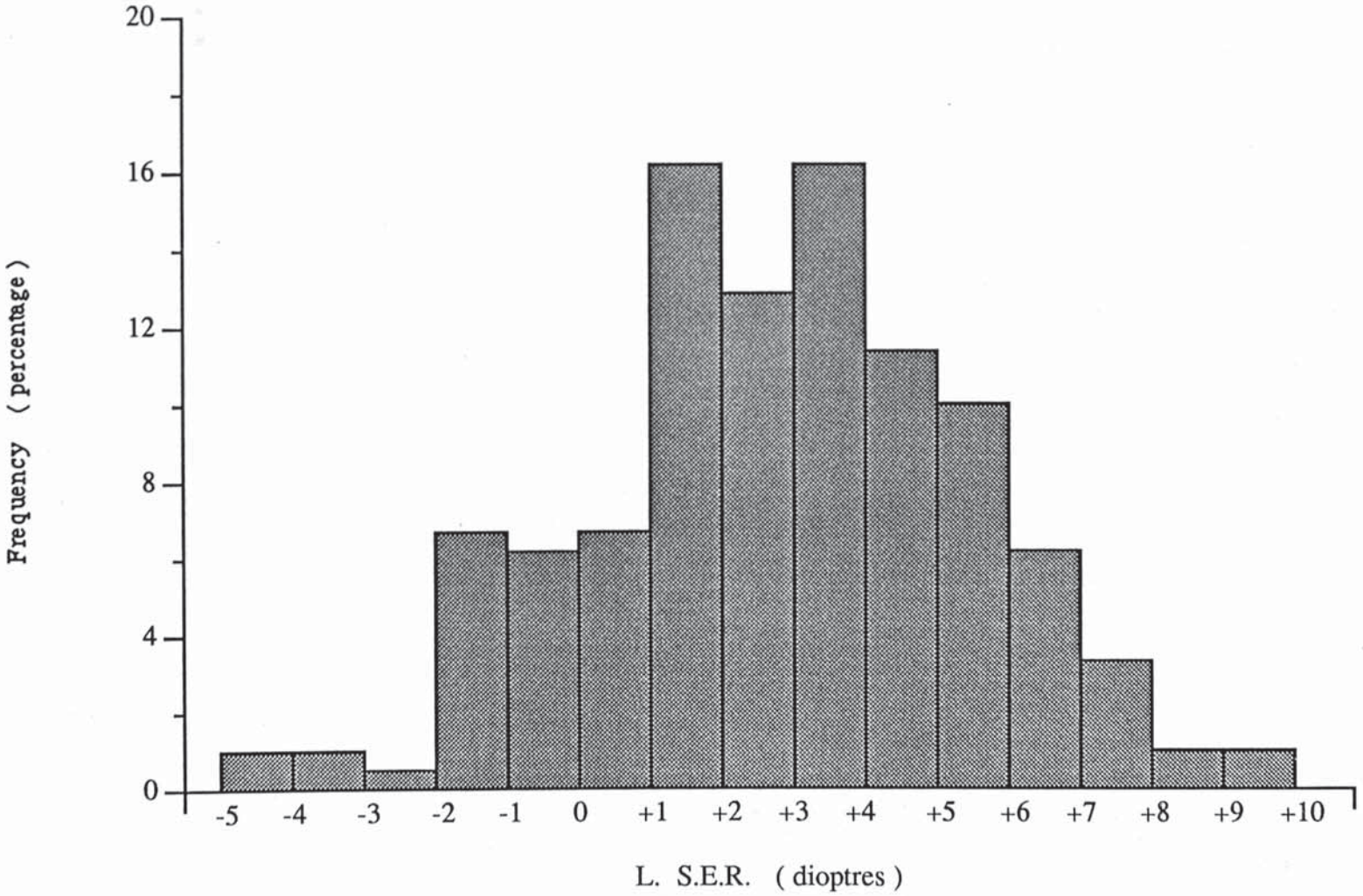


Figure 5.2 Frequency histogram illustrating the distribution of spherical equivalent refractive error findings amongst 210 newborns' left eyes. Numerical values are provided in Table 5.1.

Table 5.1 Distribution of neonatal spherical equivalent refractive findings.

Refractive Range (Dioptres)	Right Eye No.	Right Eye %	Left Eye No.	Left Eye %
- 5 < - 4	1	0.5	2	1.0
- 4 < - 3	2	1.0	2	1.0
- 3 < - 2	4	1.9	1	0.5
- 2 < - 1	11	5.3	14	6.7
- 1 < 0	5	2.4	13	6.2
0 < + 1	20	9.6	14	6.7
+ 1 < + 2	34	16.3	34	16.2
+ 2 < + 3	29	13.9	27	12.9
+ 3 < + 4	29	13.9	34	16.2
+ 4 < + 5	28	13.4	24	11.4
+ 5 < + 6	20	9.6	21	10.0
+ 6 < + 7	15	7.2	13	6.2
+ 7 < + 8	6	2.9	7	3.3
+ 8 < + 9	3	1.4	2	1.0
+ 9 < +10	2	1.0	2	1.0

Table 5.2 Summary of neonatal refractive findings (210 infants; 209 right eyes and 210 left eyes). Means, S.D. and group S.E. of power values for spherical and cylindrical refractive data.

Variable	Mean	S.D. (Dioptres)	S.E.
R. S.E.R.	2.78	2.57	0.18
L. S.E.R.	2.70	2.63	0.18
Anisometropia	0.59	0.57	0.04
R. CYL.	1.67	1.39	0.10
L. CYL.	1.72	1.25	0.09

5.1.2 Effect of maturity on neonatal S.E.R. findings

The newborn data has been statistically analysed to investigate possible factors that might correlate with the infants refractive status at birth. It appears feasible that part of the spread in newborn refraction could be explained by differences in the maturity of individual infants. For this reason tests have been conducted to study whether spherical equivalent refraction is correlated with the infants' post-conceptional age or post-natal age at the time of retinoscopy. The results of these statistical regression tests are summarised in Table 5.3 (more details are provided in Appendix Table A5.1). Infant's post-conceptional ages did not influence S.E.R. findings. In contrast, post-natal age at the time of refraction was found to have a significant effect on newborn S.E.R. (although the correlation coefficients - of around 0.2 - were not high). The right eye spherical equivalent refraction data is plotted versus day of examination in Figure 5.3. The level of hyperopia decreased by about two dioptres during the first five days of life. Analysing the data in terms of post-natal age in hours rather than in days only marginally improved the correlation (data illustrated in Figure 5.4). The highest correlations and significance levels were obtained when post-natal age was expressed in terms of log. hours (data plotted in Figure 5.5).

Table 5.3 Summary of correlations between newborn spherical equivalent refraction or cylindrical power and various factors.
Key to significance levels: * = 0.05; ** = 0.01; *** = 0.005; **** = 0.001; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Variables		Right Eye		Left Eye	
	n	r	p	r	p
S.E.R. v. :					
Post-conceptional age (wks)	210	0.02	ns	0.01	ns
Post-natal age (days)	210	0.20	***	0.17	**
Post-natal age (hours)	210	0.21	***	0.18	**
Post-natal age (log. hrs)	210	0.23	****	0.19	**
Birth weight (kg.)	210	0.13	(ns)	0.11	(ns)
Head circumference (cm.)	210	0.16	*	0.15	*
Length (cm.)	208	0.05	ns	0.05	ns
Maternal age (years)	210	0.04	ns	0.04	ns
Duration of cycloplegia (mins)	202	0.00	ns	0.05	ns
Cylinder power v. :					
Duration of cycloplegia (mins)	202	0.13	(ns)	0.19	**

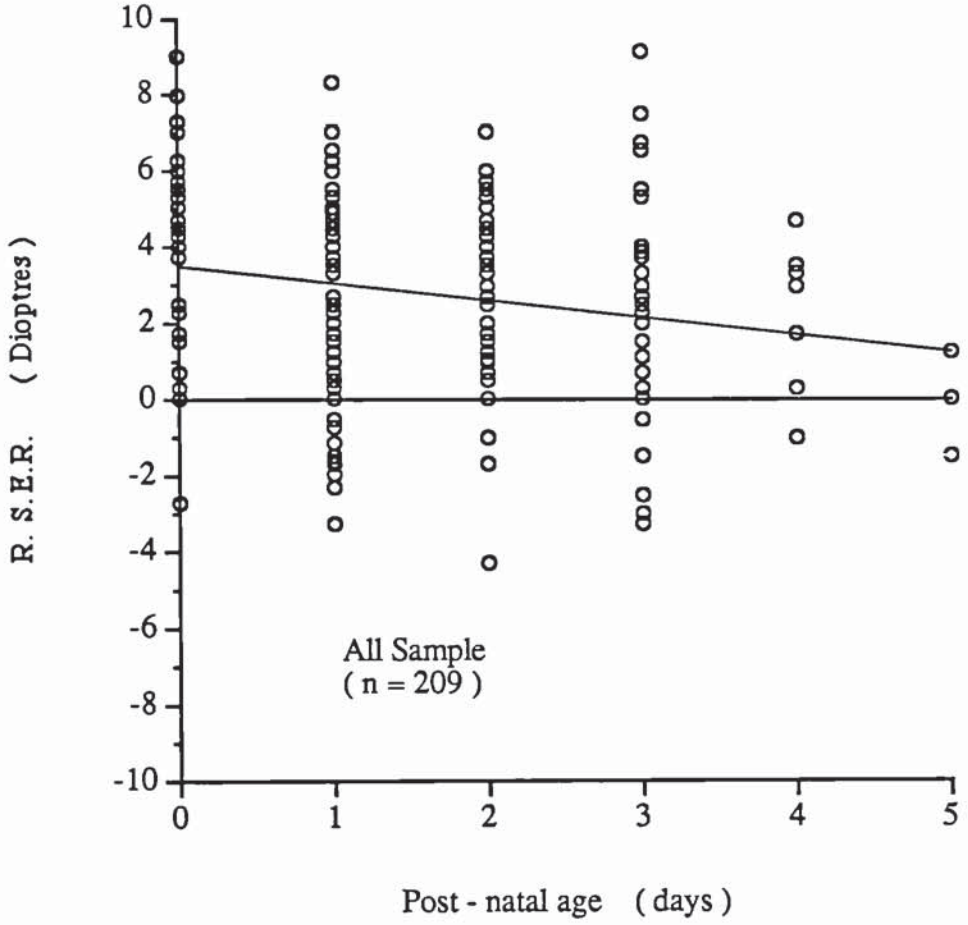


Figure 5.3 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (days). Data is from the right eye. Equation of regression line:
$y = -0.45\ x + 3.50$ ($r = 0.20$; d.f. 1,207; $p < 0.005$).

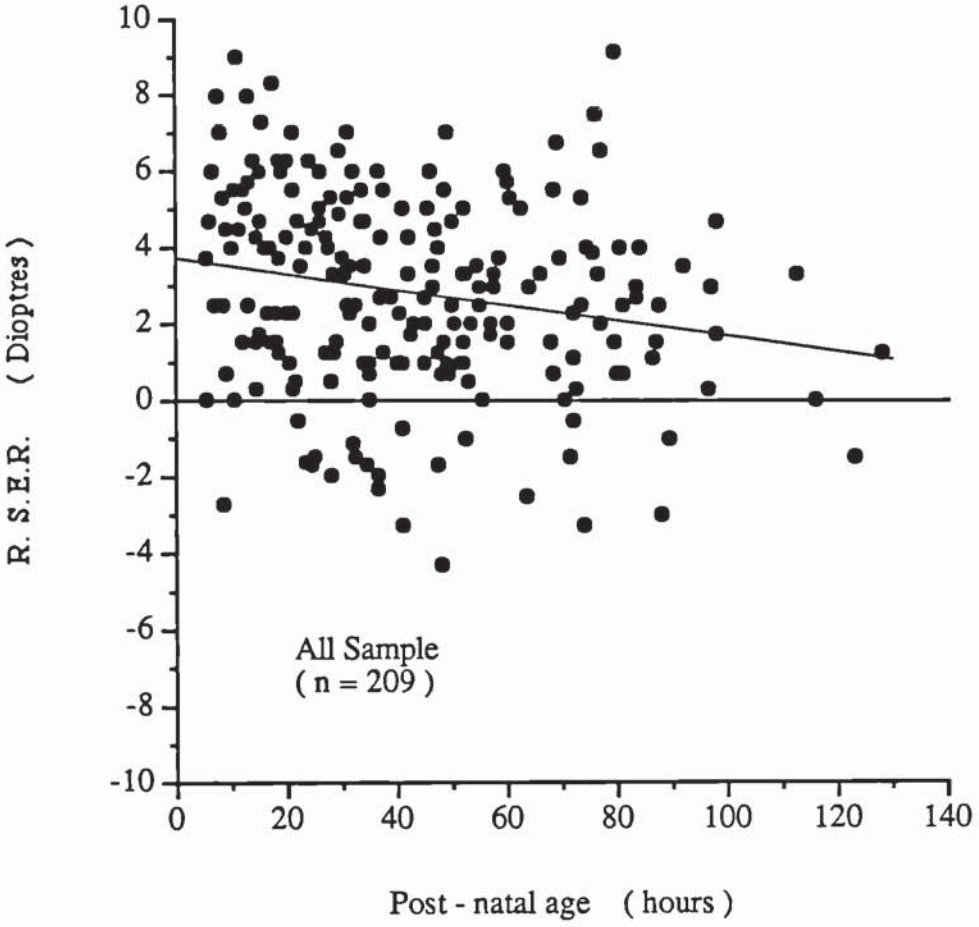


Figure 5.4 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (hours). Data is from the right eye. Equation of regression line:
$y = -0.02\ x + 3.68$ ($r = 0.21$; d.f. 1,207; $p < 0.005$).

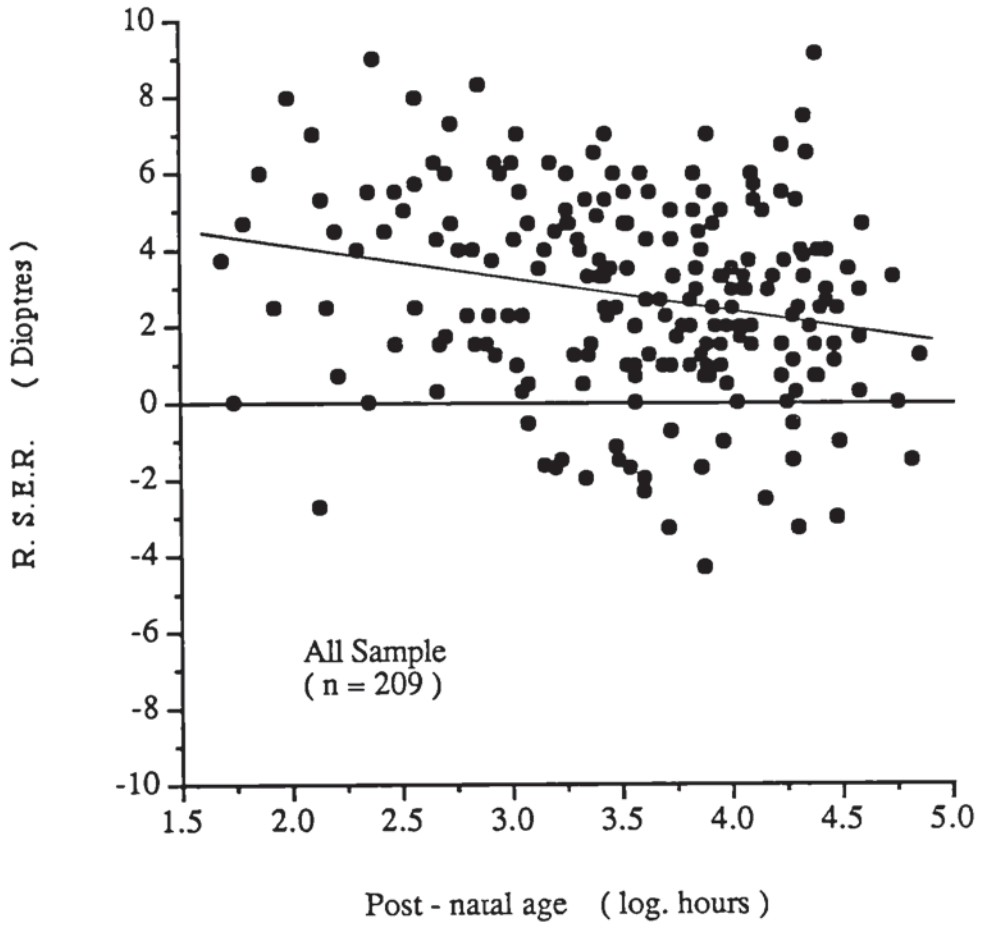


Figure 5.5 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eye. Equation of regression line:
$y = -0.84 x + 5.76$ ($r = 0.23$; d.f. 1,207; $p = 0.001$).

5.1.3 Effect of physical size on neonatal S.E.R. findings

The possible influence of newborn infant's size (i.e. birth weight, head circumference and length) on their spherical refractive findings has been investigated. There was a tendency in all data for larger infants to be more hypermetropic. A scatterplot of the right eye S.E.R. data versus infant's head circumference is presented in Figure 5.6. The statistical data for linear regression analyses is summarised in Table 5.3 (more details are given in Appendix Table A5.2). These tests suggest that only head circumference has a significant effect on S.E.R. although the findings for birth weight almost reached significance.

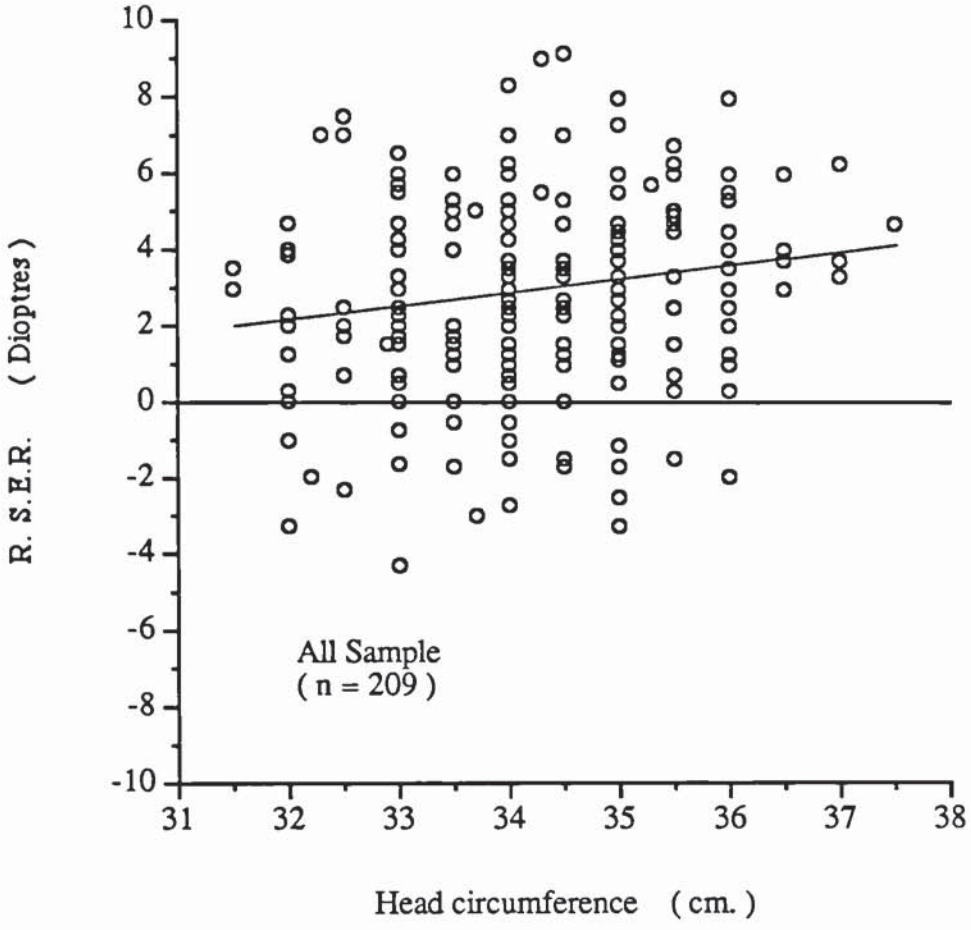


Figure 5.6 Scatterplot of neonatal spherical equivalent refraction data versus head circumference (cm.). Data is from the right eye. Equation of regression line:
$y = 0.35\ x - 9.06$ ($r = 0.16$; d.f. 1,207; $p < 0.05$).

5.1.4 Effect of probable birth trauma on neonatal S.E.R. findings

The finding that S.E.R. values decrease significantly during the first few days of life prompts the suggestion that these changes are related to recovery from the birth process - since the rapidity and magnitude of changes are difficult to reconcile with a true developmental shift. The correlation between S.E.R. and head circumference may also be related to increased birth trauma of infants having larger heads. To investigate this possibility further the newborn sample was, in each of four comparisons, divided into two subgroups which were chosen to isolate, from the remaining sample, infants noted to or likely to have suffered increased birth trauma. The increased trauma groups comprised infants having birth complications, low Apgar score at one minute after birth, retinal haemorrhage or those borne by primiparous mothers. It was expected that higher group averaged S.E.R. values would be found in the samples having more traumatic births. Average refractive findings for these subgroups are included in Table 5.4. Independent t - tests were performed to test for the significance of differences in the group averaged refractive findings of the paired samples. T - tests were also conducted to check for differences between groups in post-natal age and head circumference. Regression analyses were performed for each sample to determine whether S.E.R. findings were correlated with post-natal age at the time of retinoscopy (log. hours) or with head circumference. The results of regression analyses to investigate the relationships between S.E.R. and post-natal age in the two samples are summarised in Table 5.5. Regression analyses studying the relationships between S.E.R. and head circumference are given in Table 5.6. It was thought that the relationships with post-natal age may be more pronounced for infants in the increased trauma groups, whereas the relationships with head circumference could be more emphatic for the reduced trauma groups.

a) Birth complications

Sixty-two infants were classified as belonging to a high trauma group on the basis of noted birth complications. The remaining 148 newborns were allocated to a low trauma group. The high trauma group comprised infants having malpresentation or bradycardia during labour, those requiring assisted (ventouse or forceps) delivery and those who at birth were noted to have meconium stained liquor, asphyxia requiring oxygen resuscitation or the placenta knotted or tightly coiled around their neck. Head circumference was not significantly different in the two groups (mean 34.4, S.E. 0.18 cm. in the high trauma and 34.1, S.E. 0.10 cm. in the low trauma group; independent t - test $p > 0.05$). Infants in the high trauma group were significantly older at the time of retinoscopy than infants in the remaining sample (mean 39.4, S.E. 3.0 hrs. in the high trauma and 53.1, S.E. 2.4 hrs. in the low trauma group; independent t - test $p < 0.001$). This difference is inevitably caused by the practice of delaying mother and infants' discharge from hospital if complications have been noted. Group averaged refractive findings of the two samples are included in Table 5.4. The S.E.R.s were higher for the high trauma group (other refractive findings were similar in both groups). Larger differences would be anticipated if the samples had been equated for age. Independent t - tests did not reveal any differences to be significant ($p > 0.05$).

Table 5.4 Averaged refractive findings of full newborn sample and various subgroups. Means and standard errors are given.

		GROUP AVERAGED REFRACTIVE ERRORS (Dioptres)				
SAMPLE	n	R. S.E.R.	L. S.E.R.	ANISO.	R. CYL.	L. CYL.
All	210	2.78 (0.18)	2.70 (0.18)	0.59 (0.04)	1.67 (0.10)	1.72 (0.09)
Male	105	3.01 (0.25)	2.83 (0.26)	0.60 (0.06)	1.41 (0.12)	1.50 (0.12)
Female	105	2.56 (0.25)	2.57 (0.26)	0.59 (0.06)	1.94 (0.15)	1.94 (0.12)
Asian	113	2.58 (0.26)	2.60 (0.26)	0.61 (0.05)	1.90 (0.15)	1.89 (0.13)
Caucasian	61	3.21 (0.34)	3.10 (0.33)	0.46 (0.06)	1.36 (0.13)	1.42 (0.13)
Negroid	25	2.51 (0.42)	2.22 (0.44)	0.61 (0.12)	1.53 (0.25)	1.54 (0.23)
Other	11	3.06 (0.50)	2.61 (0.65)	1.06 (0.32)	1.39 (0.39)	2.00 (0.32)
Pethidine	96	3.02 (0.24)	2.99 (0.24)	0.56 (0.06)	1.58 (0.16)	1.64 (0.13)
No pethidine	114	2.58 (0.26)	2.45 (0.27)	0.62 (0.06)	1.75 (0.12)	1.79 (0.12)
Birth complications	62	2.90 (0.31)	3.00 (0.30)	0.60 (0.07)	1.83 (0.23)	1.68 (0.17)
No birth comps.	148	2.74 (0.22)	2.57 (0.23)	0.59 (0.05)	1.61 (0.10)	1.74 (0.10)
Low Apgar	113	2.85 (0.23)	2.82 (0.22)	0.59 (0.05)	1.61 (0.14)	1.72 (0.13)
High Apgar	96	2.72 (0.29)	2.57 (0.30)	0.59 (0.07)	1.72 (0.13)	1.71 (0.12)
Retinal haemorrhage	60	2.92 (0.36)	2.76 (0.34)	0.53 (0.07)	1.27 (0.14)	1.38 (0.15)
No retinal haems.	149	2.74 (0.21)	2.68 (0.22)	0.59 (0.05)	1.83 (0.12)	1.85 (0.10)
Primipara	70	2.78 (0.30)	2.75 (0.31)	0.60 (0.07)	1.73 (0.18)	1.67 (0.14)
Multipara	140	2.79 (0.22)	2.67 (0.23)	0.59 (0.05)	1.64 (0.11)	1.75 (0.11)

Correlation coefficients between S.E.R. and post-natal age were higher for infants in the high trauma group (≈ 0.25 cf. ≈ 0.21 in the low trauma group). The smaller sample size of the high trauma group may explain the lower significance levels found for this effect in the high trauma rather than low trauma group. Head circumference was found to exert a significant influence on S.E.R. findings of infants in the low trauma group but to have no effect on the findings of high trauma infants. Details of regression equations fitted to the data are provided in Appendix Table A5.4 (summarised findings are given in Tables 5.5 and 5.6).

Table 5.5 Summary of correlations between newborn spherical equivalent refraction and post-natal age (log. hrs) for various samples.
Key to significance levels: * = 0.05; ** = 0.01; *** = 0.005; **** = 0.001; ***** = 0.0005; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Sample		Right Eye		Left Eye	
	n	r	p	r	p
All	210	0.23	****	0.19	**
Male	105	0.30	***	0.27	**
Female	105	0.13	ns	0.09	ns
Asian	113	0.13	ns	0.10	(ns)
Caucasian	61	0.45	*****	0.44	*****
Pethidine	96	0.18	(ns)	0.10	ns
No pethidine	114	0.27	***	0.27	***
Birth complications	62	0.27	*	0.23	(ns)
No birth complications	148	0.22	**	0.20	**
Low Apgar	113	0.28	***	0.20	*
High Apgar	96	0.18	(ns)	0.18	(ns)
Retinal haemorrhage	60	0.16	ns	0.09	ns
No retinal haemorrhage	149	0.25	***	0.23	**
Primiparous	70	0.16	ns	0.07	ns
Multiparous	140	0.26	***	0.25	***

Table 5.6 Summary of correlations between newborn spherical equivalent refraction and head circumference for various samples.
Key to significance levels: * = 0.05; ** = 0.01; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Sample		Right Eye		Left Eye	
	n	r	p	r	p
All	210	0.16	*	0.15	*
Male	105	0.05	ns	0.04	ns
Female	105	0.24	**	0.25	**
Asian	113	0.17	(ns)	0.16	(ns)
Caucasian	61	0.20	(ns)	0.19	ns
Pethidine	96	0.23	*	0.22	*
No pethidine	114	0.11	(ns)	0.10	*
Birth complications	62	0.05	ns	0.02	ns
No birth complications	148	0.21	**	0.20	**
Low Apgar	113	0.21	*	0.20	*
High Apgar	96	0.12	ns	0.10	ns
Retinal haemorrhage	60	0.18	ns	0.20	(ns)
No retinal haemorrhage	149	0.17	*	0.14	(ns)
Primiparous	70	0.27	*	0.25	*
Multiparous	140	0.11	ns	0.11	ns

b) Apgar score

The sample was divided into two groups on the basis of Apgar score at one minute after birth. In order to have acceptable numbers in each group a division was made between infants having Apgar scores of up to eight and those having scores of above eight (only 38 infants had scores of less than eight which was considered too low for statistical analysis). Mean head circumference was identical in the two groups (34.2 cm., S.E. 0.12 cm. in both). Infants in the low Apgar group were slightly, but not significantly older at the time of retinoscopy than infants in the remaining sample (mean 44.7, S.E. 2.5 hrs. in the low score and 42.0, S.E. 2.7 hrs. in the high score group; independent t - test $p > 0.05$). Group averaged refractive findings of the two samples are summarised in Table 5.4. The S.E.R.s were slightly higher for the group having lower Apgar scores. Other refractive findings were similar in both groups. Independent t - tests did not reveal any differences between groups to be significant.

Correlation coefficients between S.E.R. and post-natal age were higher for the low Apgar group (≈ 0.24; $p < 0.05$ cf. 0.18; $p > 0.05$ in the high Apgar group). Correlation coefficients between S.E.R. and head circumference were also higher for the low Apgar group (≈ 0.20; $p < 0.05$ cf. ≈ 0.11; $p > 0.05$ in the high Apgar group). Details of regression equations fitted to the data are provided in Appendix Table A5.5 (summarised findings are given in Tables 5.5 and 5.6).

c) Retinal haemorrhage

Birth trauma has been suggested as a cause of retinal haemorrhage although the true aetiology is not certain. The sample was divided into 60 infants noted to have retinal haemorrhage at birth and 149 that were not found to have retinal haemorrhage. Head circumference was not significantly different in the two groups (mean 34.4, S.E. 0.16 cm. in the retinal haemorrhage and 34.1, S.E. 0.10 cm. in the low trauma group; independent t - test $p > 0.05$). Infants in the non retinal haemorrhage group were slightly but not significantly older at the time of retinoscopy than infants in the remaining sample (mean 44.6, S.E. 2.1 hrs. in newborns without haemorrhage and 40.6, S.E. 3.4 hrs. in the retinal haemorrhage group; independent t - test $p > 0.05$). Group averaged refractive findings of the two samples are included in Table 5.4. The S.E.R.s were slightly higher (and the cylinder powers were lower) for the retinal haemorrhage group. Anisometropic levels were similar in both groups. Independent t - tests did not reveal differences in spherical findings to be significant. The results of t - tests on cylindrical data are described in section 5.3.2.

Correlation coefficients between S.E.R. and post-natal age were higher for infants without retinal haemorrhages (≈ 0.24; $p < 0.01$ cf. 0.12; $p > 0.05$ in the retinal haemorrhage group). Correlation coefficients between S.E.R. and head circumference were similar for the two groups. Head circumference was found to exert a significant influence on S.E.R. findings of infants without retinal haemorrhage. Failure of this effect to reach significance for the retinal haemorrhage group is likely to relate to the smaller sample size. Details of regression equations fitted to the data are provided in Appendix Table A5.6 (summarised findings are given in Tables 5.5 and 5.6).

d) Parity

The sample was divided into 70 infants from 'first-time' mothers (primiparas) and 140 newborns from mothers borne more than one viable infant (multiparas). This comparison was made because it is well established that duration of labour (and risk of birth trauma) is longer for first born than for subsequent children. Head circumference was not significantly different in the two groups (mean 34.1, S.E. 0.16 cm. in the primiparous and 34.3, S.E. 0.10 cm. in the multiparous group; independent t - test $p > 0.05$). Infants in the primiparous group were, however, significantly older at the time of retinoscopy than other infants (mean 49.1 S.E. 3.4 hrs. in the primiparous and 40.6, S.E. 2.1 hrs. in the multiparous group; independent t - test $p = 0.03$). Group averaged refractive findings of the two samples are summarised in Table 5.4. Refractive findings were similar in both groups. Independent t - tests did not reveal any differences in the data to be significant.

Correlation coefficients between S.E.R. and post-natal age were higher for the offspring of multiparous mothers (≈ 0.25; $p \leq 0.05$ cf. ≈ 0.11; $p > 0.05$ in the primiparous group). In contrast, correlation coefficients between S.E.R. and head circumference were higher for the primiparous group (≈ 0.26; $p < 0.05$ cf. 0.11; $p > 0.05$ in the multiparous group). Details of regression equations fitted to the data are

provided in Appendix Table A5.7 (summarised findings are given in Tables 5.5 and 5.6).

e) Summary

Infants from the increased trauma groups all had higher group averaged S.E.R. data but statistical tests did not, in any instance, reveal significant differences in spherical refractive findings. Infants with positive evidence of increased birth trauma i.e. the high 'birth complications' trauma group and low Apgar score groups both showed a more pronounced effect of post-natal age on S.E.R. findings than the groups with which they were paired (results are included in Table 5.5). The opposite was true of newborns merely assumed to have suffered increased birth trauma i.e. the retinal haemorrhage and primiparous groups.

No clear picture emerged from the results of the regression analyses between S.E.R. findings and head circumference (summarised in Table 5.6). Apart from the high 'birth complications' trauma group higher correlation coefficients were evident for the high trauma groups. Of the subgroups discussed in this section, the low 'birth complications' trauma group demonstrated the most significant correlation between S.E.R. and head circumference ($r \approx 0.20$; $p \leq 0.01$).

5.1.5 Effect of other factors on neonatal S.E.R. findings

Regression analyses were performed to investigate whether duration of cycloplegia or maternal age influenced newborn refractive findings. The results of these statistical tests are summarised in Table 5.3 (more details of regression equations are given in Appendix Table A5.3). No significant correlation was found between S.E.R. and either factor.

The newborn sample was subdivided on the basis of gender, ethnic group and whether pethidine analgesia was administered to the mother during labour. Independent t - tests were performed to test for the significance of differences in: group averaged refractive findings, post-natal age and head circumference. Regression analyses were performed for each sample to determine whether S.E.R. findings were correlated with post-natal age at the time of retinoscopy (log. hours) or with head circumference. Group averaged data for various subgroups is included in Table 5.4 and results of regression analyses are summarised in Tables 5.5 and 5.6.

a) Gender

The sample was subdivided into 105 male and 105 female newborns. Head circumference was significantly larger in males (mean 34.6, S.E. 0.11 cm. in males and 33.8, S.E. 0.12 cm. in the females; independent t - test $p < 0.001$). Females were on average slightly but not significantly older at the time of retinoscopy than males (mean 44.7, S.E. 2.5 hrs. in females and 42.2, S.E. 2.6 hrs. in males; independent t - test $p > 0.05$). Group averaged refractive findings of males and females are included in Table 5.4. The S.E.R.s were slightly higher (and cylindrical power findings were lower) for male newborns. Anisometropic findings were similar in males and females. Differences in spherical refractive findings were not significant (independent t - tests, $p > 0.05$). The results of t - tests applied to the cylindrical power data are given in section 5.3.2.

Correlation coefficients between S.E.R. and post-natal age were higher for the males (≈ 0.28; $p < 0.01$ cf. ≈ 0.11; $p > 0.05$ in the females). Scatterplots illustrating the relationships between these variables in males and females are given in Figures 5.7 and 5.8. In contrast to the findings for post-natal age, correlation coefficients between S.E.R. and head circumference were higher for the females (≈ 0.24; $p < 0.05$ cf. 0.04; $p > 0.05$ in the males). This data is illustrated graphically in Figures 5.9 and 5.10. Details of regression equations fitted to the data are provided in Appendix Table A5.8 (summarised findings are given in Tables 5.5 and 5.6).

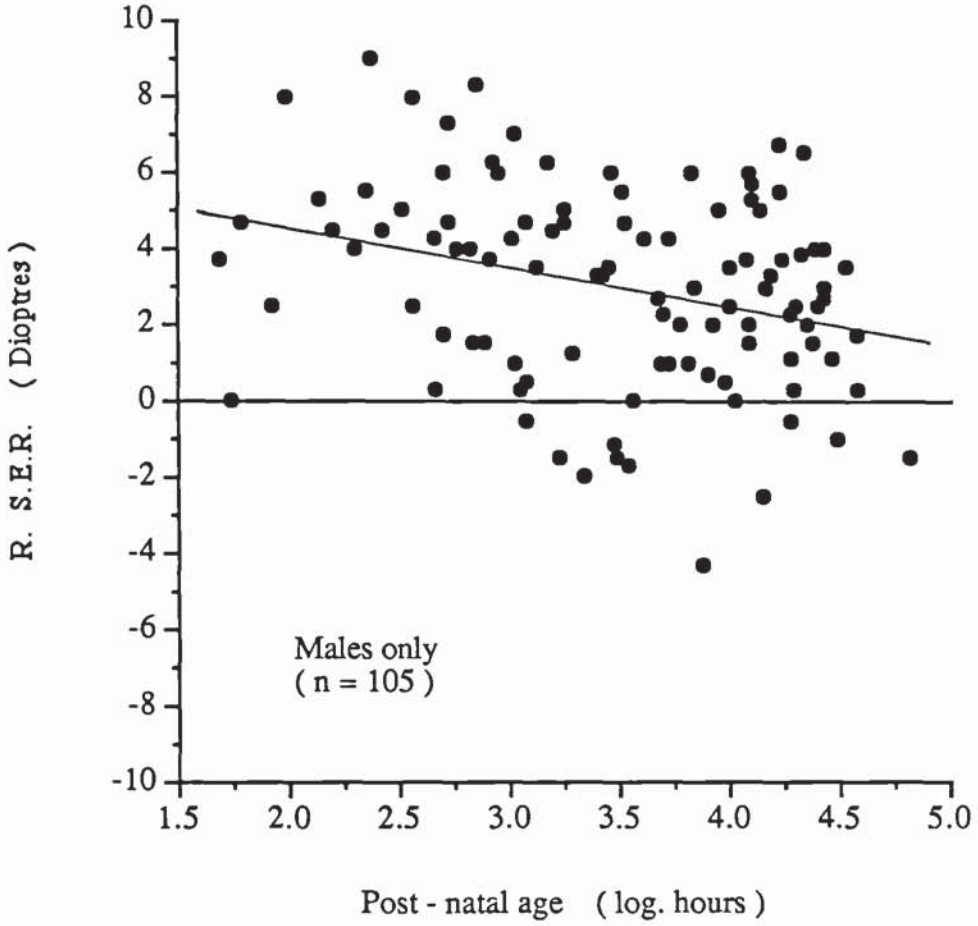


Figure 5.7 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eye of male infants. Equation of regression line:
$y = -1.02 x + 6.56$ ($r = 0.30$; d.f. 1,103; $p < 0.005$).

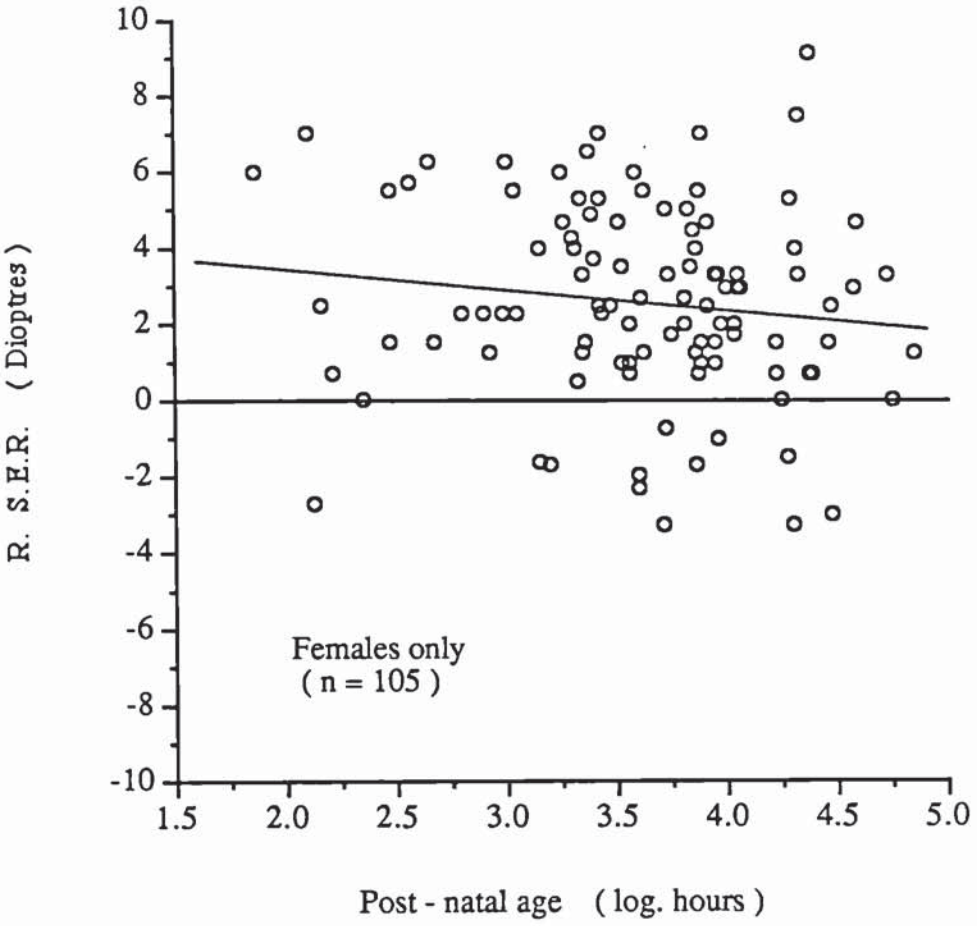


Figure 5.8 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eye of female infants. No significant correlation was found between these variables.

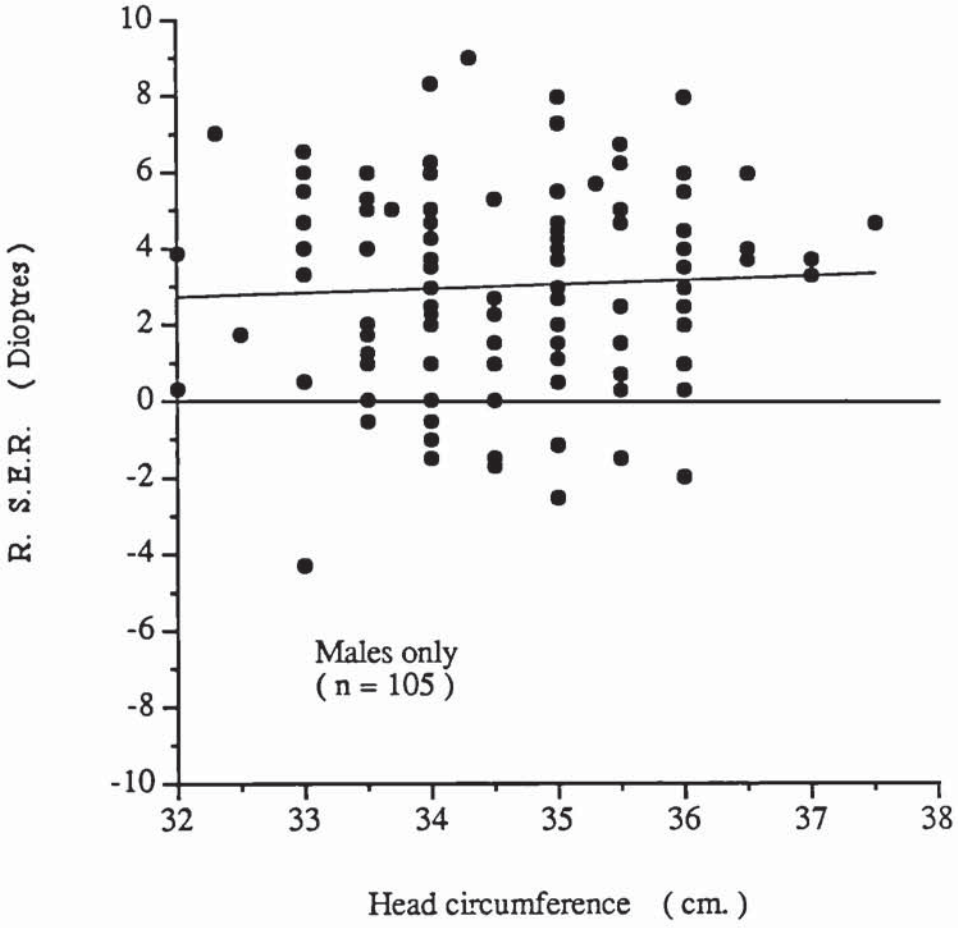


Figure 5.9 Scatterplot of neonatal spherical equivalent refraction data versus head circumference (cm.). Data is from the right eye of male infants. No significant correlation was found between these variables.

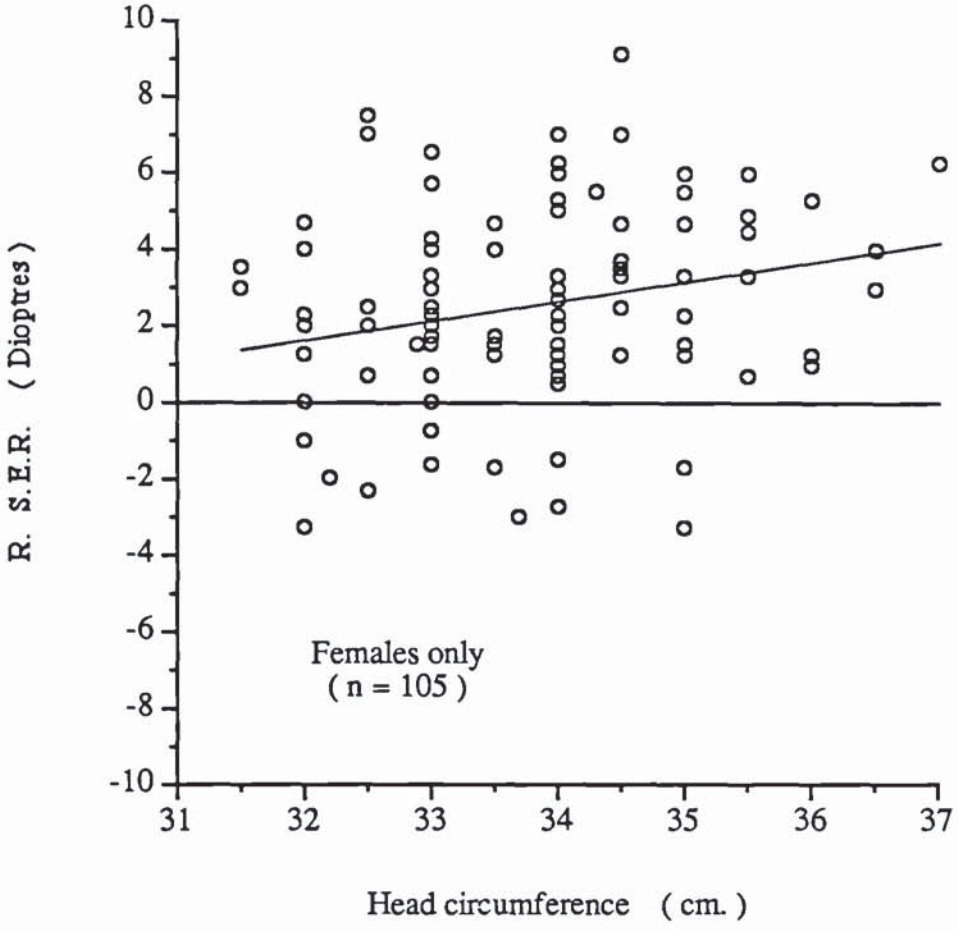


Figure 5.10 Scatterplot of neonatal spherical equivalent refraction data versus head circumference (cm.). Data is from the right eyes of female infants. Equation of regression line:
$y = 0.52\ x - 15.05$ ($r = 0.24$; d.f. 1,102; $p < 0.05$).

b) Ethnic group

Infants were allocated to one of four groups according to their ethnic origin. These groups were Asian, Caucasian, Negroid and 'other' (parents of mixed or Mongolian origin). Asian and Caucasian infants comprised all but 36 of the sample so it is probably unwise to base too many conclusions on the findings of the other groups. Statistical tests were confined to comparison between the two largest samples (113 Asian and 61 Caucasian infants). Head circumference was not significantly different in the two groups (mean 34.2, S.E. 0.11 cm. in the Asian and 34.4, S.E. 0.15 cm. in the Caucasian group; independent t - test $p > 0.05$). Infants in the Asian group were significantly older at the time of retinoscopy than Caucasian infants (mean 47.0, S.E. 2.4 hrs. in Asian infants and 35.6, S.E. 3.2 hrs. in Caucasians; independent t - test $p < 0.01$). Group averaged refractive findings of the four samples are included in Table 5.4. The S.E.R.s were noted to be highest for the Caucasian infants. Mean S.E.R. levels in the samples declined in the order Caucasian, Other, Asian and Negro. Independent t - tests did not reveal any significant differences in spherical refractive findings of Asian and Caucasian newborns. Comment on differences observed in anisometropic and cylindrical power findings is provided in sections 5.2.2 and 5.3.2.

The results of regression analyses to investigate the relationships between S.E.R. and post-natal age in the Asian and Caucasian samples are summarised in Table 5.5. The data is also illustrated in Figures 5.11 and 5.12.. Correlation coefficients between S.E.R. and post-natal age were higher for the Caucasians (≈ 0.44; $p < 0.0005$ cf. ≈ 0.11; $p > 0.05$ in the Asians). Regression analyses studying the relationships between S.E.R. and head circumference are given in Table 5.6. Correlation coefficients between S.E.R. and head circumference were similar and failed to reach significance in either group. Details of regression equations fitted to the data are provided in Appendix Table A5.9.

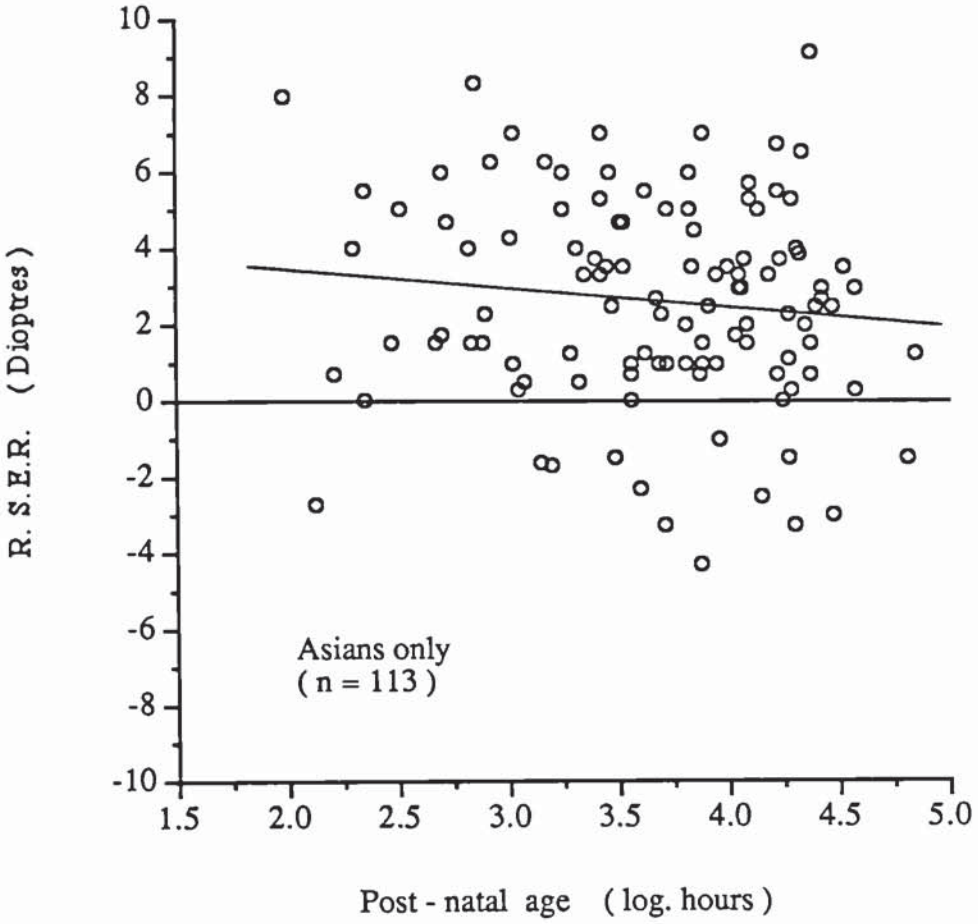


Figure 5.11 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eyes of Asian infants. No significant correlation was found between these variables.

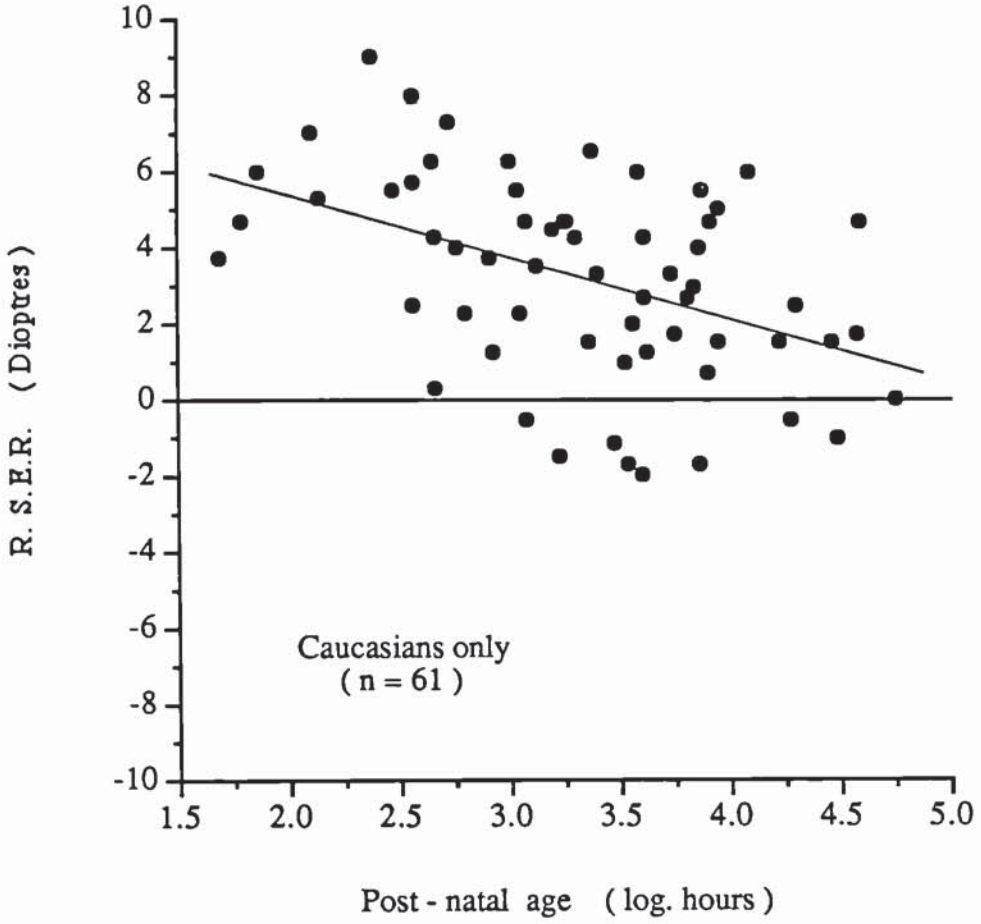


Figure 5.12 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eyes of Caucasian infants. Equation of regression line:
$y = -1.62\,x + 8.62$ ($r = 0.45$; d.f. 1,61; $p < 0.001$).

c) Maternal medication

It was considered that placental transfer of the anticholinergic agonist pethidine could lead to transient hypermetropic shifts in the refractive status of infants whose mothers had received the drug during labour. Infants were subdivided into a sample of 96 whose mothers had received pethidine analgesia and 114 whose mothers had not to investigate this possibility. Head circumference was not significantly different in the two groups (mean 34.3, S.E. 0.12 cm. in the pethidine and 34.1, S.E. 0.11 cm. in the non-pethidine group; independent t - test $p > 0.05$). Infants in the pethidine group were slightly but not significantly older at the time of retinoscopy than infants in the remaining sample (mean 45.8, S.E. 2.9 hrs. in the pethidine and 41.5, S.D. 2.2 hrs. in the non-pethidine group; independent t - test $p > 0.05$). Group averaged refractive findings of the two samples are summarised in Table 5.4. The S.E.R.s were higher (and cylindrical power findings slightly lower) for the sample whose mothers had received pethidine. Anisometropic findings were marginally higher in the non-pethidine group. Independent t - tests did not reveal any of the differences in refractive findings to be significant.

Correlation coefficients between S.E.R. and post-natal age were higher for the offspring of mothers that did not receive pethidine (0.27; $p < 0.01$ cf. ≈ 0.14; $p > 0.05$ in the pethidine group). The data is illustrated in Figures 5.13 and 5.14. In contrast to the findings for post-natal age the correlation coefficients between S.E.R. and head circumference were higher for the pethidine group (≈ 0.22; $p < 0.05$ cf. ≈ 0.10; $p > 0.05$ for the right eye and $p = 0.05$ for the left eye, in the non-pethidine group). Details of regression equations fitted to the data are provided in Appendix Table A5.10 (summarised findings are given in Tables 5.5 and 5.6).

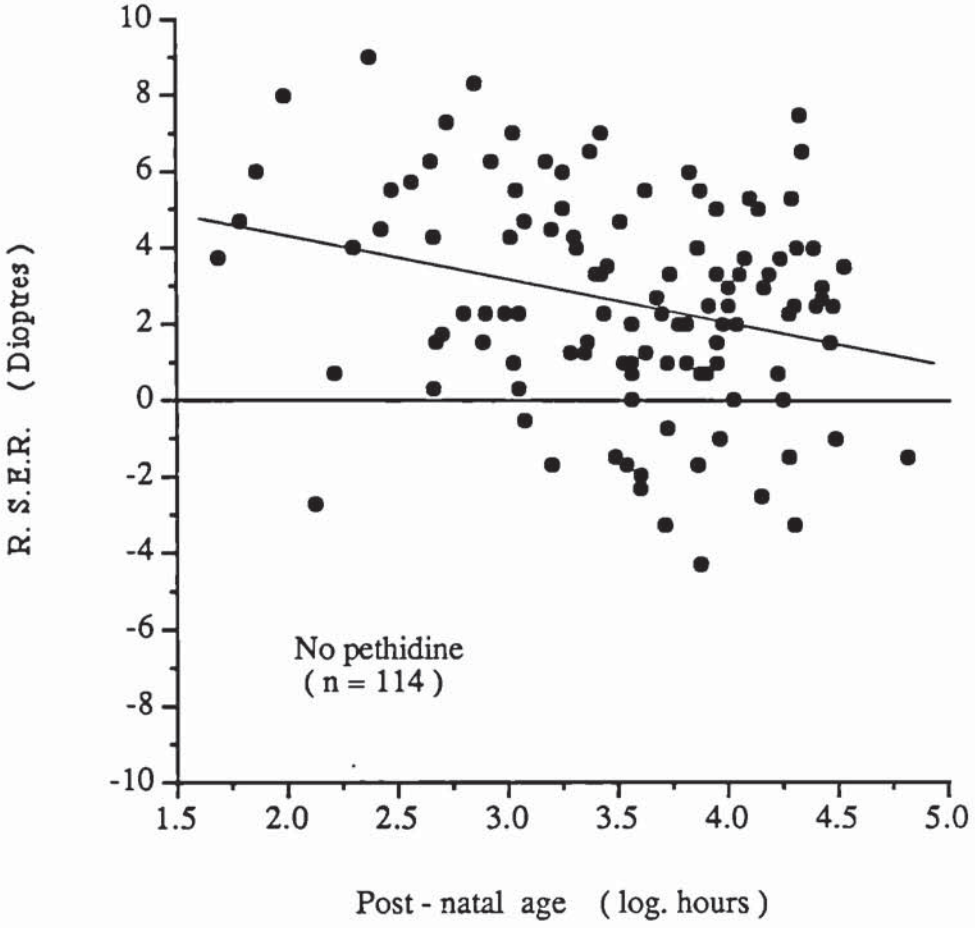


Figure 5.13 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eyes of infants whose mothers did not receive pethidine analgesia during labour. Equation of regression line:
$y = -1.11\ x + 6.50$ ($r = 0.27$; d.f. 1,112; $p < 0.005$).

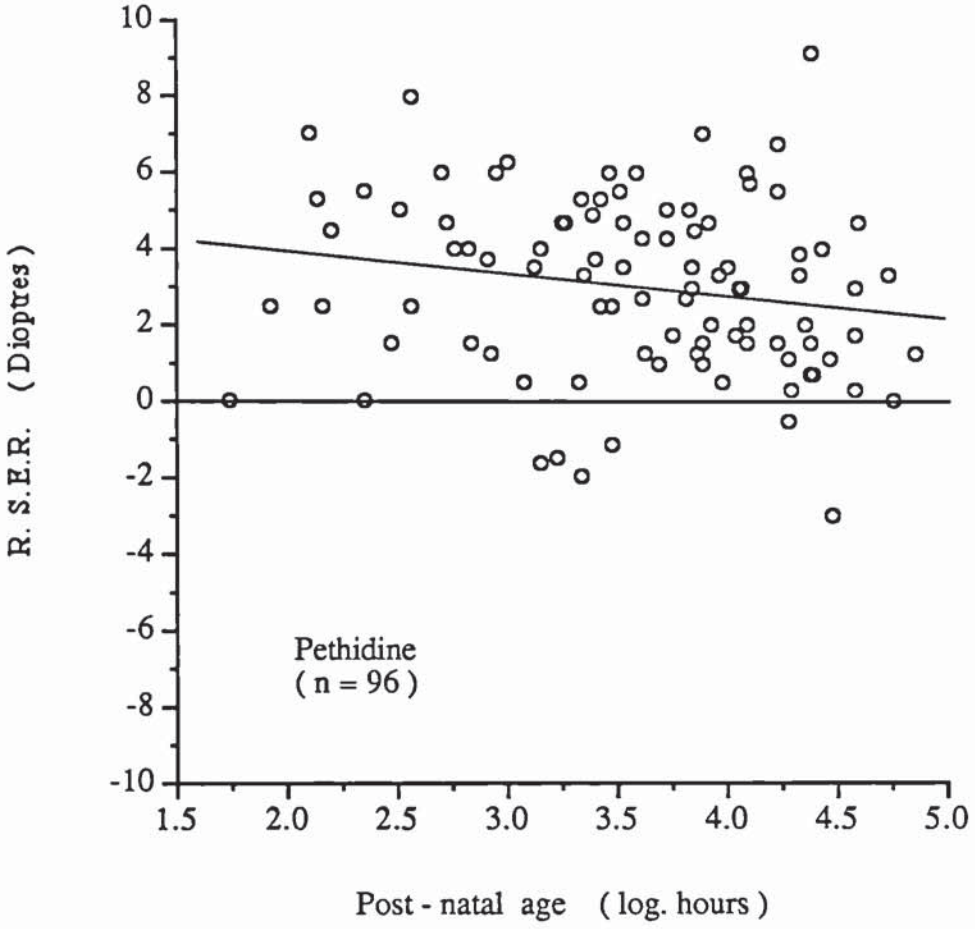


Figure 5.14 Scatterplot of neonatal spherical equivalent refraction data versus post-natal age (log. hours). Data is from the right eyes of infants whose mothers received pethidine analgesia during labour. No significant correlation was found between these variables.

5.1.6 Alterations in S.E.R. between birth and twelve months

Refractions were performed on infants of between three and seven months and on one year olds. Data was allocated to monthly age groups as defined in Table 3.7. Averaged data is presented in Table 5.7 and plotted along with newborn data in Figure 5.15. Similar trends are noted for right and left eye data. Apart from a slight increase around four months, group-averaged S.E.R. data shows a monotonic decrease from about 2.75 dioptres of hypermetropia at birth to 0.86 dioptres at one year.

Independent sample t - tests were performed to determine whether differences in refractive findings of consecutive age groups were significant (no infant was refracted twice within one month). No significant differences in spherical refractive findings were found. For this reason the three and four month and the six and seven month samples have been combined in further analysis to increase sample sizes. Only five infants were refracted in the fifth post-term month so this group has been ignored in subsequent analysis. Mean data for the new groups thus formed is also presented in Table 5.7 and is plotted in Figure 5.16 along with the newborn and twelve month data. Both independent (Table 5.8) and paired (Table 5.9) sample t - tests have been performed to check for the significance of refractive changes between groups represented in this figure. Newborn data of the various follow-up samples and of infants not attending for follow-up is given in Table 5.10. Spherical equivalent refractive error did not alter significantly between birth and three months or between six months and one year. Differences between mean findings of the remaining groups were all significant. The paired t - test data suggest that the most significant changes occur between three and six months.

Table 5.7 Averaged refractive findings of full newborn sample and various age groups between three months and one year. Means and standard errors are given. Final two groups relate to samples used for independent t - tests (more details in the text).

		GROUP AVERAGED REFRACTIVE ERRORS (Dioptres)				
AGE GROUP	n	R. S.E.R.	L. S.E.R.	ANISO.	R. CYL.	L. CYL.
Newborn	210	2.78 (0.18)	2.70 (0.18)	0.59 (0.04)	1.67 (0.10)	1.72 (0.09)
Three month	10	2.11 (0.45)	1.96 (0.50)	0.22 (0.11)	1.08 (0.33)	1.15 (0.32)
Four month	12	2.61 (0.44)	2.41 (0.46)	0.27 (0.08)	0.90 (0.13)	0.94 (0.20)
Five month	5	1.70 (0.54)	1.62 (0.52)	0.17 (0.05)	0.30 (0.18)	0.85 (0.23)
Six month	14	1.31 (0.26)	1.29 (0.22)	0.16 (0.05)	1.77 (0.32)	1.66 (0.32)
Seven month	17	0.88 (0.26)	0.96 (0.26)	0.16 (0.04)	1.60 (0.15)	1.54 (0.16)
One year	18	0.86 (0.32)	0.86 (0.33)	0.12 (0.04)	0.75 (0.17)	0.89 (0.17)
Combined 3 & 4 mth. ("3")	22	2.39 (0.32)	2.20 (0.33)	0.25 (0.06)	0.98 (0.16)	1.05 (0.18)
Combined 6 & 7 mth. ("6")	31	1.07 (0.19)	1.11 (0.17)	0.16 (0.03)	1.68 (0.16)	1.60 (0.17)
6 m. of "3" v. "6" indep. t.	19	1.10 (0.26)	1.11 (0.25)	0.14 (0.04)	1.51 (0.15)	1.46 (0.18)
12 m. of "6" v. 12 indep. t.	17	0.89 (0.35)	0.89 (0.36)	0.13 (0.04)	0.78 (0.18)	0.93 (0.18)

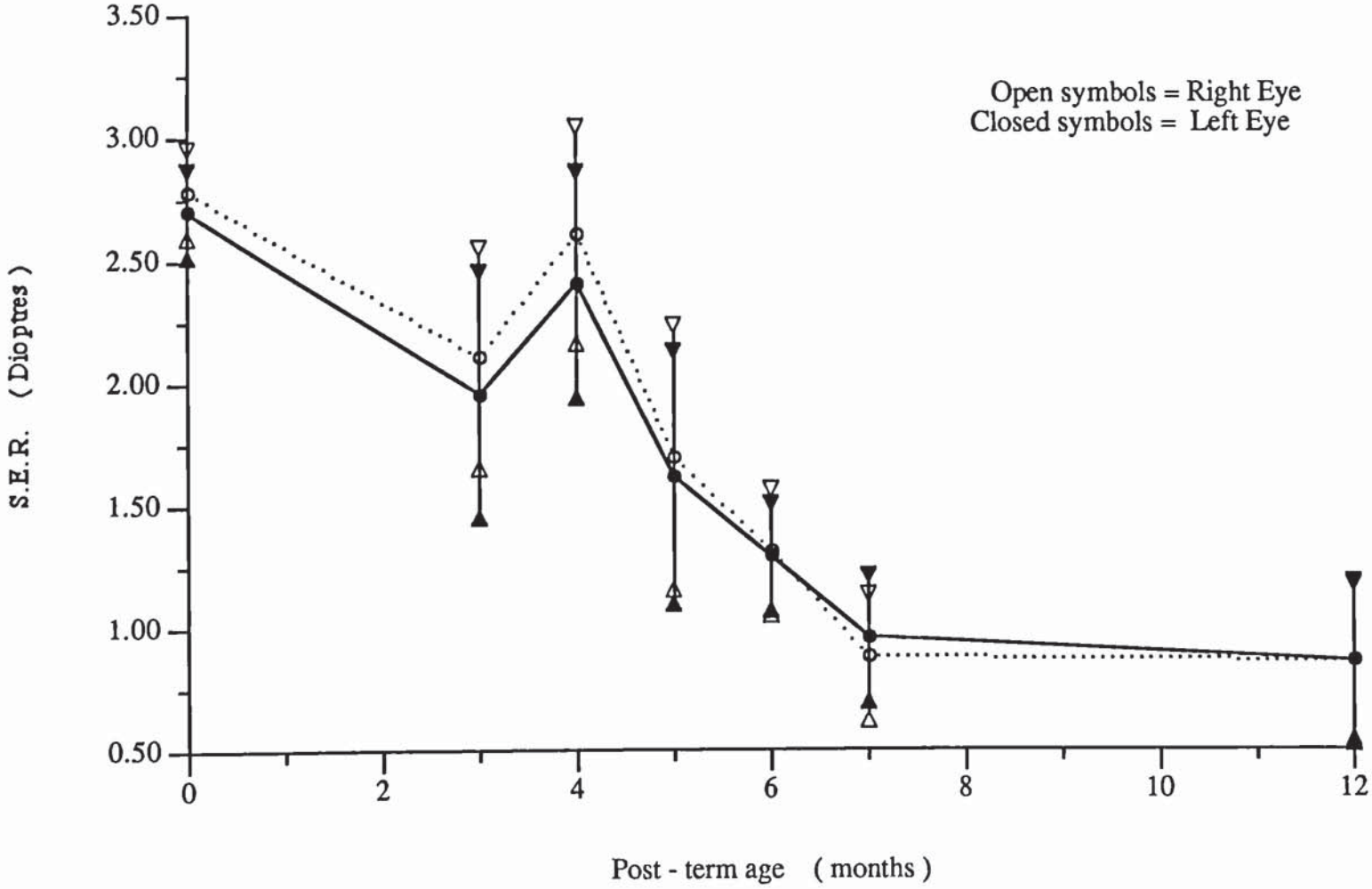


Figure 5.15 Group averaged spherical equivalent refractive findings of right and left eyes between birth and one year. *Infants segregated into monthly age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

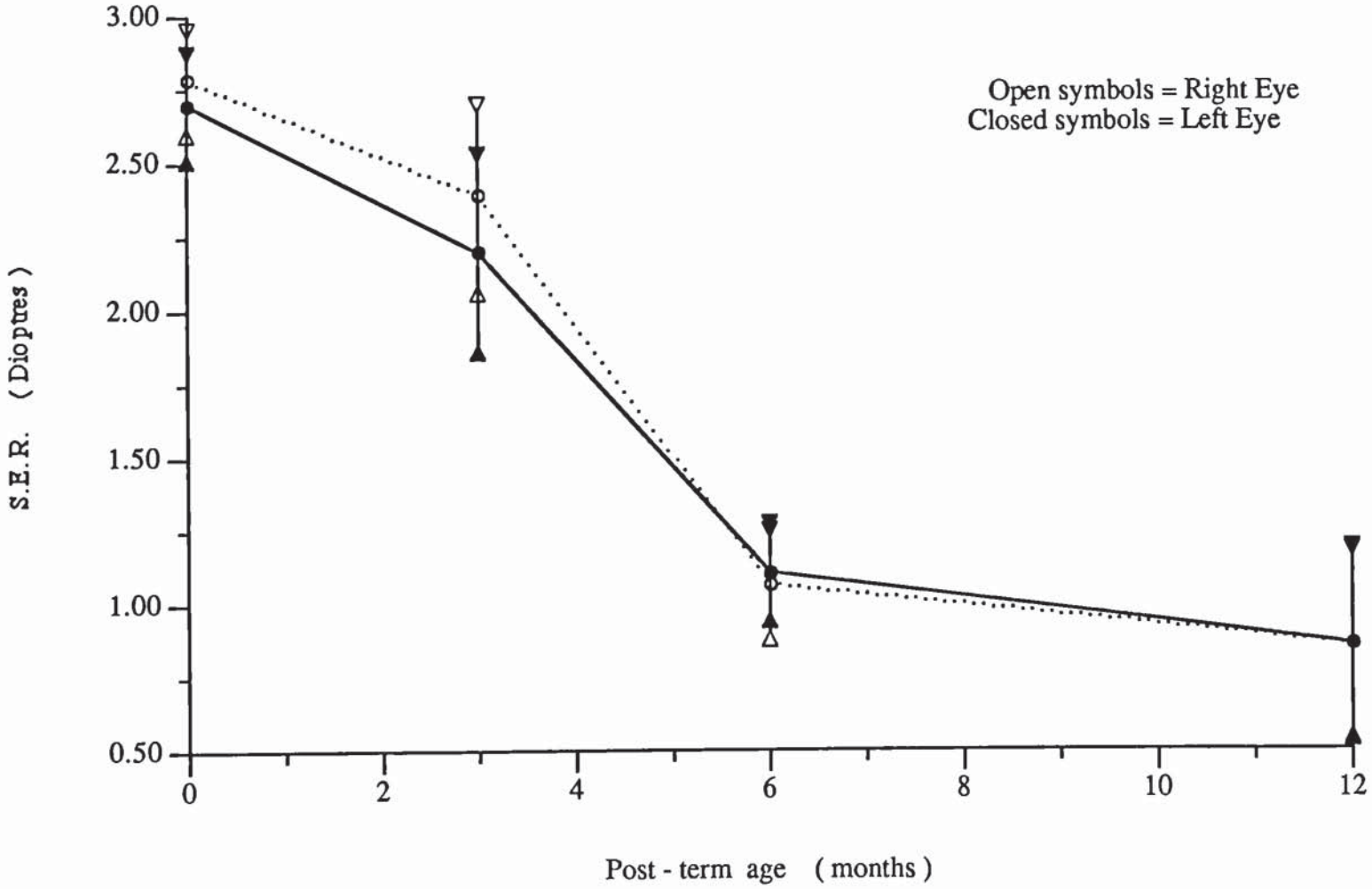


Figure 5.16 Group averaged spherical equivalent refractive findings of right and left eyes between birth and one year. *Infants segregated into newborn, three, six and twelve month age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

Table 5.8 Statistical significances for age-related S.E.R. power changes. Independent t - tests. Mean newborn data for these groups is included in Table 5.10. Mean follow-up data for relevant groups is available in Table 5.7.

Age Groups Compared	Comparison between mean S.E.R. power findings t - stat	d.f.	sig
R. S.E.R. :			
0 v "3"	0.50	182	not sig.
0 v "6"	3.21	191	p = 0.001
0 v 12	2.82	178	p = 0.005
"3" v "6"	3.11	39	p = 0.003
"3" v 12	3.37	38	p = 0.002
"6" v 12	0.52	46	not sig.
L. S.E.R. :			
0 v "3"	0.77	182	not sig.
0 v "6"	3.13	191	p = 0.002
0 v 12	2.77	178	p = 0.006
"3" v "6"	2.56	39	p = 0.014
"3" v 12	2.82	38	p = 0.008
"6" v 12	0.64	46	not sig.

Table 5.9 Statistical significances for age-related S.E.R. power changes. Paired t - tests. Mean newborn data for these groups is included in Table 5.10. Mean follow-up data for relevant groups is available in Tables 5.7 and 5.11.

Age Groups Compared	Comparison between mean S.E.R. power findings t - stat	d.f.	sig
R. S.E.R. :			
0 v "3"	0.57	20	not sig.
0 v "6"	2.13	30	p = 0.042
0 v 12	3.50	17	p = 0.003
"3" v "6"	4.51	11	p = 0.001
L. S.E.R. :			
0 v "3"	1.17	20	not sig.
0 v "6"	2.18	30	p = 0.038
0 v 12	3.02	17	p = 0.008
"3" v "6"	4.29	11	p = 0.001

Table 5.10 Group averaged neonatal S.E.R. findings of t - test samples. Means and standard errors are presented. Neonatal data of the non follow-up sample has been used in independent t - tests, the remaining data is relevant to the paired t - tests.

Sample	Newborn S.E.R. (Dioptres)		
		Right Eye	Left Eye
Non follow-up	162	2.68 (0.21)	2.66 (0.21)
"3" Month	21	2.66 (0.54)	2.72 (0.55)
"6" Month	31	2.04 (0.47)	2.10 (0.45)
12 Month	18	2.42 (0.53)	2.29 (0.60)

5.1.7 Longitudinal data

a) Observation of S.E.R. alterations in 12 individuals

Twelve infants were refracted at birth, three and six months. Group averaged S.E.R. data of these individuals is presented in Table 5.11. The mean level of hypermetropia declined in a monotonic fashion from about 2.9 dioptres at birth to around 1.1 dioptres at six months. The newborn and three month means were not significantly different whereas alterations between three and six months were ($p = 0.001$).

Table 5.11 Group averaged S.E.R. findings of 12 infants refracted at birth, three and six months. Means and standard errors are presented.

Age Group	S.E.R. (Dioptres)	
	Right Eye	Left Eye
Newborn	2.91 (0.58)	2.94 (0.58)
"3" Month	2.47 (0.34)	2.25 (0.31)
"6" Month	1.03 (0.28)	1.11 (0.24)

Alterations in the right eye S.E.R. of individual infants are shown graphically in Figures 5.17 and 5. 18. Two patterns of change were noted. In half of the sample (Figure 5.17) S.E.R. increased between birth and three months, subsequently remaining at the same level (one infant) or declining by six months. In the other six infants (Figure 5.18) S.E.R. declined between birth and three months, subsequently remaining static (one infant) or showing a further reduction by six months. Apart from one infant the trends observed for the left eye were identical to those noted for the right eye. All infants showing the second pattern of development had more than three dioptres of neonatal hypermetropia whereas only one infant in the other group exceeded this level.

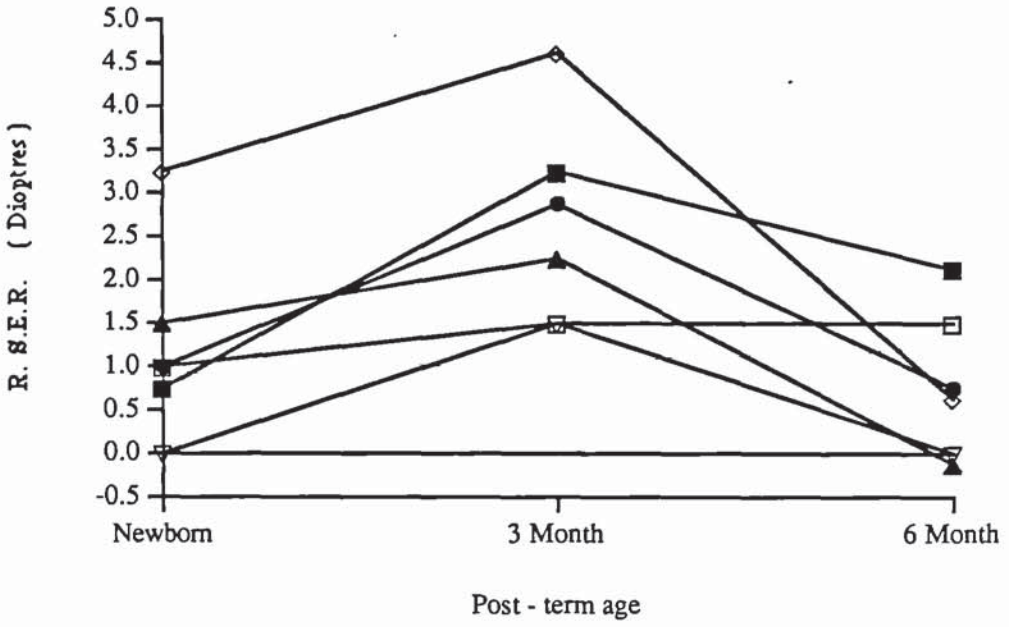


Figure 5.17 Alterations in right eye spherical equivalent refraction between birth, three and six months in six infants followed longitudinally. Data is for infants initially showing hypermetropic shifts.

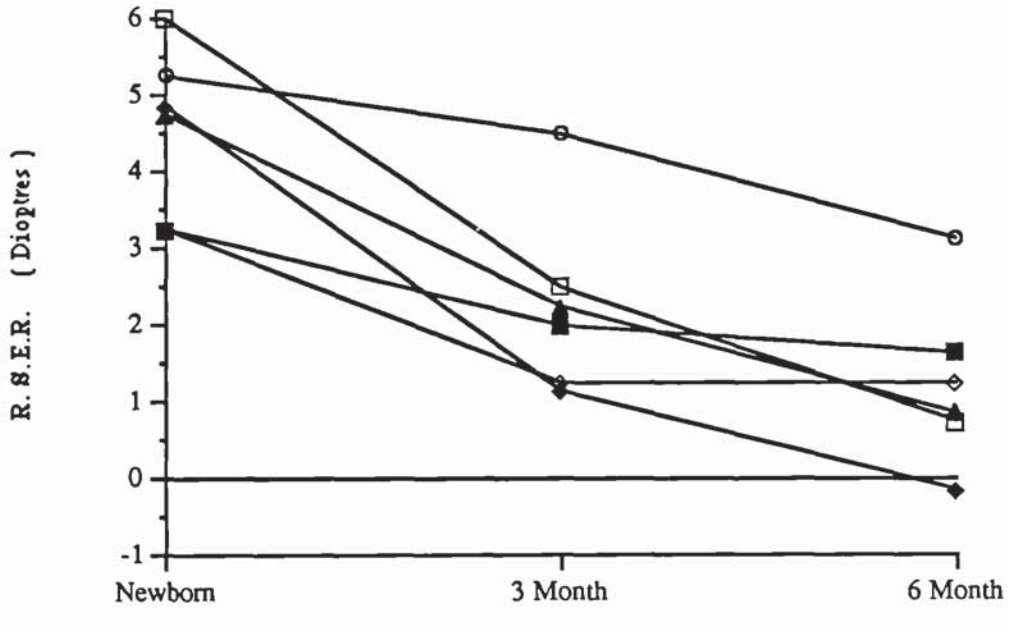


Figure 5.18 Alterations in right eye spherical equivalent refraction between birth, three and six months in six infants followed longitudinally. Data is for infants showing myopic shifts.

b) Analysis of S.E.R. alterations relative to neonatal findings

For each infant in the "3", "6" and 12 month groups magnitude of dioptric change between birth and the subsequent refraction has been computed by subtracting the second from the neonatal S.E.R. value. This computation gives positive values for myopic refractive shifts (decreases in hypermetropia) and negative values for hypermetropic shifts (increases in hypermetropia). The values thus found were divided by the delay (in weeks) between refractions to take into account variations in the age of follow-up examination. Linear regression analyses were performed to investigate whether the observed alterations in refraction (in dioptres or dioptres/week) were correlated with the individual's newborn refractions. The results of these analyses are summarised in Table 5.12 (details are given in Appendix Table A5.11). Representative data for the right eye is plotted in Figures 5.19, 5.20, 5.21, and 5.22. A high correlation between direction and amount of refractive change and magnitude of original error was observed for all age groups. This finding suggests that control processes enabling modification of ocular growth to correct for and thereby minimize spherical ametropia are in operation by at least the post-term third month.

Table 5.12 Summary of correlations between changes observed in spherical equivalent refraction (in dioptres and dioptres per week) and neonatal refraction. Significance level $*^n = p < 0.0001$.

Age Group (months)	n	Right Eye r	Right Eye p	Left Eye r	Left Eye p
Refractive change					
"3"	21	0.78	$*^n$	0.76	$*^n$
"6"	31	0.92	$*^n$	0.93	$*^n$
12	18	0.79	$*^n$	0.82	$*^n$
Rate of change					
"3"	21	0.77	$*^n$	0.75	$*^n$
"6"	31	0.92	$*^n$	0.93	$*^n$
12	18	0.79	$*^n$	0.82	$*^n$

In Figures 5.19 to 5.22 points within quadrant A represent neonatal hyperopes exhibiting myopic shifts, those within area B denote hyperopes showing hypermetropic shifts and myopes showing hypermetropic shifts are plotted within region C. Points occurring above the dashed (y = x) line represent infants with myopic subsequent refractions. In only one case did an infant that was myopic at birth subsequently demonstrate a myopic shift. In fact most myopic neonates subsequently became hypermetropic (data points below the dashed y = x lines in the figures). Apart from this case non emmetropic changes were confined to the hypermetropic neonates. With the exception of one infant (having neonatal refraction of R. S.E.R. +3.25; L. S.E.R. +2.75), hyperopes demonstrating increases in refractive error initially showed no more than 1.5 dioptres of hypermetropia at birth.

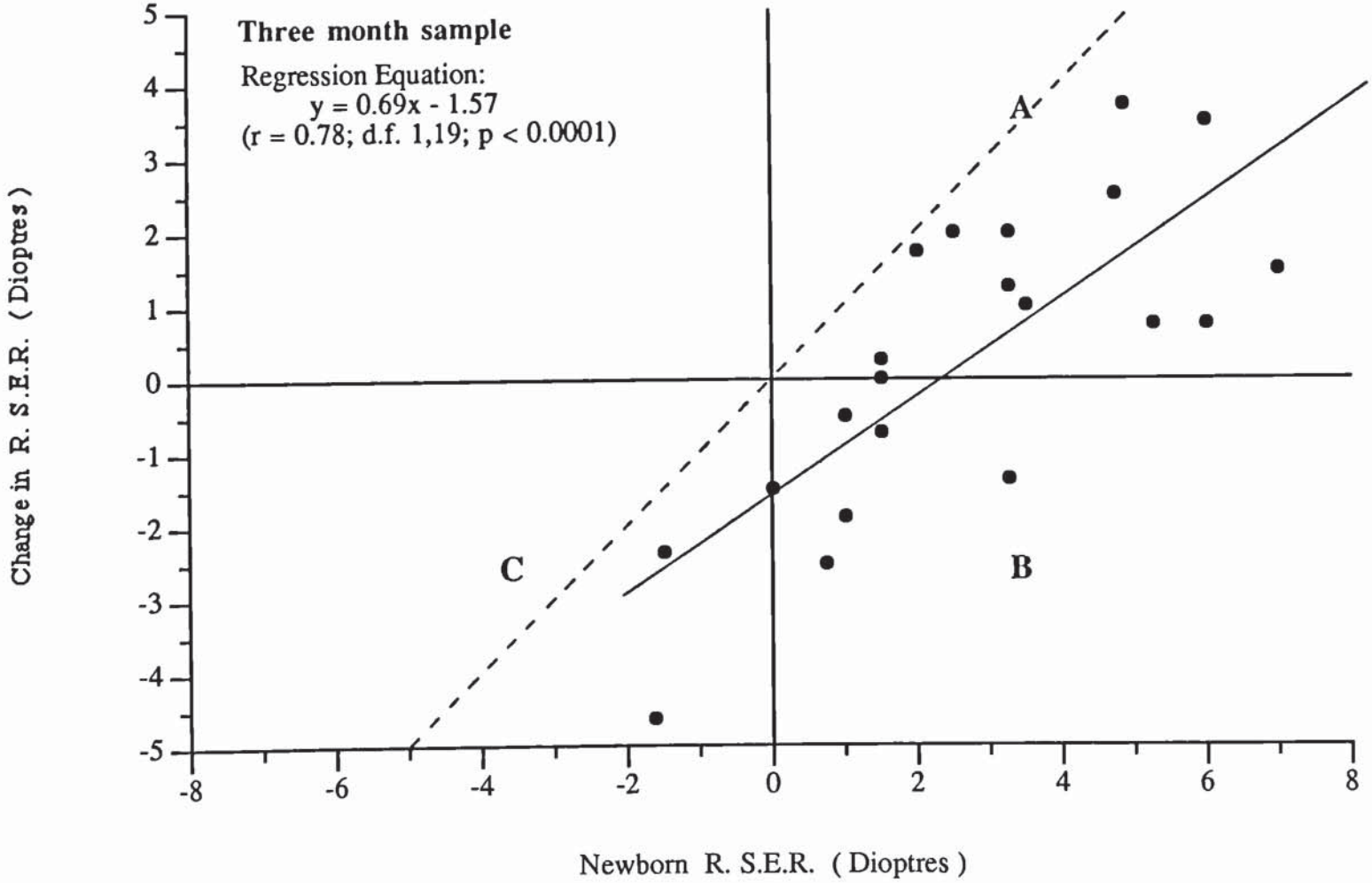


Figure 5.19 Scatterplot illustrating the dioptric alteration in spherical equivalent refractive findings of three month olds relative to their newborn findings. (Right eye data).
Data in quadrants: **A** = hyperopic neonates demonstrating myopic shifts; **B** = hyperopic neonates demonstrating hyperopic shifts and **C** = myopic neonates demonstrating myopic shifts.

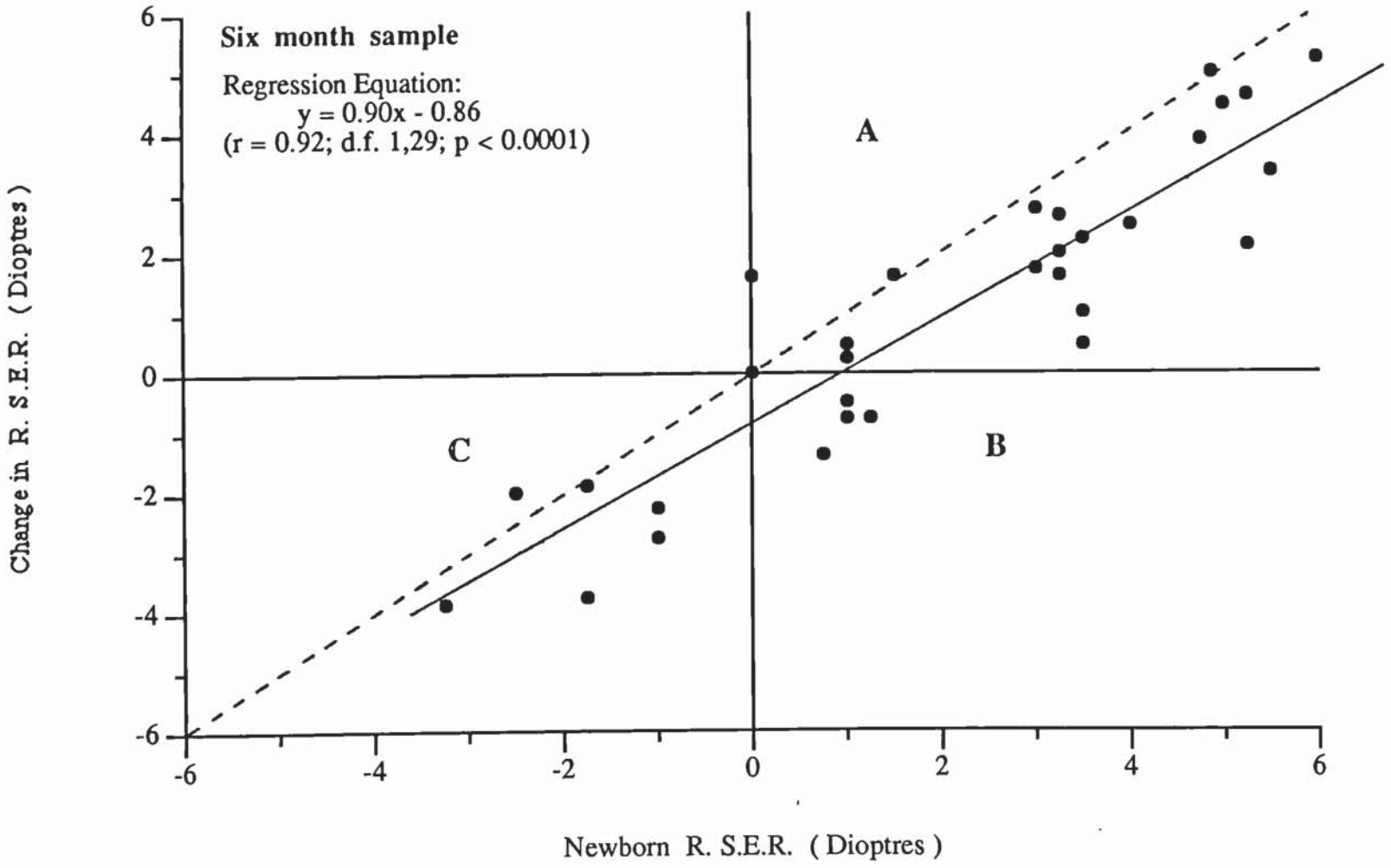


Figure 5.20 As Figure 5.19 for six month sample.

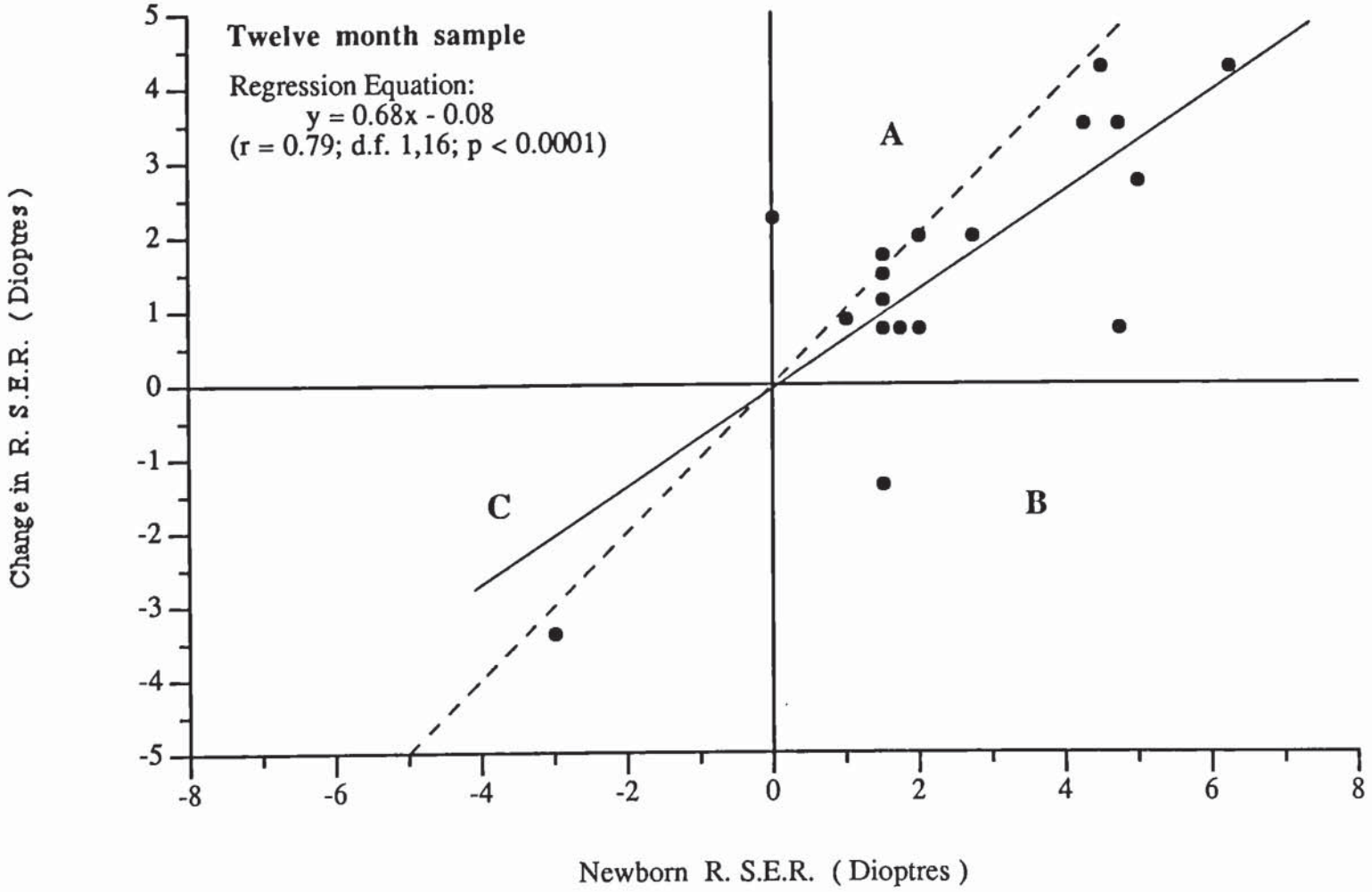


Figure 5.21 As Figure 5.19 for twelve month sample.

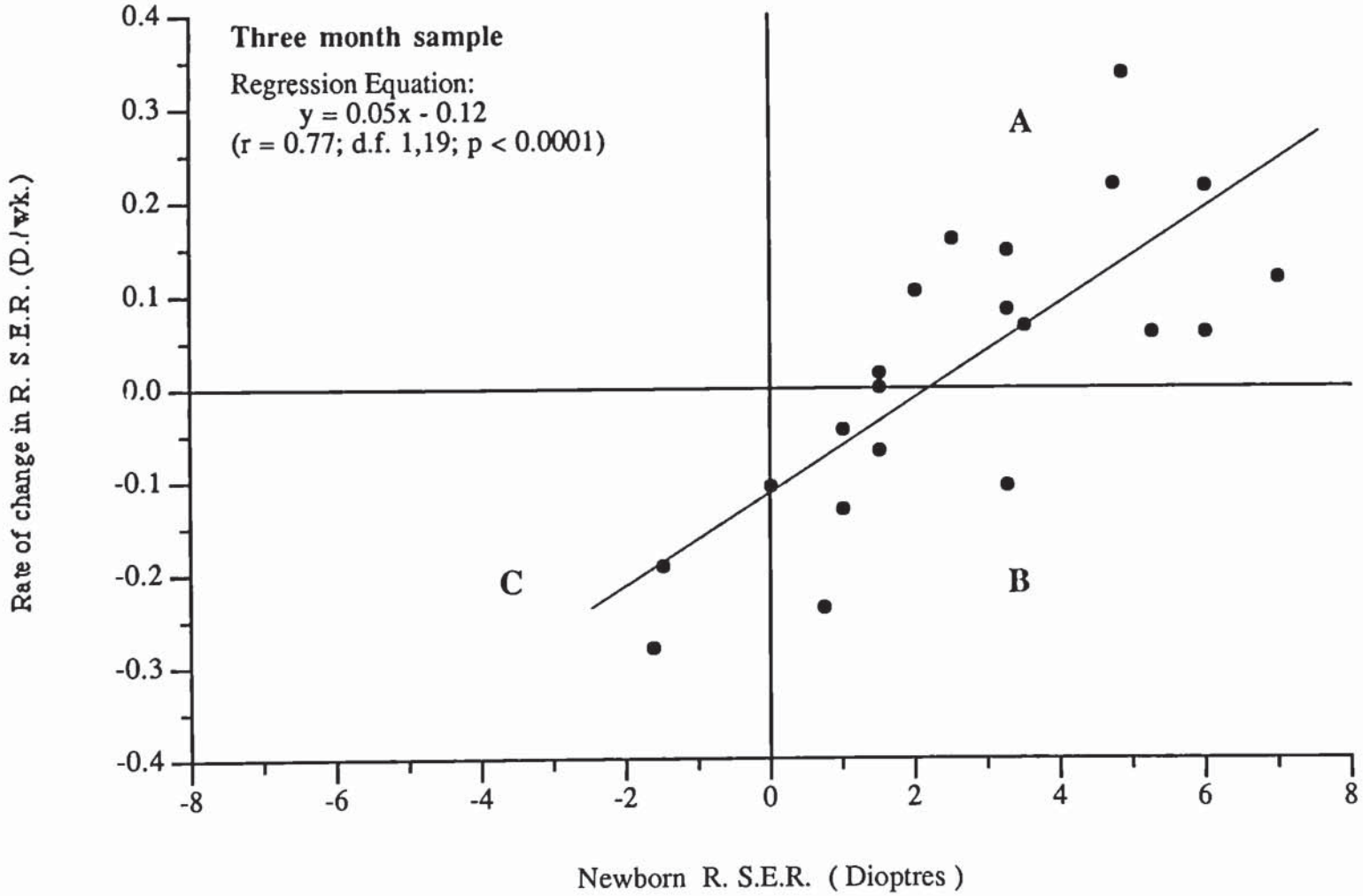


Figure 5.22 Scatterplot illustrating the rate of alteration (dioptres/week) in spherical equivalent refractive findings of three month olds relative to their newborn findings. (Right eye data). Other details as for Figure 5.19.

The number of infants showing emmetropic shifts was calculated by totalling the data points within quadrants A and C. Infants remaining within other quadrants represent those showing non-emmetropic shifts or with unchanged prescriptions. This data is summarised in Tables 5.13 and 5.14. The right eye data is illustrated in Figure 5.23. Combining right and left eye data the proportion of eyes showing emmetropic shifts increases from 75 percent at three months to 86 percent at six and twelve months.

Table 5.13 Summary of frequencies of emmetropic refractive shifts observed in right eye data at three, six and twelve months.

Age Group (months)	n	No (& %) showing various refractive shifts Emmetropic	Non emmetropic	No change
"3"	21	14 (66.7)	6 (28.6)	1 (4.8)
"6"	31	25 (80.6)	5 (16.1)	1 (3.2)
12	18	16 (88.9)	2 (11.1)	0 (0.0)

Table 5.14 Summary of frequencies of emmetropic refractive shifts observed in left eye data at three, six and twelve months.

Age Group (months)	n	No (& %) showing various refractive shifts Emmetropic	Non emmetropic	No change
"3"	21	17 (80.9)	4 (19.0)	0 (0.0)
"6"	31	28 (90.0)	3 (10.0)	0 (0.0)
12	18	15 (83.3)	3 (16.7)	0 (0.0)

An impression of the average rates of refractive change is given by the data presented in Table 5.15. Between birth and three months average change amounted to 0.13 dioptres per week, this value reduced to 0.10 dioptres per week between birth and six months and when expressed over the first year an average alteration of 0.04 dioptres per week was noted. These values represent minimums because it is uncertain and improbable that refractive change occurs in one direction.

Table 5.15 Summary of mean alterations (dioptres & dioptres/week) in S.E.R. for periods from birth to: three, six and twelve months. Means and standard errors are given.

Age Group (months)	Changes in S.E.R. R.E.	L.E.	Rate of Change in S.E.R. R.E.	L.E.
"3"	1.74 (0.26)	1.71 (0.28)	0.13 (0.02)	0.13 (0.02)
"6"	2.25 (0.26)	2.34 (0.23)	0.09 (0.01)	0.10 (0.01)
12	2.08 (0.29)	2.14 (0.27)	0.04 (0.006)	0.04 (0.005)

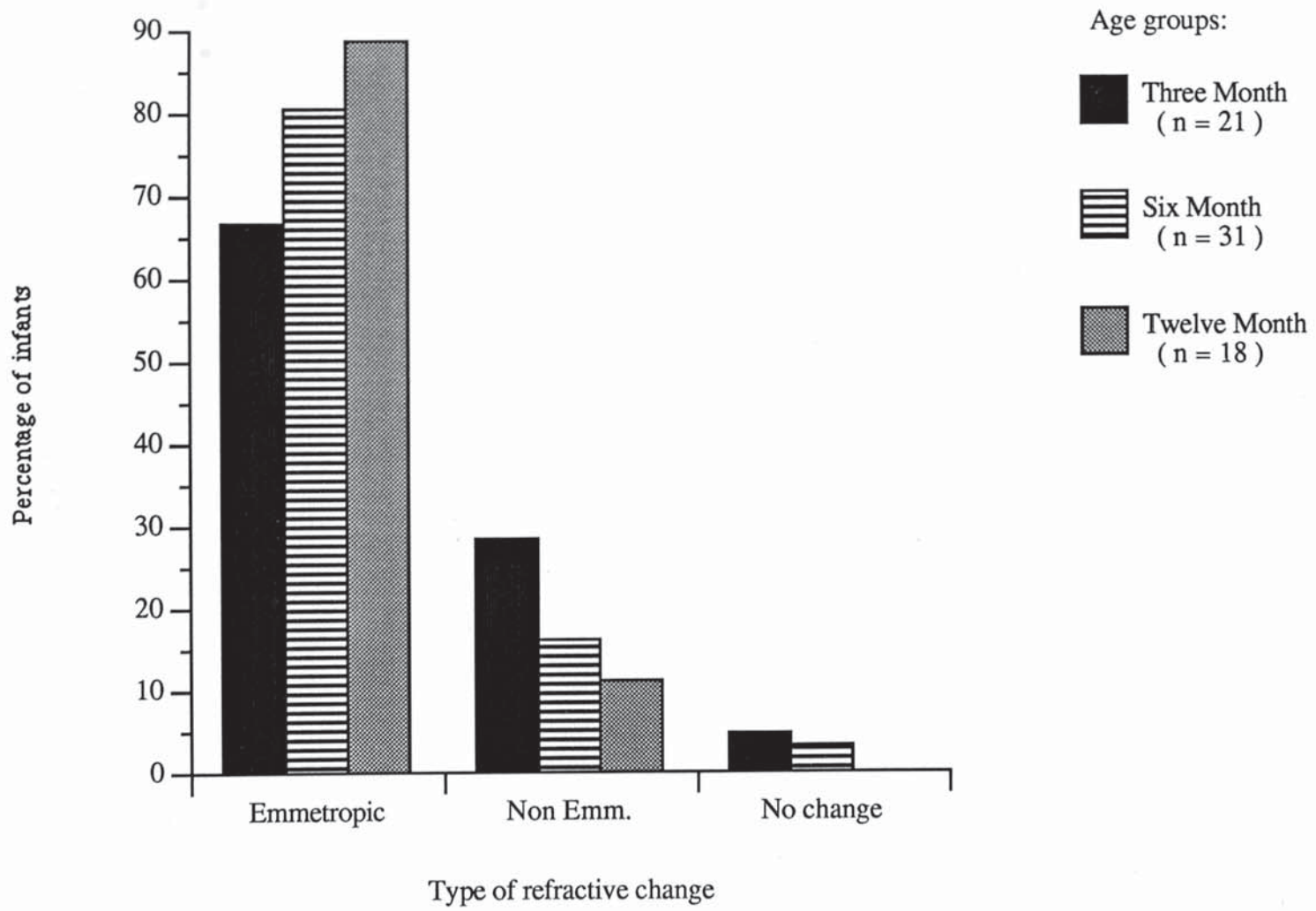


Figure 5.23 Frequency histogram illustrating the percentages of three, six and twelve month olds demonstrating emmetropic, non-emmetropic or no refractive change relative to their neonatal findings. Data is based on right eye spherical equivalent refractive findings. Numerical values are provided in Table 5.13.

5.2 Anisometropia

5.2.1 Neonatal distribution

The distribution of neonatal anisometropia is summarised (in 0.50 D. intervals) in Figure 5.24. Numerical values are given in Table 5.16. The levels of anisometropia found ranged from nought to 3.25 dioptres. Thirty five infants (16.8%) did not show any anisometropia, the most popular finding (99 infants / 47.4%) was of low degrees i.e. ≤ 0.5 dioptres; only 30 infants (14.4%) had more than one dioptre of anisometropia. Group averaged data is presented in Table 5.2 and Figure 5.25. The mean value found was around 0.6 dioptres (S.D. ≈ 0.6 dioptres).

Table 5.16 Distribution of neonatal anisometropic refractive findings.

Refractive Range (Dioptres)	Number	Percentage
0.0	35	16.8
> 0.0 - 0.5	99	47.4
> 0.5 - 1.0	45	21.5
> 1.0 - 1.5	17	8.1
> 1.5 - 2.0	6	2.9
> 2.0 - 2.5	6	2.9
> 2.5 - 3.0	0	0.0
> 3.0 - 3.5	1	0.5

5.2.2 Effect of various factors on neonatal anisometropia

Neonatal anisometropia was not significantly correlated with either maturity at the time of testing, physical size or any of the parameters described in sections 5.1.4 and 5.1.5. Group averaged values for various subgroups are provided in Table 5.4. No significant differences were found between groups (mean levels being of 0.6 dioptres for virtually all samples). Slightly more variability was found in mean levels of anisometropia when the sample was subdivided according to ethnic group. The mean for Caucasians (≈ 0.5 D.) was slightly lower than for infants of Asian or Negro extraction (≈ 0.6 D.). Newborns of mixed or Mongolian parentage demonstrated higher levels (≈ 1.1 D.) but only eleven such infants were examined. These findings are not surprising given the generally low levels of anisometropia encountered and the low sensitivity of the measurement (section 5.4).

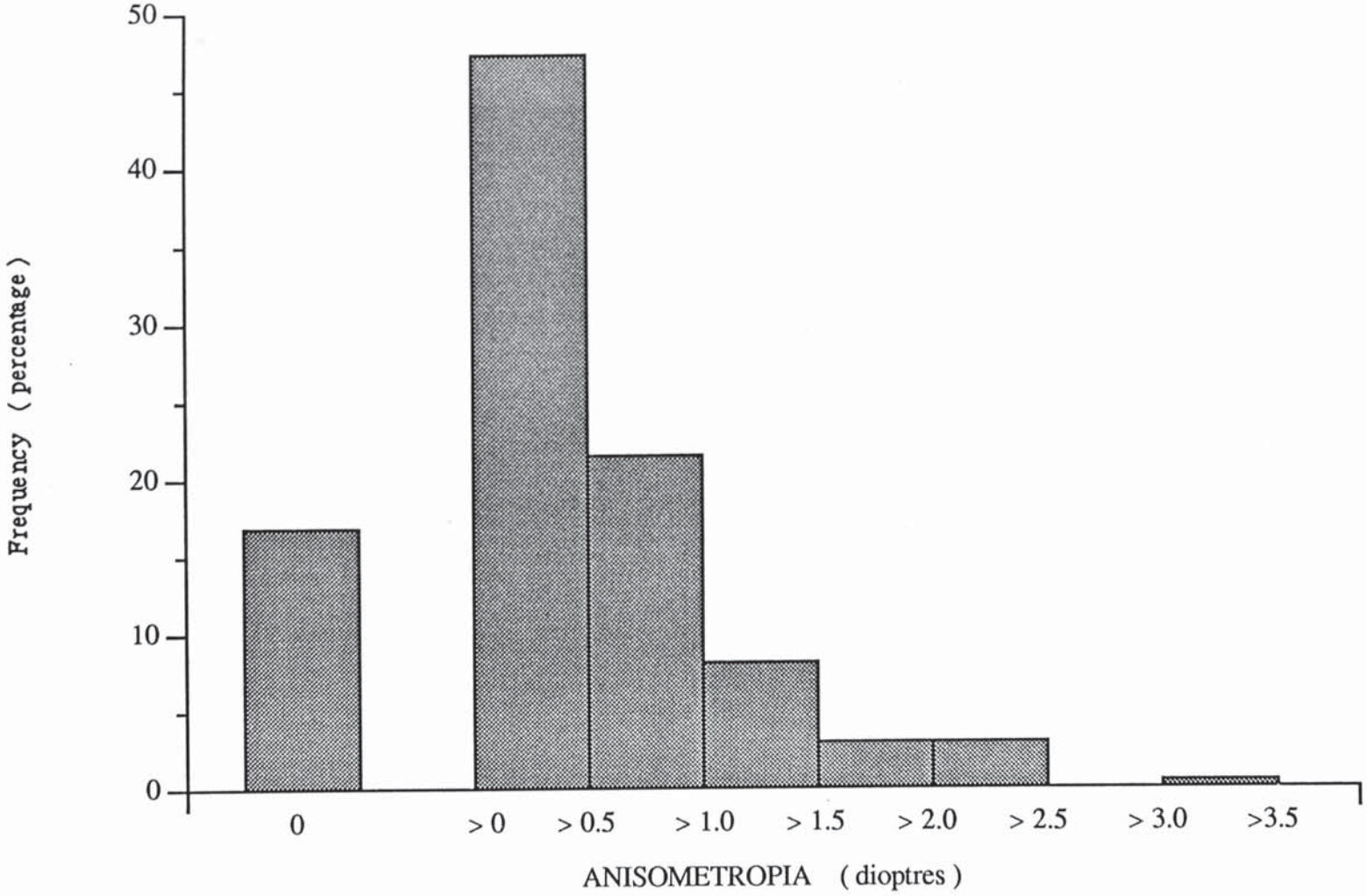


Figure 5.24 Frequency histogram illustrating the distribution of neonatal anisometropia. Numerical values are provided in Table 5.16.

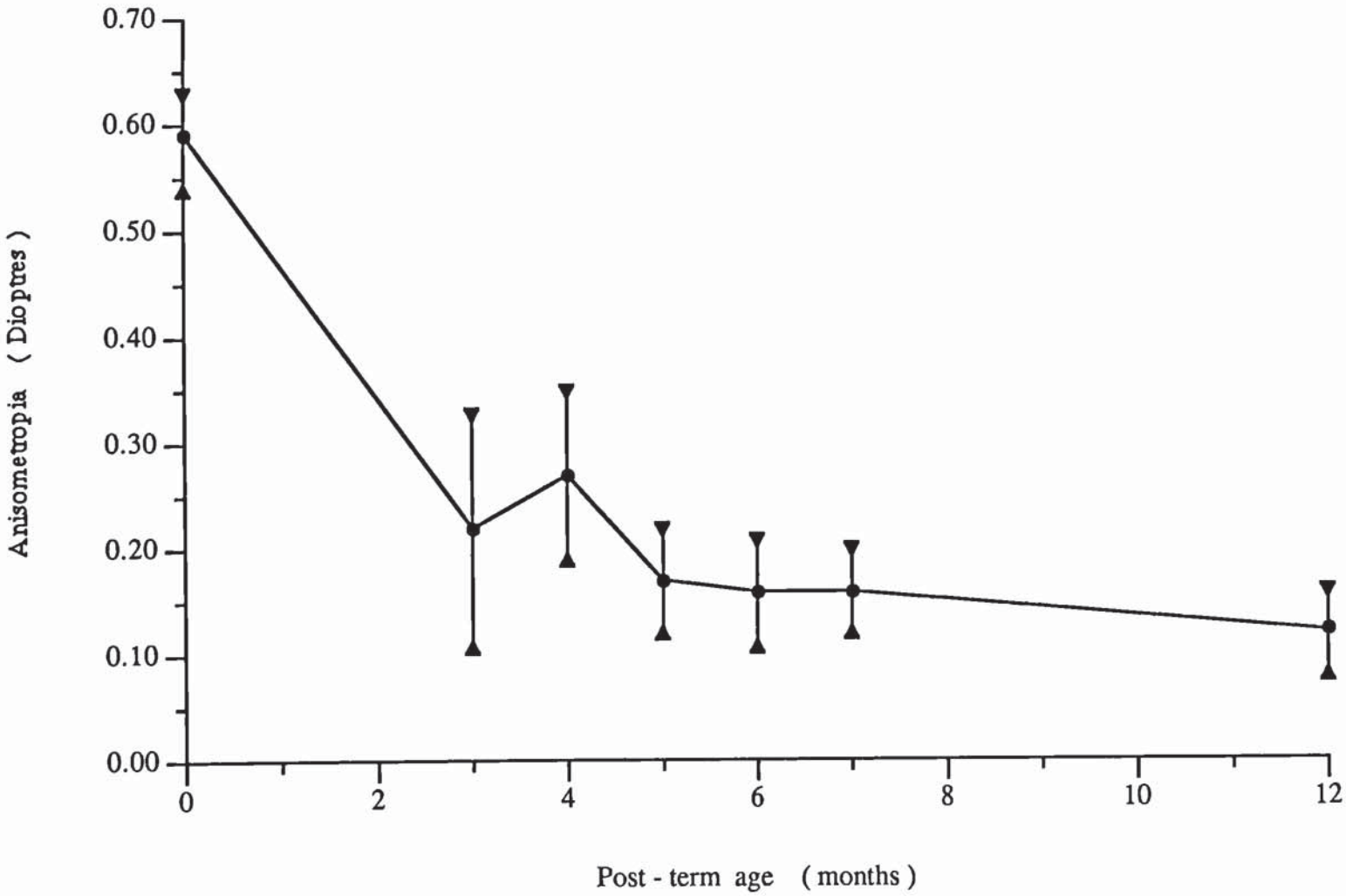


Figure 5.25 Group averaged anisometropic refractive findings between birth and one year. *Infants segregated into monthly age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

5.2.3 Alterations in anisometropia between birth and twelve months

Group-averaged anisometropic data for newborns and infants that were refracted between three and seven months or at one year is illustrated in Figure 5.25. Numerical values are given in Table 5.7. Apart from a slight increase around four months mean values decrease in a monotonic fashion from ≈ 0.6 dioptres at birth to ≈ 0.1 dioptres at one year. Most of the reduction had taken place by the third post-term month.

Independent sample t - tests were performed to determine whether any significant differences existed between mean anisometropic refractive findings of consecutive age groups (i.e. 3 month v 4 month, 4 month v 5 month etc.). No significant differences were found so the three and four month and six and seven month samples have been combined. Mean data of the larger samples thus formed are also included in Table 5.7 and these have been plotted along with the newborn and twelve month data in Figure 5. 26. The five month sample has been disregarded as only five infants were refracted at this age. Independent and paired student t - tests have been applied to infants contributing data to the groups whose mean findings appear in Figure 5.26. The results of these analyses are given in Tables 5.17 and 5.18 . The newborn data (Table 5.19 gives means) was significantly different from that of all other groups (apart from paired t - test results at three months). No other significant differences between samples were noted.

Table 5.17 Statistical significances for age-related changes in anisometropic power. Independent t - tests. Mean newborn data is included in Table 5.19. Mean follow-up data is available in Table 5.7.

Age Groups compared:	Comparison between mean Anisometropic power findings t - stat	d.f.	sig
0 v "3"	2.68	182	$p = 0.008$
0 v "6"	4.15	191	$p < 0.0001$
0 v 12	3.47	178	$p = 0.001$
"3" v "6"	1.38	39	not sig.
"3" v 12	1.61	38	ns (0.12)
"6" v 12	0.56	46	not sig.

Table 5.18 Statistical significances for age-related changes in anisometropic power. Paired t - tests. Mean newborn data for these groups is included in Table 5.19. Mean follow-up data is provided in Tables 5.7 and 5.20.

Age Groups compared:	Comparison between mean Anisometropic power findings t - stat	d.f.	sig
0 v "3"	1.68	20	ns (0.11)
0 v "6"	4.62	30	$p < 0.0001$
0 v 12	3.33	17	$p = 0.004$
"3" v "6"	0.34	11	not sig.

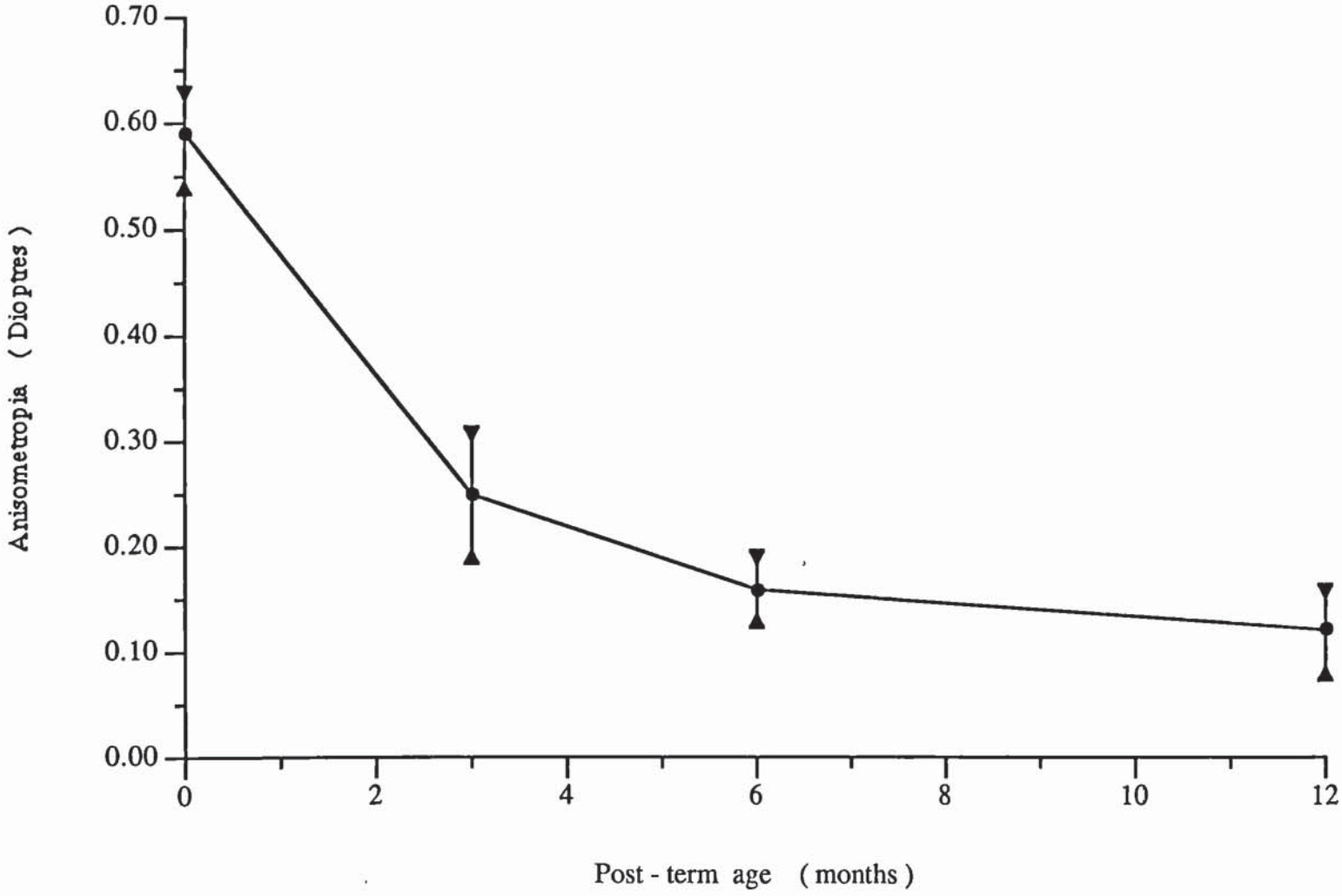


Figure 5.26 Group averaged anisometropic refractive findings between birth and one year. *Infants segregated into newborn, three, six and twelve month age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

Table 5.19 Group averaged neonatal anisometropic power findings of t - test samples. Means and standard errors are presented. Neonatal data of the non follow-up group has been used in independent t - tests, the remaining data is relevant to the paired t - tests.

Sample	Newborn Aniso. power (Dioptres).		
	n	Mean	S.E.
Non follow-up	162	0.55	0.04
"3" Month	21	0.47	0.11
"6" Month	31	0.71	0.11
12 Month	18	0.63	0.16

5.2.4 Longitudinal data

Twelve infants were refracted at birth, three and six months. Group averaged anisometropic data of these individuals is presented in Table 5.20. The mean level declined from about 0.6 dioptres at birth to around 0.2 dioptres at six months. Differences between newborn and three month means were almost significant at the 5 % level ($p = 0.08$) whereas alterations between three and six months were not.

Table 5.20 Anisometropia findings of 12 infants refracted at birth, three and six months. Means, S.D. and group S.E.

Age Group (months)	Mean	S.D.	S.E.
Newborn	0.61	0.59	0.18
"3"	0.22	0.26	0.08
"6"	0.19	0.17	0.05

5.3 Astigmatism

5.3.1 Neonatal distribution

The range of cylindrical refractive findings encountered in the newborn sample varied between 0.00 and 7.50 DC in the right eye and between 0.00 and 6.00 DC in the left eye. The distributions of neonatal cylindrical power findings are shown as frequency histograms (in 0.50 dioptre intervals) in Figures 5.27 and 5.28. Numerical values are provided in Table 5.21. Only 33 (15.8%) of right eyes and 22 (10.5%) of left eyes were noted to be not astigmatic. Most eyes were found to display cylinders of more than 0.5 up to 2.0 dioptres. Few eyes demonstrated more than 2.5 dioptres of astigmatism. Group averaged data is plotted in Figure 5.30. Numerical values are given in Table 5.2. The mean cylinder power of newborns was around 1.7 dioptres in each eye (S.D. ≈ 1.3 dioptres).

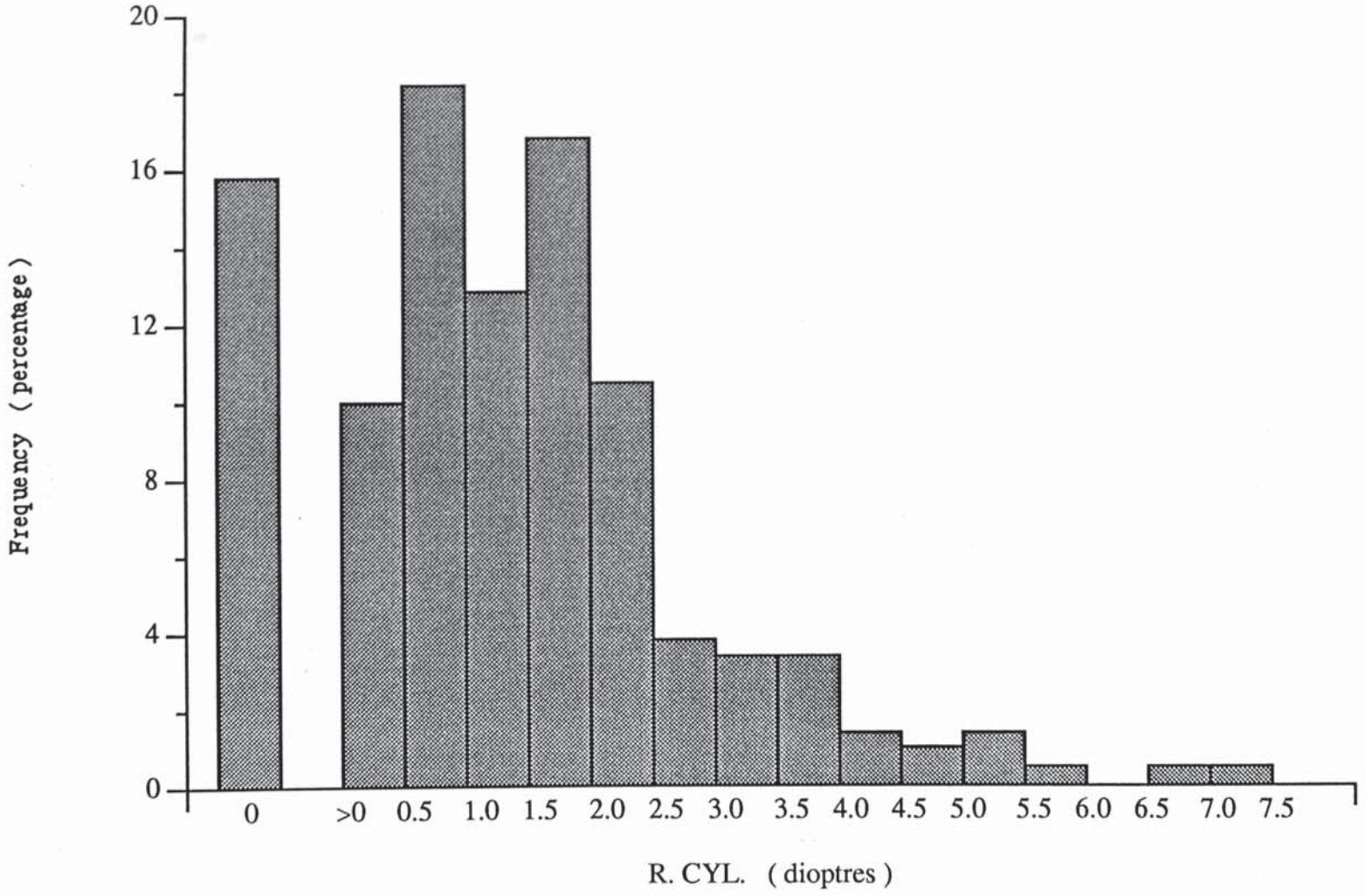


Figure 5.27 Frequency histogram illustrating the distribution of cylindrical power refractive error findings amongst 209 newborns' right eyes. Numerical values are provided in Table 5.21.

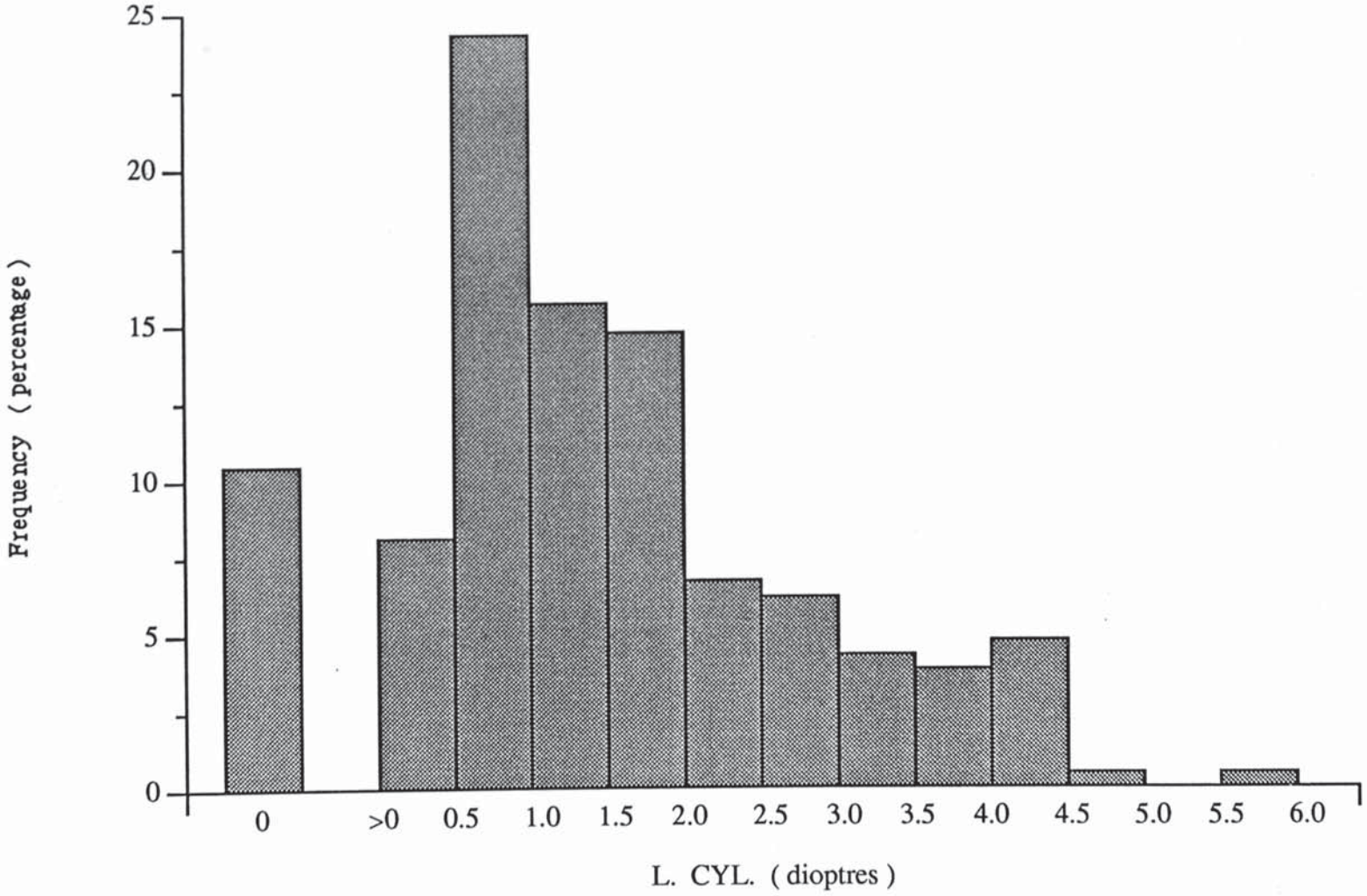


Figure 5.28 Frequency histogram illustrating the distribution of cylindrical power refractive error findings amongst 210 newborns' left eyes. Numerical values are provided in Table 5.21.

Table 5.21 Distribution of neonatal cylindrical refractive findings.

Refractive Range (Dioptres)	Right Eye No.	%	Left Eye No.	%
0.0	33	15.8	22	10.5
> 0.0 - 0.5	21	10.0	17	8.1
> 0.5 - 1.0	38	18.2	51	24.3
> 1.0 - 1.5	27	12.9	33	15.7
> 1.5 - 2.0	35	16.8	31	14.8
> 2.0 - 2.5	22	10.5	14	6.7
> 2.5 - 3.0	8	3.8	13	6.2
> 3.0 - 3.5	7	3.4	9	4.3
> 3.5 - 4.0	7	3.4	8	3.8
> 4.0 - 4.5	3	1.4	10	4.8
> 4.5 - 5.0	2	1.0	1	0.5
> 5.0 - 5.5	3	1.4	0	0.0
> 5.5 - 6.0	1	0.5	1	0.5
> 6.0 - 6.5	0	0.0	-	-
> 6.5 - 7.0	1	0.5	-	-
> 7.0 - 7.5	1	0.5	-	-

Astigmatism has been categorised into "with the rule" (axis 90 ± 15°); "against the rule" (axis 180 ± 15°) and oblique (any other axis). The frequency of each type of astigmatism amongst infant astigmats is shown in Table 5.22. Combining right and left eye figures 329 eyes (90.4%) showed with the rule astigmatism; 12 eyes (3.3%) showed against the rule and 23 eyes (6.3%) demonstrated oblique astigmatism.

Table 5.22 Incidence of particular types of astigmatism amongst newborn astigmats. W.T.R. = with the rule (90 ± 15°); A.T.R. = against the rule (180° ± 15°).

	Sample Size	No. (&%) with different types of astigmatism W.T.R.	A.T.R.	Oblique
Right Eye	176	156 (88.6)	5 (3.8)	15 (8.5)
Left Eye	188	173 (92.0)	7 (3.7)	8 (4.3)

5.3.2 Effect of various factors on neonatal astigmatism

Neonatal astigmatism was not significantly correlated with either maturity at the time of testing or physical size. However a trend was noted for higher cylinder powers to be found as duration of cycloplegia increased. This trend reached statistical significance for the left eye data ($p < 0.01$) and almost did so for the right eye ($p = 0.08$). Regression line equations and statistics are provided in Appendix Table A5.3 (these are summarised in Table 5.3). The left eye data is plotted in Figure 5.29.

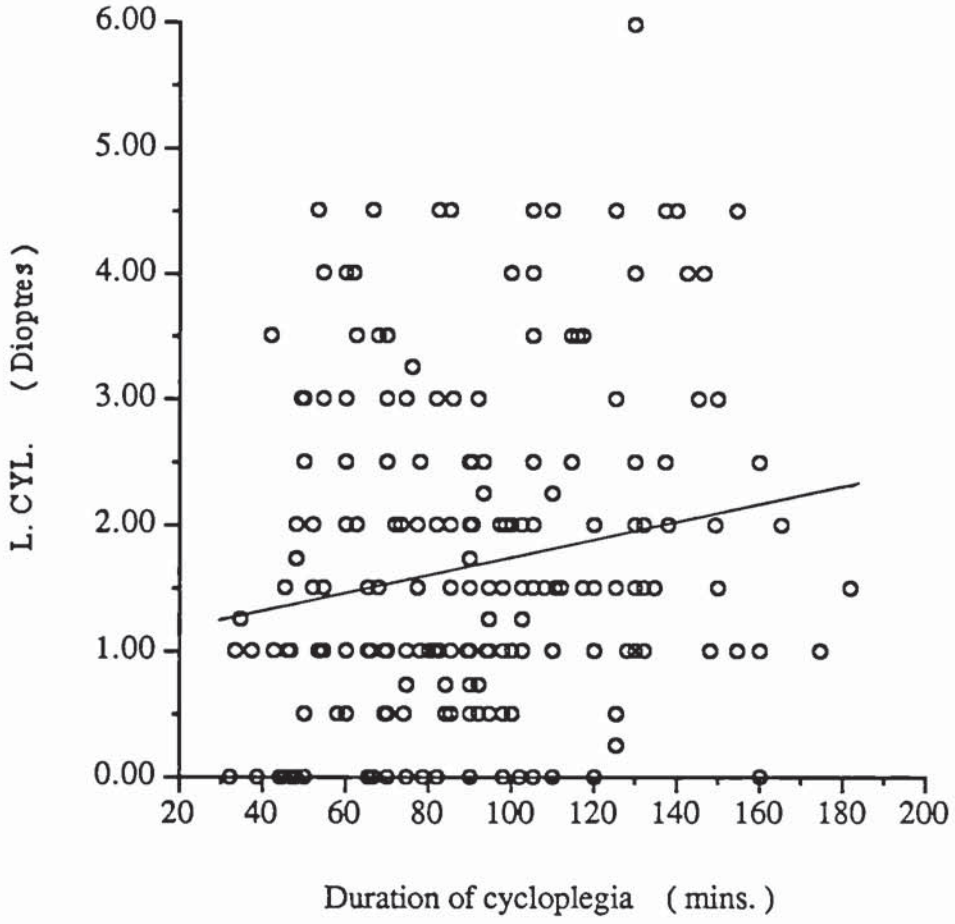


Figure 5.29 Scatterplot of neonatal cylindrical power data versus duration of cycloplegia. Data is from the left eye. Equation of regression line: $y = 0.007\ x + 1.06$ ($r = 0.19$; d.f. 1,200; $p < 0.01$).

Group averaged values for various subgroups (described in sections 5.1.4 and 5.1.5) are provided in Table 5.4. Independent t - tests were performed on the data. Significant differences were found between the cylindrical power findings of the following samples: retinal haemorrhage and non-retinal haemorrhage groups, males and females, and Asians and Caucasians. Higher levels of astigmatism were found in females, Asians and newborns without retinal haemorrage. Results of relevant statistical tests are given in Table 5.23. Independent t - tests were additionally performed to check for significant differences in duration of cycloplegia between samples. Mean duration of cycloplegia was almost identical in the retinal haemorrhage and non retinal haemorrhage samples (91.6, S.E. 4.5 mins. in the haemorrhage and 91.1, S.E. 2.6 mins. in the non retinal haemorrhage group; independent t - test $p > 0.05$). No significant differences in timing of retinoscopy were noted between the male and female samples or the Asian and Caucasian groups. In both cases duration of cycloplegia was in fact higher in the group having lower cylinder power findings (males - mean 93.4, S.E. 3.2 mins., females - mean 88.8, S.E. 3.1 mins, independent t - test $p > 0.05$; Caucasians - mean 97.6, S.E. 4.0 mins., Asians - mean 88.1, S.E. 3.0 mins, independent t - test $p = 0.06$).

Table 5.23 Statistical significances for cylindrical power data. Independent sample student t - tests.
R.H. = retinal haemorrhage, Nil = no retinal haemorrhage, F. = female and C. = Caucasian.

Groups	Variable	Comparison between mean Cyl.power findings. t - stat	d.f.	sig
R.H v Nil.	R. Cyl	- 2.62	206	p = 0.009
	L. Cyl.	- 2.51	207	p = 0.013
Male v F.	R. Cyl.	- 2.61	207	p = 0.005
	L. Cyl.	- 2.82	208	p = 0.010
Asian v C.	R. Cyl.	2.38	171	p = 0.019
	L. Cyl.	2.35	172	p = 0.020

5.3.3 Alterations in astigmatism between birth and twelve months

Data was collected from infants of between three and seven months and from one year olds. Group averaged data computed on the basis of the monthly age groups defined in Table 3.7, is illustrated graphically in Figure 5.30. Numerical values are provided in Table 5.7. Similar trends were noted for the right and left eyes. Mean levels of astigmatism decreased from 1.7 dioptres at birth to approximately 0.9 dioptres around four months. At six months levels had increased to newborn values but subsequently declined to around 0.8 dioptres by one year.

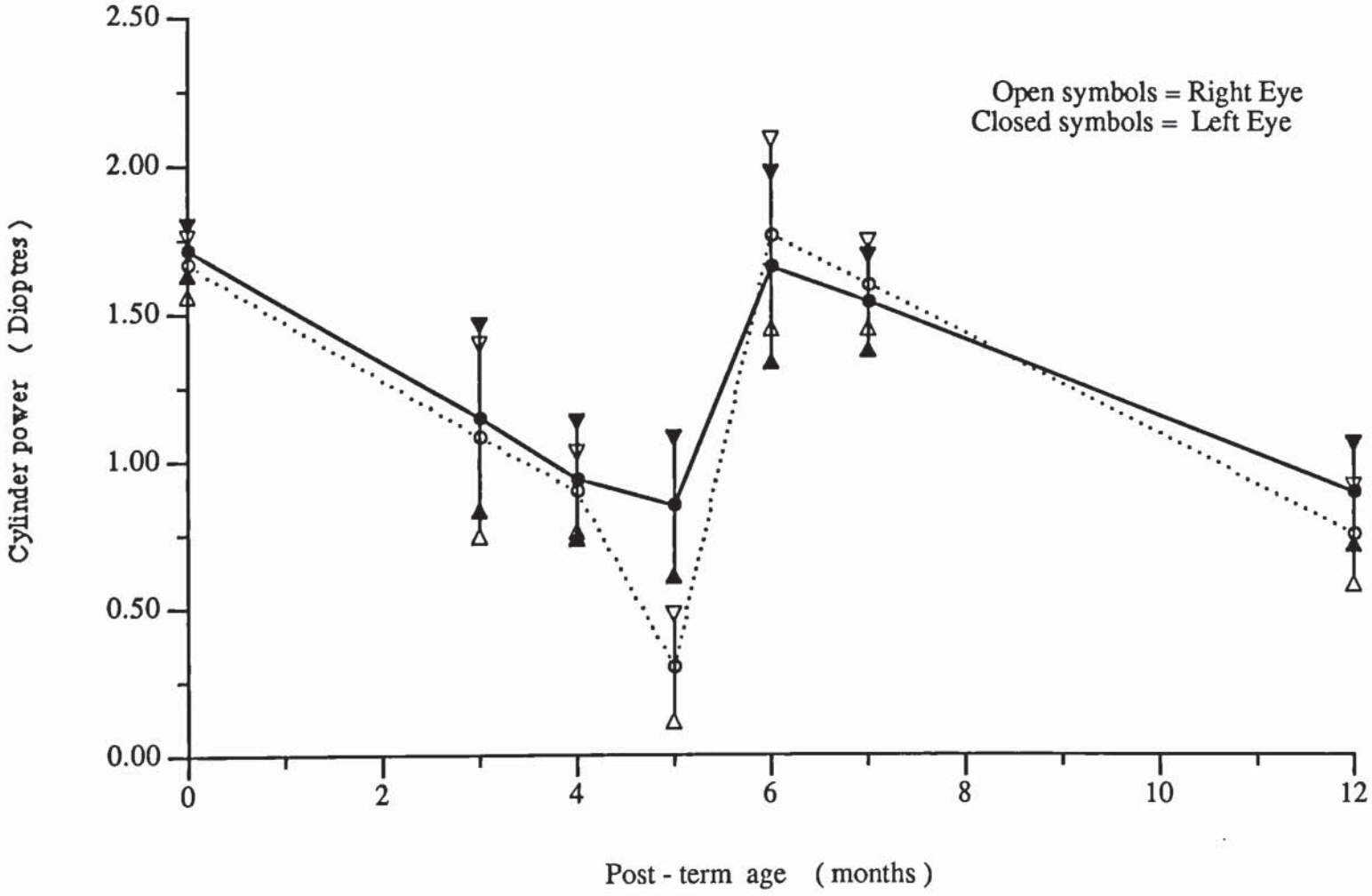


Figure 5.30 Group averaged cylindrical power refractive findings of right and left eyes between birth and one year. *Infants segregated into monthly age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

Since no infant was refracted twice within one month independent sample t - tests were performed to determine whether any significant differences existed between mean cylindrical power refractive findings of consecutive age groups (i.e. 3 month v 4 month, 4 month v 5 month etc.). Details of significant comparisons are presented in Table 5.24. The right eye cylinder power of the five month age group was significantly different from that of the four and six month groups. Mean cylinder power (both eyes) was significantly lower at one year than at seven months. No other significant differences between adjacent groups were found. For this reason the three and four month and the six and seven month samples have been combined in further analysis to increase sample sizes. Only five infants were refracted in the fifth post-term month so this group has been ignored in further analysis. Mean data of the larger samples thus formed is presented in Table 5.7 and is plotted in Figure 5.31 along with the newborn and twelve month data.

Table 5.24 Statistical significances for cylindrical power data. Independent sample student t - test. Mean data is provided in Table 5.7.

Age Groups (Months)	Variable	Comparison between mean Cyl.power findings. t - stat	d.f.	sig
4 v 5	R. Cyl.	2.51	15	p = 0.024
	L. Cyl.	0.26	15	not sig.
5 v 6	R. Cyl.	- 2.63	17	p = 0.017
	L. Cyl.	- 1.42	17	not sig.
7 v 12	R. Cyl.	3.82	33	p = 0.001
	L. Cyl.	2.75	33	p = 0.010

Independent and paired t - tests have been conducted to check the significance of refractive differences noted for age groups included in Figure 5.31. Numerical values are given in Table 5.25 and 5.26. Newborn values were not significantly different from levels at six months but were in most cases (with the exception of the three month paired t-test result) significantly different from other age groups. Alterations in the right cylinder power observed between three and six months were significant but left cylinder power differences were not quite. Changes observed between six and twelve months were significant for each eye.

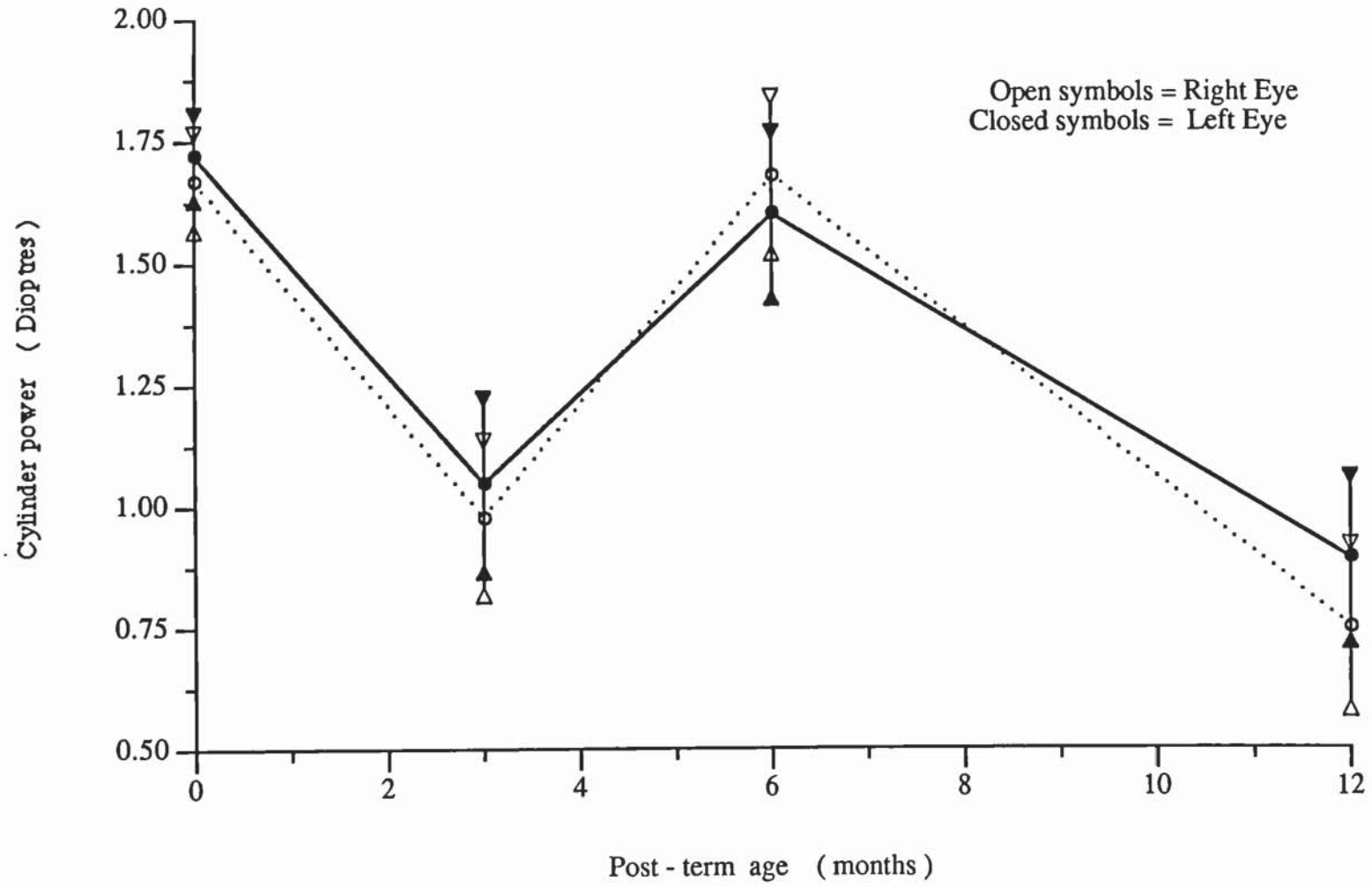


Figure 5.31 Group averaged cylindrical power refractive findings of right and left eyes between birth and one year. *Infants segregated into newborn, three, six and twelve month age groups.* Vertical bars indicate 2 SEM. Numerical values are provided in Table 5.7.

Table 5.25 Statistical significances for age-related cylinder power changes. Independent t - tests. Mean newborn data for these groups is included in Table 5.27. Mean follow-up data is available in Table 5.7.

Age Groups compared	Comparison between mean Cyl. power findings t - stat	d.f.	sig
R. Cyl. :			
0 v "3"	2.33	182	p = 0.021
0 v "6"	0.03	191	not sig.
0 v 12	2.80	178	p = 0.006
"3" v "6"	-2.43	39	p = 0.020
"3" v 12	0.97	38	not sig.
"6" v 12	3.51	46	p = 0.001
L. Cyl. :			
0 v "3"	2.46	182	p = 0.015
0 v "6"	0.46	191	not sig.
0 v 12	2.78	178	p = 0.006
"3" v "6"	-1.66	39	ns (0.10)
"3" v 12	0.63	38	not sig.
"6" v 12	2.54	46	p = 0.015

Table 5.26 As Table 5.25 for paired t - tests. Mean newborn data is included in Table 5.27. Mean follow-up data is available in Tables 5.7 and 5.28.

Age Groups Compared	Comparison between mean Cyl. power findings t - stat	d.f.	sig
R. Cyl. :			
0 v "3"	1.80	20	ns (0.09)
0 v "6"	-0.76	30	not sig.
0 v 12	3.75	17	p = 0.002
"3" v "6"	-2.86	11	p = 0.015
L. Cyl. :			
0 v "3"	2.05	20	p = 0.05
0 v "6"	-1.28	30	not sig.
0 v 12	4.31	17	p = 0.0005
"3" v "6"	-2.09	11	ns (0.06)

Table 5.27 Group averaged neonatal cylinder power findings of t - test samples. Means and standard errors are presented. Neonatal data of the non follow-up sample has been used in independent t - tests, the remaining data is relevant to the paired t - tests.

Sample	n	Newborn Cyl. power (Dioptres) Right Eye	Left Eye
Non follow-up	162	1.69 (0.11)	1.70 (0.10)
"3" Month	21	1.69 (0.35)	1.63 (0.25)
"6" Month	31	1.49 (0.26)	1.37 (0.18)
12 Month	18	1.78 (0.30)	2.33 (0.32)

5.3.4 Longitudinal data

Twelve infants were refracted at birth, three and six months. Group averaged cylinder power data of these individuals is presented in Table 5.28. The mean level of astigmatism declined between birth and three month then increased to neonatal levels at six months. The newborn and three month means were not significantly different ($p > 0.05$), whereas alterations between three and six months were significant for the right eye ($p = 0.02$) but not the left eye ($p = 0.06$).

Table 5.28 Group averaged cylindrical power findings of 12 infants refracted at birth, three and six months. Means and standard errors are presented.

Age Group	Cylinder Power (Dioptres)	
	Right Eye	Left Eye
Newborn	2.02 (0.57)	1.71 (0.35)
"3" Month	1.15 (0.28)	1.25 (0.28)
"6" Month	1.94 (0.36)	1.81 (0.34)

Alterations in the right eye cylinder power of individual infants are shown graphically in Figures 5.32 and 5.33. In half of the sample (Figure 5.32) cylinder power decreased between birth and three months, subsequently increasing by six months. The other six infants (Figure 5.33) showed varied patterns of development. In two astigmatism increased to three months then declined by six months. Two others showed a decrease between birth and three months one subsequently remaining static the other demonstrating a further reduction by six months. One infant had no astigmatism at birth or three months but developed about a dioptre by six months. The remaining infant showed minimal astigmatism (0.25 ± 0.25 DC) throughout the time period. All infants included in Figure 5.32 had at least two dioptres of neonatal astigmatism whereas infants in Figure 5.33 had no more than 1.5 dioptres. In most cases trends observed for the left eye were similar to those noted for the right eye.

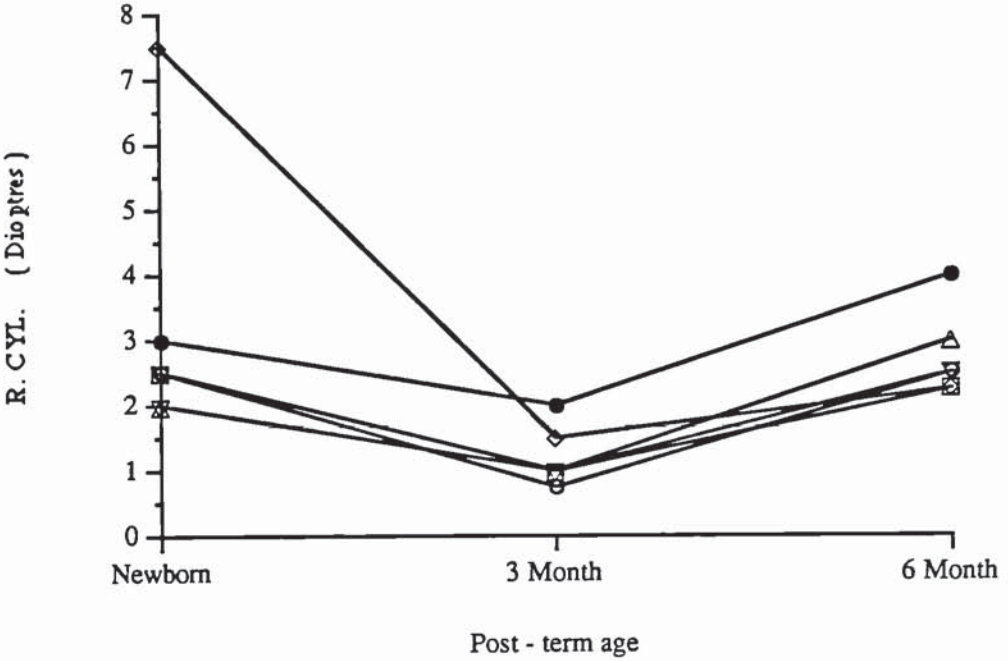


Figure 5.32 Alterations in right eye cylinder power between birth, three and six months in six infants followed longitudinally. Data is for infants initially having at least two dioptres of astigmatism.

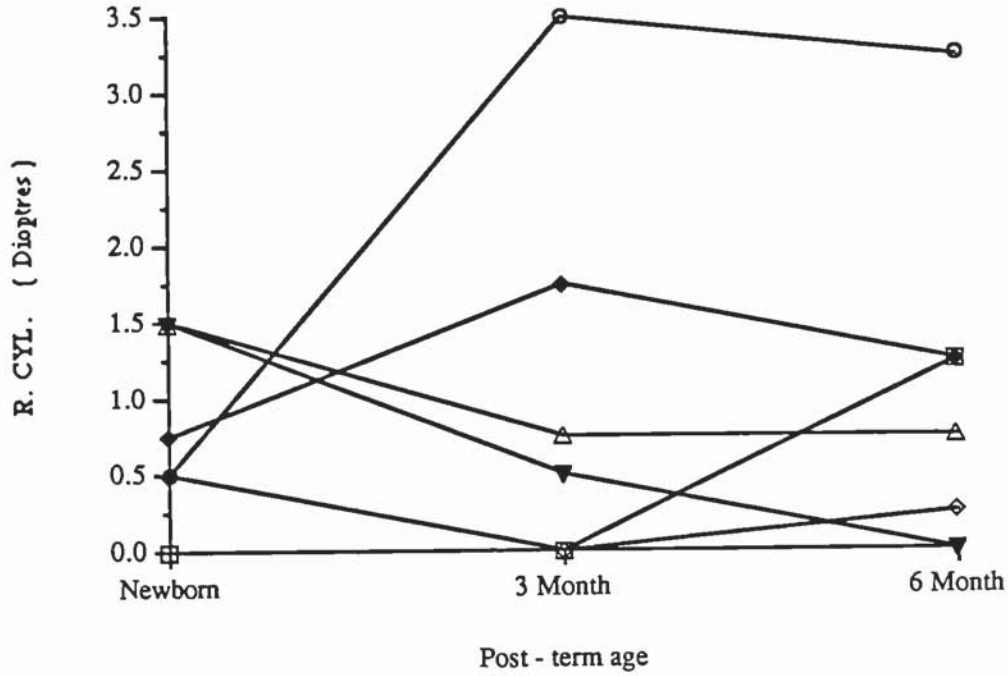


Figure 5.33 Alterations in right eye cylinder power between birth, three and six months in six infants followed longitudinally. Data is for infants initially having less than two dioptres of astigmatism.

5.4 Neonatal refractive accuracy study

Thirty five newborns participated in a repeat refraction study. Two refractions were performed during the same test session. Plate 5.1 illustrates the method of refraction - streak retinoscopy at 33 centimetres with working distance maintained by a string attached to the retinoscope head. The second refraction was conducted without reference to the previous findings. Between four and seven infants were examined during each session so the likelihood of bias in measurement is low. Duration of cycloplegia before the initial refraction varied between 45 and 99 minutes (mean 67.9; S.D. 17.8 minutes). Duration of cycloplegia before the second refraction varied between 85 and 184 minutes (mean 141.6; S.D. 25.0 minutes). Raw data is presented in Appendix Tables A5.11 and A5.12. A study of objective versus subjective refractive findings in older subjects (that were examined without cycloplegia) is provided, for comparison, in Appendix 5C.

5.4.1 Regression analyses and coefficients

The correlations obtained between initial and subsequent refractive findings are summarised in Table 5.29. Correlations between S.E.R. data were very high ($r = 0.95$ and 0.94 for the right and left eyes respectively). Data from the right eye is plotted in Figure 5.34. More scatter was evident in the cylindrical power data which is reflected in lower correlation coefficients ($r = 0.61$ and 0.65 for the right and left eyes respectively) although the findings were still highly significant ($p < 0.001$). Data from the right eye is plotted in Figure 5.35. Correlations between anisometropia on initial and subsequent refractions (plotted in Figure 5.36) did not reach statistical significance, which is not too surprising given the general low level of "significant" anisometropia and the dependence of this measure on both right and left eye refractive data.

Table 5.29 Details of regression line equations and statistics for the repeat refraction study. Format of regression equations:
$y = (m x + c)$ where y = second refraction and x = initial refraction.

Variable	Regression Coefficents			Statistics	
	m	c	r	d.f.	significance
R S.E.R.	1.02	-0.23	0.95	1,33	$p < 0.001$
L S.E.R.	0.97	-0.14	0.94	1,33	$p < 0.001$
R. CYL.	0.50	1.07	0.61	1,33	$p < 0.001$
L. CYL.	0.77	0.64	0.65	1,33	$p < 0.001$
ANISO.	0.26	0.61	0.24	1,33	$p = 0.126$

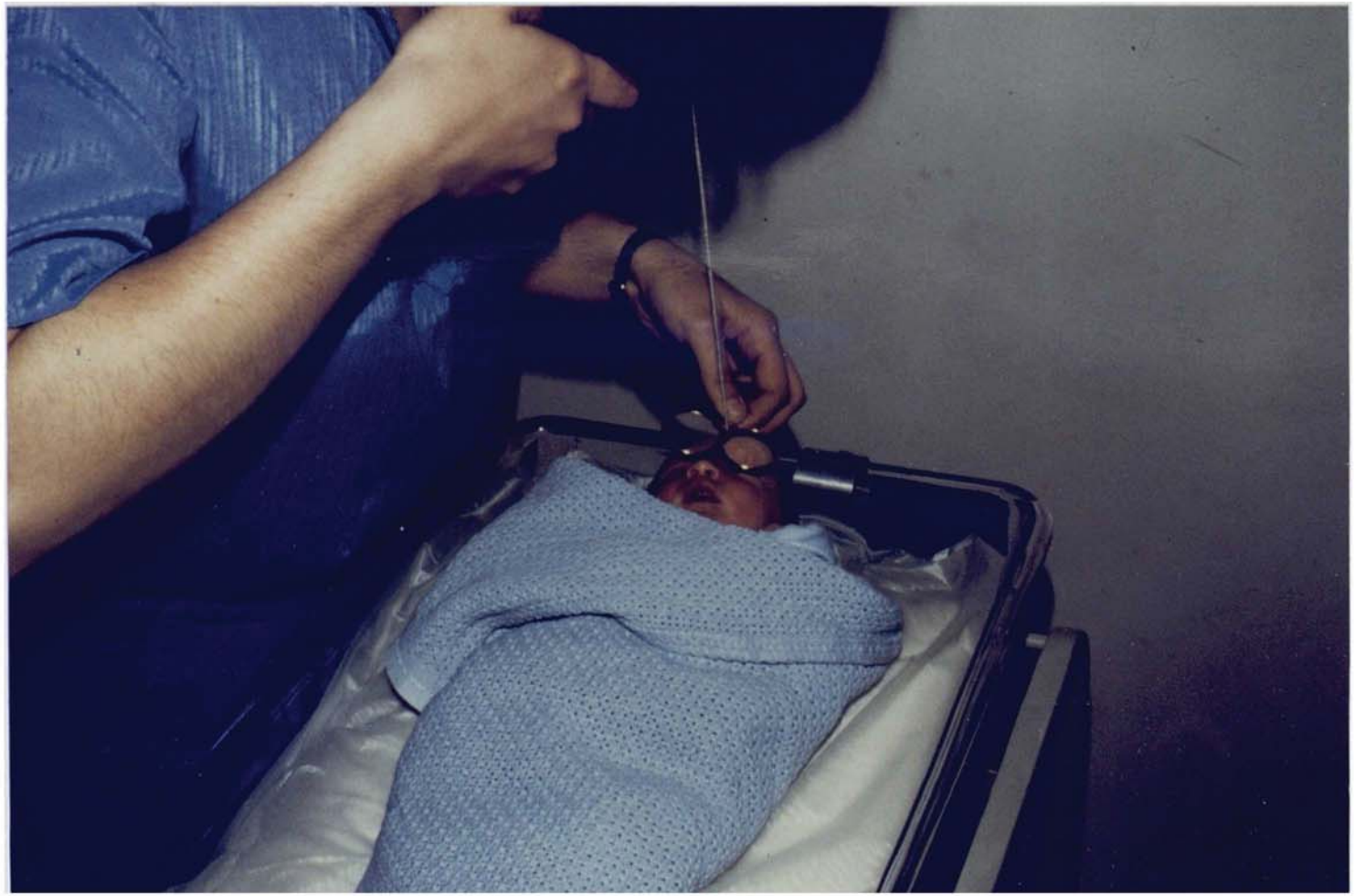


Plate 5.1

Refractive assessment of a newborn infant using streak retinoscopy.

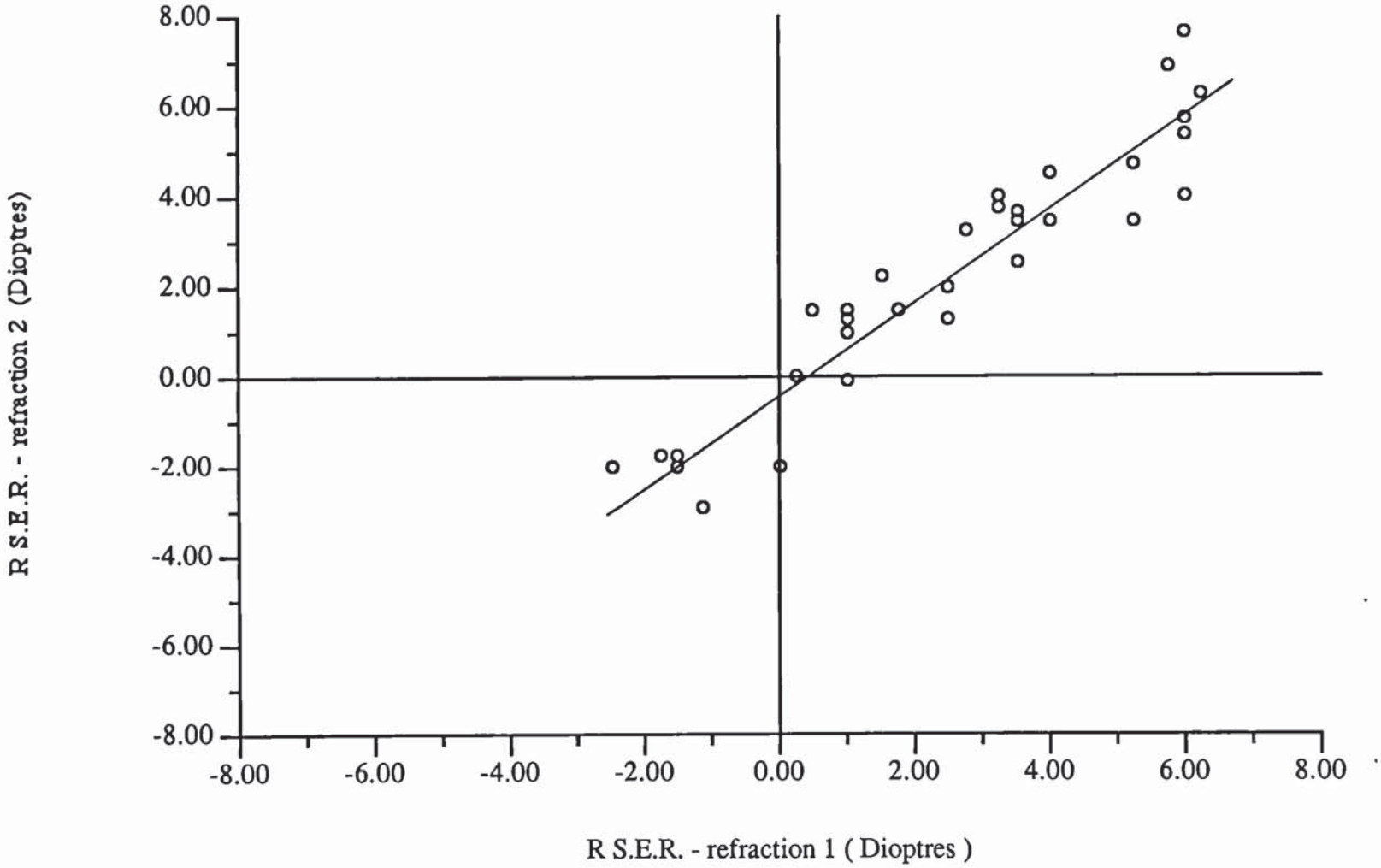


Figure 5.34 Scatterplot of right eye spherical equivalent refractive power found on second refraction versus power finding on initial refraction. The data is from 35 newborns that were refracted twice during a single session. Equation of regression line: $y = 1.02\ x - 0.23$ ($r = 0.95$; d.f. 1,33; $p < 0.001$).

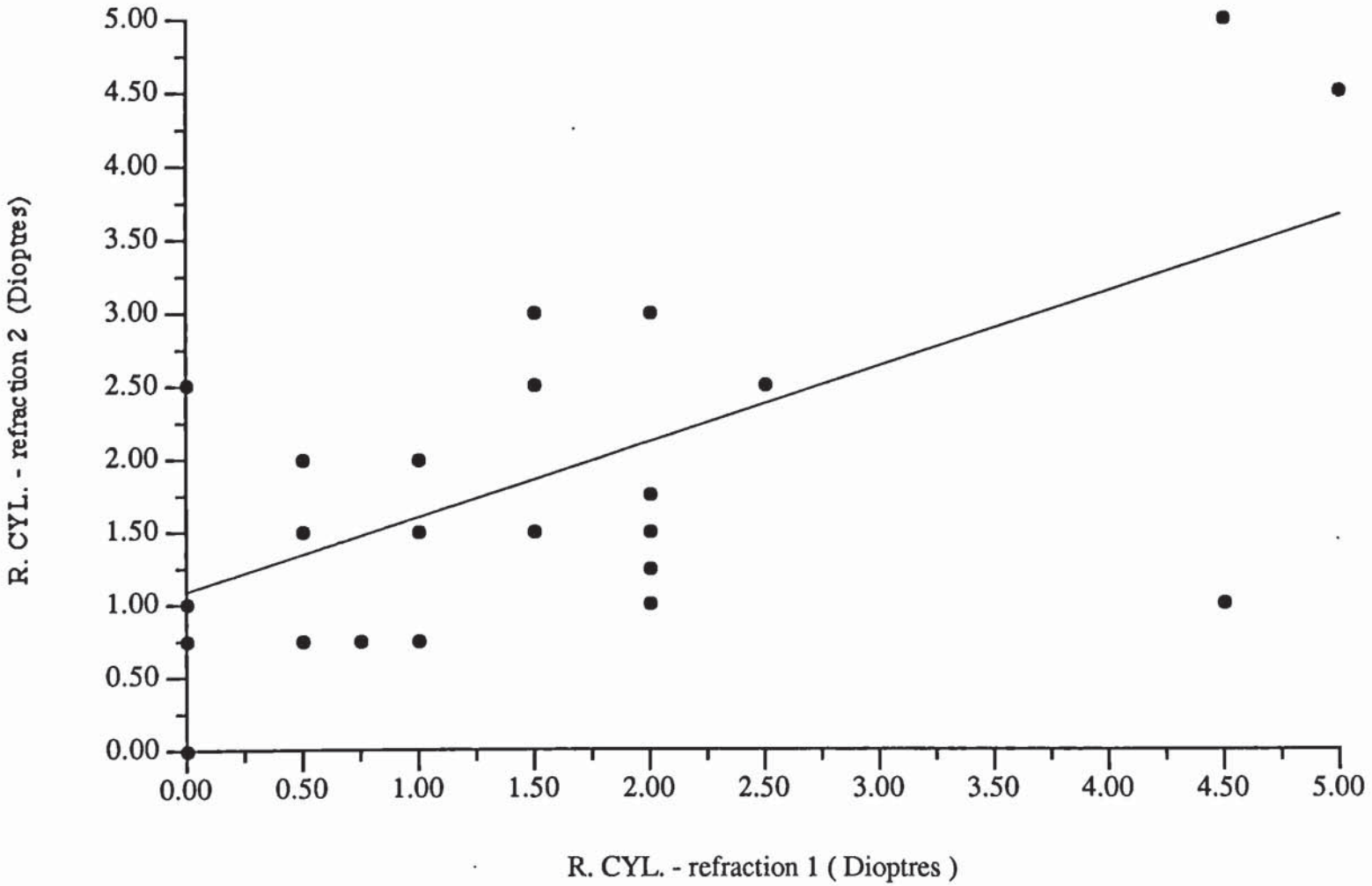


Figure 5.35 Scatterplot of right eye cylindrical refractive power found on second refraction versus power finding on initial refraction. The data is from 35 newborns that were refracted twice during a single session. Equation of regression line: $y = 0.50\ x + 1.07$ ($r = 0.61$; d.f. 1,33; $p < 0.001$).

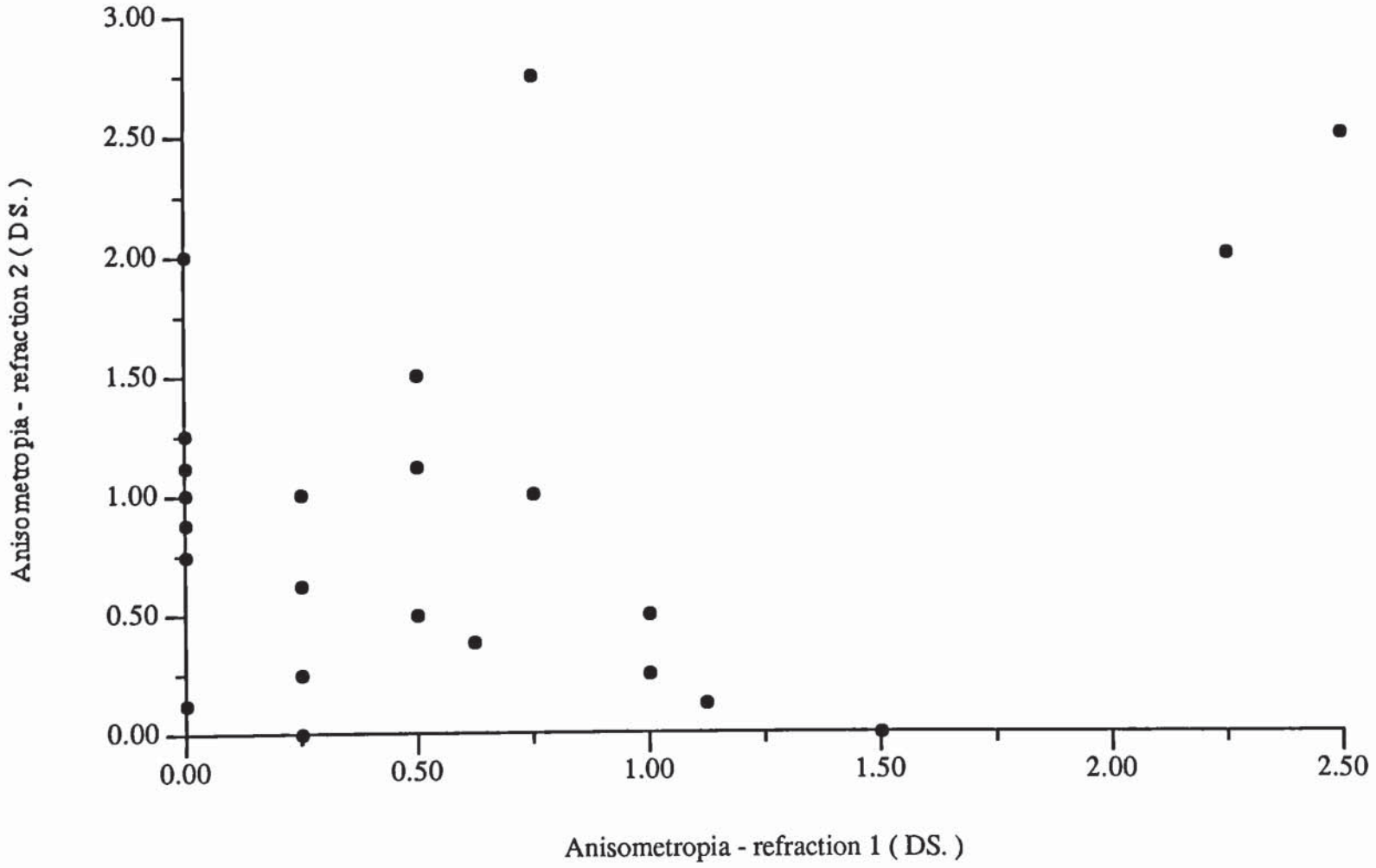


Figure 5.36 Scatterplot of anisometropia found on second refraction versus anisometropia finding on initial refraction. The data is from 35 newborns that were refracted twice during a single session. No significant correlation was found between initial and subsequent anisometropic finding.

5.4.2 Systematic differences between refractions

Group averaged data for the initial and later refraction is given in Table 5.30. Similar trends were noted for each eye. Mean S.E.R. findings were lower and the range of results higher on the second refraction. The opposite was noted for anisometropic and cylindrical power findings which were higher for the subsequent refraction. Statistical tests (paired t - tests) were performed to check whether any of the differences were significant and therefore indicative of systematic differences between the first and second refractions. The results of this analysis is given in Table 5.31. Only the changes observed in cylindrical power findings reached statistical significance. This finding is likely to be related to the increased duration of cycloplegia by the time of the second refraction. Analysis of the effect of time between instillation of cyclopentolate and retinoscopy, revealed no significant influence on spherical findings but a slight trend for higher cylindrical powers with increased time (see section 5.1.5 and Tables 5.3 and A5.3). The effect reached significance for the left eye data ($p < 0.01$) and almost did so for the right eye ($p = 0.08$).

Table 5.30 Summary of refractive power findings on initial and subsequent retinoscopy for 35 newborns that participated in a repeat refraction study.

Variable	Refractive Power (Dioptres)				
	Mean	S.D.	S.E.	Minimum	Maximum
R. S.E.R.(1)	2.38	2.59	0.44	- 2.50	6.25
R. S.E.R.(2)	2.19	2.78	0.47	- 2.88	7.62
L. S.E.R.(1)	2.50	2.47	0.42	- 1.50	6.50
L. S.E.R.(2)	2.29	2.54	0.43	- 2.25	7.00
R. CYL. (1)	1.42	1.28	0.22	0.00	5.00
R. CYL. (2)	1.79	1.06	0.18	0.00	5.00
L. CYL. (1)	1.43	0.94	0.16	0.00	3.50
L. CYL. (2)	1.74	1.11	0.19	0.00	5.50
ANISO. (1)	0.57	0.65	0.11	0.00	2.50
ANISO. (2)	0.75	0.70	0.12	0.00	2.75

Table 5.31 Statistical significances for repeat refraction study. Spherical refractive findings were not significantly different but cylindrical findings were significantly higher for the second refraction. Paired t - tests.

Variable	Comparison between initial and subsequent refractions		
	t - stat	d.f.	sig
R. S.E.R.	1.38	34	not sig.
L. S.E.R.	1.46	34	not sig.
R. CYL.	- 2.03	34	$p < 0.05$
L. CYL.	- 2.09	34	$p = 0.05$
ANISO.	- 1.26	34	not sig.

5.4.3 Accuracy of isolated measurements

Differences between initial and subsequent refractive power findings were computed for each infant (by subtracting the second refraction from the first and then converting all negative values to their positive equivalent). Table 5.32 summarises group findings and gives some impression of the degree of accuracy that might be expected in determination of newborn refraction. An accuracy of around ± 0.7 dioptres in determination of both S.E.R. and cylinder power was observed. Comparison of the maximum differences observed (around 2.0 dioptres for S.E.R. and 3.5 dioptres for the cylinder) reveals the risk of larger errors occurring in determination of cylinder power. It must be remembered that the values noted for cylindrical refraction must include a component due to the systematic difference found between the two retinoscopies (since a trend for increased astigmatism to be observed on the second refraction was significant at the 5% level).

Table 5.32 Summary of differences between initial and subsequent refractive power findings of 35 newborns that participated in a repeat refraction study.

Variable	Difference in Refractive Power Ref.1 & 2 (Dioptres)				
	Mean	S.D.	S.E.	Minimum	Maximum
R. S.E.R.	0.67	0.59	0.10	0.00	2.00
L. S.E.R.	0.65	0.58	0.10	0.00	2.25
R. CYL.	0.84	0.74	0.12	0.00	3.50
L. CYL.	0.58	0.71	0.12	0.00	3.50
ANISO.	0.74	0.31	0.09	0.00	2.00

Comparison of the initial and subsequent refractive findings revealed eight infants (i.e. 22.9% of the sample) showing an alteration in the most hypermetropic eye. None of these infants initially demonstrated more than 0.5 dioptres of anisometropia and only one showed more than this amount during the second refraction.

5.5 Incidence of 'significant' ametropia and ranges of ametropia

Refractive data has, for this analysis, been subdivided into the newborn, "3", "6" and 12 month age groups previously defined. The numbers of refractions upon which this data are based are 210, 22, 31 and 18 respectively, for the various samples. The newborn values can be assumed to reflect more accurately population norms than the remaining groups. The values quoted in this section are therefore given with this reservation in mind.

5.5.1 Spherical equivalent refraction (S.E.R.) findings

Cut-off levels for 'significant' levels of spherical equivalent refraction have been taken as values greater than or equal to one dioptre. Other values have been considered emmetropic. The incidence of hypermetropia, myopia and emmetropia, amongst right eyes of infants within the four age categories is illustrated in Figure 5.37. Numerical values for the right and left eyes are given in Tables 5.33 and 5.34. The percentage of eyes displaying emmetropic refractions increases from eleven percent at birth to around 60 percent at one year. Incidence of significant myopia was around ten percent in either eye at birth, apparently reached a minimum at three months and increased gradually to 5.6 percent at one year. The incidence of significant hyperopia was around 80 percent at birth, increased slightly at three months, decreased to about 50 percent at six months and thereafter reduced to around 35 percent at one year.

Table 5.33 Summary of right eye spherical refractive findings versus age.

		No. (& %) in various refractive groups		
Age Group (months)	Sample Size	Hyperopic (≥ 1.00 D.)	Myopic (≥1.00 D.)	Emmetropic (0.00 ± 0.99 D.)
Newborn	209	166 (79.4)	20 (9.6)	23 (11.0)
"3"	22	19 (86.4)	0 (0.0)	3 (13.6)
"6"	31	16 (51.6)	1 (3.2)	14 (45.2)
12	18	7 (38.9)	1 (5.6)	10 (55.6)

Table 5.34 Summary of left eye spherical refractive findings versus age.

		No. (& %) in various refractive groups		
Age Group (months)	Sample Size	Hyperopic (≥ 1.00 D.)	Myopic (≥1.00 D.)	Emmetropic (0.00 ± 0.99 D.)
Newborn	210	164 (78.1)	23 (10.9)	23 (10.9)
"3"	22	18 (81.8)	0 (0.0)	4 (18.2)
"6"	31	17 (54.8)	1 (3.2)	13 (41.9)
12	18	6 (33.3)	1 (5.6)	11 (61.1)

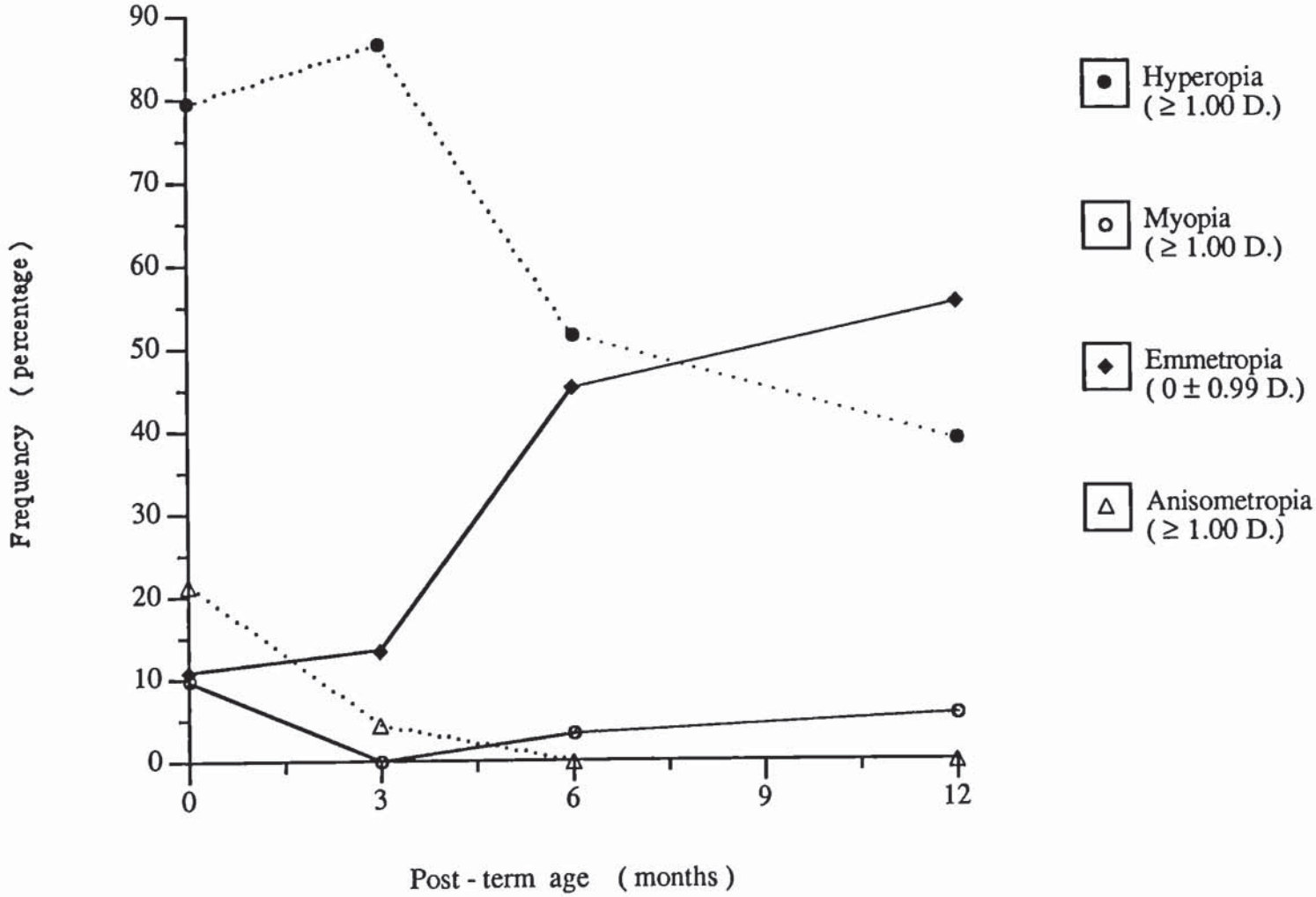


Figure 5.37 Incidence of spherical ametropia (and emmetropia) in newborn, three, six and twelve month olds. Data is from the right eye. Numerical values are provided in Table 5.33.

The ranges of S.E.R. findings encountered in the various age groups are summarised in Table 5.35. Values were highest for the newborn sample (≈ 14 D.), reduced considerably by three months (≈ 5.5 D.), showed a further decrease at six months (≈ 4.5 D.) and a slight increase by one year (≈ 6 D.).

Table 5.35 Summary of spherical refractive power ranges encountered in newborn, three, six and twelve month age groups.

Age Group (Months)	Variable	Spherical Refractive Power (Dioptres) Minimum	Maximum	Median	Range
Newborn	R. S.E.R.	- 4.25	9.13	2.75	13.38
	L. S.E.R.	- 4.50	9.75	2.75	14.25
"3"	R. S.E.R.	0.25	5.50	2.25	5.25
	L. S.E.R.	- 0.50	5.62	2.00	6.12
"6"	R. S.E.R.	- 1.62	3.12	1.25	4.75
	L. S.E.R.	- 1.50	2.75	1.25	4.25
12	R. S.E.R.	- 2.25	4.00	0.75	6.25
	L. S.E.R.	- 2.25	3.88	0.75	6.12

5.5.2 Anisometropic findings

Cut-off level for 'significant' anisometropia has been taken as values greater than or equal to one dioptre. The incidence of specific grades of anisometropia amongst infants within the four age categories is illustrated in Figure 5.38. Numerical values are given in Table 5.36. The percentage of infants displaying significant anisometropia decreased from 21.5 percent at birth to nought percent at six months (and one year). Only 16.7 percent of newborns did not demonstrate any anisometropia but by one year this value had risen to 50 percent.

Table 5.36 Incidence of anisometropia versus age.

Age Group (months)	Sample Size	No. (& %) in various anisometropic groups Nil (0.00)	Low (<1.00 D.)	Significant (≥ 1.00 D.)
Newborn	209	35 (16.7)	129 (61.7)	45 (21.5)
"3"	22	10 (45.5)	11 (50.0)	1 (4.5)
"6"	31	11 (35.5)	20 (64.5)	0 (0.0)
12	18	9 (50.0)	9 (50.0)	0 (0.0)

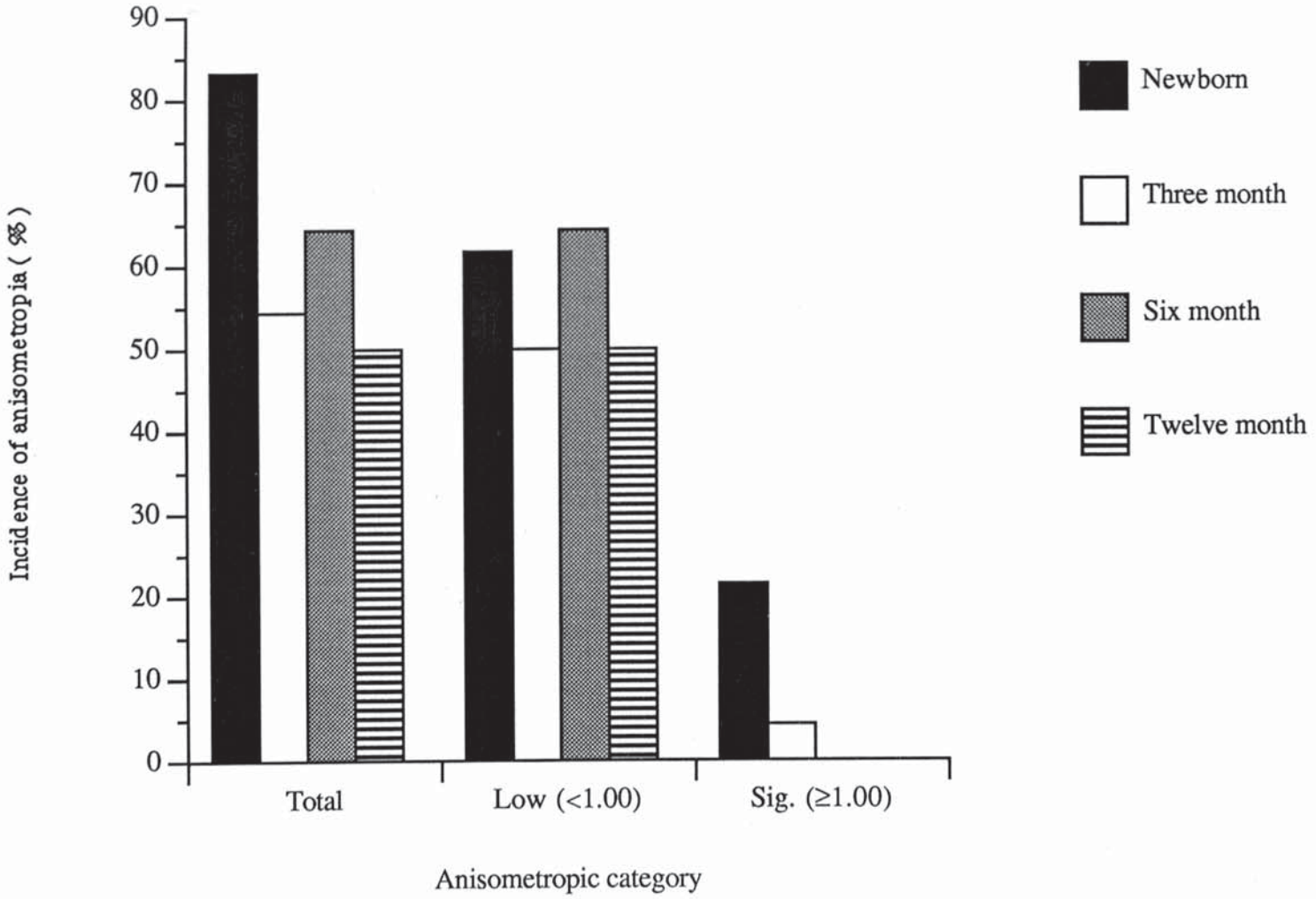


Figure 5.38 Incidence of various grades of anisometropia in newborn, three, six and twelve month olds. Numerical values are provided in Table 5.36.

The range of anisometropic power findings encountered in the various age groups are presented in Table 5.37. This value was highest for the newborn sample (3.25 D.), reduced considerably by three months (1.00 D.), showing further decreases at six months (0.62 D.) and one year (0.50 D.).

Table 5.37 Ranges of anisometropia encountered in newborn, three, six and twelve month age groups.

Age Group (Months)	Anisometropic Refractive Power (Dioptres) Minimum	Maximum	Median	Range
Newborn	0.00	3.25	0.50	3.25
"3"	0.00	1.00	0.12	1.00
"6"	0.00	0.62	0.12	0.62
12	0.00	0.50	0.06	0.50

5.5.3 Astigmatic findings

Cut-off level for 'significant' astigmatism has been taken as values greater than or equal to one dioptre. The incidence of specific grades of astigmatism amongst right eyes of infants within the four age categories is illustrated in Figure 5.39. Numerical values for the right and left eye data are presented in Tables 5.38 and 5.39. About 13 percent of newborn eyes were not astigmatic, a similar figure (13.6 %) was noted at three months but very few eyes (3.2%) were found to be not astigmatic at six months. At one year 27.8 percent of eyes were not astigmatic. The percentage of eyes displaying significant astigmatism decreased from around 76 percent at birth to 54.5 percent at three months but increased to around 76 percent at six months before declining to around 47 percent at one year.

Table 5.38 Incidence of astigmatism (right eye) versus age.

Age Group (months)	Sample Size	No. (& %) in various astigmatic groups Nil (0.00)	Low (<1.00 D.)	Significant (≥ 1.00 D.)
Newborn	209	33 (15.8)	24 (11.5)	152 (72.7)
"3"	22	3 (13.6)	7 (31.8)	12 (54.5)
"6"	31	1 (3.2)	5 (16.1)	25 (80.6)
12	18	5 (27.8)	5 (27.8)	8 (44.4)

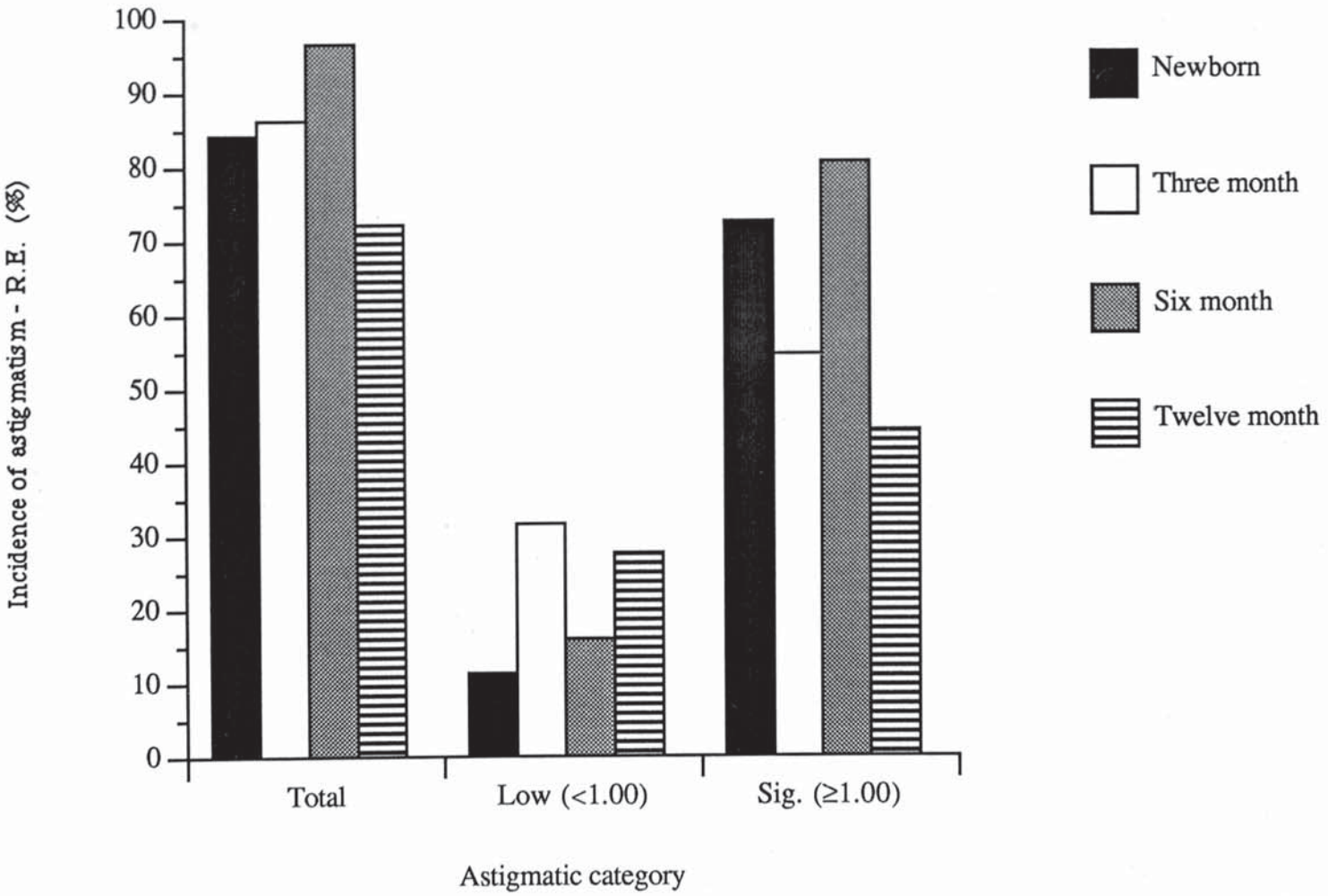


Figure 5.39 Incidence of various grades of astigmatism in newborn, three, six and twelve month olds. Data is from the right eye. Numerical values are provided in Table 5.38.

Table 5.39 Incidence of astigmatism (left eye) versus age.

Age Group (months)	Sample Size	No. (& %) in various astigmatic groups Nil (0.00)	Low (<1.00 D.)	Significant (≥ 1.00 D.)
Newborn	210	22 (10.5)	21 (10.0)	167 (79.5)
"3"	22	3 (13.6)	7 (31.8)	12 (54.5)
"6"	31	1 (3.2)	8 (25.8)	22 (71.0)
12	18	5 (27.8)	4 (22.2)	9 (50.0)

The numbers of infants (rather than eyes) in various astigmatic groups are given in Table 5.40. Only 6.2 percent of newborns were not astigmatic in either eye, whereas 27.8 percent of one year olds did not show any astigmatism. Significant astigmatism was found in about 86 % of newborns, 64 % of three month olds, 81 % of six month olds and 50 % of one year olds. The incidence of significant astigmatism for each or either eye is illustrated for each age group in Figure 5.40.

Table 5.40 Incidence of astigmatism (either eye) versus age.

Age Group (months)	Sample Size	No. (& %) in various astigmatic groups Nil (0.00 in EE)	Not significant (<1.00 D. in EE)	Significant (≥1.00. in EE)
Newborn	210	13 (6.2)	30 (14.3)	180 (85.7)
"3"	22	2 (9.1)	8 (36.4)	14 (63.6)
"6"	31	1 (3.2)	6 (19.4)	25 (80.6)
12	18	5 (27.8)	9 (50.0)	9 (50.0)

Astigmatism was predominantly of with-the-rule variety in newborn (see Table 5.22) and older infants (Table 5.41). Approximately 90 percent of newborn astigmatic eyes were of this type as were 79 percent of three month olds, 83 percent of six month olds and 88 percent of twelve month olds. Against-the-rule astigmatism was rare being found in only about three percent of newborn, three month and six month old astigmatic eyes. Oblique astigmatism contributed to six percent of the newborn, 18 percent of the three month, 13 percent of the six month and 11 percent of the one year levels.

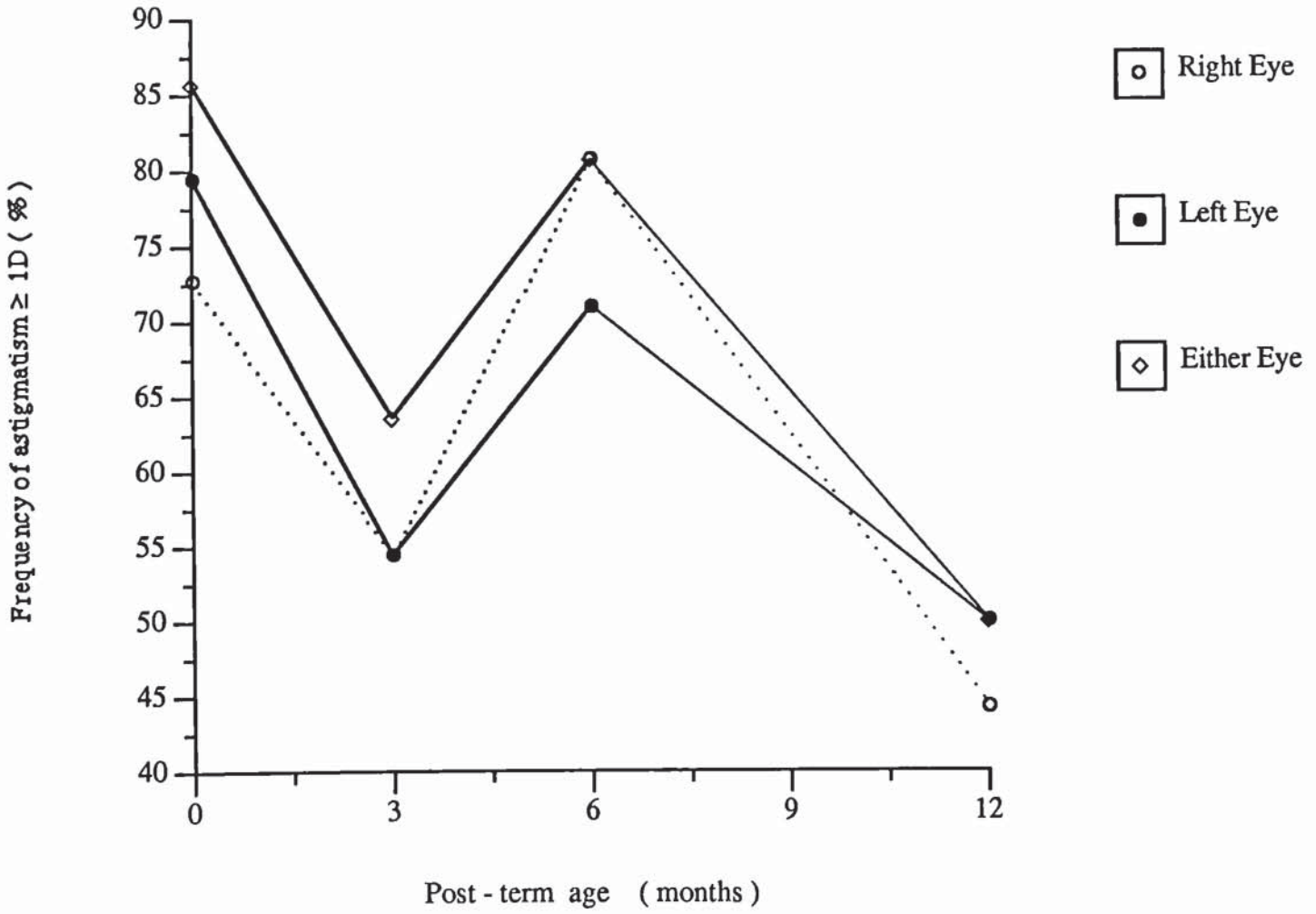


Figure 5.40 Incidence of "significant" astigmatism in newborn, three, six and twelve month olds. Data is shown for the right eye, left eye and either eye. Numerical values are provided in Tables 5.38, 5.39 and 5.40.

The ranges of cylinder power findings encountered in the various age groups are given in Table 5.42. This was highest for the newborn sample (≈ 7 D.), reduced considerably by three months (3.5 D.), showed little alteration at six months (≈ 4 D.) but decreased markedly by one year (2 D.).

Table 5.41 Incidence of particular types of astigmatism amongst astigmatic three, six and twelve month olds. W.T.R. = with the rule (90 ± 15°); A.T.R. = against the rule (180° ± 15°).

Age Group	Eye	n	No. (&%) with different types of astigmatism W.T.R.	A.T.R.	Oblique
"3"	R.	19	15 (78.9)	0 (0.0)	4 (21.0)
"3"	L.	19	15 (78.9)	1 (5.3)	3 (15.8)
"6"	R.	30	24 (80.0)	1 (3.3)	5 (16.7)
"6"	L.	30	26 (86.7)	1 (3.3)	3 (10.0)
12	R.	13	12 (92.3)	0 (0.0)	1 (7.7)
12	L.	13	11 (84.6)	0 (0.0)	2 (15.4)

Table 5.42 Summary of cylindrical refractive power ranges encountered in newborn, three, six and twelve month age groups.

Age Group (Months)	Variable	Cylindrical Refractive Power (Dioptres) Minimum	Maximum	Median	Range
Newborn	R. CYL.	0.00	7.50	1.50	7.50
	L. CYL.	0.00	6.00	1.50	6.00
"3"	R. CYL.	0.00	3.50	1.00	3.50
	L. CYL.	0.00	3.50	1.00	3.50
"6"	R. CYL.	0.00	4.00	1.50	4.00
	L. CYL.	0.00	3.75	1.75	3.75
12	R. CYL.	0.00	2.00	0.50	2.00
	L. CYL.	0.00	2.00	0.88	2.00

A summary and discussion of the findings described in this chapter can be found in Chapter 7.

6. NORMATIVE STUDY - RESULTS III : POSSIBLE INFLUENCES ON POSTNATAL VISUAL ACUITY DEVELOPMENT

6.1 Refractive error

Linear regression analyses have been performed to investigate possible relationships between infants' acuity and refractive error. The tests were applied to newborn, "three", "six" and "twelve" month data although the sample sizes were unfortunately relatively small for all except the newborn group. Two hundred and twenty seven newborns were examined. Acuity *and* refractive assessment was attempted on 157 of these infants with 137 completing both tests. Most of the neonatal acuity data collected was for vertical gratings viewed binocularly (109 infants). Several infants completed binocular tests using horizontal gratings. Horizontal and vertical acuity data was combined by computing means if both values were obtained (i.e. genuine mean binocular acuity) or taking either value if only one was available. This resulted in 112 sets of newborn "mean" binocular acuity and refractive data being available for analysis. Twenty five newborns contributed only monocular acuity data so their data has not been used in analysis here. Regression analyses have been performed to investigate possible correlations between neonatal acuity and refraction. Both binocular vertical grating and binocular "mean" acuity have been used in this analysis.

Eighty seven infants attended a total of 151 follow-up sessions. Preferential looking was attempted, followed by cycloplegic retinoscopy on 72 visits. Both tests were successful (at least one acuity determined) during 70 of such sessions, which involved infants between the third and seventh post-term month and one year olds. The data of the five month age group (five infants) has been omitted from analysis and that of the three and four month groups and six and seven month groups combined to enlarge samples. No significant differences between refractive findings of these combined groups was noted (see sections 5.1.6, 5.2.3 and 5.3.3). Regression analyses have been performed on the 65 sets of data (22 three month, 27 six month and 16 twelve month olds) to investigate possible correlations between acuity and refraction. The acuity values used in this analysis were vertical, "mean" and best acuity data obtained from the right eye, left eye and binocularly.

6.1.1 Spherical equivalent refraction (S.E.R.)

a) Neonatal data

Linear regression analyses were conducted to investigate the correlation between neonatal binocular acuity findings and spherical equivalent refraction. Summarised results of these analyses which were performed separately for the right and left eyes are included in Table 6.1 (more details are provided in Appendix Tables A6.1 and A6.2). Only a weak correlation (for lower acuity with increasing hypermetropia) was noted ($r \approx 0.06$) and this did not reach statistical significance. Similar results were obtained when acuity was compared with optical defocus (i.e. with S.E.R. findings plus 2.50 dioptres to account for the 40 cm. viewing distance employed). Some of the data is illustrated in Figure 6.1, which plots binocular vertical grating acuity versus optical defocus of the right eye. Correlations between right and left eye S.E.R. were sufficiently high to justify analysis of binocular acuity versus monocular refraction. Regression analysis revealed the following relationship: L. S.E.R = 0.97 (R. S.E.R.) - 0.01 ($r = 0.95$, d.f. 1,207 $p < 0.0001$).

Table 6.1 Summary of correlations between newborn acuity (M.A.R., mins. of arc) and refractive data. "Mean" binocular = average M.A.R. for horizontal and vertical gratings.
Key to significance levels: * = 0.05; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Variables	Binoc. acuity (vertical)			"Mean" binocular acuity		
	n	r	p	n	r	p
Acuity v. :						
R. S.E.R.	109	0.07	ns	112	0.08	ns
L. S.E.R.	109	0.05	ns	112	0.05	ns
R. defocus	109	0.07	ns	112	0.08	ns
L. defocus	109	0.05	ns	112	0.05	ns
Anisometropia	109	0.17	(ns)	112	0.20	*
R. Cylinder power	109	0.02	ns	112	0.00	ns
L. Cylinder power	109	0.02	ns	112	0.04	ns

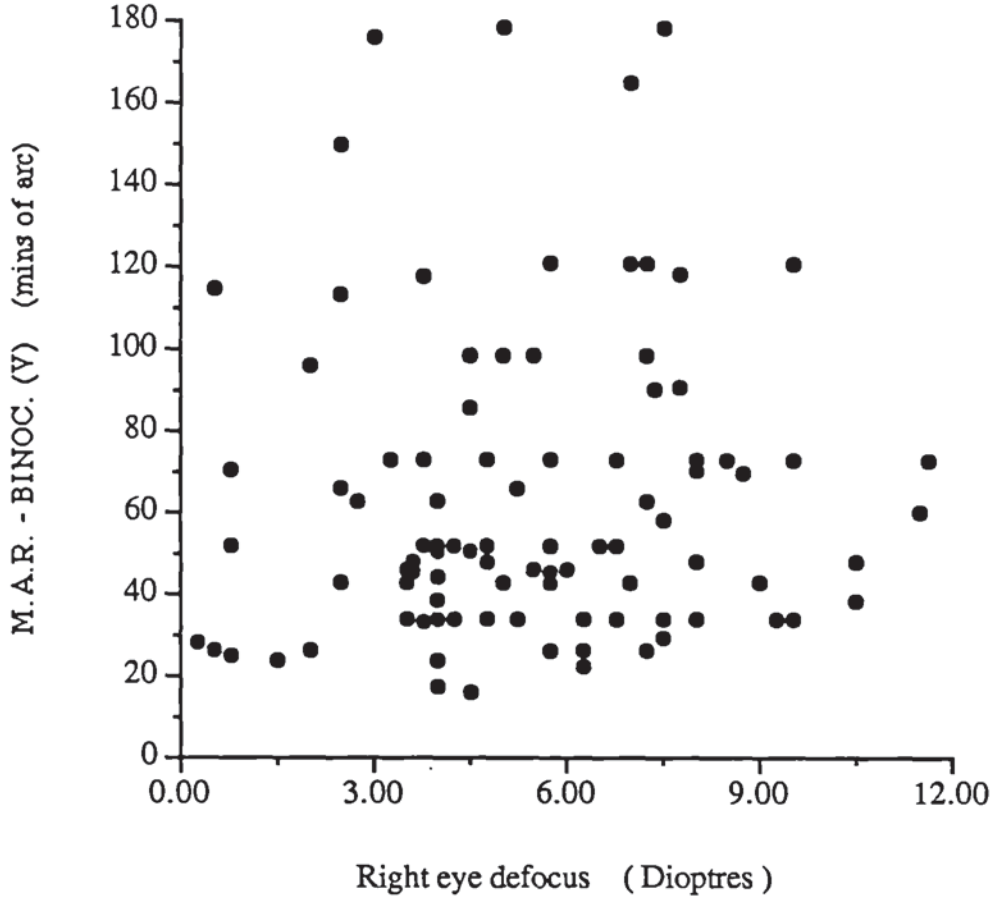


Figure 6.1 Scatterplot of neonatal binocular acuity (vertical gratings) versus optical defocus of the right eye (assuming relaxed accommodation). No significant correlation was noted between these variables although statistical tests suggested a slight trend for poorer acuity with increasing defocus.

b) Follow-up data

A summary of correlation coefficients between monocular acuity and refractive findings of the three month sample is provided in Table 6.2. No significant correlations were found although in all cases the highest correlation coefficients were evident when acuity was compared with the minimum level of ametropia. The lowest correlations were observed for the relationships between acuity and maximum ametropia (with intermediate values for S.E.R. data). In all cases slight trends were observed for poorer acuity with increasing hypermetropia. Some of the data is illustrated in Figure 6.2 which plots left eye vertical grating acuity versus minimum ametropia.

Table 6.2 Summary of correlations between "three" month monocular acuity (M.A.R., mins. of arc) and refractive data. V = vertical gratings, "Mean" acuity = average M.A.R. for horizontal and vertical gratings, Best acuity = lowest M.A.R. for horizontal and vertical gratings. ns = not significant ($p > 0.1$ for all comparisons).

Variables	Right eye			Left eye		
	n	r	p	n	r	p
Acuity (V.) v. :						
S.E.R.	13	0.30	ns	15	0.39	ns
Defocus	13	0.30	ns	15	0.39	ns
Maximum ametropia	13	0.27	ns	15	0.34	ns
Minimum ametropia	13	0.31	ns	15	0.40	ns
Acuity ("Mean") v. :						
S.E.R.	14	0.30	ns	15	0.33	ns
Defocus	14	0.30	ns	15	0.33	ns
Maximum ametropia	14	0.27	ns	15	0.29	ns
Minimum ametropia	14	0.32	ns	15	0.35	ns
Acuity (Best) v. :						
S.E.R.	14	0.32	ns	15	0.26	ns
Defocus	14	0.32	ns	15	0.26	ns
Maximum ametropia	14	0.28	ns	15	0.20	ns
Minimum ametropia	14	0.34	ns	15	0.30	ns

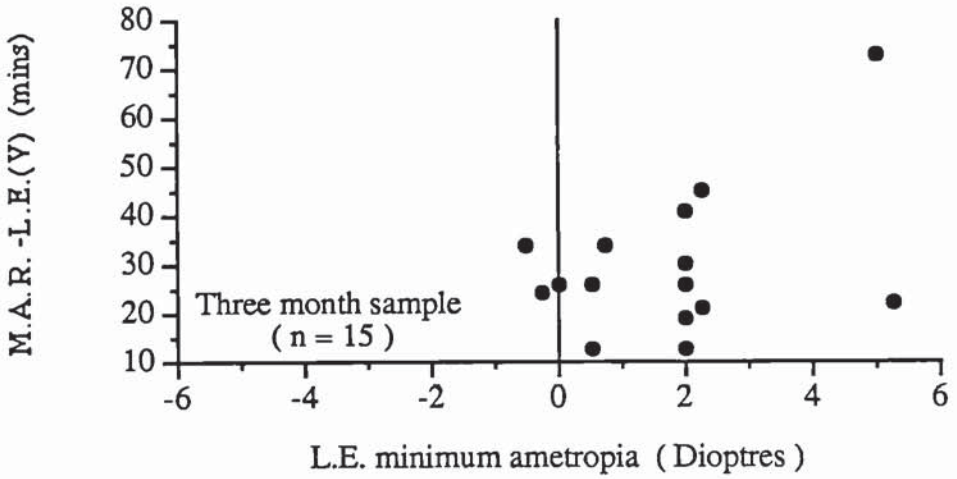


Figure 6.2 Scatterplot of left eye acuity (vertical gratings) versus minimum ametropia for the three month sample. No significant correlation was noted between these variables although statistical tests suggested a slight trend for poorer acuity with increasing ametropia.

A summary of correlation coefficients between monocular acuity and refractive findings of the six month sample is provided in Table 6.3. (more details are given in Appendix Table A 6.4). In general (all left eye and most right eye data) trends noted were for better acuity to be associated with increased hypermetropia. No significant correlations were noted for the right eye - though the trend (except for the best right eye acuity) was for highest correlations with maximum ametropia and lowest with minimum ametropia (for which opposite trends - poorer acuity with increases in hypermetropia were generally noted). A significant relationship was observed between "mean" left eye acuity and minimum level of ametropia and between best left eye acuity and each refractive measure. The highest correlation (0.55) was noted between best left eye acuity and left S.E.R., this data is plotted in Figure 6.3. In general (except for best left acuity data) poorest correlations were found between acuity and maximum ametropia.

Table 6.3 Summary of correlations between "six" month monocular acuity (M.A.R., mins. of arc) and refractive data. V = vertical gratings, "Mean" acuity = average M.A.R. for horizontal and vertical gratings, Best acuity = lowest M.A.R. for horizontal and vertical gratings.
Key to significance levels: * = 0.05; ** = 0.01; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Variables	Right eye			Left eye		
	n	r	p	n	r	p
Acuity (V) v. :						
S.E.R.	22	0.12	ns	24	0.36	(ns)
Defocus	22	0.12	ns	24	0.36	(ns)
Maximum ametropia	22	0.14	ns	24	0.29	ns
Minimum ametropia	22	0.08	ns	24	0.35	(ns)
Acuity ("Mean") v. :						
S.E.R.	22	0.06	ns	24	0.40	(ns)
Defocus	22	0.06	ns	24	0.40	(ns)
Maximum ametropia	22	0.13	ns	24	0.28	ns
Minimum ametropia	22	0.02	ns	24	0.44	*
Acuity (Best) v. :						
S.E.R.	22	0.02	ns	24	0.55	**
Defocus	22	0.02	ns	24	0.55	**
Maximum ametropia	22	0.09	ns	24	0.51	**
Minimum ametropia	22	0.13	ns	24	0.48	*

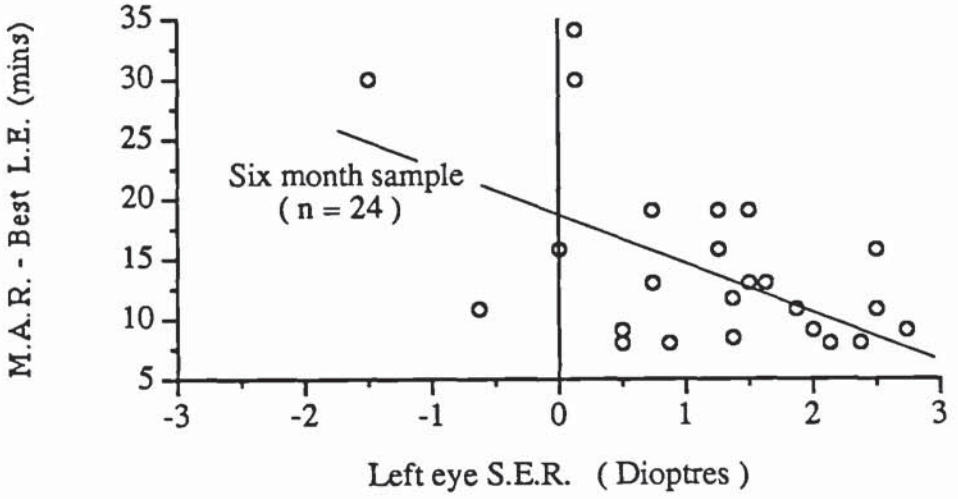


Figure 6.3 Scatterplot of left eye (best) acuity versus spherical equivalent refraction for the six month sample. A significant trend for better acuity with increasing hypermetropia was observed.
(Regression line equation: $y = -3.88x + 19.0$, $r = 0.55$, d.f. 1,22, $p = 0.006$).

A summary of correlation coefficients between monocular acuity and refractive findings of the twelve month sample is provided in Table 6.4 (more details are given in Appendix Table A6.5). Only six sets of data were available from the right eye and nine from the left eye. Right eye data showed a slight trend for better acuity with increasing hypermetropia. No significant correlations were noted for the right eye - though the trend found was for highest correlations with maximum ametropia and lowest with minimum ametropia (except for the "mean" right eye acuity). Left eye data showed trends for poorer acuity with increasing hypermetropia. A significant relationship was observed between left eye vertical grating acuity and "mean" left eye acuity and minimum level of ametropia. The highest correlation (0.69) was noted between "mean" left eye acuity and left minimum level of ametropia, this data is plotted in Figure 6.4. In all cases poorest correlations were found between left eye acuity and maximum ametropia and intermediate values were obtained for the relationship with S.E.R.

Table 6.4 Summary of correlations between twelve month acuity (M.A.R., mins. of arc) and refractive data. V = vertical gratings, "Mean" acuity = average M.A.R. for horizontal and vertical gratings, Best acuity = lowest M.A.R. for horizontal and vertical gratings.
Key to significance levels: * = 0.05; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Variables	Right eye			Left eye		
	n	r	p	n	r	p
Acuity (V) v. :						
S.E.R.	6	0.27	ns	9	0.60	(ns)
Defocus	6	0.27	ns	9	0.60	(ns)
Maximum ametropia	6	0.32	ns	9	0.54	ns
Minimum ametropia	6	0.18	ns	9	0.66	*
Acuity ("Mean") v. :						
S.E.R.	6	0.01	ns	9	0.59	(ns)
Defocus	6	0.01	ns	9	0.59	(ns)
Maximum ametropia	6	0.11	ns	9	0.50	ns
Minimum ametropia	6	0.12	ns	9	0.69	*
Acuity (Best) v. :						
S.E.R.	6	0.27	ns	9	0.60	(ns)
Defocus	6	0.27	ns	9	0.60	(ns)
Maximum ametropia	6	0.32	ns	9	0.55	ns
Minimum ametropia	6	0.18	ns	9	0.65	(ns)

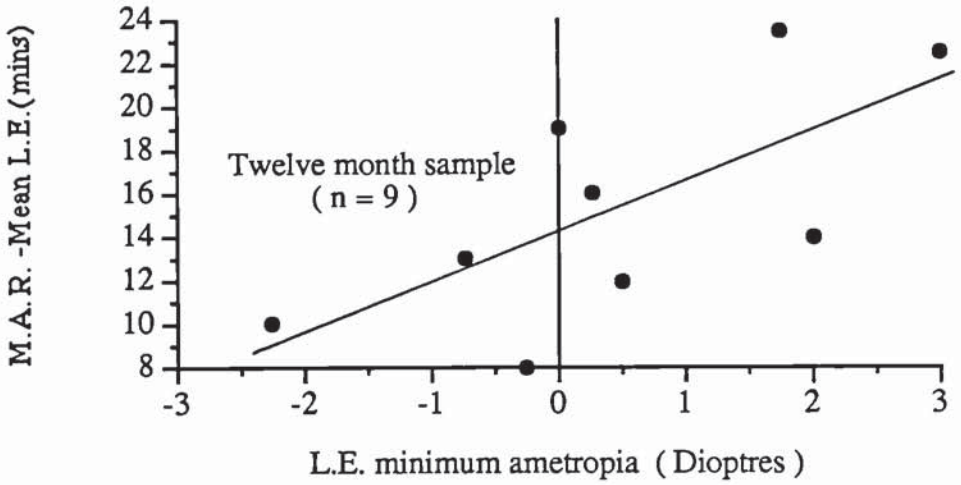


Figure 6.4 Scatterplot of left eye (mean) acuity versus minimum ametropia for the twelve month sample. A trend for poorer acuity with increasing hypermetropia was noted and just reached statistical significance.
(Regression line equation: $y = 2.35 x + 14.2$, $r = 0.69$, d.f. 1,7, $p = 0.04$).

6.1.2 Anisometropia

a) Neonatal data

Trends were observed for poorer binocular acuity with increasing anisometropia. Linear regression analysis revealed a significant relationship between neonatal "mean" binocular acuity and anisometropia ($r = 0.20$, $p < 0.05$). This data is plotted in Figure 6.5. The summarised results of the analyses are included in Table 6.1 (more details are provided in Appendix Tables A6.1 and A6.2).

b) Follow-up data

No significant relationship was noted between anisometropia and binocular acuity for any of the follow-up samples. Trends shown by the three and twelve months samples were for better acuity with increasing anisometropia but six month olds showed poorer acuity with greater anisometropia. A summary of correlation coefficients is given in Table 6.5 (more details are provided in Appendix Table A6.6). Figure 6.6 illustrates "mean" binocular acuity and anisometropia data of the three month group.

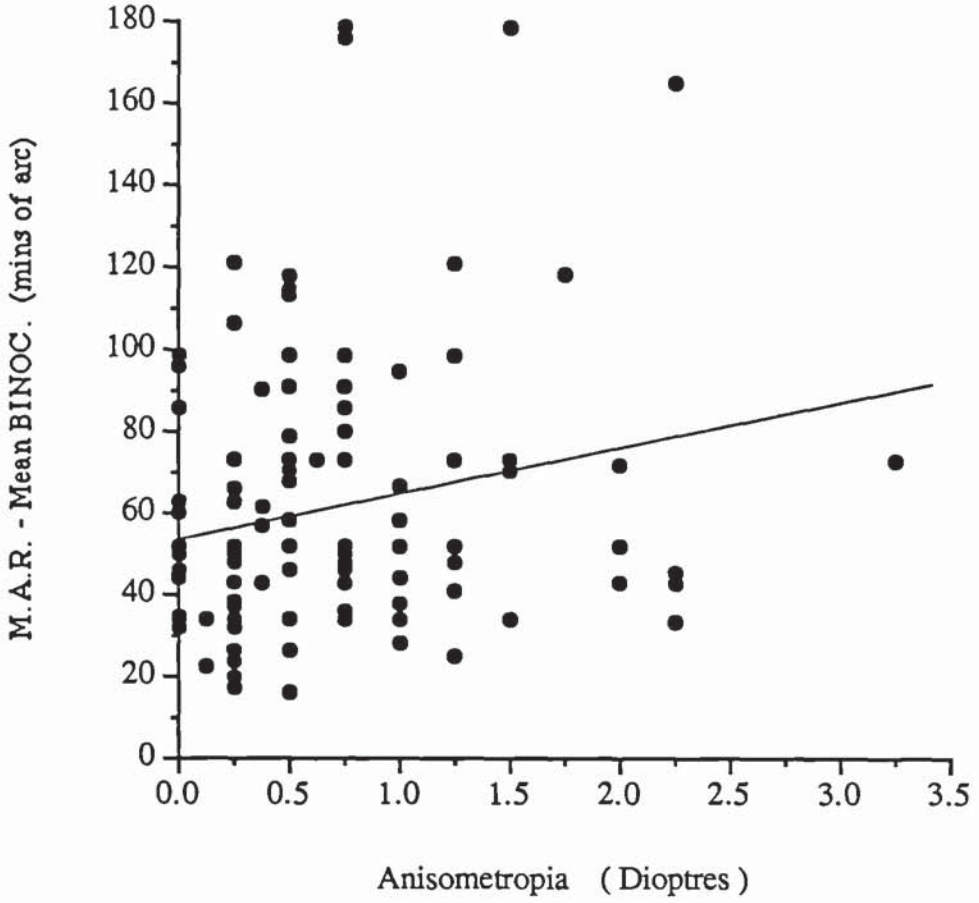


Figure 6.5 Scatterplot of neonatal "mean" binocular acuity (M.A.R., mins of arc) versus anisometropia. A significant trend for poorer acuity with increased anisometrtopia was observed. Equation of regression line:
$y = 11.1 x + 54.5$ ($r = 0.20$, d.f. 1,110, $p < 0.05$).

Table 6.5 Summary of correlations between binocular acuity findings (M.A.R., mins. of arc) and anisometropia data of follow-up sample. "Mean" acuity = average M.A.R. for horizontal and vertical gratings, Best acuity = lowest M.A.R. for horizontal and vertical gratings.
ns = not significant ($p > 0.4$ for all comparisons).

Sample and acuity variable	Correlation with anisometropia (DS.) n	r	p
"Three" Month			
Binocular vertical	17	0.16	ns
"Mean" binocular	17	0.21	ns
Best binocular	17	0.15	ns
"Six" Month			
Binocular vertical	15	0.05	ns
"Mean" binocular	15	0.05	ns
Best binocular	15	0.03	ns
Twelve Month			
Binocular vertical	8	0.31	ns
"Mean" binocular	12	0.26	ns
Best binocular	12	0.24	ns

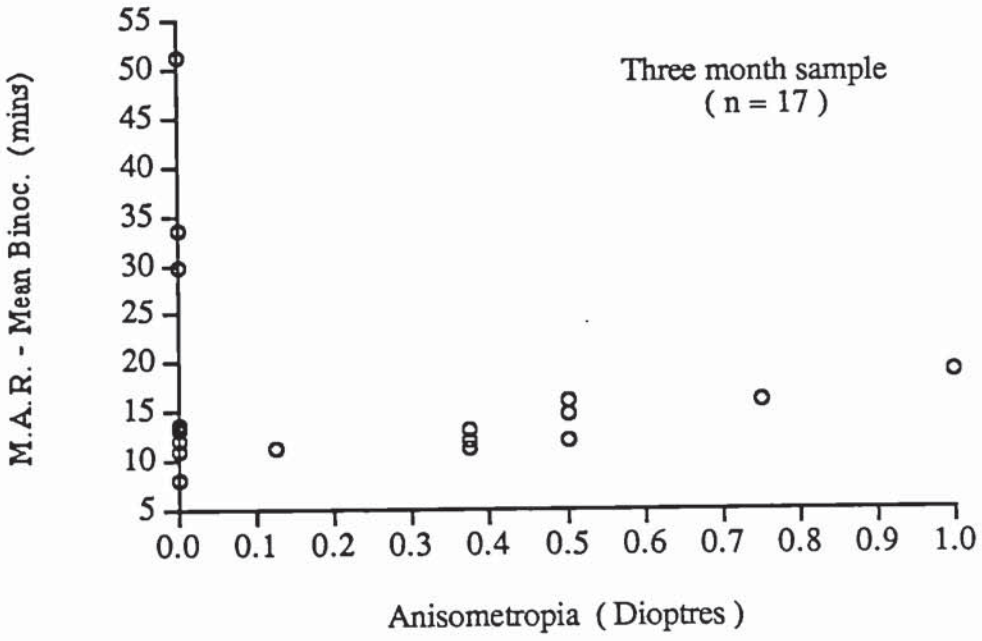


Figure 6.6 Scatterplot of binocular (mean) acuity versus anisometropia for the three month sample. No significant correlation was noted between these variables although statistical tests favoured a slight trend for better acuity with *increasing* anisometropia ($p > 0.4$).

6.1.3 Astigmatism

a) Neonatal data

Linear regression analyses conducted to investigate correlations between neonatal binocular acuity findings and cylindrical power findings failed to produce any significant effects. The results of the analyses are summarised in Table 6.1 (more details are provided in Appendix Tables A6.1 and A6.2). Correlation coefficients were extremely low ($r \approx 0.02$). Binocular (vertical grating) acuity is plotted versus right eye astigmatism in Figure 6.7.

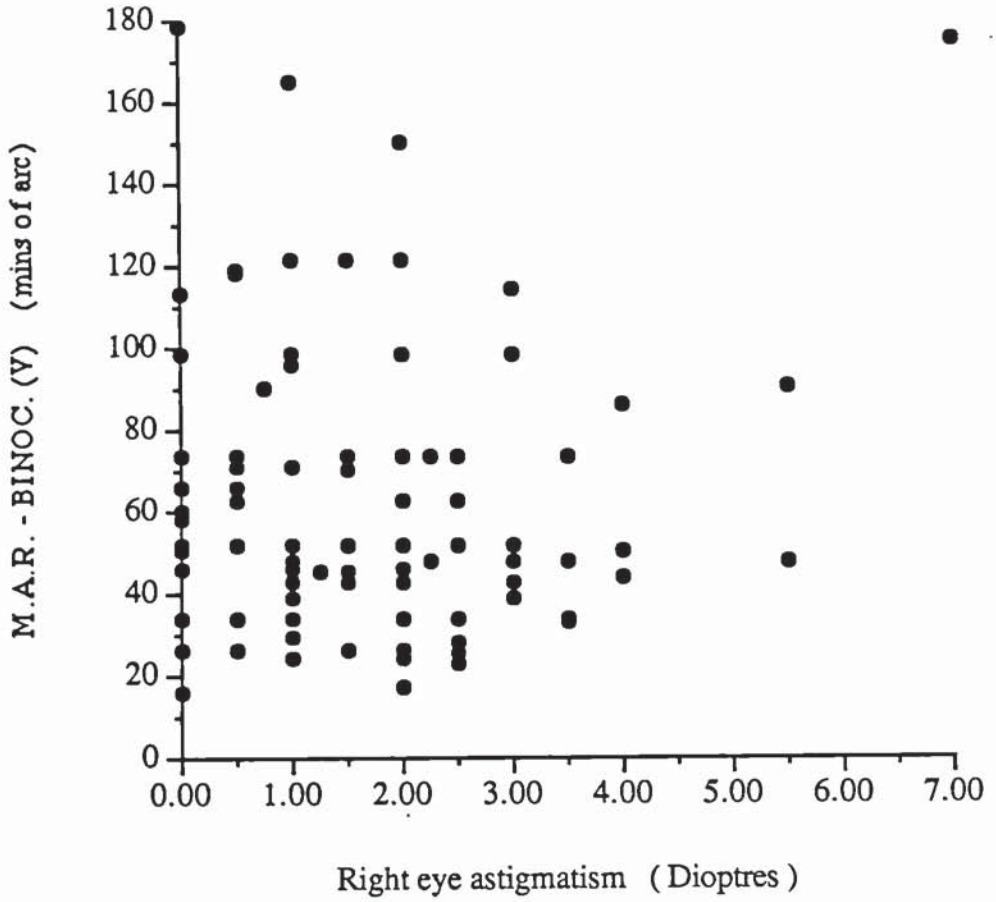


Figure 6.7 Scatterplot of neonatal binocular (vertical grating) acuity versus right eye astigmatism. No significant relationship was noted between these variables.

b) Follow-up data

No significant relationship was noted between astigmatism and monocular acuity for any of the follow-up samples. Trends observed at three months were for better acuity with increasing astigmatism. The same slight tendency was noted for right eye data at six and twelve months, but the left eye data tended to show the reverse trend. The strongest relationship was noted for the six month group - between right eye (best) acuity and astigmatism, this data is plotted in Figure 6.8. Details of correlation coefficients are given in Table 6.6 (more details are provided in Appendix Table A6.7).

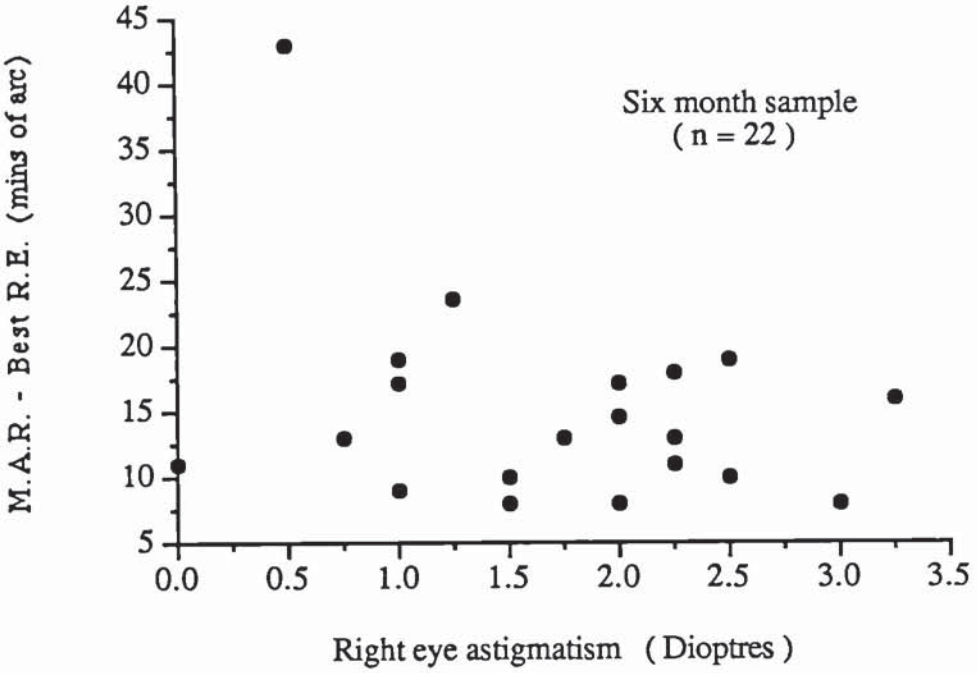


Figure 6.8 Scatterplot of right eye (best) acuity versus astigmatism for the six month sample. No significant correlation was noted between these variables although statistical tests suggested a slight trend for better acuity with increasing astigmatism ($p > 0.1$).

Table 6.6 Summary of correlations between monocular acuity (M.A.R., mins. of arc) and astigmatic power data for follow-up samples. V = vertical gratings, "Mean" acuity = average M.A.R. for horizontal and vertical gratings, Best acuity = lowest M.A.R. for horizontal and vertical gratings, ns = not significant ($p > 0.1$ for all comparisons).

Acuity variable and sample	Right eye Cyl. power n	r	p	Left eye Cyl. power n	r	p
Acuity (V.)						
"3" Month	13	0.10	ns	15	0.11	ns
"6" Month	22	0.08	ns	24	0.07	ns
12 Month	6	0.32	ns	9	0.15	ns
Acuity ("Mean")						
"3" Month	14	0.09	ns	15	0.12	ns
"6" Month	22	0.21	ns	24	0.17	ns
12 Month	6	0.31	ns	9	0.00	ns
Acuity (Best)						
"3" Month	14	0.08	ns	15	0.18	ns
"6" Month	22	0.32	ns	24	0.04	ns
12 Month	6	0.32	ns	9	0.22	ns

6.2 Neonatal retinal haemorrhage

Indirect ophthalmoscopy was performed on 209 neonates (plate 6.1). Bilateral retinal haemorrhage was noted in 34 (16.3%) and unilateral retinal haemorrhage encounted in 26 (12.4%) others. The remaining 149 (71.3%) infants did not demonstrate fundus haemorrhage. Mostly retinal haemorrhages were located at the posterior pole. Binocular acuity data was obtained from 32 of the 60 newborns noted to have retinal haemorrhage and from 80 others.

6.2.1 Neonatal acuity findings

Mean binocular acuity findings for newborn samples with and without retinal haemorrhage are included in Table 6.9. Acuity findings were slightly higher amongst neonates having retinal haemorrhage but differences between groups were not significant (independent t - tests $p > 0.05$).

6.2.2 Subsequent acuity development

Sixteen of the infants noted to have bilateral neonatal retinal haemorrhage attended for follow-up examination. The mean acuity data of these infants is shown along with that of sixteen age and sex matched control subjects (that did not demonstrate retinal haemorrhage at birth) in Table 6.7. Retinal haemorrhage subjects were paired with infants of similar "testability" if more than one control infant was available. Independent t - tests revealed no significant differences between the acuity findings of either group (t - statistic < 1.0 in all comparisons). Scatterplots of mean binocular and monocular acuities of the two samples are given in Figures 6.9 and 6.10.

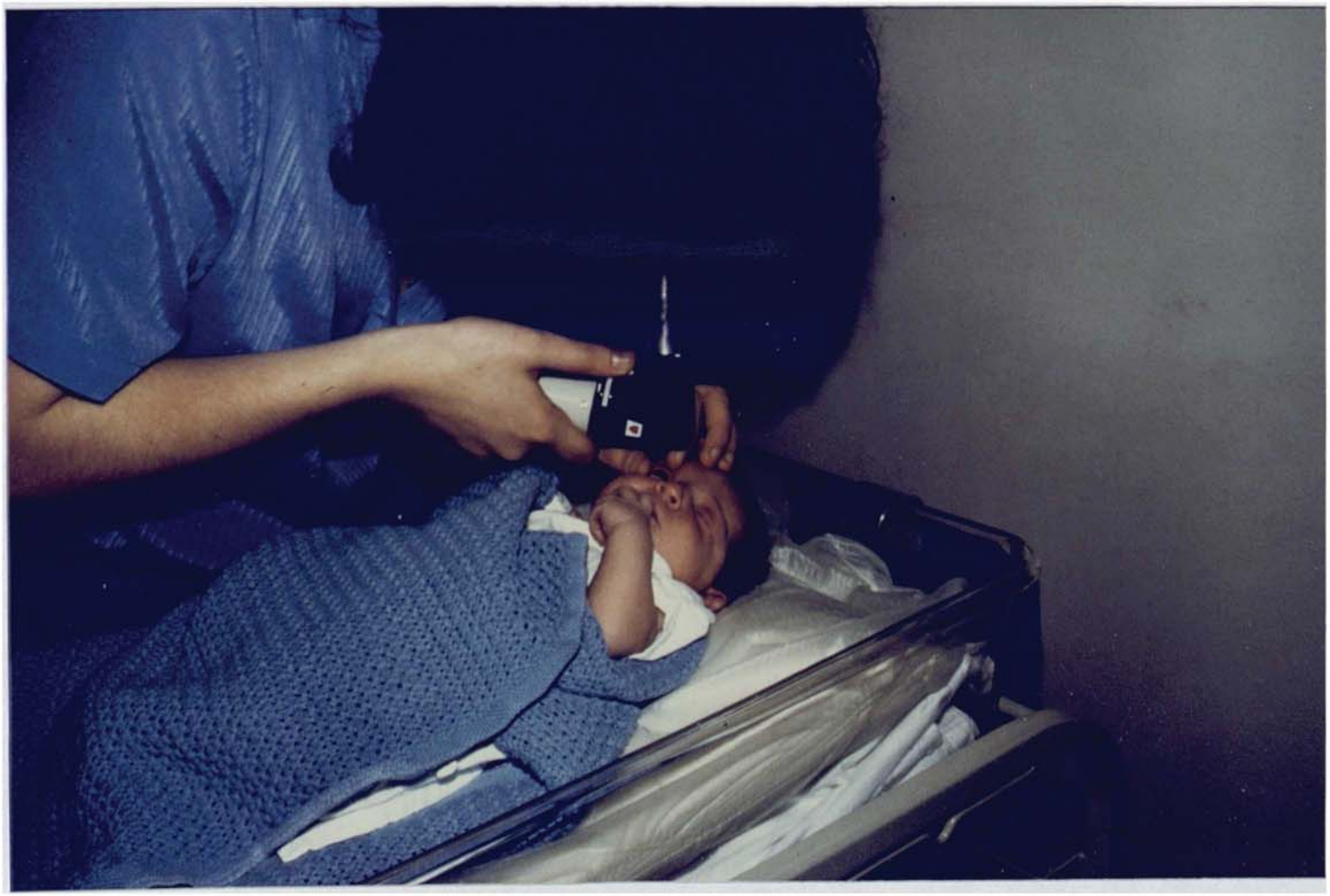


Plate 6.1

Ophthalmoscopic examination of a newborn infant using AO indirect ophthalmoscope.

Table 6.7 Summary of follow-up acuity findings of 16 infants noted to have bilateral neonatal retinal haemorrhage and 16 age and sex matched controls that were not found to have haemorrhage at birth. Mean right eye, left eye and binocular M.A.R. findings are given.

Retinal Haemorrhage Group					Control Group				
		Mean M.A.R. (mins)					Mean M.A.R. (mins)		
No.	Age	Right	Left	Binoc.	No.	Age	Right	Left	Binoc.
1	0.7	-	-	70.5	1	0.0	-	-	-
2	4.6	-	-	53.5	2	4.6	-	-	26.8
3	4.7	26.0	52.0	21.8	3	4.7	-	42.5	31.8
4	5.7	43.0	22.5	67.3	4	5.3	82.5	51.0	30.8
5	9.6	-	-	22.5	5	9.0	-	-	25.5
6	11.9	-	-	8.0	6	11.1	-	-	16.8
7	12.0	16.0	-	16.0	7	12.1	12.5	-	15.0
8	13.3	23.0	18.0	10.0	8	12.4	18.0	11.5	-
9	14.6	34.0	52.0	9.0	9	14.3	19.0	19.0	16.0
10	20.6	-	11.0	10.8	10	21.7	11.0	8.5	8.5
11	23.9	12.0	16.0	-	11	23.9	12.0	16.0	-
12	24.0	18.5	16.0	-	12	24.0	34.3	64.5	14.5
13	24.9	13.0	8.5	8.5	13	25.3	19.0	-	9.0
14	25.9	8.0	-	-	14	26.0	10.5	10.5	-
15	54.6	-	19.0	-	15	54.0	-	-	16.0
16	55.4	-	-	12.0	16	55.0	-	16.0	-
Group Mean		21.5	23.9	25.8	Group Mean		24.3	26.6	19.1
	S.E.	4.0	5.8	7.1		S.E.	8.1	7.3	2.6

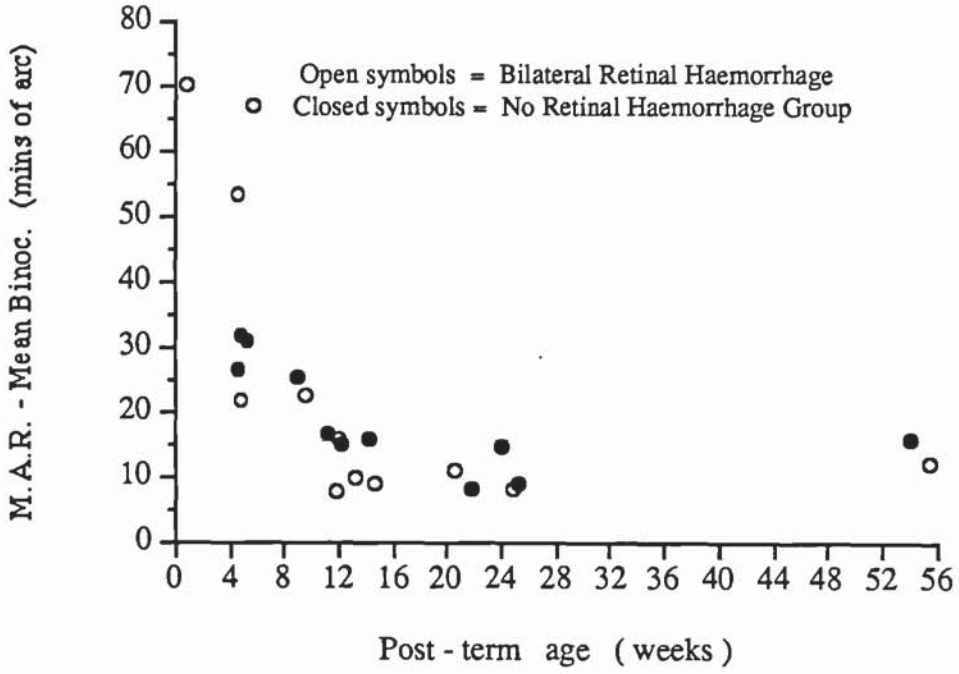


Figure 6.9 Scatterplot showing raw "mean" binocular minimum angle of resolution data obtained during follow-up from age and sex matched infants with and without neonatal retinal haemorrhage. No significant differences between groups were noted.

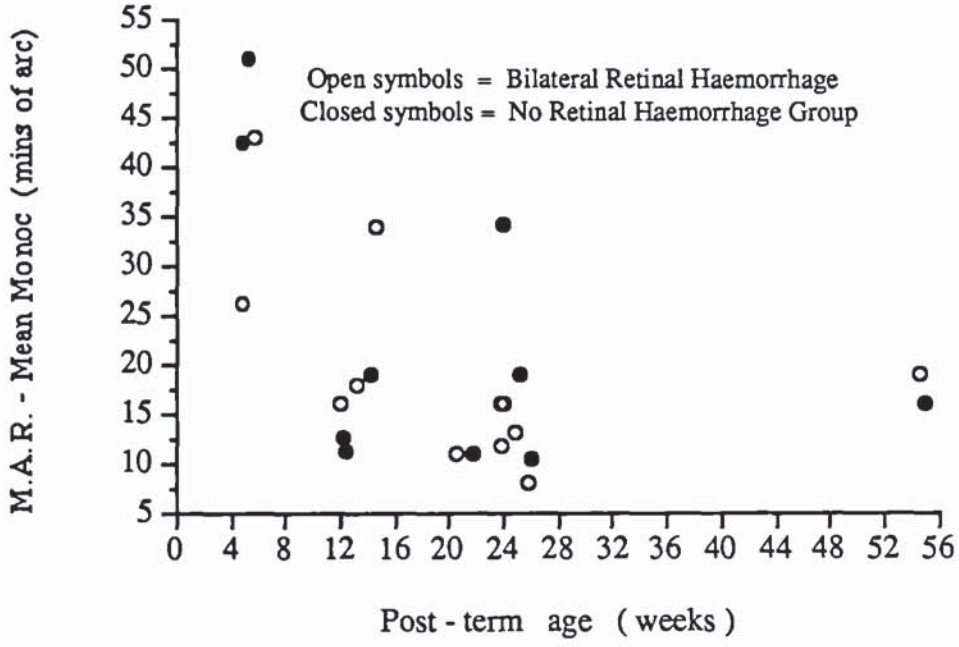


Figure 6.10 Scatterplot of raw "mean" monocular minimum angle of resolution data for the samples in Figure 6.9. No significant differences between groups were noted.

6.3 Other factors

6.3.1 Neonatal data

a) Correlation of acuity data with infant maturity, physical size and other factors

Regression analyses were performed to determine whether binocular minimum angle of resolution data was correlated with any of several factors. Results of statistical tests are summarised in Table 6.8, full details are given in Appendix Table A6.8. Binocular acuity for vertical gratings and "mean" binocular acuity tended to improve (lower M.A.R.s) with increases in: infants' post-conceptional or post-natal age, maternal age, birth weight, head circumference and length (minimal effect) and to reduce (higher M.A.R.s) as duration of labour increased. Scatterplots illustrating the relationships between binocular (vertical grating) acuity and post-natal age, head circumference and duration of labour are presented in Figures 6.11, 6.12 and 6.13 respectively. The only significant correlations occurred for the relationship with post-natal age (when expressed in log. hours). Duration of labour was not known for most of the sample because this detail was not originally extracted from the case history and some difficulty was experienced in obtaining access to hospital notes on completion of the study.

Table 6.8 Summary of correlations between newborn acuity (M.A.R., mins. of arc) and various factors. Mean binocular = average M.A.R. for horizontal and vertical gratings.
Key to significance levels: ** ≤ 0.01; ns = not significant; (ns) = not significant but p ≤ 0.1.

Variables	Binoc. acuity (vertical)			Mean binocular acuity		
	n	r	p	n	r	p
Acuity v. :						
Post-conceptional age (wks)	124	0.16	(ns)	127	0.11	ns
Post-natal age (hours)	124	0.16	(ns)	127	0.16	(ns)
Post-natal age (log. hrs)	124	0.23	**	127	0.22	**
Labour (hours)	47	0.20	ns	49	0.18	ns
Birth weight (kg.)	124	0.04	ns	127	0.01	ns
Head circumference (cm.)	124	0.10	(ns)	127	0.06	ns
Length (cm.)	124	0.11	ns	127	0.10	(ns)
Maternal age (years)	124	0.11	ns	127	0.10	(ns)

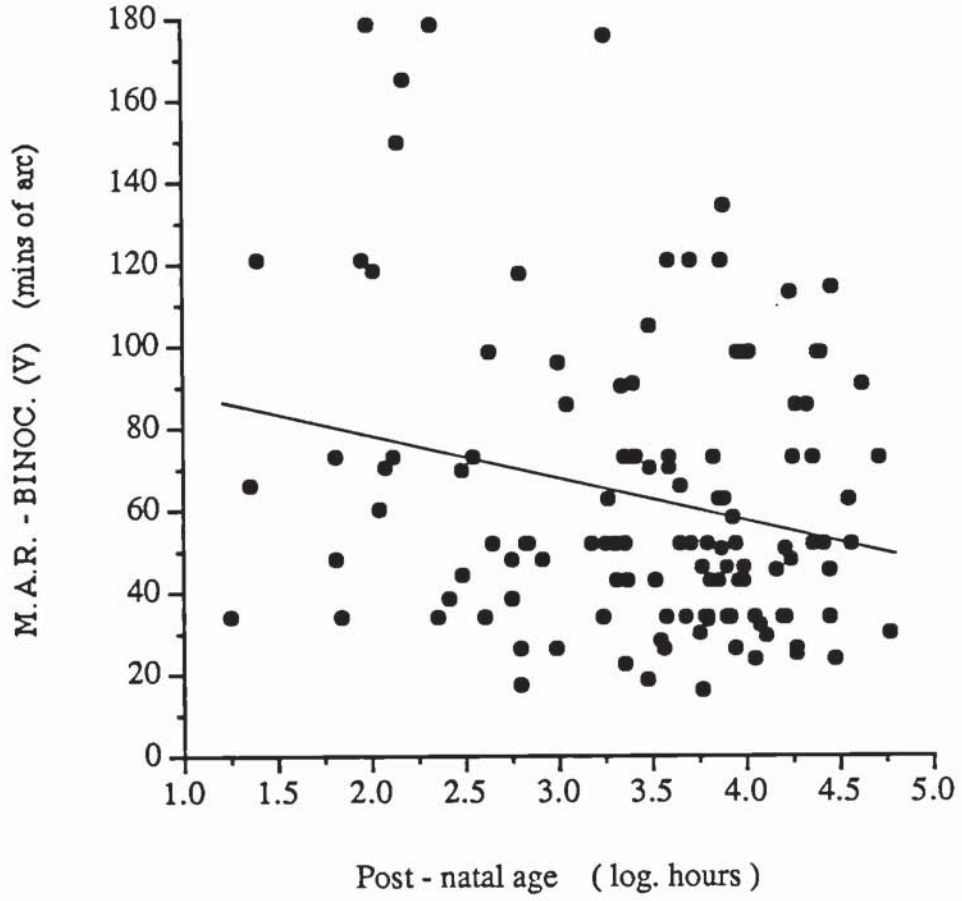


Figure 6.11 Scatterplot of neonatal binocular (vertical grating) acuity data versus post-natal age in log. hours. A significant relationship for better acuity with increased age was observed. Equation of regression line:
$y = -10.2x + 97.9$ ($r = 0.23$, d.f. 1,122, $p = 0.01$).

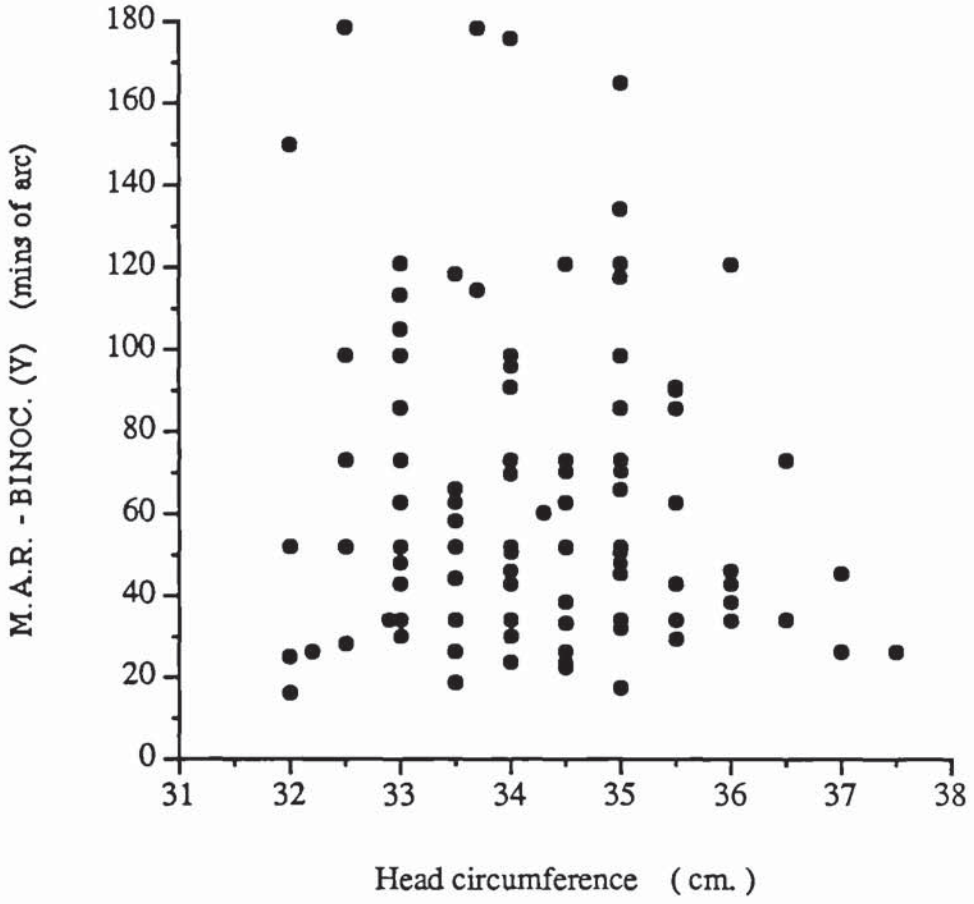


Figure 6.12 Scatterplot of neonatal binocular (vertical grating) acuity data versus head circumference (cm.). No significant correlation was found between these variables although statistical tests suggested a slight trend for better acuity with increasing head circumference ($p = 0.1$).

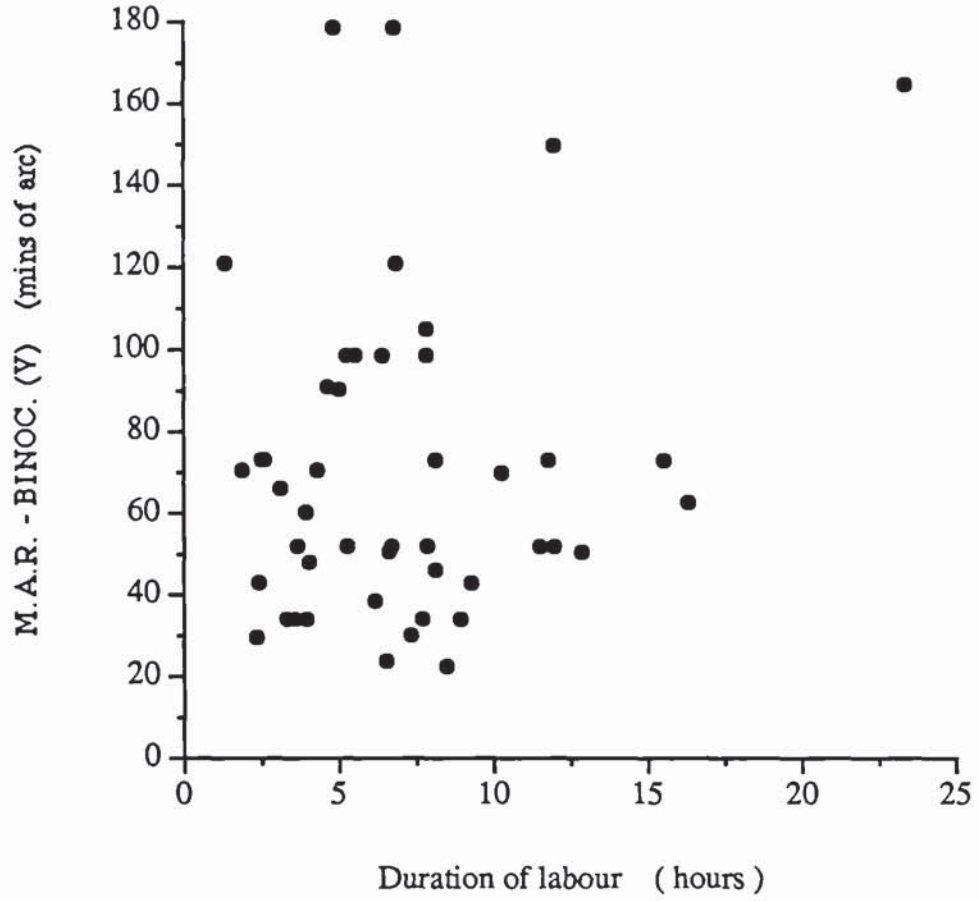


Figure 6.13 Scatterplot of neonatal binocular (vertical grating) acuity data versus duration of labour (hours). No significant relationship was found between these variables although statistical tests suggested a slight trend for poorer acuity with increasing duration of labour ($p > 0.1$).

b) Effect of birth history

A tendency was noted for lower acuity levels to be encountered amongst infants that experienced more prolonged labour. This raises the possibility that increased birth trauma could be reflected in impaired visual performance during the initial days of life. As previously described for the refractive data, newborns were, in each of four comparisons, divided into two subgroups selected to isolate from the remaining sample infants noted to or likely to have suffered increased birth trauma. The increased trauma groups comprised infants having birth complications, low Apgar score at one minute after birth, retinal haemorrhage or borne by primiparous mothers. In a further subdivision the sample was subdivided into offspring of mothers that had received pethidine analgesia during labour and those that had not. The results of the retinal haemorrhage comparison have been described earlier (see section 6.2.1).

Averaged binocular acuity findings of the various neonatal subgroups are included in Table 6.9. Higher mean acuity was noted for infants with high Apgar scores and for the offspring of mothers that did not receive pethidine analgesia. Higher levels were also noted for newborns with birth complications but findings were similar amongst the primiparous and multiparous groups. No significant differences were observed between groups (independent t - tests $p > 0.05$). The strength of the relationship between acuity and post-natal age (log. hours) was evaluated for each subgroup. Summarised results of statistical tests are included in Table 6.10 (more details are provided in Appendix Tables A 6.9 to A 6.13). Correlation coefficients were in all cases higher for the increased trauma samples (ranging between 0.31 and 0.48 cf. 0.13 to 0.19 in the low trauma samples). Higher correlation coefficients were also noted for the pethidine group ($r \approx 0.37$, $p = 0.005$ cf. $r \approx 0.07$, $p > 0.05$ in the non pethidine group). The latter data is plotted in Figures 6.14 and 6.15.

Table 6.9 Summary of average newborn binocular acuity findings (M.A.R., mins. of arc) of various subgroups. "Mean" binocular = average M.A.R. for horizontal and vertical gratings.

Variables	Binocular acuity (vertical)			"Mean" binocular acuity		
	n	Mean	S.E.	n	Mean	S.E.
All	124	62.9	3.2	127	62.5	3.0
Male	62	60.4	4.4	62	60.8	4.4
Female	62	65.4	4.6	65	64.2	4.2
Asian	62	63.0	4.6	63	61.9	4.3
Caucasian	43	56.5	4.5	45	58.1	4.3
Negroid	13	85.8	12.9	13	83.0	13.3
Pethidine	54	67.2	5.7	57	66.3	5.3
No pethidine	70	59.5	3.5	70	59.5	3.4
Birth complications	35	58.9	6.6	35	58.4	6.7
No birth complications	89	64.4	3.6	92	64.1	3.3
Low Apgar	61	67.1	5.0	64	66.7	4.8
High Apgar	62	59.0	4.0	62	58.3	3.6
Retinal haemorrhage	30	58.7	5.9	32	59.2	5.6
No retinal haemorrhage	79	63.7	4.1	80	62.9	3.9
Primiparous	33	64.1	5.7	33	62.0	5.0
Multiparous	91	62.4	3.8	94	62.7	3.7

Table 6.10 Summary of correlations between newborn binocular acuity and post-natal age (log. hrs) for various samples.
Key to significance levels: * = 0.05; ** = 0.01; *** = 0.005; ns = not significant; (ns) = not significant but $p \leq 0.1$.

Sample	n	Binoc. (Vertical) r	p	"Mean" Binoc. r	p
All	127	0.23	**	0.22	**
Male	62	0.31	*	0.29	*
Female	65	0.15	ns	0.16	ns
Asian	63	0.14	(ns)	0.10	ns
Caucasian	45	0.20	ns	0.21	ns
Pethidine	57	0.38	***	0.36	**
No pethidine	70	0.07	ns	0.08	ns
Birth complications	35	0.31	(ns)	0.34	*
No birth complications	92	0.19	(ns)	0.17	(ns)
Low Apgar	64	0.32	*	0.35	***
High Apgar	62	0.13	ns	0.06	ns
Retinal haemorrhage	32	0.48	**	0.47	**
No retinal haemorrhage	80	0.21	(ns)	0.19	(ns)
Primiparous	33	0.48	***	0.46	**
Multiparous	94	0.15	ns	0.16	(ns)

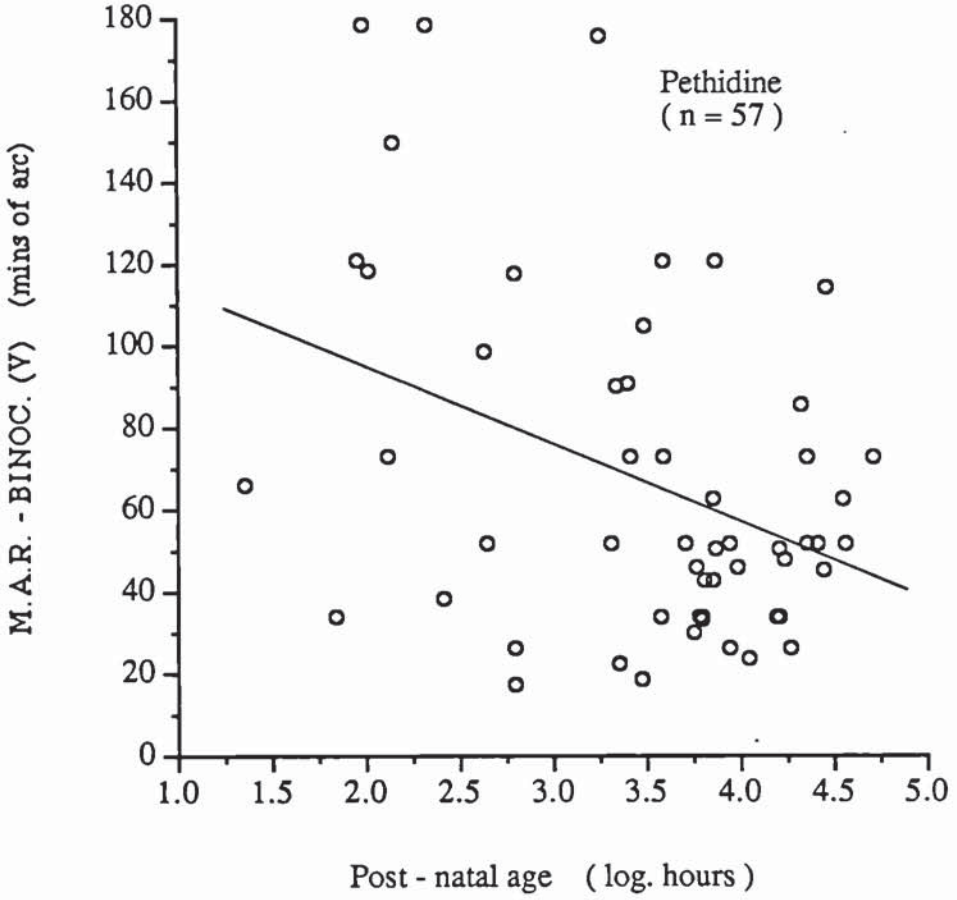


Figure 6.14 Scatterplot of neonatal binocular (vertical grating) acuity data of infants whose mothers received pethidine during labour versus post-natal age in log. hours. A significant relationship for better acuity with increased age was observed.
Equation of regression line:
$y = -19.3x + 134.5$ ($r = 0.38$, d.f. 1,52, $p < 0.005$).

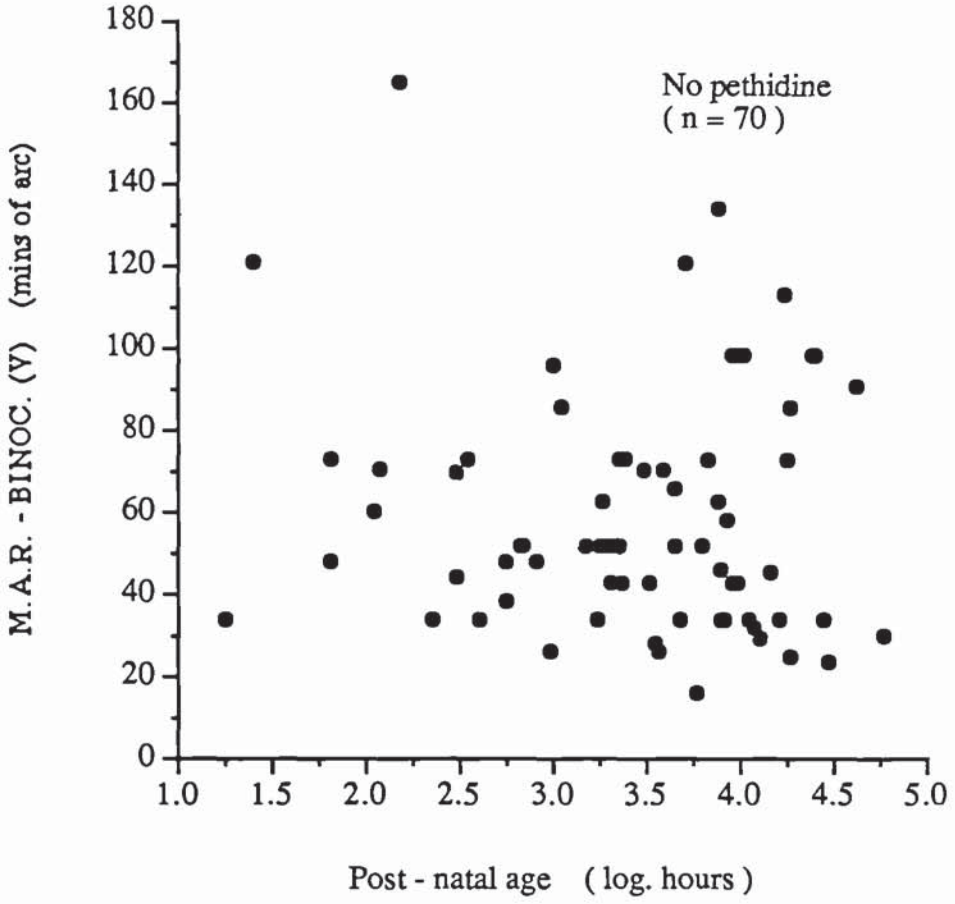


Figure 6.15 Scatterplot of neonatal binocular (vertical grating) acuity data of infants whose mothers did not received pethidine during labour versus post-natal age in log. hours. A slight trend for better acuity with increased age was observed but did not reach statistical significance ($r = 0.7$, $p > 0.1$).

c) Effect of gender and ethnic group

Mean acuity findings of males and females are included in Table 6.9. Acuity was slightly higher in male newborns but the differences between groups were not significant (independent t - tests, $p > 0.05$). Correlations of acuity with post-natal age were higher for males than females ($r \approx 0.30$, $p < 0.05$ for males cf. $r \approx 0.15$, $p > 0.05$ for females). Statistical data is summarised in Table 6.10 (more details are provided in Appendix Table A6.14). Scatterplots of binocular (vertical grating) acuity versus post-natal age are presented in Figures 6.16 and 6.17, respectively for males and females.

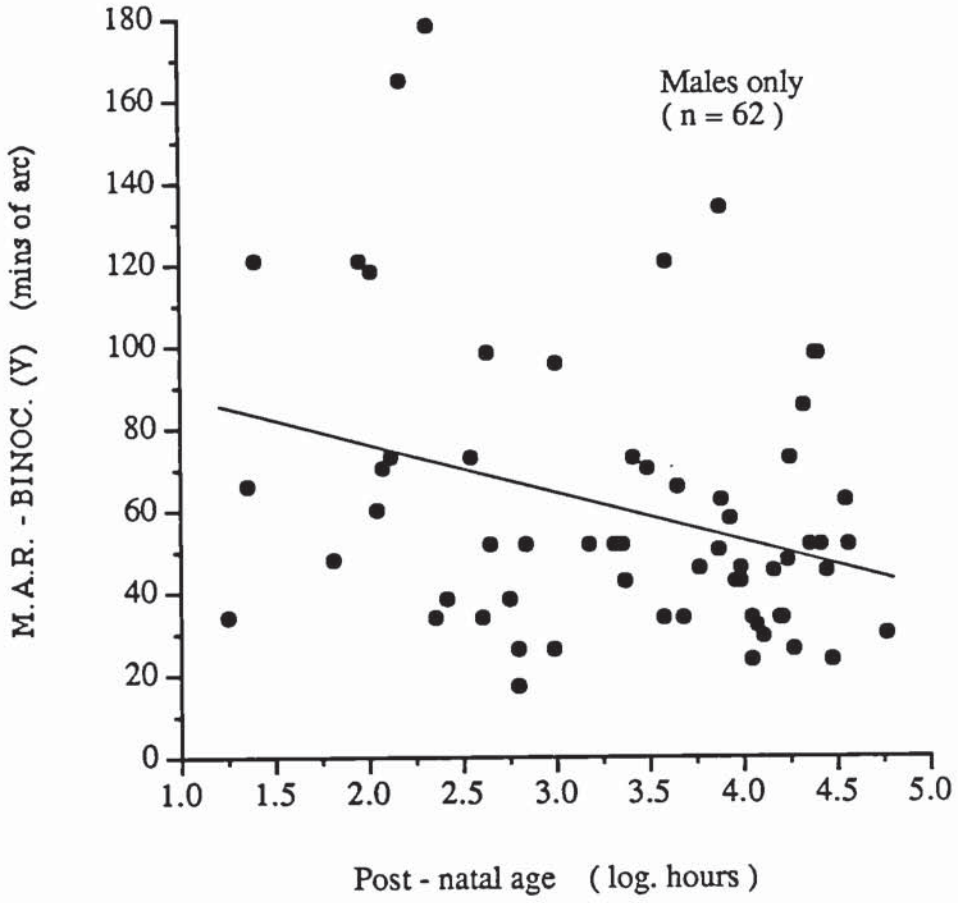


Figure 6.16 Scatterplot of newborn males binocular (vertical grating) acuity data versus post-natal age in log. hours. A significant relationship for better acuity with increased age was observed. Equation of regression line:
$y = -11.4x + 98.6$ ($r = 0.31$, d.f. 1,60, $p < 0.05$).

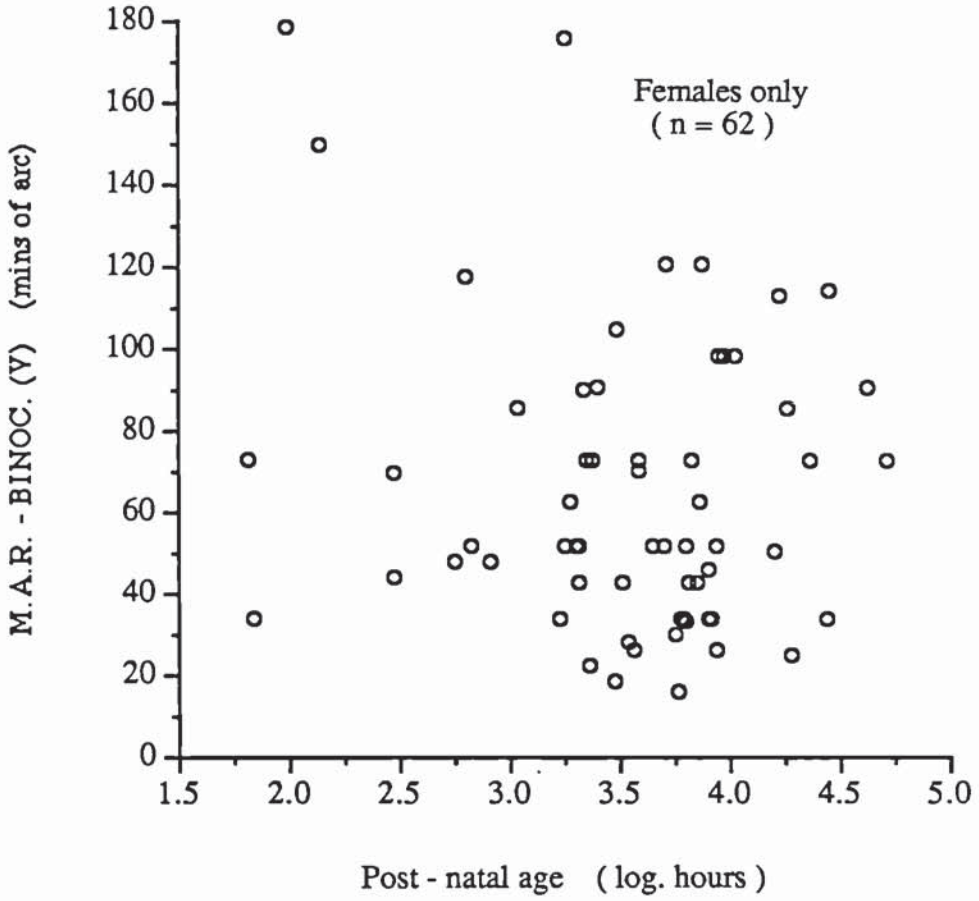


Figure 6.17 Scatterplot of newborn females binocular (vertical grating) acuity data versus post-natal age in log. hours. A trend for better acuity with increased age was observed but did not reach statistical significance ($p > 0.1$).

When the newborn sample was subdivided on the basis of ethnic group a trend was noted for mean acuities to improve in the order Negroid, Asian and Caucasian. Mean acuities are presented in Table 6.9. Differences in mean findings of the two largest groups were not significant (independent t - tests, $p > 0.05$). Correlations of acuity with post-natal age were higher for Caucasians than Asians, but did not reach significance for either group. Statistical data is summarised in Table 6.10 (more details are provided in Appendix Table A6.15).

d) Effect of alertness

The initial 88 newborns participating in preferential looking testing were not selected for alertness. The test was attempted providing the mother was willing and the child was not obviously deeply asleep. The remaining sample were examined if reasonably alert (preferably, but not always with eyes open). Infants that were selected for alertness could be tested more successfully (see section 4.7.1). The mean acuity findings of the unselected and selected groups are provided in Table 6.11. Minimum angle of resolution tended to be lower for the selected infants but the differences between groups were not significant (independent t - tests; $p > 0.05$ - values are given in Table 6.12).

Table 6.11 Summary of neonatal binocular acuity findings of unselected and selected samples. Means, S.D. and group S.E. are given.

Sample	n	Mean	S.D. (Mins. of arc)	S.E.
B (V):				
Unselected	70	66.1	39.6	4.7
Selected	54	58.7	29.3	4.0
Mean Binoc:				
Unselected	71	66.5	39.2	4.7
Selected	56	57.5	25.8	3.4

Table 6.12 Statistical significances for acuity differences in unselected and selected newborns. Independent t - tests.

	Comparison between mean acuity findings		
Variable	t - stat	d.f.	sig
B (V)	1.16	122	0.249
Mean Binoc.	1.50	125	0.137

6.3.2 Follow-up data

a) Effect of gender

Of the 147 follow-up sessions in which acuity tests were performed 64 involved females and 83 involved males. Mean post-term age of the male infants was slightly but not significantly higher than that of females (19.0, S.E. 1.7 weeks for males cf. 16.8, S.E. 1.5 weeks for females; independent t - test $p > 0.05$). "Mean" binocular and monocular acuity data of the two groups is given in Table 6.13 and the binocular data is plotted in Figure 6.18. Differences between groups were not significant (independent t - tests, $p > 0.05$).

Table 6.13 Summary of mean binocular and monocular acuity findings of male and females attending follow-up. Means, S.D. and group S.E. are given.

Sample	n	Mean	S.D. (Mins. of arc)	S.E.
Mean Binoc :				
Male	64	21.1	16.6	2.1
Female	45	20.8	11.8	1.8
Mean Monoc :				
Male	61	22.2	14.3	1.9
Female	45	23.4	15.9	2.4

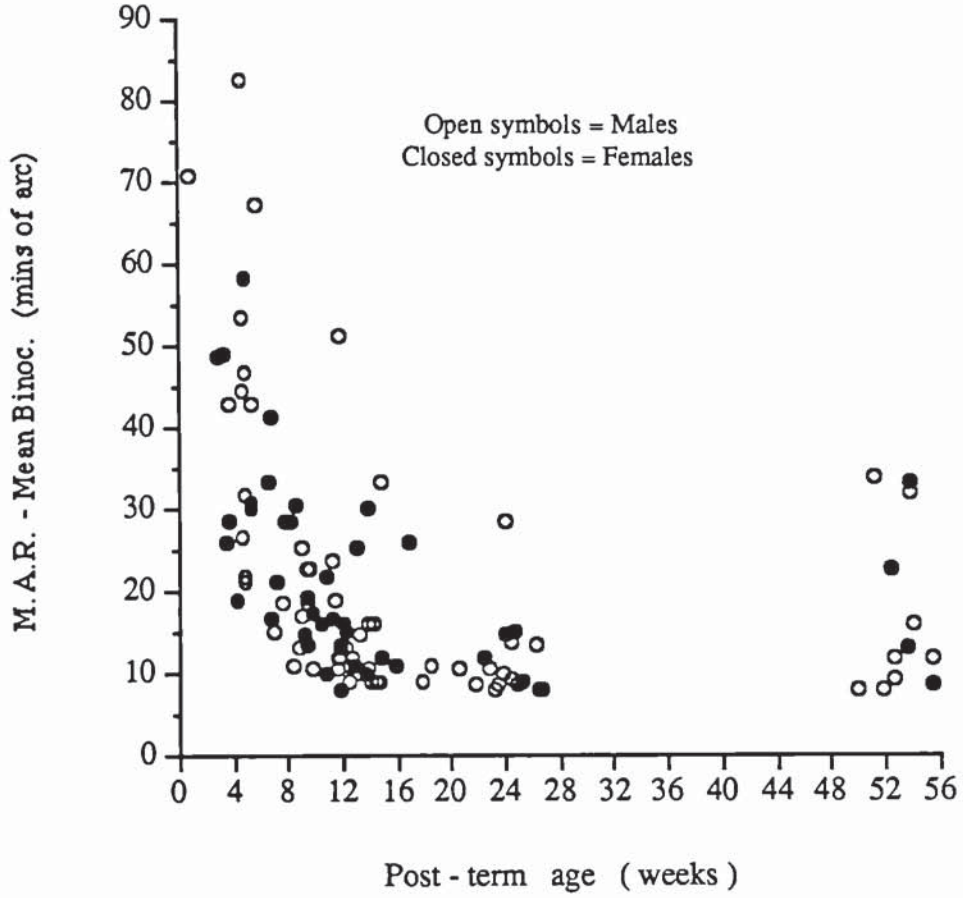


Figure 6.18 Scatterplot showing raw "mean" binocular minimum angle of resolution data obtained from male and female infants during follow-up visits. No significant difference was found between groups.

b) Effect of order of testing

Statistical analysis of monocular acuity data collected from three, four, five, six, seven and twelve month olds was performed to investigate whether testing order influenced findings. Acuity values of individuals were organised according to the order of testing (i.e. first, second, third or fourth monocular estimates were listed separately). For each age group paired t - tests were conducted to determine whether mean acuity differences between "staircases" were significant. Six comparisons were performed for each age group (i.e. 1 v. 2, 1 v. 3, 1 v. 4, 2 v. 3, 2 v. 4 and 3 v. 4). Mean acuity data is available in Appendix Table 6.16.

A summary of the findings on consecutive staircases is given in Table 6.14. Mean acuity on staircase two was better than that on staircase one in three of the six age groups. A trend for lower acuity on staircase three was noted in five age categories. Mean acuity on staircase four was higher than on staircase three in four groups. Of the 36 paired t - tests conducted only one reached statistical significance - this was the comparison between acuity on staircases two and three for five month olds (denoted by an asterisk in Table 6.14; t - statistic - 3.36, d.f. 3, $p = 0.04$). The trends for poorer acuity on staircase three described are likely to relate to the fact that the testing procedure was to secure two separate acuity determinations from one eye (vertical and horizontal) before switching the eyepatch and commencing testing the fellow eye. Recovery from eyepatching could therefore have contributed to poorer acuity values on staircase three.

Table 6.14 Summary of trends in mean monocular acuity findings according to order of testing.
(* = significant difference between means, paired t - test $p < 0.05$).

Age Group (months)	Acuity estimate higher on staircase number		
	2 v. 1	3 v. 2	4 v. 3
3	Yes	No	Yes
4	No	No	Yes
5	Yes	No*	No
6	No	Yes	No
7	Yes	No	Yes
12	No	No	Yes

A summary and discussion of the findings described in this chapter can be found in Chapter 7.

7. REVIEW AND DISCUSSIONS OF FINDINGS

7.1 Summary of pilot study findings

The pilot study was initiated to derive clinical versions of three objective methods applicable to the assessment of infant visual acuity. These techniques are based respectively on pattern visual evoked potentials, optokinetic responses and preferential looking. Reviews of the literature enabled proposals to be made on clinically suitable optokinetic (section 2.3.2, pages 111 - 117) and preferential looking methods (section 2.4.3, pages 127 - 130). More difficulty was experienced in deciding on the most clinically appropriate pattern VEP method (section 2.2.2 a, pages 94 - 95). Preliminary studies in adults were unable to suggest a method that was both speedy and reasonably accurate (section 2.2.2 b and c, pages 95 - 106).

Equipment suitable for the OKN and preferential looking tests was constructed. Technical complications were encountered with the arresting of OKN equipment (section 2.3.2 b, pages 113 - 117) and it was therefore not used in the pilot study proper (section 2.6, pages 143 - 162).

During the pilot study 23 infants attended a total of 57 sessions. Twenty of the sample were clinical patients, the most common diagnosis was of bilateral aphakia, following removal of congenital cataract, three others were normal infants. In most sessions both preferential looking and evoked potential recording was attempted. Preferential looking tests were performed first. Binocular testing was attempted, followed, if successful by monocular. If the infant was sufficiently awake following application of electrodes an attempt was made to record pattern VEPs. In other cases only flash VEPs were recorded.

An indication of the increased success rate of the preferential looking rather than pattern VEP tests is apparent from Figure 2.23 (page 161). Estimates of binocular acuity were obtained in almost 90 percent of preferential looking test sessions and monocular acuities were determined in about half of the sessions. In contrast to these findings, only a quarter of sessions involving pattern VEPs resulted in the recording of *any* acceptable responses. This value decreased to 13 percent when normal infants were removed from the sample. The poor results did not appear to be related to the order of testing (as equally disappointing results were obtained when preferential looking was not performed) or technical problems (since acceptable flash responses were obtained during almost 80 percent of sessions).

The preferential looking test was often completed in less time than was required for the application of electrodes for VEP testing and was more favourably accepted by parents.

7.2 Summary of normative study findings

The methodology relating to the normative study is described in Chapter 3 (pages 163 - 187). The main methods used were preferential looking acuity testing and objective refraction using streak retinoscopy. Newborn infants were examined and follow up assessments conducted up to the age of one year in some cases. Indirect ophthalmoscopy was performed on most of the newborn sample.

7.2.1 Visual acuity findings (Chapter 4)

Preferential looking testing of 174 newborns was attempted. Of this sample 87 infants were followed up during the first year of life. A total of 147 follow-up assessments were conducted. Up to six different acuity measurements were attempted during each testing session - vertical and horizontal gratings presented to the right eye, left eye or binocularly. Infants were subdivided into nine different age categories (newborns, one, two, three, four, five, six, seven and twelve months post-term). Group averaged acuity data were computed for each of these age categories.

a) Binocular and monocular acuity norms

Trends of acuity development did not vary for vertical or horizontal grating orientation. In order to increase the numbers of infants providing specific acuity data within each age group "mean" right eye, "mean" left eye and "mean" binocular acuity was calculated by combining vertical and horizontal grating M.A.R. data. Monocular data was further compressed by selecting a representative value ("mean" right eye or "mean" left eye acuity). Binocular acuity was significantly better than monocular acuity for the overall sample and for the newborn and three, four and seven month age groups. The average disparity between binocular and monocular acuity was highest ($\approx$ 0.75 octaves) during post-term months three to five.

The stimulus gratings used in the study were calibrated in minutes of arc so M.A.R. values have been used throughout Chapter 4. Since it is customary in many studies to measure acuity in cycles per degree the mean monocular and mean binocular data has been reprocessed in these units. Unfortunately the relationship between M.A.R. and cycles per degree is not linear which necessitated laboriously reprocessing the original raw data (converting each M.A.R. value to its cycle per degree equivalent) in order to arrive at the required group averaged figures. These values are presented in Tables 7.1 and 7.2 and illustrated in Figure 7.1. The monocular data was also processed by selecting the "best" monocular acuity from each infant. The group averaged data based on this analysis is presented in Table 7.3 and illustrated in Figure 7.2. Figures 7.1 and 7.2 summarize the normative acuity data collected during this study.

Table 7.1 Binocular acuity norms (cycles/degree) means, S.D. and group S.E. for each of nine age groups.

Age Group (months)	Mean	S.D.	S.E.
Newborn	0.64	0.33	0.03
1	0.76	0.26	0.12
2	1.08	0.48	0.11
3	2.05	0.68	0.13
4	2.41	0.73	0.16
5	2.50	0.82	0.47
6	3.18	0.41	0.17
7	2.74	0.86	0.29
12	2.29	1.07	0.32

Table 7.2 Monocular acuity norms (cycles/degree) means, S.D. and group S.E. for each of eight age groups. No data was obtained at one month.

Age Group (months)	Mean	S.D.	S.E.
Newborn	0.55	0.19	0.03
1	-	-	-
2	0.97	0.43	0.14
3	1.28	0.59	0.14
4	1.67	0.78	0.15
5	2.19	0.95	0.32
6	2.30	0.77	0.20
7	2.05	0.78	0.21
12	2.31	0.67	0.22

Table 7.3 Representative "best" monocular acuity data (cycles/degree) means, S.D. and group S.E. for each of eight age groups. No data was obtained at one month.

Age Group (months)	Mean	S.D.	S.E.
Newborn	0.57	0.20	0.03
1	-	-	-
2	1.09	0.47	0.16
3	1.61	0.88	0.21
4	1.88	0.76	0.15
5	2.48	1.09	0.36
6	2.87	0.80	0.21
7	2.72	0.80	0.21
12	2.64	0.83	0.28

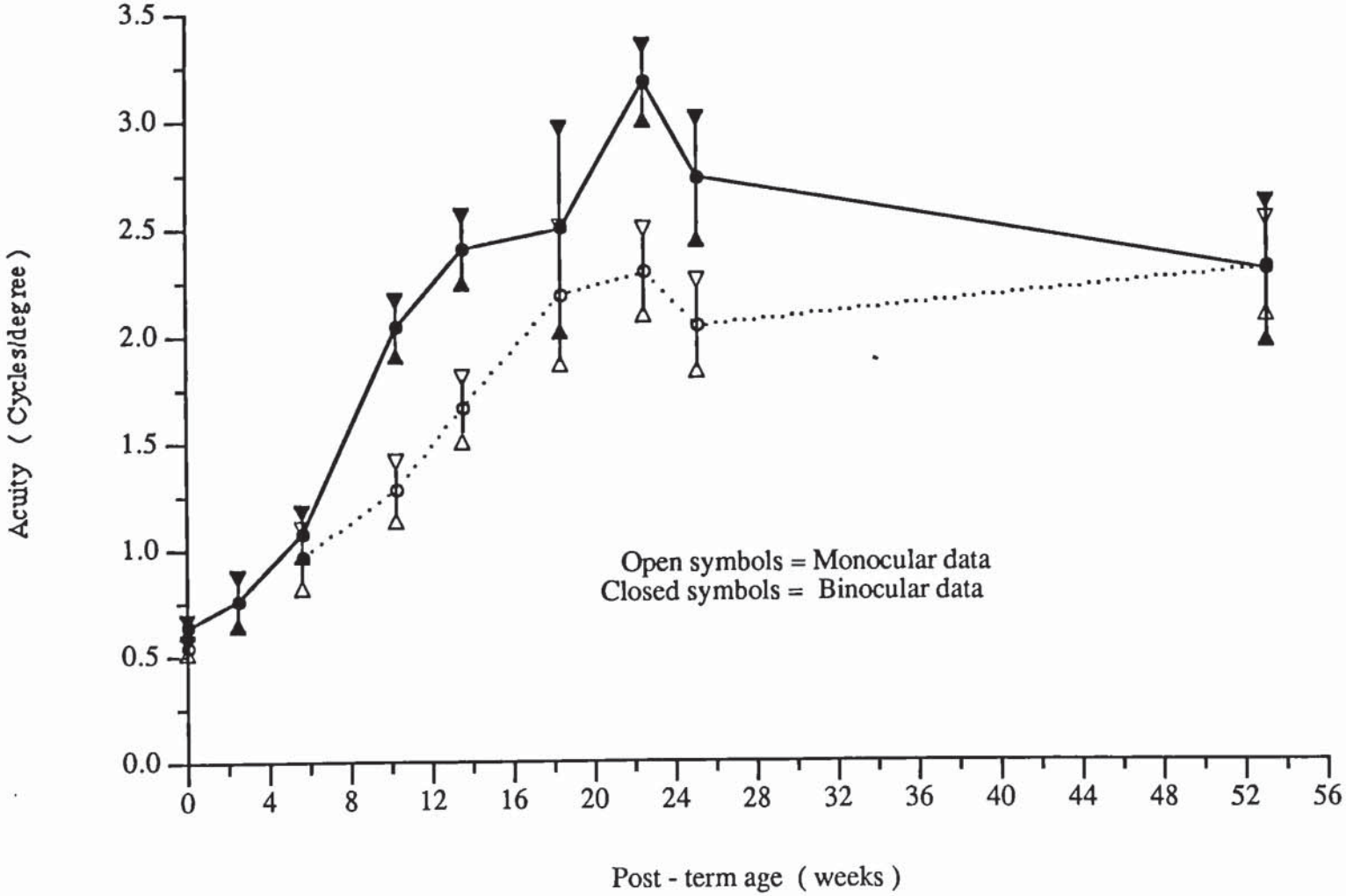


Figure 7.1 Group averaged binocular and monocular acuity norms derived in this study expressed in cycles per degree. Vertical bars indicate 2 SEM. Numerical values are provided in Tables 7.1 and 7.2. Axes selected to be comparable with clinical data of pilot study samples (Figures 2.20 and 2.21).

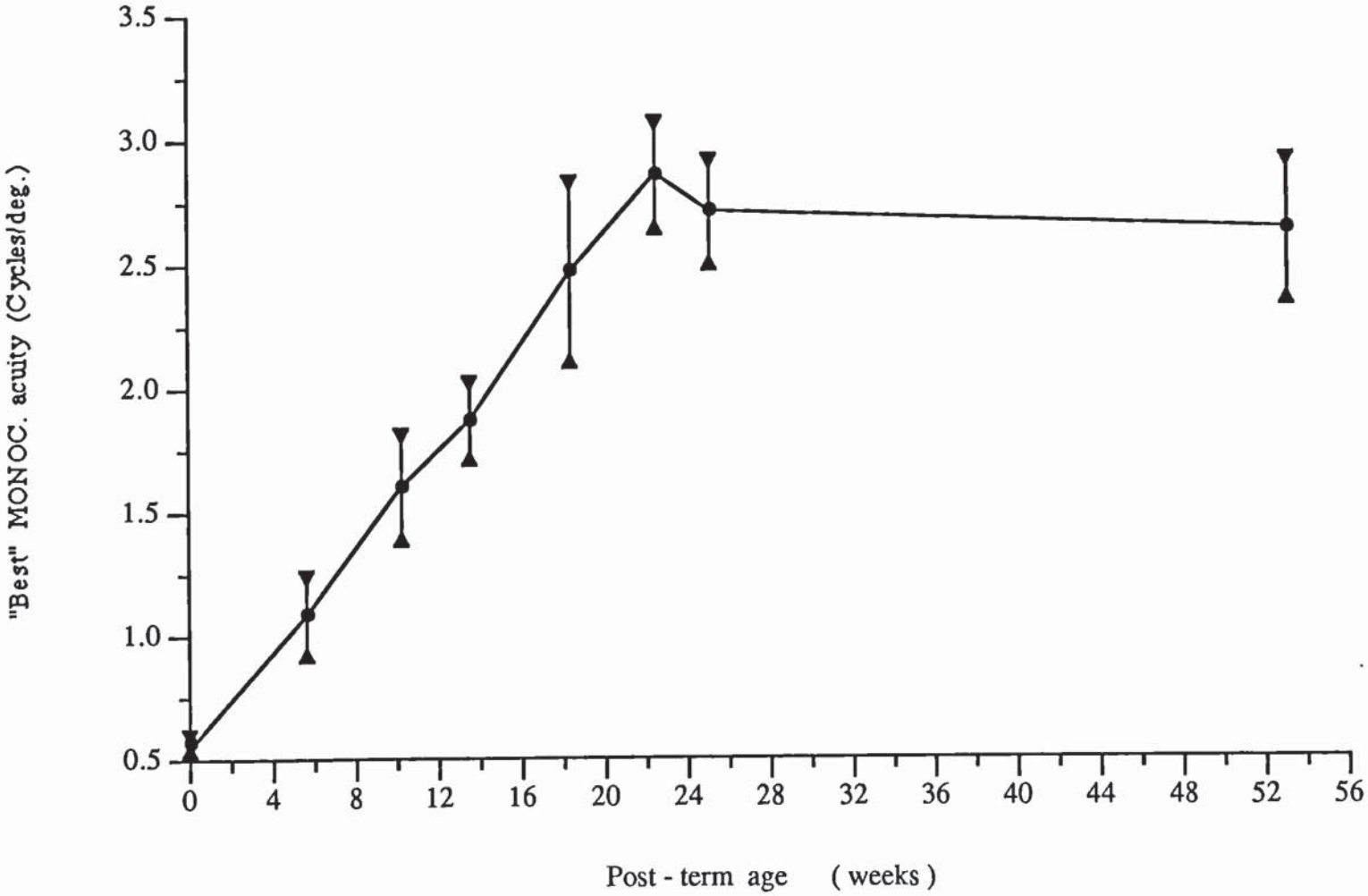


Figure 7.2 Group averaged "best" representative monocular acuity norms. Values expressed in cycles per degree. Vertical bars indicate 2 SEM. Numerical values are provided in Table 7.3.

b) Interocular acuity differences

Average interocular acuity differences declined from 1.3 octaves at birth to 0.4 octaves at 12 months (Figure 4.10, page 204). This trend for an age related reduction in interocular acuity difference reached statistical significance (p=0.05).

c) Longitudinal data

Nine infants were tested on five or more occasions between birth and seven months. Only one of these infants did not display any apparent set-back in acuity development. Apart from one infant, no set-backs in acuity development were noted until the thirteenth post-term week (Table 4.17, page 212).

d) Success rate

The success rate of the test varied with age; 87.4% of newborns and 98.0% of older infants were testable (details are available in Tables 4.21 and 4.23 - pages 216 and 219 respectively). Infants younger than two months were difficult to test particularly monocularly. Success rate increased steadily with age - infants of seven months post-term age being the most successfully tested. One year olds did not respond favourably to the test, which was reflected in both reduced testability and (in general) slightly reduced mean acuity findings compared to the seven month age group. Although test sessions were not strictly timed most were completed within 20 minutes.

7.2.2 Refractive development (Chapter 5 findings)

Refractive development from birth to one year has been studied in 210 newborn infants of which 63 were re-refracted (on up to two occasions) during follow-up visits. Newborns were all healthy full-term infants examined within their first week of life prior to discharge from a hospital maternity ward.

a) Spherical equivalent refraction (S.E.R.)

i) Neonatal data

At birth almost 80 percent of the sample demonstrated one or more dioptres of hypermetropia. The average spherical equivalent refraction (S.E.R.) was $\approx$ 2.75 (S.D. $\pm$ 2.6) dioptres. A wide range of refractions were encountered varying between 4.50 dioptres of myopia and 9.75 dioptres of hyperopia.

The newborn data was statistically analysed to investigate possible factors that might correlate with the infants refractive status and perhaps explain some of the variation found. Regression analyses indicated that post-natal age at the time of retinoscopy had a significant effect on newborn S.E.R.. The level of

hyperopia decreased by about two dioptres during the first five days of life. This relationship was most marked when age was expressed in log. hours (right eye: $r = 0.23$, $p \leq 0.001$; left eye $r = 0.19$, $p \leq 0.01$). Neither post-conceptional age or duration of cycloplegia appeared to affect S.E.R. findings. A tendency was noted for larger infants to be more hyperopic. Linear regression analysis revealed a significant positive correlation between S.E.R. and head circumference, although the correlation was weaker than for post-natal age (right eye: $r = 0.16$, $p \leq 0.05$; left eye $r = 0.15$, $p \leq 0.05$). S.E.R. findings were not significantly correlated with either birth weight or length. In an attempt to elaborate possible causes for these findings the strengths of the relationships were investigated for various newborn subgroups. A simplified summary of these analyses is provided in Table 7.4 (more details can be found in Tables 5.4, 5.5 and 5.6). Similar acuity data provided in Table 7.5 is presented here for the purpose of comparision.

Newborns were, in each of four comparisons, divided into two subgroups chosen to isolate from the remaining sample, infants noted to or likely to have suffered increased birth trauma. The increased trauma groups comprised infants having birth complications, low Apgar score at one minute after birth, retinal haemorrhage or those borne to primiparous mothers. Head circumferences were not significantly different between groups. Newborns having birth complications or borne to primiparous mothers were significantly older when refracted due to the practice of discharging such infants from hospital later. Infants from the increased trauma categories had higher group averaged S.E.R.'s compared with their paired samples, although differences were not significant. Infants with clear evidence of increased birth trauma (with complications or low Apgar) demonstrated higher correlations with age ($r \approx 0.27$ for the right eye and ≈ 0.21 for the left eye). The opposite was true of newborns merely assumed to have suffered increased trauma (with retinal haemorrhage or primiparous). Apart from the infants with birth complications higher correlation coefficients between S.E.R. and head circumference were found for the high trauma groups. Infants from primiparous mothers demonstrated the highest correlation coefficients ($r \approx 0.26$) for this effect. The correlation coefficient was very low ($r \approx 0.04$) for infants having birth complications.

Male newborns mean S.E.R. values were slightly but not significantly higher than females'. Correlations between S.E.R. and post-natal age were higher for males ($r \approx 0.28$; $p < 0.01$ cf. ≈ 0.11; $p > 0.05$) whereas correlations with head circumference were higher for females ($r \approx 0.24$; $p < 0.05$ cf. 0.04; $p < 0.05$). Head circumference was significantly larger for males ($p < 0.001$) but post-natal age was not significantly different between groups.

Mean S.E.R. levels in different neonatal ethnic groups declined in the order Caucasian, 'Other', Asian and Negro. Differences in spherical refractive findings (and head circumferences) of the two largest samples (Asian and Caucasian) were not significant. Asian infants were significantly older at the time of retinoscopy than Caucasians ($p < 0.01$). Correlations between S.E.R. and post-natal age were much higher for Caucasians than Asians ($r \approx 0.44$; $p < 0.0005$ cf. ≈ 0.11; $p > 0.05$) whereas correlations with head circumference were similar and failed to reach significance in either group.

Mean neonatal S.E.R. levels were slightly but not significantly higher in the offspring of mothers that received pethidine analgesia during labour. Correlations between S.E.R. and post-natal age were, however, higher for the sample that did not receive pethidine ($r = 0.27$; $p < 0.01$ cf.≈ 0.14; $p > 0.05$). The opposite was true of the correlation with head circumference. No significant differences in head circumference or post-natal age were observed between groups.

Table 7.4 Summary of comparisons between mean spherical equivalent refractive findings and correlations with post-natal ages and head circumference for various paired newborn subgroups.
* A > B = higher S.E.R. (greater hypermetropia) in group A.

Newborn subgroups			Spherical equivalent refraction data		
				Correlations with:	
No.	A	B	Mean S.E.R.*	Postnatal age	Head circumference
1	Male	Female	A > B	A > B	A < B
2	Caucasian	Asian	A > B	A > B	A = B
3	Pethidine	No pethidine	A > B	A < B	A > B
4	Birth complications	No complications	A > B	A > B	A < B
5	Low Apgar	High Apgar	A > B	A > B	A > B
6	Retinal haemorrhage	No retinal haems.	A > B	A < B	A = B
7	Primipara	Multipara	A = B	A < B	A > B
More details available in		Table	5.4	5.5	5.6
		Page	239	240	241

Table 7.5 Summary of comparisons between mean M.A.R. acuity findings and correlations with post-natal ages for various paired newborn subgroups.
* A > B = higher M.A.R. (poorer acuity) in group A.
** A > B = correlation coefficient higher for group A.

Newborn subgroups			Binocular acuity data (vertical and "mean")	
				Correlation with:
No.	A	B	Mean acuity *	Postnatal age **
1	Male	Female	A < B	A > B
2	Caucasian	Asian	A < B	A > B
3	Pethidine	No pethidine	A > B	A > B
4	Birth complications	No complications	A < B	A > B
5	Low Apgar	High Apgar	A > B	A > B
6	Retinal haemorrhage	No retinal haems.	A < B	A > B
7	Primipara	Multipara	A = B	A > B
More details available in		Table	6.9	6.10
		Page	324	325

ii) Follow-up data

Group averaged S.E.R. data showed a monotonic decrease from about 2.75 dioptres of hypermetropia at birth to 0.86 dioptres at one year. Alterations occurring between birth and three months or between six months and one year did not reach statistical significance (student t - tests, $p > 0.05$). The largest (> 1 D.) and most significant changes occurred between three and six months (paired t - tests, $p = 0.001$).

Two patterns of S.E.R. alteration were noted in twelve infants refracted at birth, three and six months. Most infants that had more than three dioptres of neonatal hypermetropia showed a reduction in prescription at three and six months. The hypermetropia of infants that demonstrated less than three dioptres at birth tended to increase by three months then reduce by six months.

Refractive changes of individual infants at three, six, and twelve months were compared with neonatal S.E.R. A high correlation was found between direction and amount of refractive change and original error for all age groups ($r > 0.77$; $p < 0.0001$). The proportion of eyes showing emmetropic shifts increased from 75 percent at three months to 86 percent at both six and twelve months. Approximate estimates of mean dioptric change per week based on the samples followed-up are 0.13 D. between birth and three months, 0.10 D. between birth and six months and 0.04 D. between birth and twelve months. The proportion of eyes displaying emmetropic refractions (i.e. 0.00 ± 0.99 D.) increased from 11 percent at birth to around 60 percent at one year. This alteration was largely due to a reduction in the number of hypermetropic infants.

b) Anisometropia

At birth only 16.7 percent of infants were isometropic. Despite this 'significant' anisometropia (i.e. $\geq$ 1.00 D.) was relatively rare affecting only 21.5 percent of the sample. The mean value of neonatal anisometropia was $\approx 0.6 \pm 0.6$ dioptres and did this not vary much for different samples. The maximum level encountered was of 3.25 dioptres. Mean values decreased in a monotonic fashion reaching about 0.1 dioptres at twelve months. Most of the reduction had taken place by the third post-term month and changes thereafter did not reach statistical significance. No six or twelve month olds showed 'significant' anisometropia. The maximum amount noted at one year was 0.50 dioptres.

c) Astigmatism

Astigmatism was common and predominantly ($\approx$ 80 - 90 %) of with-the-rule variety in all age groups examined. Against-the-rule astigmatism was very rare affecting only about three percent of astigmatic eyes. About 13 percent of newborn's eyes were not astigmatic. 'Significant' astigmatism (i.e. $\geq$ 1.00 D.) was noted in about 86 percent of newborns. The average cylinder power was $\approx 1.7 \pm 1.3$ dioptres. The highest level found was of 7.5 dioptres. A trend was noted for higher cylinder powers to be found as duration of cycloplegia increased. Cylinder power findings were significantly higher amongst females,

Asians (cf. Caucasians) and newborns without retinal haemorrhage. These results were not caused by differences in duration of cycloplegia between groups.

Mean levels of astigmatism decreased from 1.7 dioptres at birth to approximately 1.0 dioptre around three months. At six months levels had increased to newborn values but subsequently declined to around 0.8 dioptres by one year. Newborn levels were not significantly different from those at six months but were, in most cases significantly different from other age groups. Changes observed between six and twelve months were significant. 'Significant' astigmatism was noted in 64 percent of three month olds, 81 percent of six month olds and 50 percent of one year olds.

Twelve infants were refracted at birth, three and six months. Astigmatism only increased between birth and three months in two infants. In infants having more than two dioptres of astigmatism at birth cylinder power reduced by three months then increased slightly by six months. Varied patterns of development were observed in infants having less than two dioptres of neonatal astigmatism.

d) Accuracy of neonatal refraction

A separate study involving the repeat refraction of 35 newborns was conducted to investigate the accuracy of neonatal refraction. The results suggested greater repeatability for spherical rather than cylindrical power findings on the two refractions ($r \approx 0.94$ for S.E.R. cf. $r = 0.63$ for cylinder power determination). Some of the scatter in cylinder power results could have been explained by a systematic increase in astigmatism by the time of the second refraction (related to the duration of cycloplegia). A mean accuracy for isolated measurements of around $\pm$ 0.7 dioptres in determination of both spherical (S.E.R.) and cylindrical powers was found. Anisometropia found on initial refraction was not significantly correlated with the level encountered on the second refraction.

7.2.3 Possible influences on post-natal visual acuity development (Chapter 6 findings)

a) Neonatal data

Linear regression analyses were performed to investigate possible relationships between newborns' acuity and refractive error. Acuity *and* refractive data was available from 137 infants. No strong or significant correlations were found between neonatal acuity and either spherical equivalent refraction, optical defocus (relative to the stimulus screen - assuming relaxed accommodation) or astigmatism. A significant correlation was noted between "mean" binocular acuity and anisometropia ($r = 0.20$, $p < 0.05$).

Regression analyses indicated that post-natal age (log. hours) at the time of preferential looking testing had a significant effect on newborn binocular acuity. Acuity improved as post-natal age increased ($r = 0.23$ for vertical and $r = 0.22$ for mean binocular acuity, $p \leq 0.01$ for both). No significant effects of

head circumference or duration of labour were observed (the trends noted were for better acuity with larger head circumference and shorter labour).

In an attempt to elaborate possible causes for the association with post-natal age the strength of the relationship was investigated for various newborn subgroups. A simplified summary of these analyses is provided in Table 7.5. Correlation coefficients for the relationship with post-natal age were higher for males than females and for offspring of mothers given pethidine during labour. This was also the case for infants allocated to increased trauma groups on the basis of birth complications, low Apgar score at one minute after birth, retinal haemorrhage or being borne by primiparous mothers.

Mean binocular acuity findings were not significantly different in newborns demonstrating retinal haemorrhage and in those without haemorrhage. Differences between other increased and low birth trauma groups, between males and females, and between Asians and Caucasians were also not significant (independent t - tests, $p > 0.05$).

Acuity findings were slightly higher for newborns that were selected for alertness than in those that were not but differences between groups were not significant (independent t - tests, $p > 0.05$).

b) Follow-up data

i) Refractive error

Linear regression analyses were performed to investigate possible relationships between infants' acuity and refractive error. Acuity *and* refractive data was obtained from three to twelve month olds on 70 follow-up sessions. The data of the five month age group (five infants) was omitted from analysis and that of the three and four month groups and six and seven month groups combined to enlarge samples. The regression tests were applied to "three", "six" and "twelve" month data although the sample sizes were unfortunately relatively small (22, 27 and 16 infants respectively). The acuity values used in this analysis were vertical, "mean" and best acuity data obtained from the right eye, left eye and binocularly.

Summaries of correlation coefficients between monocular acuity and spherical refractive findings of the three, six and twelve month sample are provided in Tables 6.2 (page 305), 6.3 (page 306) and 6.4 (page 307) respectively. No significant correlations were found for three month olds, although in all cases the highest correlation coefficients were evident when acuity was compared with the minimum level of ametropia. In all cases slight trends were observed for poorer acuity with increasing hypermetropia.

In general trends noted in the six month sample were for *better* acuity to be associated with increased hypermetropia. No significant correlations were noted for the right eye - though the trend was for highest correlations with maximum ametropia. A significant relationship was observed between "mean" left eye acuity and minimum level of ametropia and between best left eye acuity and each refractive measure. The

highest correlation (0.55) was noted between best left eye acuity and left S.E.R.. In general poorest correlations were found between left eye acuity and maximum ametropia.

Only six sets of data were available from the right eye and nine from the left eye for the twelve month sample. Right eye data showed a slight trend for *better* acuity with increasing hypermetropia (and highest correlations with maximum ametropia) whereas left eye data showed the reverse. No significant correlations were noted for the right eye. A significant relationship was observed between left eye vertical grating acuity and "mean" left eye acuity and minimum level of ametropia. The highest correlation (0.69) was noted between "mean" left eye acuity and left minimum level of ametropia.

No significant relationship or consistent trends were noted between *anisometropia* and binocular acuity for any of the follow-up samples. A summary of correlation coefficients is given in Table 6.5 (page 311).

No significant relationship was noted between *astigmatism* and monocular acuity for any of the follow-up samples. Generally trends were observed for *better* acuity with increasing astigmatism (all three month and right eye six and twelve month data). Details of correlation coefficients are given in Table 6.6 (page 314).

ii) Retinal haemorrhage

Acuity development was not significantly different in 16 infants noted to have retinal haemorrhage at birth and in 16 age and sex matched controls that did not demonstrate neonatal retinal haemorrhage (independent t - test, $p > 0.05$). Development was also not significantly different among males and females.

iii) Order of testing

A tendency was noted in follow-up samples for monocular acuity to be poorer for the third monocular staircase estimate. This staircase number occurred after the switching of the eyepatch in order to test the second eye. Only one of 36 comparisons produced a significant difference between acuities based on order of testing.

7.3 Discussions

7.3.1 Pilot study findings

Our difficulties experienced in recording pattern VEPs are not shared by all previous investigators. Other workers have reported greater success in recording of pattern VEPs in infants (Sokol et al., 1983; Odom and Green, 1984b; Skarf and Panton, 1987). Mohn and van Hof-van Duin (1983b), considered that pattern VEPs provided little or no extra information about visual function in children that could be tested behaviourally and could be misleading e.g positive responses were obtained in one cortically blind child. Preferential looking methods and pattern VEPs were used to assess visual function in neurologically impaired paediatric patients between 10 weeks and 15 years of age. PL acuities were obtained in 70 percent of patients tested. Pattern VEPs could be recorded in six of seven patients.

Sokol and associates examined 172 paediatric patients (aged between 4 months and 10 years) using both transient pattern reversal VEPs (amplitude versus check size extrapolation technique) and either of two formal forced-choice preferential looking staircase procedures. Children younger than two years were more successful in completing monocular testing by VEP than by preferential looking. Criteria for success in binocular testing was the recording of data for at least three check sizes. Successful completion of monocular VEP testing was dependent on obtaining data for 15 minute checks from each eye. Monocular PL thresholds were obtained from only 23 percent (5/22) of patients younger than one year, whereas 77 percent of the same group (17 infants) provided useful VEP results. VEP testing took about 15 minutes (including application and removal of electrodes) whilst PL testing took 15 minutes for binocular and 20 to 30 minutes for monocular acuities. The success rate reported for monocular PL tests (≈ 60% for infants and young children up to five years) was, however, inferior to that found in comparable studies (e.g. 85 %; Mayer et al., 1982). The difference may be related to the use of operant testing methods by Mayer's group.

The sample of children examined by Sokol's group were heavily weighted towards individuals with strabismus (n=99) or abnormal refraction (n=19). The remaining patients consisted of 22 with structural anomalies (five with cataracts), six with congenital nystagmus and 26 without ocular pathology (presumably neurologically impaired). This range of diagnoses is quite different from that of patients within the clinical sample assessed in the present study, which was comprised almost exclusively of infants with structural ocular pathology - generally congenital cataract. Details of individual diagnoses are provided in Table A2.2 of Appendix 2C. Some of the reasons contributing to our failure could be that the sample was biased towards those with ocular pathologies resulting in poor visual acuity. It seems reasonable to presume that this (coupled in some cases with associated neurological impairment producing high background activity in the EEG) would cause more interference in electrophysiological testing than when using behavioural techniques. Sokol and co-workers (1983), do not give any indication of the comparative success of their methods according to clinical diagnosis.

A further major difference between the study of Sokol's group and the present investigation is the preparation time required for the application of electrodes. Only one channel recording was used by Sokol - requiring three electodes (one taped 1 to 2 centimetres anterior to the inion along the midline and two ear electrodes). The six channel hemianopic phase reversal electrode montage of Harding (1977) was used where possible in the present study. Most infants resisted application of electrodes, some of the older individuals were quite proficient at pulling electrodes off before they had all been applied. Taped electrodes often fell off because the infants skin became hot and sweaty through agitation. Typical preparation time in the present study exceeded the total test time reported for VEP testing by Sokol et al., (1983).

Skarf and Panton (1987), report a 67 percent success rate in obtaining binocular or monocular VEP acuity estimates from neurologically impaired and developmentally delayed infants of less than one year. Odom and Green (1984b), noted that acuity estimates based on VEP recording could be obtained from 75 percent of a clinical sample of infants and young children (of up to three years). No details were given of the proportion of under one year olds in the sample although a comment was made that the greatest difficulty was found in testing infants of less than four months who tended to fall asleep before reliable information was obtained.

Preferential looking tests were applied prior to electrophysiological assessment during the pilot study. Infant fatigue may therefore be expected to impair performance on VEP tests more than during preferential looking. This is not thought to have affected the findings of the pilot study to any great extent as equally poor performance on pattern VEP tests was noted in infants that were not assessed with preferential looking.

Poor electrophysiological recording technique is not thought to have influenced the results since satisfactory flash VEPs were recorded in almost 80 percent of test sessions.

7.3.2 Normative study findings I : Acuity data

a) Binocular and monocular acuity norms

The PL acuity norms derived in this study are comparable to those derived using acuity card procedures but are lower than levels indicated by extended laboratory methods. Binocular and monocular (mean) acuity levels from the present study are plotted along with the binocular acuity data of Allen, (1979) and monocular data of McDonald and co-workers (1986a) in Figure 1 of the scientific poster included in Appendix 7. The similarity of the monocular data is even more striking if "best" (Table 7.3) rather than "mean" data is selected for the comparison (not illustrated).

Comparison of the acuity data of the clinical patients examined during the pilot study with the normative data is possible by inspection of Figures 2.20, 2.21 and 7.1. Acuity findings amongst the clinical patients are in most cases clearly considerably lower than mean data of the normal sample.

Monocular acuity data was established for neonates in this study although the attrition rate in obtaining data was high. Neonatal monocular acuity does not appear to have been determined in previous studies. Mean values for neonatal binocular acuity found were of 0.64 cycles per degree this compares with values of 0.69 (Brown and Yamamoto, 1986) and 1.0 cycles per degree (Dobson et al., 1986b) using acuity cards. Average monocular acuity was of 0.55 cycles per degree. Binocular acuity was superior to monocular for newborns and all age groups apart from at twelve months. Differences between monocular and binocular acuity were significant for the newborn, three, four and seven month groups (paired sample t-tests).

Earlier workers, using laboratory PL techniques, have suggested that the performance of infants tested monocularly is one half (Atkinson et al., 1982) to three quarters (Dobson, 1983) of an octave below that on binocular tests. Birch (1985), however, found no *significant* difference between monocular and binocular findings until after six months using a formal method of constant stimuli. After this age binocular findings were superior. Comparison of the mean binocular and monocular data of McDonald and co-workers (1986a), provided in Table 7.6, suggests that the finding of poorer monocular data may be a feature of restricted testing procedures. It is possible that this difference between acuities obtained using extended and informal PL methods could relate to an artifact caused by failure to adapt to or recover from eyepatching in the time available for testing during the latter procedures. Some support for this opinion is given by the trend for poorer mean acuity in the uncovered eye after switching of the eyepatch in the present study (section 6.3.2.b, page 333).

A decline in mean binocular and monocular acuity is apparent between the seven month sample and one year olds. This finding is consistent with the results of previous preferential looking acuity studies, including some that have used formal, lengthy psychophysical methods. Awaya and co-workers' (1983) mean acuity data demonstrated a slight fall-off at about one year (relative to the value at ten months). A similar decline between nine and twelve months is noticed in the monocular acuity card data of McDonald and associates (1986a).

It has been predicted, from theoretical calculation, that the modulation transfer of horizontal gratings is slightly better at higher spatial frequencies than that of vertical gratings (Van Meeteran, 1974). No difference was noted between acuity development for horizontal and vertical gratings in this study. This finding is in accordance with the results of Gwiazda and associates (1980a) using a PL staircase method.

b) Interocular acuity differences

Interocular acuity differences noted in this study are comparable to those reported by Birch (1985) using a method of constant stimuli. This finding was encouraging as it was anticipated that the faster technique used for acuity determination could result in less accuracy and therefore increases in interocular differences. In both studies differences in acuities between eyes were greater in the youngest infants and reduced during the first year. Mean values derived during this study are given in Table 4.11 (page 205) and those of Birch are quoted on page 29. It has been suggested that acuity differences of or above one octave should be regarded with suspicion (Awaya et al., 1983; Yamamoto et al., 1984) and that repeat testing is advisable in such cases (Handbook, Teller acuity cards, 1986). Acuity differences were generally not in excess of that value in our data: excluding newborns 12.5 percent of infants had differences of above one octave but levels above 1.5 octaves were found in only 3.1 percent. A scatterplot of findings for individual infants is given in Figure 4.9 (page 203). These values compare with levels of 7.1% (≥ 1 octave) and 1.8% (≥ 1.5 octaves) in the data of Awaya and associates (1983). If one octave difference between eyes is taken as a cut off point for reassessment approximately one in ten infants of equivalent age would require further tests. This level may be rather high if preferential looking were to be used for mass screening and a 1.5 octave difference between eyes therefore seems a more reasonable cut-off point in the absence of abnormal findings on other screening tests. Interocular PL acuity differences of similar magnitude to those observed in normals are found in strabismic infants (Birch and Stager, 1985), which suggests a limitation to preferential looking for screening purposes.

In a preliminary study using the acuity card procedure, (Appendix 7, page 422), interocular acuity differences of up to 1.5 octaves were found in approximately one third of normals (aged 3 to 52 months), but each of five re-examined children (> 18 months) showed equal acuity on retesting. In clinical patients acuity differences were more common and tended to be of at least one octave.

c) Longitudinal data

Nine infants in the sample were assessed on at least five occasions. Acuity data of these infants can be found in Table 4.17 (page 212). Apparent set-backs in acuity development were noted in all but one infant. Only one infant demonstrated a reduction in estimated acuity prior to 13 weeks post-term. This finding is rather disconcerting and suggests a limitation of the testing procedure on first inspection. Very little data is available for comparison since most previous studies have presented group averages, which, of course, mask the findings of individual infants. Allen (1979), included in her data binocular acuity findings of five infants that were followed from two weeks to six months. Infants were examined at fortnightly or monthly intervals using a method of constant stimuli preferential looking technique (page 120). The individual data of these infants has been plotted in Figure 7.3. Mean data (Table 1.1, page 28) showed a reasonably steady improvement with age. It is clear from this that even extended laboratory methods do not show monotonic alteration in acuity with age for individual infants. This raises the question of whether these findings are genuine or an artifact relating to inaccuracies of the method.

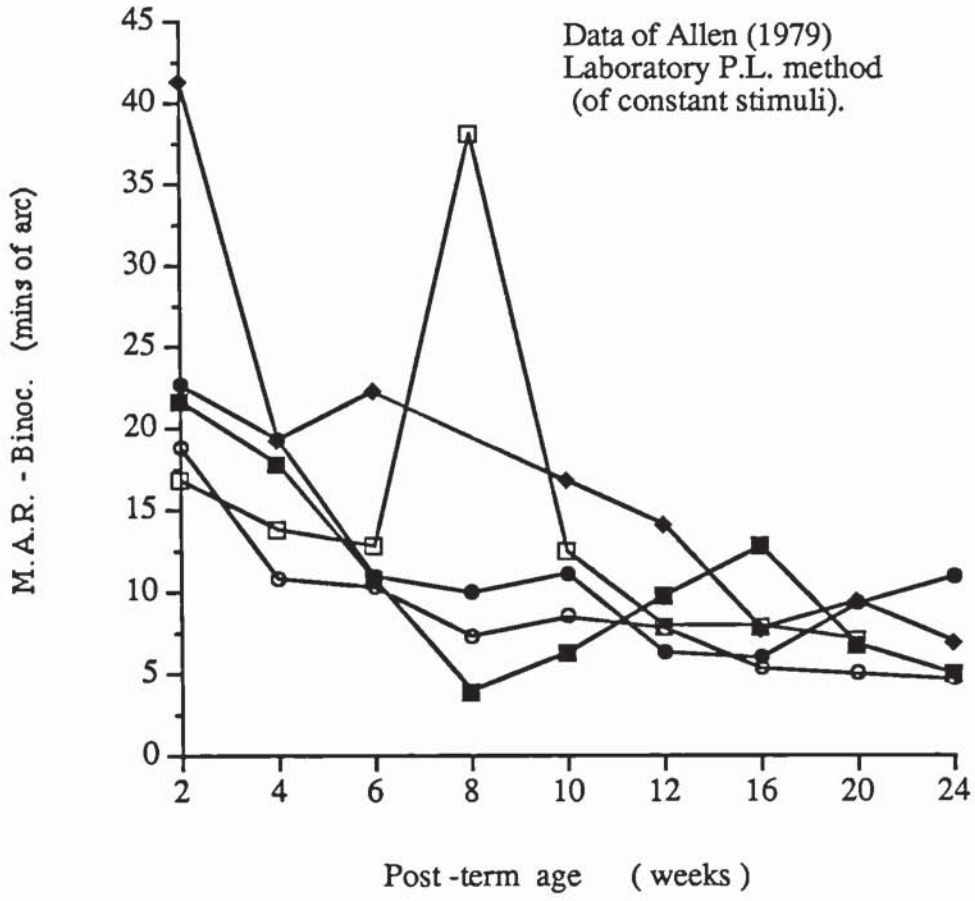


Figure 7.3 Preferential looking acuity development in five infants followed longitudinally from two weeks to six months (data of Allen, 1979). A formal laboratory method was used.

Atkinson (1984) refers to a non uniformity in acuity development observed by their group. The rate of improvement in mean PL acuity being greater between one and two months than later or earlier than this time. Some support for this discontinuity was mentioned from studies of Fiorentini (personal communication - Atkinson, 1984), who found a greater rate of change in ERG and VEP acuity estimates between two and four months than between four and six months. Discontinuities in development are suggestive of additional pathways or processes coming into play. Alterations occurring towards the end of the second post-term month could relate to the possible switching in visual responsiveness from subcortical to cortical control previously discussed (section 1.3.4 c, pages 63-67). It is possible that suspension of improvements in binocular acuity between four and six months could be related to the development and improvement in stereopsis which occur around this time (section 1.2.4d, page 37-41).

Shimojo and co-workers (1986), have suggested that the visual system may be incapable of interocular suppression prior to the development of stereopsis (page 36). If this is the case, it is tempting to speculate that some disturbance of visual function may be associated with the emergence of stereopsis. This could be reflected in poorer binocular acuity findings due, perhaps, to initial confusion in

processing of monocular images until the neural pathways responsible for stereopsis become established. The fact that workers, such as Allen, (1979), do not find discontinuities in their *mean* PL data could be explained by differences in the age of onset of stereopsis of individual infants masking the effect.

It is possible that discontinuities in development could be explained purely on the basis of experimental error in determination of acuity. In view of the formality of the method used in Allen's study this possibility seems unlikely.

d) Success rate

The success rate of the preferential looking test was determined separately for newborn infants and for monthly age groups between one and seven months and for the one year olds. Approximately 87 percent of newborns were testable. This value compares with approximately 80 percent of neonates examined with acuity card procedures in two studies (Yamamoto and Brown, 1985; Dobson et al., 1986b). The slightly higher overall success rate for newborns in the present study may relate to the selection procedure adopted for the second half of the sample. When no selection procedure was adopted 81 percent of infants were testable compared with 94 percent when neonates were selected for alertness (Table 4.21, page 216). Details of these studies and acuity card studies in older infants and young children are included in Table 7.6.

Success rate steadily increased with age between birth and seven months. One year old infants were more difficult to test than the six or seven month age groups. This general increase in testability with age has been noted by previous workers (Sokol et al., 1983; Awaya et al., 1983). Decline in testability occurring around the end of the first year has also been found (Awaya et al., 1983). Success rates for the acuity card procedure show a decline occurring around 18 to 24 months (Table 7.6). Difficulty in establishing diagnostic stripe widths (section 2.4.1b, page 120) has been reported at eighteen months (Dobson et al., 1985). The present author notes a similar fall off in testability in the second half of the first year when using the acuity card method (Figure 5 of scientific poster presented in Appendix 7).

The success rate of the Gwiazda staircase method (described in section 2.4.1; page 122) has been evaluated by Awaya and co-workers (1983). Normal infants between the ages of three months and two years were examined. Acuity was successfully measured on 64 percent of test sessions. The authors comment on a general trend for success rate to increase as a function of age (29 percent at three to four months, 50 percent at nine to ten months, 54 percent at eleven to twelve months and 56 percent at 17 to 18 months). Inspection of Figure 3 of the paper reveals that the test success rate increased until seven to eight months (≈ 80%) then dropped to 50 percent in the next age group, before showing a steady increase (apart from a slight dip around eighteen months) to two years (≈ 90%). These values are obviously much lower than those of the present study or various acuity card studies (Table 7.6). Reasons for failure were categorised into poor attention to the gratings (18%); rejection of the eyepatch (13%); and psychological aversion to the testing environment (6%). The first cause was encountered most in younger infants the

second produced more problems from 11 to 18 months and the third cause was noted most often in 21 to 22 month and 13 to 14 month olds.

Table 7.6 Summary statistics for acuity card studies of normal infants and young children (modified after Teller et al., 1986). Studies included are:

1 - Dobson et al. (1986b); 2 - Yamamoto and Brown (1985); 3 - McDonald et al. (1985); 4 - McDonald et al. (1986a); 5 - McDonald et al. (1986b); 6 - Mohn and van Hof-van Duin (1986).

Figure in brackets indicate sample sizes.

Age	Study	Percent testable		Mean acuity (C/deg.)		Standard deviation (Octaves)	
		Binoc.	Monoc.	Binoc.	Monoc.	Binoc.	Monoc.
Neonate	1 (63)	81		1.0		0.6	
(≤ 7 days)	2 (30)	80		0.7		0.5	
4 wks	3 (10)	80		1.1		1.1	
	4 (7)	86	86	0.8	0.6	0.7	0.7
	6 (7)	100		1.3		1.0	
8 wks	3 (9)	89		2.1		0.9	
	4 (6)	100	100	2.0	1.4	0.7	1.4
	6 (16)	94		1.4		0.7	
12 wks	6 (10)	100		4.1		0.6	
16 wks	3 (8)	100		3.7		0.7	
	4 (6)	100	100	4.5	2.3	0.5	0.7
	6 (7)	100		4.9		0.6	
20 wks	6 (9)	100		4.3		0.9	
6 mths	3 (8)	100		4.7		0.8	
	4 (6)	100	100	5.3	3.7	0.5	0.9
	6 (5)	100		7.8		0.5	
9 mths	4 (6)	100	100	5.0	4.1	1.0	0.9
	6 (5)	100		9.6		0.2	
12 mths	4 (6)	100	100	6.3	3.3	0.7	0.9
	6 (5)	100		10.2		0.5	
18 mths	5 (10)	90	90	9.8	7.3	0.4	0.6
	6 (4)	100		10.7		0.5	
24 mths	5 (12)	100	75	14.9	13.2	0.6	0.6
30 mths	5 (9)	100	100	23.4	18.4	0.3	0.5
36 mths	5 (9)	100	100	27.7	25.3	0.5	0.5

7.3.3 Normative study findings II : Refractive development

Refractive data was collected from newborns, infants between three and seven months and one year olds.

a) Spherical equivalent refraction (S.E.R.) findings

i) Neonatal data

The average neonatal S.E.R finding (2.75 ± 2.6 D.) and incidence of hypermetropia observed in the present study are compatible with values encountered in previous newborn samples. A summary of earlier studies in full-term neonates is provided in Table 7.7 (based on a review by Banks, 1980b). Some exasperation was experienced by the present author in checking the accuracy of figures quoted by Banks. In compiling this table information given by later reviewers has been assumed to be correct whenever limited information regarding technique has been supplied in the original paper. To add to the complication of providing accurate information in certain cases, e.g. Gernet (1964), values quoted in the text by the original author do not correspond to those computed from individual data plotted in figures. An average figure for newborn S.E.R. derived from the values in Table 7.7 (excluding the data obtained by extrapolation and that of Mohindra and Held, (1981), which includes infants of up to one month) is 2.4 ± 1.7 dioptres. The findings in the present study show slightly higher mean values and greater spread than average.

The trend for higher S.E.R. levels amongst males noted in the study is in accordance with the results of Luyckx (1966) and Goldschmidt (1969) but not of Blomdahl (1979). The standard deviation of the results provided by Blomdahl is rather low and this suggests a possible inaccuracy of the measurements in that investigation. Zonis and Miller (1974) and Chattergee and Mukherji (1979) both report higher incidence of myopia amongst females.

In the first week of life a significant trend for decrease in mean levels of hypermetropia with increase in postnatal age was observed in the experimental findings. It was thought that this might explain some of the spread in the mean values reported in the literature. Inspection of Table 7.7 does not reveal any support for this hypothesis. No obvious rank correlation appears to exist between mean levels of S.E.R. and the ages of infants examined. The author is aware of only two studies that have considered refractive changes during the initial days of life, both were cited by Goldschmidt (1969) and depended on ophthalmoscopy. Bjerrum (1886) examined infants from seven hours to 14 days old and noted that hyperopia was particularly pronounced in the youngest infants (< 5 days) but decreased in older infants. Schleich (1890), mentioned that no fluctuations in refraction were evident in the first 14 days of life. It could be argued that the failure to find any relationship with post-natal age in earlier studies was related to the use of a more powerful cycloplegic (generally atropine). However, in view of the limited accommodation of newborn infants Cyclopentolate hydrochloride would be expected to provide adequate depth of cycloplegia.

Table 7.7 Summary of studies of neonatal spherical refractions in fullterm infants.

Abbreviations: *Techniques* N = near retinoscopy; O = ophthalmoscopy; P = photorefraction; R = retinoscopy and V = visuscope. *Cycloplegics* A = atropine; C = cyclopentolate; H = homatropine; M = mydriaticum; T = Tropamide; V = visummidriaticum
* = one eye examined (otherwise both eyes or details not given).
M. = male; F = female; N.R. = not reported.

Investigator(s)		Technique (and cycloplegic)	Age Range Days	Number of infants	Spherical Equivalent Mean	S.D.	Ref. (DS) Percentage ≥ 0.0 D.
Data obtained directly :							
Herrnheiser	(1892)	O.	8 to 14	960	2.3	N.R.	99
Santonastaso	(1930)	R. (1% A.)	1 to 7	30	N.R.	N.R.	75
Franceschetti	(1935)	R.	3 to 6	100	2.0	N.R.	N.R.
Cook & Glasscock	(1951)	R. (1% A.)	N.R.	500	1.8	3.1	75
Molnar	(1961)	R. (A.)	N.R.	81	3.2	1.5	N.R.
Graham & Grey	(1963)	R. (0.05% H.)	1 to 7	98	2.4	2.3	94
Gernet	(1964)	R. (A.)	1 to 5	21 M.	3.0 (text)	(*fig 1.* 2.6 ± 1.8, 95%)	
				15 F.	2.6 (text)	(*fig 3.* 2.6 ± 0.9,100%)	
Gonzalez	(1965)	R. (A.)	N.R.	87	3.0	N.R.	85
Mehra et al.	(1965)	R. (1% A.)	0 to 1	100	N.R.	N.R.	89
Luyckx	(1966)	(1% C.)	4 to 7	52	2.4	N.R.	N.R.
				27 M.	2.6		
				25 F.	2.2		
Khukhrina	(1968)	(1% H.)	0 to 9	186	N.R.	N.R.	76
Goldschmidt	(1969)	R. (0.5% A.)	2 to 10	356	0.6	2.2	76
				186 M.	0.8	2.2	
				170 F.	0.5	2.2	
Guseva	(1969)	R. (? drug)	0 to 9	52	3.6	N.R.	N.R.
Mathew & Sawney	(1970)	R. (1% A.)	0	200	N.R.	N.R.	94
Patel et al.	(1970)	R. (1% A.)	0 to 1	250	2.3	1.2	88
Hosaka	(1971)	R. (1% A.)	0 to 1	280	2.2	1.8	95
Zonis & Miller	(1974)	R. (M.)	2 to 3	300	1.1	1.6	86
Blomdahl	(1979)	R. (1% C.)	1 to 4	28 *	3.6	0.9	100
				14 M. *	3.4	0.6	"
				14 F. *	3.9	1.1	"
Mohindra & Held	(1981)	N. (nil)	0 to 28	48	- 0.7	3.2	N.R.
Stampalija	(1981)	P. (0.5% V.)	0 to 1	154	N.R.	N.R.	79
Yankov	(1982)	R. (C.)	0 to 5	100 M.	2.7	1.0	N.R.
				100 F.	2.1	1.0	N.R.
Data obtained indirectly :							
Andree	(1964)	V. (A.)	≥ 6 mth		≈ 1.0	(by extrapolation)	
Grignolo & Rivara	(1968)	R. (0.5% T.)	1 to 19	10	≈1.4	(from best fit curve 0 to 1 yr).	

A tendency was noted in the present study for larger neonates to be more hypermetropic. S.E.R. findings were significantly correlated with head circumference data (although the relationship was weaker than that for post-natal age) but not with birth weight or length. Previous studies have investigated the relationship between physical size (mostly birth weight) and neonatal refraction. Mathew and Sawney (1970), commented that larger hypermetropic errors were associated with heavier full term infants but gave no supporting evidence for this statement. Patel and co-workers (1970), found no relation between newborn refractive condition and either birth weight, head or chest circumference. Zonis and Miller (1974), could find no difference in the distribution of refractive findings when the sample was subdivided into four on the basis of birth weight. Chattergee and Mukherji (1979), noted that fullterm infants with lower birth weights were more myopic than those with higher birth weights.

The newborn samples were divided into various subgroups in the present study in an attempt to elaborate possible causes for the relationships of S.E.R. with postnatal age and head circumference. It was thought that the relationship with post-natal age may be associated with recovery from birth trauma so several subgroups were selected to try to isolate from the remaining sample those infants likely to have suffered increased trauma. A summary of the comparative strengths of the relationships between S.E.R. and post-natal age and head circumference and of mean S.E.R. data for various newborn subgroups is given in Table 7.4. Infants in high trauma groups have been allocated to groups 4, 5, 6, and 7A. Mean S.E.R. values were higher in all of the high trauma groups and also amongst males, Caucasians and infants whose mothers received pethidine. No consistent results were found for the strengths of the relationship with post-natal age or head circumference amongst high and low-trauma groups.

Infants with definite indication of birth trauma i.e. complications or low Apgar score showed more pronounced relationships with age (as did males and Caucasians) but this was not the case for offspring of primiparous mothers or infants with retinal haemorrhage. The subdivision which produced the greatest disparity in the strength of this relationship was that between Asians and Caucasians. A weak correlation was noted for Asians and a much stronger effect noted for Caucasians. Male infants also demonstrated a much stronger relationship with postnatal age than females. No obvious pattern was noted for the relationship with head circumference although it was interesting to note that the subdivision which produced the greatest disparity in the strength of this relationship was that between male and female infants. A very weak correlation was noted for males and a much stronger effect noted for females.

A tentative explanation suggested for the relationship between S.E.R. and head circumference could be that newborns with larger heads are more likely to experience birth trauma and that the mechanism for increase in hyperopia is associated with transient cerebral hypoxia. As a group males are known to experience more traumatic births and the relationship with postnatal age is more marked for these infants. The lack of a significant relationship with head circumference in males could possibly occur because the average head size of male neonates is sufficient to surpass a threshold level at which head circumference begins to influence the incidence of birth trauma. Female newborns' head circumference is, as a group, significantly less than males, so it is feasible that a significant correlation with head

circumference could occur because increased trauma would tend to exclusively affect those females with large heads. Head trauma is obviously related to maternal internal pelvic dimensions as well as infant size. A summary of average internal measurements is provided in Table 7.8. The narrowest individual measurement is of 10 to 11 centimetres for the transverse dimension of the pelvic outlet. Average head circumferences of male and female newborns in this study were 34.6 and 33.8 cm. respectively. Assuming, for simplicity, a spherical head shape gives an average head diameter of 11 centimetres for males and of 10.8 centimetres for females. These figures give an impression of the increased likelihood of most males surpassing the head circumference at which head trauma or moulding takes place.

Table 7.8 Average internal measurements of female pelvis (After Adams, 1983).

	Anteroposterior	Right and left oblique diameters	Transverse
Brim	11 cm.	12 cm.	13 cm.
Cavity	12 cm.	12 cm.	12 cm.
Outlet	13 cm.	12 cm.	10-11 cm.

It is of interest that correlations of S.E.R. with postnatal age are more marked for infants whose mothers did not receive pethidine analgesia during labour. This findings is important as it means that the relationship with post-natal age is not simply caused by a wearing-off of the antimuscarinic enhancing effects of this drug. Pethidine appears to mask the decrease in hypermetropia observed with postnatal age. No comparable studies of the effects of pethidine on newborn refraction are known to the author. The finding of a more pronounced effect of post-natal age in Caucasians compared with Asians, may be related to the greater homogenity of the former than latter sample. More spread was noted in the mean findings of the Asian group.

The failure to find any simple correlate of neonatal refraction is presumably due to multifactorial influences affecting this parameter.

ii) Follow-up data

No significant change in mean S.E.R. level was noted between birth and three months although 75 percent of eyes' refractions were noted to alter in an emmetropic direction. Between three and six months a significant decrease in level of hypermetropia was noted (86 percent of eyes showed emmetropic shifts relative to their neonatal refractions). A trend was observed for further decrease in mean S.E.R. level by twelve months although group findings were not significantly different from those at six months.

Longitudinal data (12 infants), suggested that newborns with more than three dioptres of hypermetropia initially tended to show hyperopic shifts at three months then myopic shifts by six months. If more than three dioptres of hypermetropia was noted at birth decreases were observed by three months and by

six months. The sample was equally divided into infants showing both patterns of refractive development. The initial increase in hypermetropia in newborns having less than three dioptres at birth is compatible with the view that young infants are relatively insensitive to the effects of optical defocus due to their small eye size and low acuity giving them an increased depth of focus (Green et al., 1980).

The individual differences in refractive changes observed here could explain the lack of agreement within the literature on the pattern of refractive development after birth. As few early studies used statistical analyses to support their findings it is difficult to established whether trends reported reached acceptable significance levels. The data selected by Banks (1980b) is reproduced in Figure 7.4 and gives the impression of consistency in the direction of refractive change following birth. One study, (Grignolo and Rivara, 1968), compared refractive development in premature and full term infants during the first year. Corrected age (from conception) was used. Initial increases in hypermetropia were noted in both groups. The data were fitted by polynomial regression equations. Supplementary tests included measurement of axial length. Increases in this parameter were noted in both groups particularly during the first three months. Refractive findings were the same in each group after four months.

Molnar (1970), however, considers that hypermetropia begins to reduce immediately after birth. Bias in sampling was avoided in this study, by examination of individuals within a closed community. Refractions were performed on 81 newborns, 426 babies, 48 children under two years and the total population of a German village of 2084 inhabitants. The alterations with age were similar but less marked than found in the present study. Levels of hypermetropia encountered were of 3.2 ± 1.5 dioptres at birth, 3.0 ± 1.86 dioptres in the first month, 2.8 ± 1.9 dioptres at six months and 2.65 ± 1.5 dioptres at one year. The subsequent average yearly decrease was of about 0.18 dioptres during the first decade.

The refractive data of Mohindra and Held (1981), obtained using near retinoscopy suggest a shift from low myopia to low hypermetropia in the initial months of life. Kohl and co-workers in a recent study (1986) were unable to find significant alteration in spherical equivalent refractive error between two and twelve months. Near retinoscopy was used in the study and refractive data allocated to two-monthly age groups. Mean refractive findings of adjacent groups never differed by more than 0.5 dioptres. Trends shown were a decrease (in hypermetropia) between two and four months followed by increases to a maximum (1.00 D.) at eight months followed by a gradual decline (0.625) at one year. Average findings were the same at six and twelve months. An opposite trend for decrease in hypermetropia between four and seven months was found in the present study (Table 5.7, page 256). Mean data in Kohl's study was lower than that found in the present study, particularly for the youngest infants. This is not too surprising given that the technique used does not depend on cycloplegia.

The proportion of infants demonstrating emmetropic refractions increased steadily with age in this study, largely as a result of a decline in the numbers with hypermetropic refractions. A similar age related increase in the numbers of emmetropic infants was observed by Mohindra and Held (1981), although this was associated with reduction in the incidence of myopia. The incidence of emmetropia (0 ± 0.99 D.) at

around one year are similar in the two studies (≈ 60 %). As the reliability of Mohindra's near retinoscopy technique has been questioned (Kohl et al., 1987), these differences could simply relate to the method of refraction.

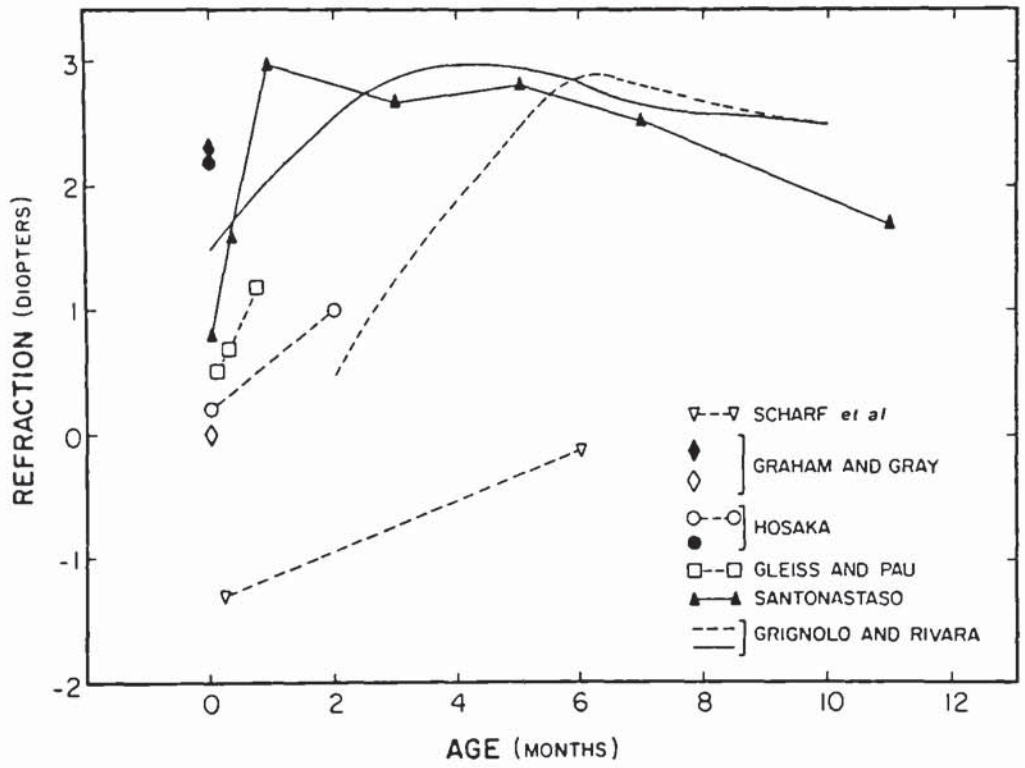


Figure 7.4 Summary of refractive development from birth to one year in various studies reported in the literature (after Banks, 1980b). Data is based on retinoscopic examination of full-term (solid symbols) and premature (open symbols) infants.

Dates of studies: Scharf et al., (1975); Graham and Gray, (1963); Hosaka, (1971); Gleiss and Pau, (1952); Santonastaso, (1930) and Grignolo and Rivara, (1968).

b) Anisometropia

At birth 'significant' anisometropia was found in 21.5 percent of infants. This value is similar to the incidence of 17.4 percent reported by Zonis and Miller (1974). Neonatal anisometropia of above two dioptres was rare and levels above 3.25 dioptres were not found in either study. The mean value was of 0.6 dioptres at birth and levels subsequently showed a monotonic decline, most of the alteration occurring in the first three months. Significant anisometropia was not found in any infants older than three months. This compares with a incidence of 1.3 percent found in a large sample of six to nine month olds screened using photorefraction (Atkinson et al., 1984).

c) Astigmatism

This study revealed a rather erratic series of changes in the astigmatic component of the refraction. 'Significant' astigmatism was found in about 86 percent of newborns. Comparison of this figure with a range of values found in the literature (Table 7.9), suggests that this level is considerably higher than average. The criteria for grading of astigmatism was not specified in many of the studies, so it possible that some of the disparity could be caused by higher threshold levels in these investigations. Astigmatism tended to decrease between birth and three months, increased significantly from three to six months and decreased significantly from six to twelve months.

Mohindra and Held (1981), found that significant astigmatism increased in incidence from the first month of life, reaching a peak of about 60 % for infants between 17 and 32 weeks before demonstrating a steady decline. The findings are roughly comparable with those of this study, although the data did not include a group of newborns so there is no comparable data for the changes occurring between birth and three months. Atkinson and co-workers (1979), found monotonic declines in the levels of astigmatism of all but one of a sample of 20 infants in whom astigmatism was first noted at one, three or six months.

Astigmatism was predominantly of with the rule variety throughout the first year in this sample. Large variations in the incidence of particular types of infantile astigmatism in different populations have been reported previously (Atkinson and Braddick, 1983a, Dobson et al., 1984). One recent study suggested that a preponderance of against the rule astigmatism may be expected at two to three years because early astigmatism of with the rule variety, disappears more readily (Atkinson et al., 1987). This suggestion does not correlate with the observations of Gwiazda and co-workers (1984), who noted that the incidence of against the rule astigmatism declined with age. Whether these disparities relate simply to population differences or are affected by refractive technique is uncertain.

Table 7.9 Summary of studies of infant astigmatism.

Abbreviations: *Techniques* N = near retinoscopy; P = photorefraction; and R = retinoscopy. *Cycloplegics* A = atropine; C = cyclopentolate; H = homatropine; M = mydriaticum; V = visummidriaticum.
N.R. = not reported.

Investigator(s)		Technique (and cycloplegic)	Age Range Days	Number of infants	Incidence of astigmatism
Santonastaso	(1930)	R. (1% A.)	1 to 7	30	47% (1 to 2 dioptres)
Cook & Glasscock	(1951)	R. (1% A.)	N.R.	500	38.4% astigmatic
Gonzalez	(1965)	R. (A.)	N.R.	87	73.5% astigmatic
Mehra et al.	(1965)	R. (1% A.)	0 to 1	100	10%<1D. 12% > 2D.
Khukhrina	(1968)	(1% H.)	0 to 9	186	11.5% astigmatic
Mathew & Sawney	(1970)	R. (1% A.)	0	200	30% >1D.
Patel et al.	(1970)	R. (1% A.)	0 to 1	250	20% astigmatic
Zonis & Miller	(1974)	R. (M.)	2 to 3	300	14.6% astigmatic
Howland et al.	(1978)	P. (nil)	1 to 9	15	27% (1 to 2 dioptres)
Blomdahl	(1979)	R. (1% C.)	1 to 4	28	42.9% astigmatic
Chattergee and Mukherji	(1979)	R. (0.5% A.)	> 0	250	18.6% astigmatic
Mohindra & Held	(1981)	N. (nil)	0 to 28	48	≈ 30% ≥ 1D.
Stampalija	(1981)	P. (0.5% V.)	0 to 1	154	3.9% astigmatic

d) Accuracy of neonatal refraction

A mean accuracy of ± 0.7 dioptres in determination of both neonatal spherical equivalent refraction and cylindrical power was found in this study. The author is unaware of any comparable studies in the literature. Moore, (1985), has commented on the need for such studies. The correlation between initial and repeated refractive findings was much better for S.E.R. than for cylindrical power data. This finding could be explained if it is assumed that transient fluctuations in globe or corneal shape may occur in newborns. Alterations in corneal toricity of this type do not affect S.E.R. power because flattening of one corneal meridian compensates for steepening of an orthogonal meridian. In adults lifting of the eyelids causes alterations in corneal toricity (Wilson et al., 1982). The newborn eye is likely to be more susceptible to the effects of changes in mechanical pressure of the lids (or extraocular muscles) because of its thinner, more flexible sclera. Unfortunately details regarding whether or not eyelids were held during retinoscopy were not kept in the present study.

The findings may explain some of the variation in the literature and suggest that caution is required in the interpretation of astigmatic findings in young infants.

7.3.4 Normative study findings III : Influences on acuity development

a) Refractive error

Combined acuity and refractive data from 137 newborn and 70 follow-up examinations were evaluated for correlations between these variables. Despite high levels of hypermetropia (≤ 9.75 D.S.) and astigmatism (≤ 7.5 D.C.) encountered in the newborn sample only anisometropia was found to be significantly correlated with acuity findings. The relationship found was for poorer "mean" binocular acuity with increases in anisometropia ($r = 0.20$, $p < 0.05$). No equivalent studies are known to the author.

No consistent trends or correlations were found between monocular acuity data and spherical equivalent refraction or astigmatism for three, six or twelve month olds. Similarly no significant relationships between anisometropia and binocular acuity were observed for follow-up samples. Kohl and co-workers (1986) were also unable to find significant correlations between acuity and spherical equivalent refraction data in two to twelve month olds. The acuity card method and near retinoscopy were used in their study.

Laboratory studies have failed to reach consensus on the sensitivity to optical defocus of visual acuity during early infancy. Powers and Dobson (1982) studied the effects of induced optical blur on the binocular PL acuity of six week olds and adults. Acuity was degraded by less than half an octave in infants using six dioptre lenses. This value compared with more than an octave decline in adult acuity. Boltz and co-workers (1983) found that one to two dioptres of induced optical blur were sufficient to significantly decrease monocular PL acuities of many three to seven month olds. A major difference between these studies is the age range of infants examined. Theoretical arguments predict that young human infants should have larger depths of focus than adults (Green et al., 1980) due to their smaller eye size and lower acuity. Acuity improves and eye size increases rapidly during the first six months of life. The visual system at six months is much more adult like and liable to the effects of optical defocus than at six weeks. Grating acuity is, however, much less sensitive to the effects of dioptric blur than Snellen acuity in adult subjects (Thorn and Schwartz, 1986). The failure to find correlations between infant ametropia and acuity is therefore not surprising in view of the use of grating stimuli in most studies.

Gwiazda and co-workers (1985) were unable to demonstrate significant difference in acuity development of astigmatic and non-astigmatic infants. Recent research has shown that vernier acuity (the inverse of the smallest detectable misalignment of edges) can provide robust measures of meridional differences in visual sensitivity (Bauer et al., 1987). It is likely that this measure will be more useful than grating acuity in determining the effects of early astigmatism on visual development. Vernier acuity development has been studied in infancy and is initially poorer than grating acuity but subsequently develops at a faster rate (Shimojo et al., 1984; Manny and Klein, 1985; Shimojo and Held, 1987). To date, studies of vernier acuity have been restricted to the laboratory environment and formal testing procedures.

b) Retinal haemorrhage

The presence of neonatal retinal haemorrhage did not influence acuity findings at birth or impair acuity development. These results are not too surprising since no cases of macula haemorrhage were observed in the sample and it is probable that only this more severe form of haemorrhage would be capable of interfering with visual function sufficiently to impair performance on acuity tests. No other studies are available for comparison.

c) Other factors

Neonatal binocular acuity improved as post-natal age increased. This relationship was more pronounced for all infants allocated to increased trauma groups (as shown in Table 7.5) and additionally for males, Caucasians and infants whose mothers were given pethidine during labour. The effect is likely to relate to recovery from birth trauma or in the case of the latter group increasing visual attention with recovery from the effects of the pethidine. Decreases of visual attention in neonates (aged 2 to 4 days) associated with maternal medication has been reported previously (Stechler, 1964) but no attempts were made to measure acuity in that study.

No significant relationship was found between neonatal acuity and gestational age. Brown and Yamamoto (1986), found a significant correlation between gestational age and acuity ($r = 0.53$, $p < 0.001$) but their study involved both fullterm and preterm newborns. Grating acuity improved at a rate of 0.46 octaves per month between 34 and 44 weeks of gestation. Gestational age varied from 36 to 42 weeks in the present study but the majority of infants were of between 38 and 41 weeks gestation.

A tendency was noted for poorer acuity to be found on testing an eye immediately following removal of an eyepatch. This finding suggests that some time for recovery should be allowed between tests or if possible more than one test should be performed on each eye to provide confirmation of initial results. Use of an additional grating orientation, as in the present study, may help to maintain interest in the test. No equivalent studies are available for comparison.

7.4 Conclusions

i) Pilot study:

Preferential looking (PL) acuity methods were more successful than *transient* pattern VEP techniques in quantifying visual function in clinical samples having a high proportion of infants with ocular and/or neurological abnormalities.

ii) Evaluation of a clinically appropriate PL acuity method in normals:

High success rates were generally obtained although testability varied with age during the first year of life. Below two months monocular acuities were difficult to secure; infants were most testable around six months and became less so at one year.

The acuity norms produced were similar to published data using the acuity card procedure and slightly lower than, but comparable with acuity data derived using extended PL methods.

Average acuity findings for normals were clearly higher than for most clinical patients with ocular and/or neurological abnormalities assessed (in the pilot study) using a comparable technique.

Average acuity findings for vertical and horizontal grating were not significantly different during the first year.

Interocular acuity differences were very common in normal infants but levels tended to decrease during the first year of life. Differences of above one octave were observed in 12.5 percent of infants (excluding newborns) that completed testing. Only 3.5 percent demonstrated differences above 1.5 octaves.

Average binocular acuity findings were higher than monocular during the first seven months of life (differences between means were significant for most age groups).

iii) Analysis of refractive development in normal infants:

Most newborns (80%) were hyperopic and showed significant astigmatism (86%). Significant anisometropia was comparatively rare (22%) and did not exceed 3.25 dioptres in the sample examined.

A repeat refraction study suggested difficulties in obtaining stable measurements of astigmatism (or anisometropia) in newborns. Acceptable accuracy ($r \geq 0.94$) was obtained in determining the spherical equivalent refraction.

Decreases in levels of hyperopia over the first week of life (which reached statistical significance) were suggestive of recovery from minor birth trauma. A tendency for greater hyperopia in infants with larger heads was thought to be linked to the same effect.

No significant alteration in spherical equivalent refraction was observed between birth and three months, a significant reduction in hyperopia was evident by six months and this trend continued until one year.

The proportions of eyes showing emmetropic shifts relative to their newborn S.E.R. findings were 75 percent at three months and 86 percent at six months and at twelve months.

Observations on the astigmatic component of the refractive error revealed a rather erratic series of changes. Astigmatism tended to decrease between birth and three months, increased significantly from three to six months and decreased significantly from six to twelve months.

A constant decrease in the degree of anisometropia was evident throughout the first year. Most of the change occurs within the first three months.

iv) Studies of possible influences on postnatal acuity development:

A significant relationship was found between newborn binocular acuity and anisometropia but not with other refractive findings. No strong or consistent correlations between grating acuity and refractive findings were evident for three, six or twelve month olds.

Grating acuity levels at birth or at follow-up examination were not affected by the finding of neonatal retinal haemorrhages.

Improvements in acuity over the first week of life were suggestive of recovery from minor birth trauma.

A tendency was noted for poorer acuity to be found on testing an eye immediately following removal of an occluder.

7.5 Proposals for further work

Investigation of acuity development in infants with more subtle visual impairment than the clinical patients examined in the pilot study would be of benefit in evaluating the sensitivity of the preferential looking technique. A suitable population would be a sample of early squinters. Particular attention should be focussed on the magnitude and stability of interocular acuity differences since this information would be helpful in establishing whether a one octave cut-off is appropriate (or too low) for referral or repeat testing in preferential looking screening of normal infants.

A longitudinal study of acuity development in normal infants bracketing the period during which stereopsis develops (eight to twenty weeks) would be of interest, particularly if combined with testing of stereopsis. This may help to determine whether set-backs in acuity development in individual infants are related to the onset of stereopsis.

A repeat refraction study suggested difficulties in obtaining stable measurements of astigmatism in newborns. Repetition of the study with the addition of photokeratometric measurements, if feasible, and observations on the effect of lid retraction on astigmatism may explain the reasons for variability.

Decreases in mean levels of hypermetropia and improvements in acuity observed over the first week of life in the present study were thought to be related to recovery from birth trauma. Examination of a sample of infants born via Caesarian section may help to elucidate the mechanism for these changes.

APPENDICES

Appendices 1 to 7 relate to the relevant Chapters in the text.

Appendix 1 Details of methods used in infant binocularity studies

VEP study of interocular suppression, Odom and Harter (1983):

A dichoptic masking paradigm was used; a stimulus was continuously presented to one eye (darkness/diffuse green light/20' or 80' green dot pattern) while a second stimulus (diffuse red light or a flashed on 20' or 80' red dot pattern) was intermittently presented to the other. Independent stimulation of the two eyes was achieved by an anaglyphic method (two projectors one equipped with a red the other with a green filter and the subject wearing goggles having one red and one green filter). Reduction in the amplitude of the VEP elicited by the intermittently presented stimulus was taken as evidence of interocular suppression.

Behavioural study of stereopsis, Fox and co-workers (1980):

A moving anaglyphic form (composed of red-green elements) generated on a colour television monitor was presented on a rear-projection screen and viewed through spectacles equipped with one red and one green filter. The presence of visual tracking of this stereoscopic form was determined using a forced-choice decision by the observer.

VEP studies of stereopsis (e.g. Lehmann et al., 1978; Julesz et al., 1980):

a) A *correlogram* stimulus consisting of a dynamic random-dot pattern (i.e. a dot pattern randomly generated at 50 Hz.) is presented to one eye with an identical or inverse pattern alternatingly presented to the other eye. Subjects with normal binocular vision perceive alternating binocular rivalry and fusion.
b) A *stereogram* stimulus periodically alternates between a flat random-dot pattern and one in which there is an impression of depth (e.g. the central portion may appear displaced towards the observer).
VEPs time locked to the alternations can only arise from interaction of the two eyes' signals at a binocular neural site.

Interocular transfer studies:

a) Interocular transfer of the tilt after-effect. (IOT) - Banks et al., (1975). An adapting grating (7.5 c/d) tilted 10 ° clockwise from vertical was presented for three minutes to one eye then the subjects adjusted a lower-contrast grating of the same SF to the apparent vertical using both adapted and unadapted eyes (tested in succession). The procedure was then repeated with the other eye adapted.
b) The transferred tilt after-effect (TTA) - Hohmann and Creutzfeldt (1975). Children adapted monocularly for 2.5 minutes to a grating orientated 10° anticlockwise to vertical. Following adaptation they judged with their other eye when a bar of the same SF as the grating appeared vertical. The test was repeated for the other eye. The normal children in the sample judged the bar to be vertical when 4 to 5° clockwise.

Appendix 2

2A. Details of preliminary adult VEP acuity studies

i) Direct location of threshold

Transient pattern appearance VEPs were recorded in two co-operative adult emmetropic subjects having monocular Snellen acuities of 6/6 or better. Stimulation was provided via an optical projection system, having a circular display of 30° diameter at 45 centimetres viewing distance. Pattern presentation was for 150 msec within each 550 msec recording epoch. An attempt was made to determine the finest high contrast square-wave grating stimulus capable of producing clearly recognisable or repeatable VEPs. Gratings of 5, 10 and 15 minutes of arc were employed. Bipolar recording utilising electrode positions O_1 - C_3 and O_2 - C_4 (F_z earthed) of the International 10-20 system (Jasper, 1958) was used and 50 responses averaged using a Hewlett Packard PDP8 averaging computer. The input signal was filtered using 1 to 30 Hz bandpass filters.

ii) EP amplitude versus spatial frequency functions

Steady state EPs were recorded to the 4 Hz reversal of a high contrast pattern generated on a television monitor. The stimulus display subtended 3.5 ° x 2.5° at the 4 m. viewing distance which was needed to produce the high spatial frequencies required. The three subjects were either emmetropic or wearing full optical correction. Bipolar recording utilising electrode positions O_1 - C_3 and O_2 - C_4 (F_z earthed) of the International 10-20 system (Jasper, 1958) was used and 64 responses averaged. A narrow bandpass filter (Q = 5) tuned to a central frequency of 8 Hz allowed analysis of the fundamantal frequency component of the pattern reversal EP. Two responses were recorded for each of five check sizes (ranging from 1.97 to 31.5 cycles per degree in octave steps). A permanent record was provided by an XY plotter and response amplitudes were measured by hand. The mean EP amplitude was plotted versus stimulus spatial frequency.

iii) Electrophysiological determination of contrast sensitivity

Steady state EPs were recorded to checkerboard stimuli reversing at frequencies of 4 or 7.5 Hz (i.e. 8 or 15 pattern reversals per second). An I.O.L. grating generator was used to produce the checks, because this allowed almost continuous contrast variation. Pattern reversal was controlled by the square wave output of a signal generator. A viewing distance of 175 cm providing a stimulus field subtending 8° x 6° was selected because high spatial frequency patterns were not needed. Evoked potentials were recorded from either electrode positions O_1 - C_3 or O_2 - C_4 (C_z earthed) during binocular and monocular viewing. Initial results using a bandpass filter with a Q factor of 5 produced unsatisfactory controls so a Q factor of 50 was subsequently used. The filter was tuned to a central frequency of 8 or 15 Hz depending on the reversal rate of the stimulus. Either 64 or 128 responses were averaged. The time window was

adjusted to the minimum value which allowed measurement of EP amplitude (just less than a whole cycle) to reduce recording time.

Checks subtending 7.5 minutes of arc (fundamental spatial frequency of 5.7 c/d) and 15 minutes of arc were used. Pattern contrast was adjusted from below 1% to 90% in nine (x 2) steps. Up to four stimulus runs were conducted per spatial frequency during a test session. One highly motivated adult emmetropic subject (the author), having monocular acuities of $^{6}/_{5}$ in each eye was used throughout several recording sessions. Stimulus trials and control trials (monitor covered) were interspersed in ABBA sequence throughout testing. A permanent record was provided by an XY plotter and response amplitudes were measured by hand. The average amplitude on control trials was computed and average amplitudes were calculated for multiple trials conducted at particular contrast levels within recording sessions. EP amplitude was plotted versus log contrast. In an additional experiment the influence of dioptric blur (on checks of 45 % contrast) was investigated by successively adding lenses (in +0.50 DS steps) to the +0.50 DS "working distance" lens worn in a trial frame.

2B. Details of the arresting of OKN equipment and procedure

i) Apparatus

A saw tooth (OKN) stimulus (labelled C in Figure A2.1), is projected onto an opal screen after reflection in a small mirror (M). This is mounted on, and rotated about its vertical axis by a motor which is driven by the output of a triangular wave generator. Rotation of the mirror causes the projected pattern to be swept continually, first in one direction then in the reverse direction across the screen. Approximately eight pairs of teeth are in view at any time (Figure A2.2). A second projector, is equipped with a magazine (T) holding a series of arresting gratings arranged in $\sqrt{2}$ steps of spatial frequency (Table A2.1). The central band of the projected grating subtends five degrees at 50 cm. A test grating is projected in sharp focus onto the opal screen whenever a diffusing shutter (S), a piece of clear dimpled perspex mounted on a motor, is rotated from its resting position. A neutral density filter attached to the diffuser ensures that grating presentation is achieved without alteration in screen luminance. The shutter is positioned through the nodal point of the projection system P2 so that as it is deflected the whole pattern appears simultaneously.

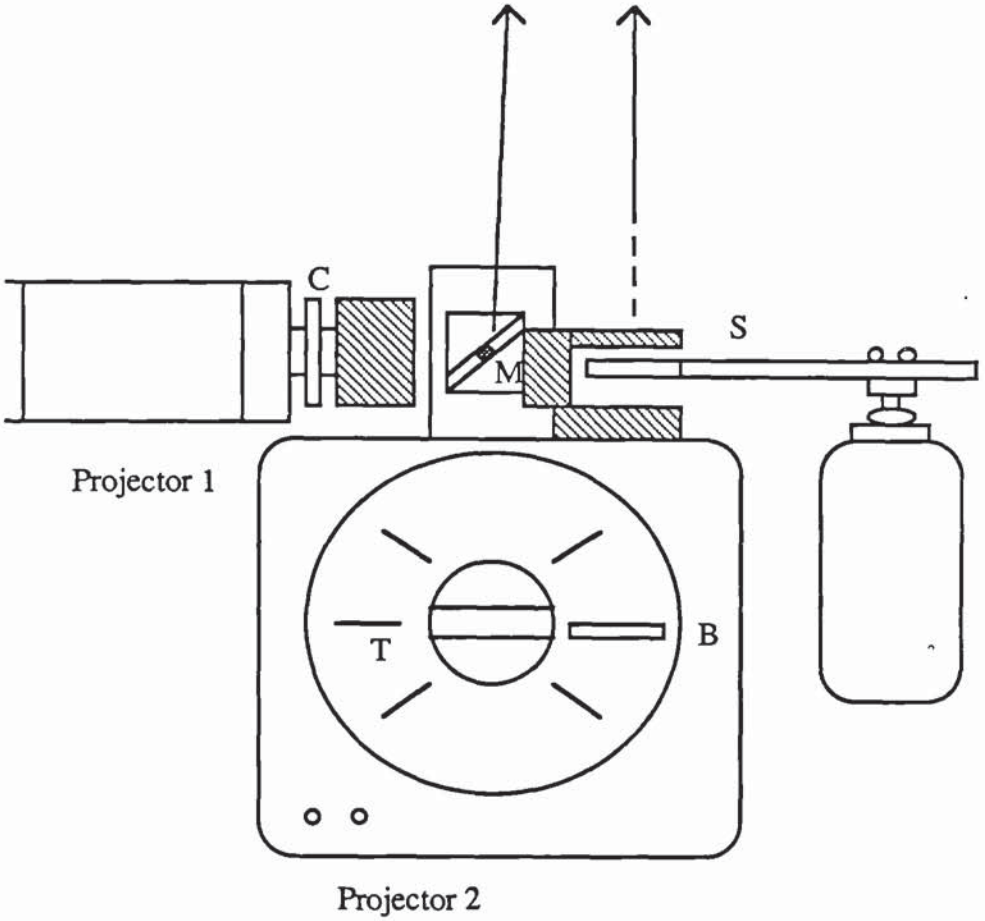


Figure A2.1 Plan of OKN apparatus constructed in the present study (opal display screen is not shown).
B = test grating stimulus slide
C = saw-tooth (O.K.N.) stimulus slide
M = oscillating mirror
S = diffusing shutter
T = magazine holding test grating stimulus slides.

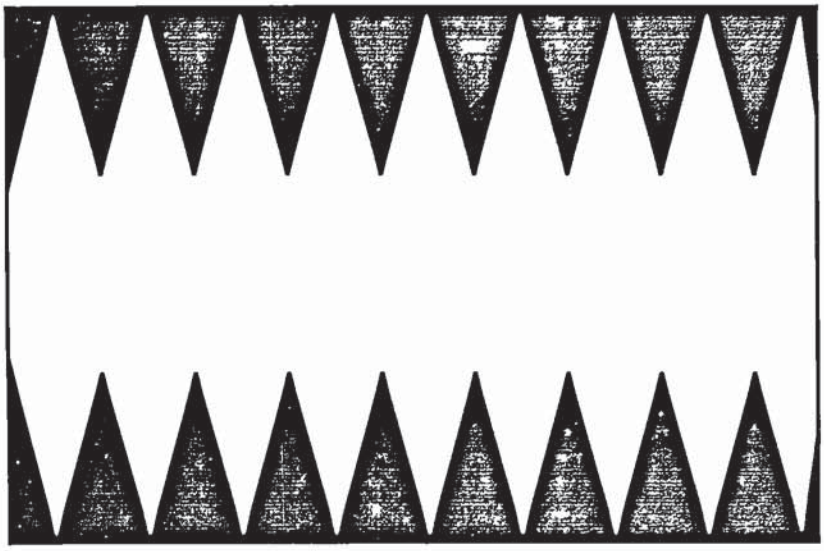


Figure A2.2 Saw-tooth O.K.N. stimulus

Table A2.1 Spatial frequencies of proposed OKN test gratings.

Slide Number	Spatial Frequency Cycles/degree	Snellen Equivalent
1	30.0	$^{6}/_{6}$
2	21.2	$^{6}/_{8.5}$
3	15.0	$^{6}/_{12}$
4	10.6	$^{6}/_{17}$
5	7.5	$^{6}/_{24}$
6	5.3	$^{6}/_{34}$
7	3.75	$^{6}/_{48}$
8	2.65	$^{6}/_{68}$
9	1.88	$^{6}/_{98}$
10	1.33	$^{6}/_{135}$

ii) Automated sequence

At various points in the procedure, slide changes are initiated by trigger pulses to projector 2. The position of a switch on the front panel of the main box of electronics determines when trigger signals occur. In position 1 there is a slide change once per cycle corresponding to the trough of the sweep waveform. In this case the same arresting grating is presented twice per cycle. In slide position 2, there are two pulses and hence slide changes per cycle, one at the peak and the other at the trough of the sweep waveform. Two different gratings are therefore presented during each cycle.

An understanding of the automated control sequence is gained by studying the timing diagram (Figure A2.3). This shows the synchronised square-wave and triangular wave outputs of the generator chip (Figures A2.3a and b respectively). The triangular wave controls rotation of the mirror causing a change in the direction of movement of the OKN stimulus at the end of each half cycle, e.g at points A and B. Additionally the rectified signal (c) is supplied to a comparator, the output of which (d) initiates a shutter delay pulse (h) which subsequently operates the shutter pulse (i). The output of the comparator is also responsible for triggering a slide change (f) twice per cycle, providing that the front panel switch is in position 2. When the switch is in position 1, the positive-going edge of the clamped square-wave output (e) is used to trigger a slide change (g) once per cycle. Figures A2.4a and b represent simplified versions of the automated sequence. The frequency of the sweep waveforms and the duration of the shutter delay pulse can be altered independently, using front panel controls. The preset values could be used for serial measurements of visual acuity if advantageous. In the fixed mode the period of each cycle is 13 seconds, with a stimulus delay of 2.5 seconds. This setting gives an observed angular velocity of the OKN stimulus of 25 degrees per second for a subject viewing at 25 cm. The arresting stimulus is presented for approximately one second. Ten cycles would be required to present each spatial frequency in the series twice, giving a test duration of 130 seconds in the preset mode.

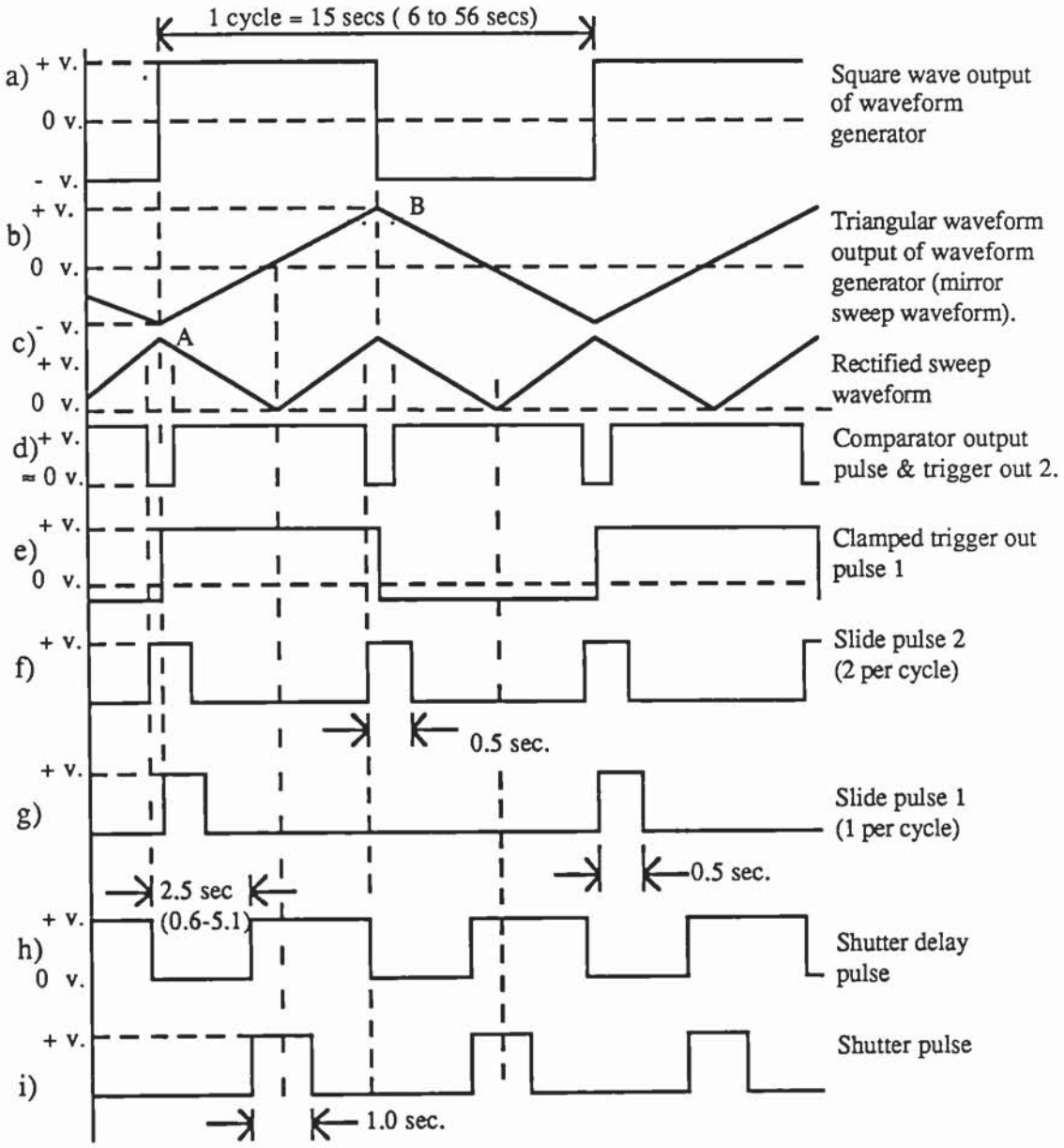
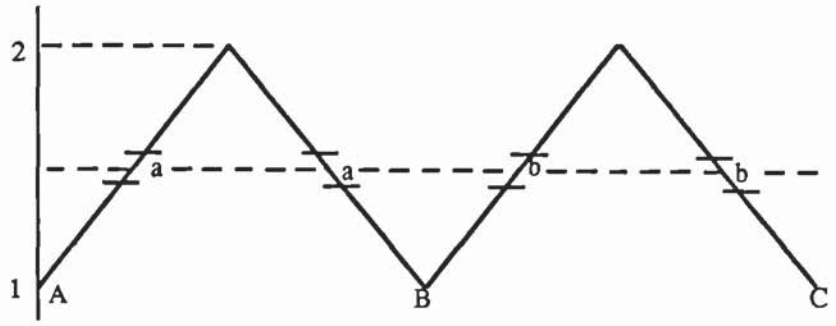
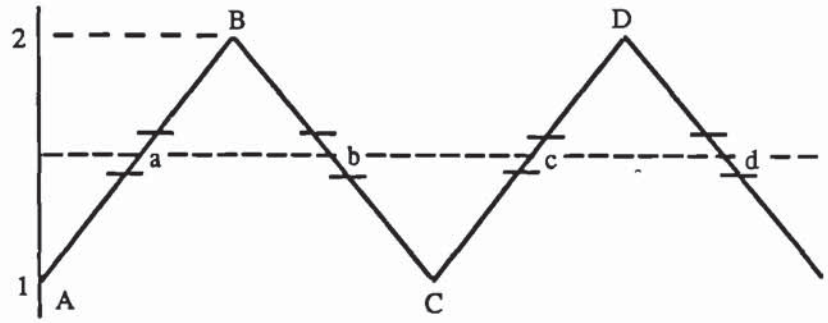


Figure A2.3 OKN stimulator timing diagram - showing synchronization with the main sweep waveform. Fixed values are given and range of values in brackets.

a) Slide position 1.



b) Slide position 2.



KEY

1 and 2 = extremes of mirror rotation
A = First slide change
B = Second slide change
C = Third slide change
D = Fourth slide change
a = Presentation of first slide (shutter open)
b = Presentation of second slide
c = Presentation of third slide
d = presentation of fourth slide

Figure A2.4 Simplified versions of automated sequence relating slide changes and test grating appearances to the triangular waveform controlling the OKN stimulus.

2C Clinical diagnoses of patients in pilot study

Table A2.2 Individual diagnoses of the infant patients in the pilot study.

Initials	Diagnosis
MA	Unilateral (R.) congenital cataract (operated).
M Ay	Downs; bilateral congenital cataract (operated), alternating convergent squint.
AB	Bilateral congenital cataract (unoperated).
KB	Rubella; bilateral cataract (operated) with microphthalmos.
PB	Unilateral (R.) congenital cataract (operated & I.O.L. fitted), salt and pepper fundus (left eye). Slight nystagmus.
CC	Bilateral corneal opacities (grafted).
AF	Congenital cataract - right eye (operated at 3 weeks). Partial cataract left eye (unoperated).
CF	Developmentally slow; bilateral chorio-retinal scarring (involving both maculae), left optic atrophy.
LG	Bilateral congenital cataract (not operated).
SH	Rubella; unilateral (L.) congenital cataract with microphthalmos and bilateral retinal changes.
MI	Bilateral congenital cataract (operated).
TK	Unilateral (R.) anterior segment anomaly - operation to form pupil.
JM	Bilateral traumatic retinal haemorrhage (reabsorbed).
CO	Premature, cortical damage.
DP	Bilateral gross microphthalmos with unoperated cataracts.
JR	Bilateral corneal opacities (progressive and requiring grafts).
MS	Poor visual attention, cortical deficit?
JU	Albino.
PW	Bilateral aphakic, microphthalmos, nystagmus.
TW	Hallerman Streiff syndrome; bilateral developmental cataracts (operated).

2D. Incidence of successful preferential looking tests in pilot study subgroups

Table A2.3 Numbers (and percentages) of preferential looking test sessions in which particular numbers of acuity estimates were obtained. Values are for the sample participating in PL and pattern VEP tests (n = 24).

Total number of acuity estimates	Numbers of sessions	Cumulative n	Cumulative %
0	1	24	100.0
1	4	23	95.8
2	8	19	79.2
3	2	11	45.6
4	4	9	37.5
5	2	5	20.8
6	3	3	12.5

Table A2.4 Number and percentages of successful (binocular, right eye and left eye) preferential looking test sessions from the total number of PL sessions Data is for the sample participating in PL and pattern VEP tests (n = 24).

Total number of successful tests (R.E./L.E./Binoc)	n	Cumulative n	Cumulative %
0	1	24	100.0
1	11	23	95.8
2	6	12	50.0
3	6	6	25.0

Table A2.5 Numbers (and percentages) of preferential looking test sessions in which particular numbers of acuity estimates were obtained. Values are for the sample participating in PL and flash VEP tests (n = 26).

Total number of acuity estimates	Numbers of sessions	Cumulative n	Cumulative %
0	1	26	100.0
1	4	25	96.1
2	6	21	80.8
3	5	15	57.7
4	6	10	38.5
5	1	4	15.4
6	3	3	11.5

Table A2.6 Number and percentages of successful (binocular, right eye and left eye) preferential looking test sessions from the total number of PL sessions Data is for the sample participating in PL and flash VEP tests (n=26).

Total number of successful tests (R.E./L.E./Binoc)	n	Cumulative n	Cumulative %
0	1	26	100.0
1	9	25	96.1
2	11	16	61.5
3	5	5	19.2

Appendix 3

3A. Specimen appointment card

Approximately 80 % real size. Details relate to Woodcock Street premises which were in use at the start of the study, new cards were made when the department was re-housed in Duke Street.

CLINICAL NEUROPHYSIOLOGY UNIT

WOODCOCK ST. BIRMINGHAM 4.

We would be pleased if you could bring your baby .....

for vision/hearing tests.

on ..... at .....

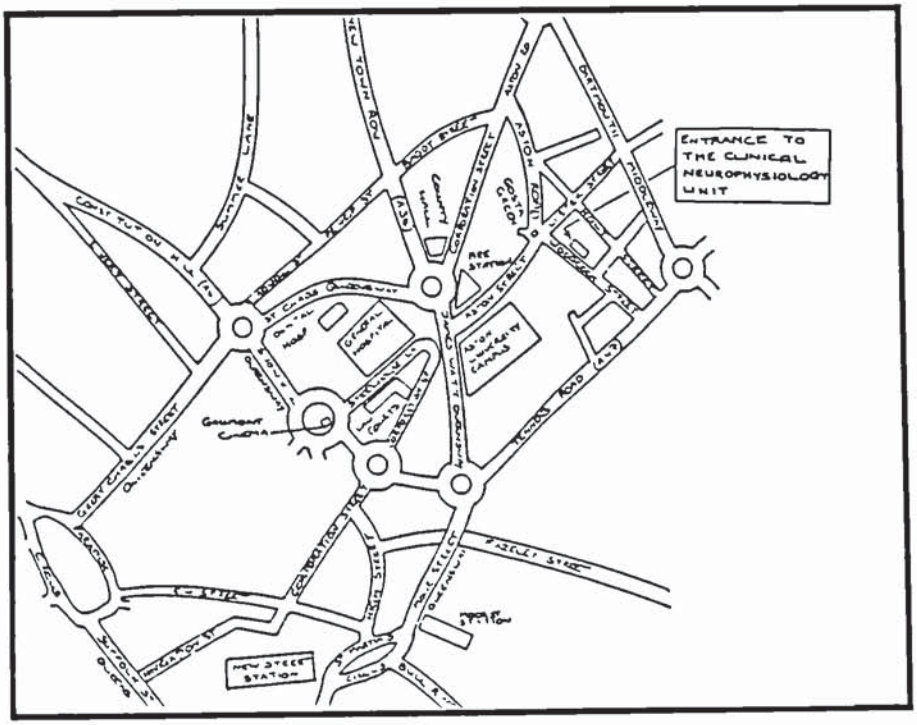
....

....

Please telephone the clinic if you are unable to attend this appointment.

Tel. 359 3611 Ext. 5200

A fund is available to assist with travel expenses if necessary.



3B. Specimen appointment letter

A copy of a current Aston University campus map was included with the letter.

CLINICAL NEUROPHYSIOLOGY UNIT

Duke Street

Aston Triangle

Birmingham B4 7ET

Tel. No: 021 359 3611 Extension
5200/5100

Dear

You will remember that whilst you were at Dudley Road Hospital we examined your baby eyes which were found to be healthy and of equal focussing ability. As eyes grow considerably during the first few months of life we should like to offer you a follow-up appointment in order to re-check the focussing of each eye (there is a higher risk of a baby developing a squint or lazy eye when there is a large imbalance between eyes).

An appointment has been arranged for

at

(If necessary, there is a fund available to cover your travel costs).

Please would you telephone to re-arrange the appointment if you find the present time inconvenient or if you do not wish to attend (so that we can offer the appointment to another mother).

Yours sincerely,

C. M. THOMPSON BSc, MBCO.
Clinical Fellow

3C. Convergence abilities (demonstrated by three, six and twelve month olds).

Assessments were performed following preferential looking tests and prior to the instillation of Cyclopentolate hydrochloride eye drops.

Table A3.1 Summary of convergence abilities demonstrated by three, six and twelve month olds. Numbers and percentages showing, nil, weak, moderate or strong convergence response are given.

Age Group (mths)	Sample size	No. (&%) showing particular convergence responses			
		Nil	Weak	Moderate	Strong
3	22	12 (54.5)	9 (40.9)	0 (0.0)	1 (4.5)
6	31	0 (0.0)	6 (19.4)	6 (19.4)	19 (61.3)
12	18	0 (0.0)	0 (0.0)	2 (11.1)	16 (88.9)

Appendix 4

4A. Scatterplots of monocular acuity versus age

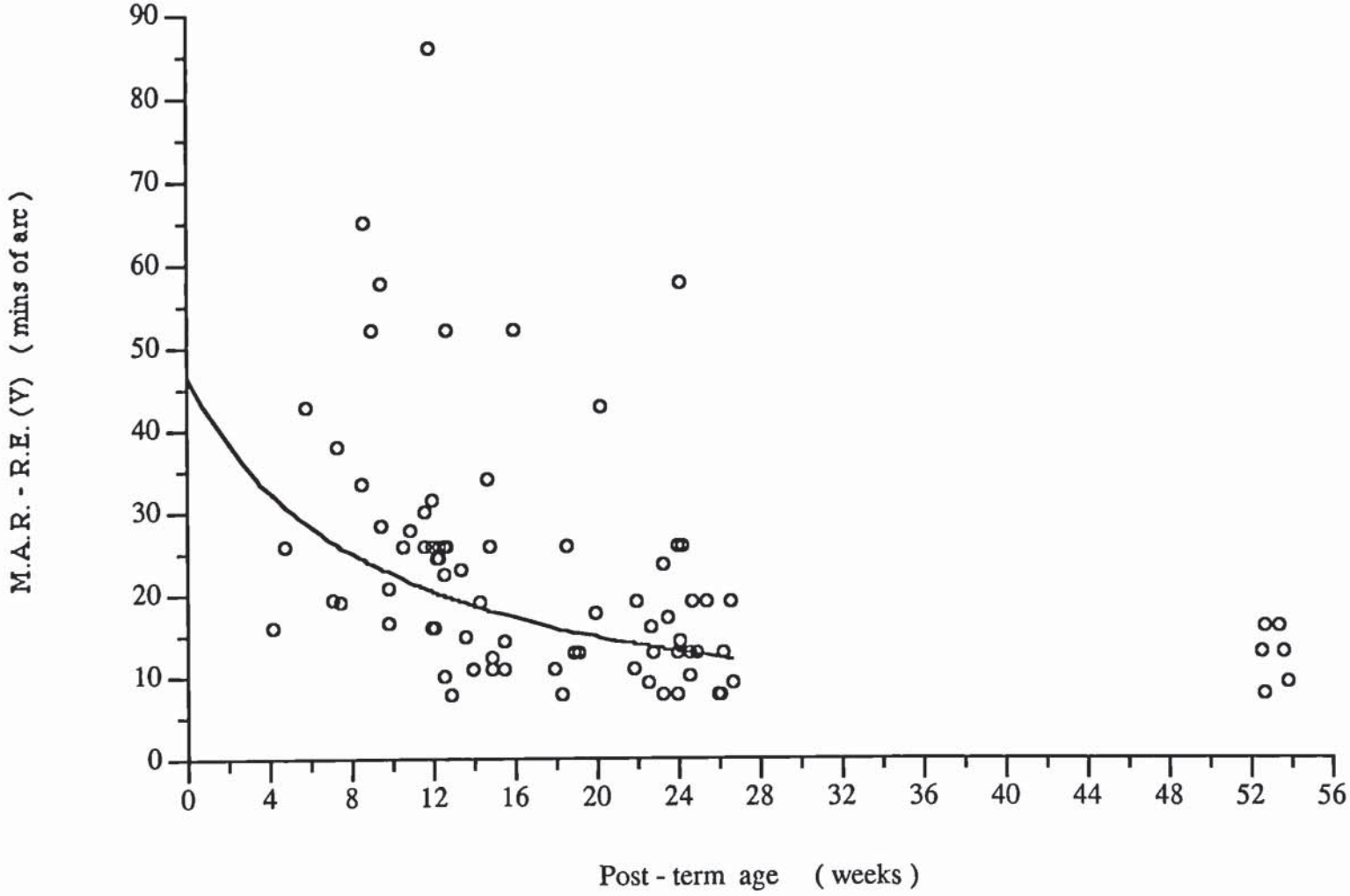


Figure A4.1 Scatterplot showing raw minimum angle of resolution (M.A.R.) data obtained for the right eye vertical gratings test condition, plotted versus infants' post-term age (weeks). All available follow-up data is included but newborn data has been omitted to improve clarity. Equation of regression curve (based on data excluding newborns and one year olds): $y = \text{reciprocal}\ (0.0023\ x + 0.022)$; $r = 0.49$; d.f. 1,71; $p < 0.001$.

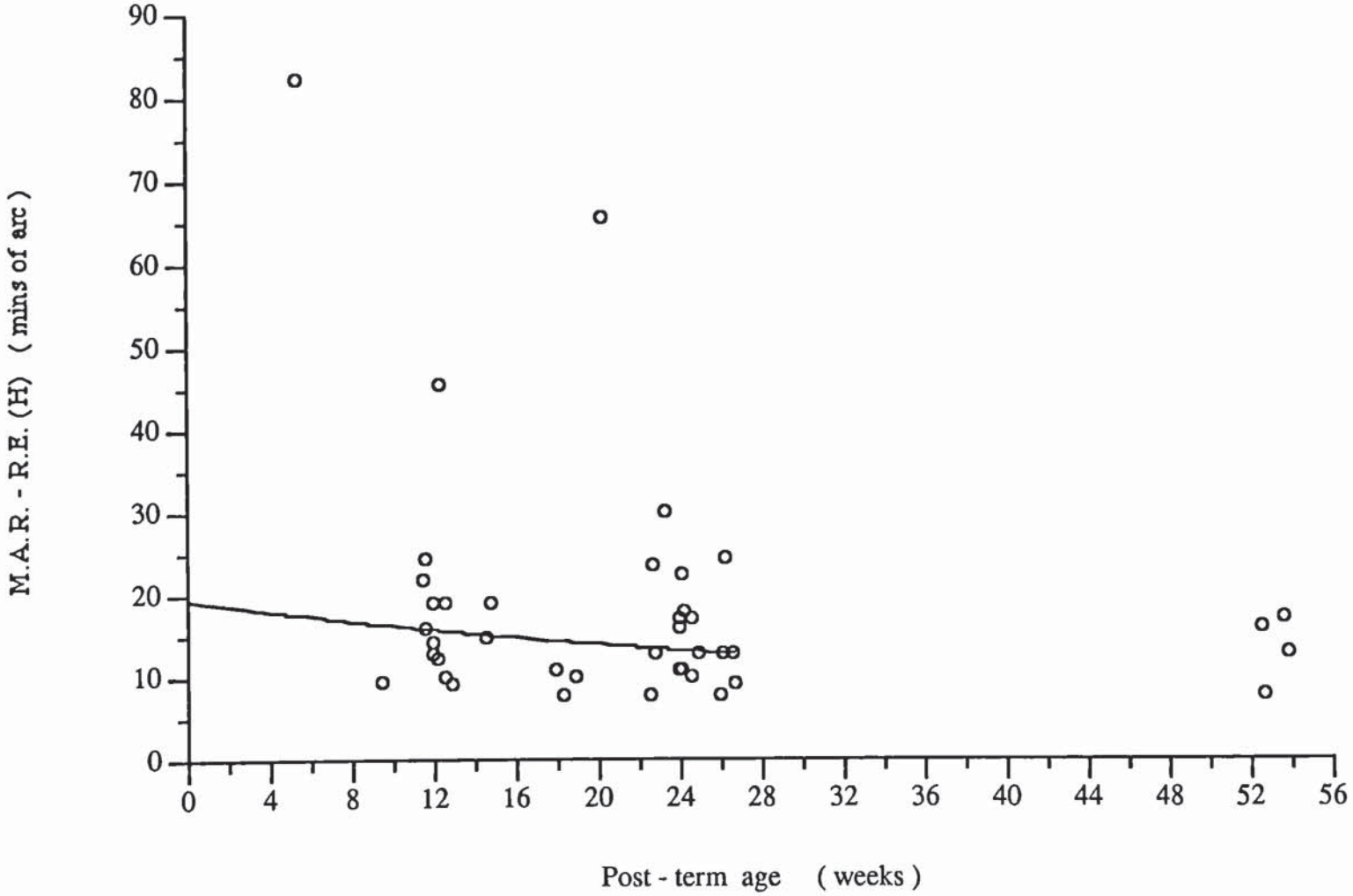


Figure A4.2 As Figure A4.1 for right eye horizontal gratings test condition. Equation of regression curve: y = reciprocal (0.0010 x + 0.051); r = 0.22; d.f. 1,35; p = 0.131.

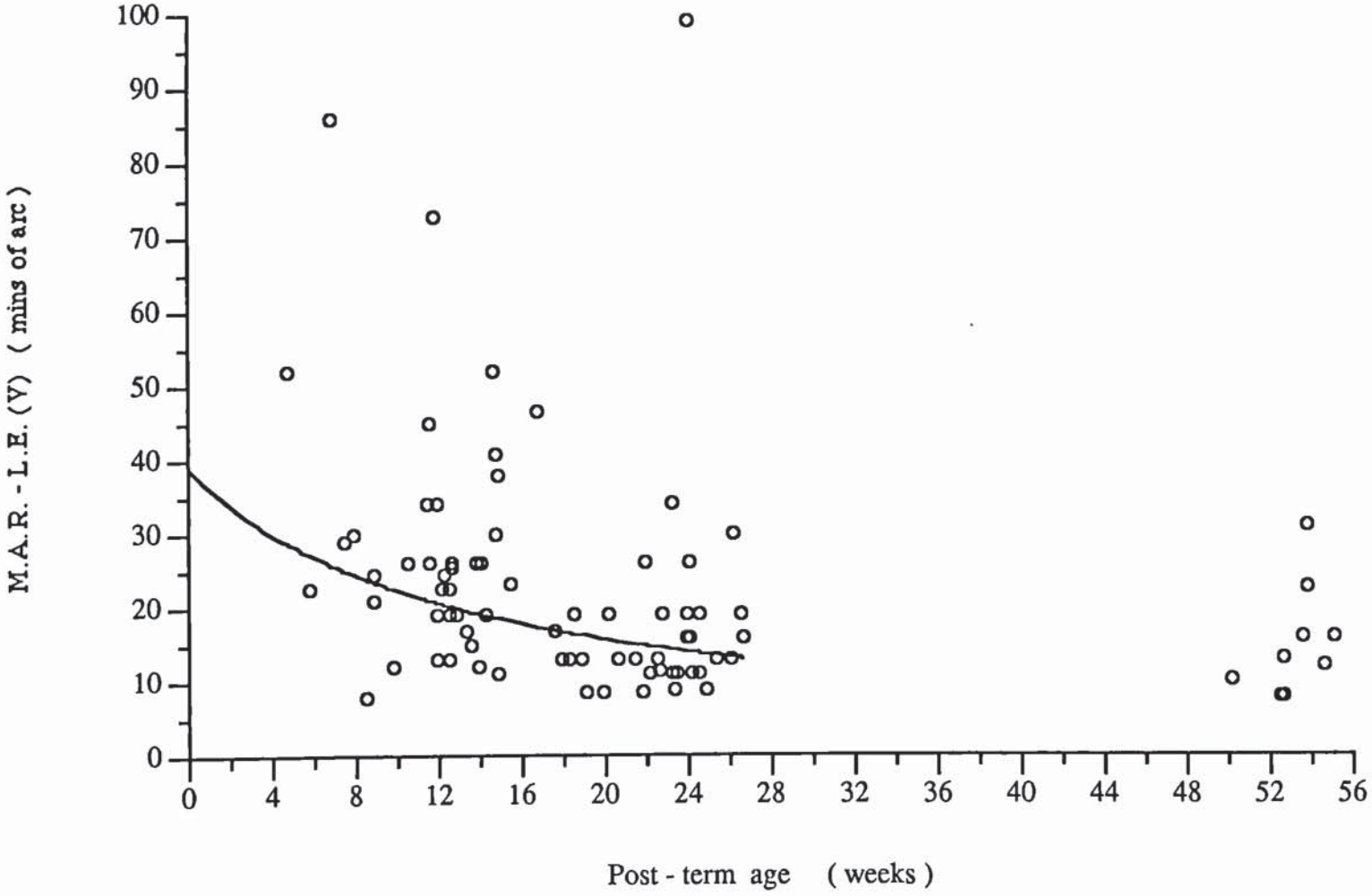


Figure A4.3 As Figure A4.1 for left eye vertical gratings test condition. Equation of regression curve: y = reciprocal (0.0019 x + 0.026); r = 0.39; d.f. 1,73; p = 0.001.

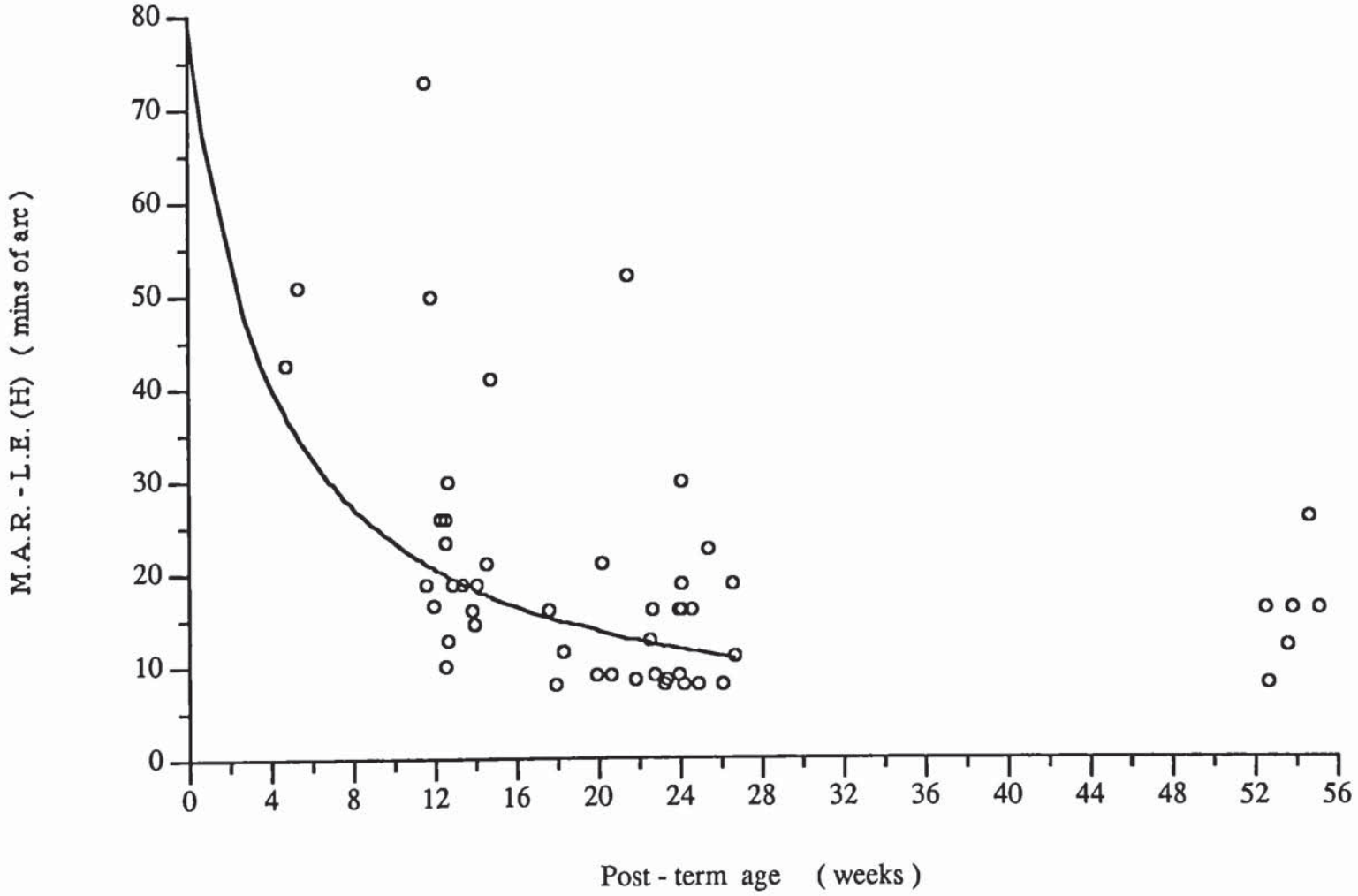


Figure A4.4 As Figure A4.1 for left eye horizontal gratings test condition. Equation of regression curve: y = reciprocal (0.0030 x + 0.013); r = 0.51; d.f. 1,43; $p < 0.001$.

4B. Paired Orientation Data

i) Binocular

Table A4.1 Paired binocular vertical and horizontal data of the subjects within the one month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
0.7	68.0	73.0
2.7	46.5	51.0
Mean	57.3	62.0
S.D.	15.2	15.6
S.E.	15.2	15.6

Table A4.2 Paired binocular vertical and horizontal data of the subjects within the two month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
4.6	38.0	51.0
4.6	28.0	25.5
4.6	73.0	34.0
4.7	21.0	42.5
4.7	24.5	19.0
4.9	74.0	42.5
5.3	23.5	38.0
5.4	52.0	34.0
5.7	62.5	72.0
6.6	36.5	30.0
6.9	12.5	21.0
7.6	26.0	11.0
7.9	30.0	27.0
Mean	38.6	34.4
S.D.	20.3	15.7
S.E.	5.9	4.5

Table A4.3 Paired binocular vertical and horizontal data of the subjects within the three month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
8.6	35.0	25.5
9.1	12.0	17.5
9.4	8.0	19.0
9.4	18.0	21.0
9.4	19.0	26.0
9.6	30.0	15.0
9.7	12.5	9.0
10.9	24.5	19.0
11.1	23.5	10.0
11.3	21.0	26.5
11.4	26.0	12.0
11.6	13.0	11.0
11.6	10.0	11.5
11.7	89.5	13.0
11.7	9.0	18.0
11.9	11.0	13.0
11.9	8.0	8.0
Mean	21.8	16.2
S.D.	19.3	6.0
S.E.	4.8	1.5

Table A4.4 Paired binocular vertical and horizontal data of the subjects within the four month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
12.4	11.0	11.0
12.6	13.0	11.0
12.9	11.0	11.0
13.0	21.0	30.0
13.1	13.0	16.0
13.3	11.0	9.0
13.6	10.0	10.0
13.9	9.0	12.0
14.0	9.0	9.0
14.7	11.0	13.0
Mean	11.9	13.2
S.D.	3.5	6.3
S.E.	1.2	2.1

Table A4.5 Paired binocular vertical and horizontal data of the subjects within the five month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
16.7	26.0	26.0
17.9	10.0	8.0
Mean	18.0	14.3
S.D.	11.3	12.7
S.E.	11.3	12.7

Table A4.6 Paired binocular vertical and horizontal data of the subjects within the six month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
20.6	8.5	13.0
21.7	8.5	8.5
22.7	8.0	13.0
23.3	8.0	8.0
Mean	8.3	10.6
S.D.	0.3	2.8
S.E.	0.2	1.6

Table A4.7 Paired binocular vertical and horizontal data of the subjects within the seven month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
24.0	26.0	31.0
24.4	10.0	9.0
24.4	13.0	14.5
24.6	19.0	11.0
24.9	9.0	8.0
25.3	10.0	8.0
26.1	11.0	15.5
26.6	8.0	8.0
Mean	13.3	13.1
S.D.	6.2	7.8
S.E.	2.3	3.0

Table A4.8 Paired binocular vertical and horizontal data of the subjects within the twelve month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
50.0	8.0	8.0
51.7	8.0	8.0
52.6	8.0	11.0
53.7	30.0	34.0
55.4	8.0	9.0
Mean	12.4	14.0
S.D.	9.8	11.3
S.E.	4.9	5.6

ii) Right Eye

Table A4.9 Paired right eye vertical and horizontal data of newborn subjects completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Subject	M.A.R. (Mins of arc) Vertical	Horizontal
1 (96)	46	49
2 (100)	48	93
3 (170)	51	34
Mean	48.3	58.7
S.D.	2.1	25.0
S.E.	1.5	17.7

Table A4.10 Paired right eye vertical and horizontal data of the subjects within the three month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
9.4	28.5	9.5
11.6	26.0	16.0
11.6	30.0	24.5
11.9	16.0	13.0
11.9	26.0	14.5
11.9	31.5	19.0
Mean	26.3	16.1
S.D.	5.5	5.2
S.E.	2.5	2.3

Table A4.11 Paired right eye vertical and horizontal data of the subjects within the four month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
12.3	26.0	45.5
12.4	22.5	19.0
12.4	26.0	10.0
12.9	8.0	9.0
14.7	26.0	19.0
Mean	21.7	20.5
S.D.	7.8	14.8
S.E.	3.9	7.4

Table A4.12 Paired right eye vertical and horizontal data of the subjects within the five month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
17.9	11.0	11.0
18.3	8.0	8.0
18.9	13.0	10.0
Mean	10.7	9.7
S.D.	2.5	1.5
S.E.	1.8	1.1

Table A4.13 Paired right eye vertical and horizontal data of the subjects within the six month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
20.1	43.0	65.5
22.4	9.0	8.0
22.6	16.0	23.5
22.7	13.0	13.0
23.1	23.5	30.0
23.9	26.0	17.0
23.9	8.0	16.0
23.9	13.0	11.0
Mean	18.9	23.0
S.D.	11.6	18.6
S.E.	4.4	7.0

Table A4.14 Paired right eye vertical and horizontal data of the subjects within the seven month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
24.0	14.5	22.5
24.0	57.5	11.0
24.1	26.0	18.0
24.4	13.0	10.0
24.4	10.0	17.0
24.9	13.0.	13.0
25.9	8.0	8.0
26.0	8.0	13.0
26.1	13.0	24.5
26.4	19.0	13.0
26.6	9.0	9.0
Mean	17.4	14.5
S.D.	14.3	5.4
S.E.	4.5	1.7

Table A4.15 Paired right eye vertical and horizontal data of the subjects within the twelve month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
52.4	13.0	16.0
52.6	8.0	8.0
53.6	13.0	17.0
53.7	9.0	13.0
Mean	10.8	13.5
S.D.	2.6	4.0
S.E.	1.5	2.3

Table A4.16 Averaged right eye vertical and horizontal data of 37 subjects within the follow-up completing both tests. Mean, S.D. and S.E. are presented.

	M.A.R. (Mins of arc) Vertical	Horizontal
Mean	18.5	16.9
S.D.	10.9	11.1
S.E.	1.8	1.8

Table A4.17 Statistical significances for group mean right eye vertical versus horizontal grating M.A.R. data. The differences between mean findings for each orientation did not reach significance for any age group apart from at three months.

Age Group	Comparison of Vertical and Horizontal M.A.R. Means t - stat	d.f.	sig
Newborn	0.57	2	p = 0.629
3	4.46	5	p = 0.007
4	0.20	5	p = 0.848
5	1.00	2	p = 0.423
6	-1.22	7	p = 0.263
7	0.62	10	p = 0.551
12	-2.91	3	p = 0.062
Follow-up Sample	0.85	36	p = 0.403

iii) Left Eye

Table A4.18 Paired left eye vertical and horizontal data of the subjects within the three month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
11.6	45.0	73.0
11.6	26.0	19.0
11.7	73.0	50.0
11.9	13.0	16.5
Mean	39.3	39.6
S.D.	26.1	27.0
S.E.	15.0	15.6

Table A4.19 Paired left eye vertical and horizontal data of subjects within the four month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
12.3	24.5	26.0
12.4	22.5	23.5
12.4	19.0	26.0
12.4	13.0	10.0
12.6	25.5	30.0
12.6	26.0	13.0
12.9	19.0	19.0
13.3	17.0	19.0
13.7	26.0	16.0
13.9	12.0	14.5
14.0	26.0	19.0
14.7	30.0	41.0
Mean	21.7	21.4
S.D.	5.7	8.5
S.E.	1.7	2.6

Table A4.20 Paired left eye vertical and horizontal data of the subjects within the five month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
17.6	17.0	16.0
17.9	13.0	8.0
18.3	13.0	11.5
19.9	8.5	9.0
Mean	12.9	11.1
S.D.	3.5	3.6
S.E.	2.0	2.1

Table A4.21 Paired left eye vertical and horizontal data of the subjects within the six month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
20.1	19.0	21.0
20.6	13.0	9.0
21.4	13.0	52.0
21.7	8.5	8.5
22.4	13.0	13.0
22.6	11.5	16.0
22.7	19.0	9.0
23.1	11.0	8.0
23.3	9.0	8.5
23.9	19.0	9.0
23.9	16.0	16.0
23.9	16.0	16.0
Mean	14.0	15.5
S.D.	3.8	12.3
S.E.	1.1	3.7

Table A4.22 Paired left eye vertical and horizontal data of the subjects within the seven month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
24.0	16.0	16.0
24.0	99.0	30.0
24.0	26.0	19.0
24.1	11.0	8.0
24.4	11.0	16.0
24.9	9.0	8.0
25.3	13.0	22.5
26.0	13.0	8.0
26.4	19.0	19.0
26.6	16.0	11.0
Mean	23.3	15.8
S.D.	27.0	7.3
S.E.	9.0	2.4

Table A4.23 Paired left eye vertical and horizontal data of the subjects within the twelve month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Vertical	Horizontal
52.4	8.0	16.0
52.6	8.0	8.0
53.6	16.0	12.0
53.7	31.0	16.0
54.6	12.0	26.0
55.0	16.0	16.0
Mean	15.2	15.7
S.D.	8.5	6.0
S.E.	3.8	2.7

Table A4.24 Averaged left eye vertical and horizontal data of 48 subjects within the follow-up sample completing both tests. Mean, S.D. and S.E. are presented.

	M.A.R. (Mins of arc) Vertical	Horizontal
Mean	20.0	18.7
S.D.	15.9	12.8
S.E.	2.3	1.9

Table A4.25 Statistical significances for group mean left eye vertical versus horizontal grating M.A.R. data. The differences between mean findings for each orientation did not reach significance for any age group.

Age Group	Comparison of Vertical and Horizontal M.A.R. Means		
	t - stat	d.f.	sig
3	-0.04	3	p = 0.974
4	0.15	12	p = 0.887
5	1.50	3	p = 0.230
6	-0.41	11	p = 0.688
7	1.08	9	p = 0.309
12	-0.12	5	p = 0.907
Follow-up Sample	0.66	47	p = 0.513

4C. Monocular : binocular acuity comparisons (follow-up sample)

Table A4.26 Paired monocular and binocular data of subjects within the two month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc)	
	Mean Monocular	Mean Binocular
4.1	16.0	19.0
4.7	42.5	31.8
4.7	26.0	21.8
5.3	51.0	30.8
5.7	43.0	67.3
6.9	86.0	41.5
7.0	19.5	15.0
7.3	38.0	21.0
7.9	30.0	28.5
Mean	39.1	30.7
S.D.	21.0	15.9
S.E.	7.4	5.6

Table A4.27 Paired monocular and binocular data of subjects within the three month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
8.4	33.5	11.0
8.6	65.0	30.3
8.9	21.0	13.0
9.0	52.0	17.0
9.4	19.0	18.5
9.4	57.5	22.5
9.7	12.0	17.5
9.7	16.5	10.8
10.4	26.0	16.0
10.9	28.0	21.8
11.4	34.0	19.0
11.6	21.0	12.0
11.6	22.5	10.8
11.7	86.0	51.3
11.9	20.3	12.0
11.9	19.0	13.0
Mean	33.3	18.5
S.D.	20.9	10.2
S.E.	5.4	2.6

Table A4.28 Paired monocular and binocular data of the subjects within the four month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
12.0	16.0	16.0
12.1	12.5	15.0
12.1	24.5	13.0
12.3	35.8	13.0
12.4	20.8	11.0
12.4	10.0	9.0
12.6	52.0	12.0
12.9	8.5	11.0
13.3	18.0	10.0
13.6	15.0	10.0
13.7	21.0	16.0
13.9	13.3	10.5
14.0	22.5	9.0
14.3	19.0	16.0
14.4	21.0	9.0
14.6	34.0	9.0
14.7	35.5	12.0
14.7	41.0	33.5
15.9	52.0	11.0
Mean	24.9	13.0
S.D.	13.2	5.6
S.E.	3.1	1.3

Table A4.29 Paired monocular and binocular data of the subjects within the five month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
16.7	46.5	26.0
17.9	10.5	9.0
18.4	19.0	11.0
18.4	19.0	11.0
Mean	23.8	14.3
S.D.	15.7	7.9
S.E.	9.1	4.6

Table A4.30 Paired monocular and binocular data of the subjects within the six month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
20.6	11.0	10.8
21.7	11.0	8.5
22.4	8.5	12.0
22.7	13.0	10.5
23.3	8.8	8.0
23.4	11.0	8.5
23.9	21.5	10.0
Mean	12.1	9.8
S.D.	4.4	1.5
S.E.	1.8	0.6

Table A4.31 Paired monocular and binocular data of the subjects within the seven month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
24.0	34.3	14.5
24.0	22.5	28.5
24.3	11.5	9.5
24.3	13.5	13.8
24.6	19.0	15.0
24.9	13.0	8.5
25.3	19.0	9.0
26.1	18.8	13.3
26.4	19.0	8.0
26.6	9.0	8.0
Mean	18.0	12.8
S.D.	7.1	6.2
S.E.	2.4	2.1

Table A4.32 Paired monocular and binocular data of the subjects within the twelve month age group completing both tests. Raw data plus mean, S.D. and S.E. are presented.

Post - term Age (Wks)	M.A.R. (Mins of arc) Mean Monocular	Mean Binocular
52.4	12.0	22.5
52.6	16.0	12.0
52.6	8.0	9.5
53.6	15.0	13.0
53.7	23.5	32.0
53.7	22.5	33.5
Mean	16.2	20.4
S.D.	6.0	10.5
S.E.	2.7	4.7

Appendix 5

5A. Details of statistical tests (refractive data).

Asterisks denote significant findings

i) Full newborn sample

Table A5.1 Details of regression line equations and statistics for the newborn spherical refraction v maturity study.
P.C.A. = post-conceptional age (weeks), P.N.A. = post-natal age (days), P.N. (h) = post-natal age (hours) and P.N. (l.h.) = post-natal age (log. hours). Format of regression equations :
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R S.E.R. v P.C.A.	0.03	1.60	0.02	1,207	p = 0.825
L S.E.R. v P.C.A.	0.02	2.00	0.01	1,208	p = 0.898
R S.E.R. v P.N.A.	-0.45	3.50	0.20	1,207	p = 0.004 *
L S.E.R. v P.N.A.	-0.40	3.34	0.17	1,208	p = 0.012 *
R S.E.R. v P.N.(h)	-0.02	3.68	0.21	1,207	p = 0.003 *
L S.E.R. v P.N.(h)	-0.02	3.48	0.18	1,208	p = 0.010 *
R S.E.R. v P.N.(l.h)	-0.84	5.76	0.23	1,207	p = 0.001 *
L S.E.R. v P.N.(l.h)	-0.71	5.23	0.19	1,208	p = 0.006 *

Table A5.2 Details of regression line equations and statistics for the newborn spherical refraction v physical size study.
B.W. = birth weight (kg.), H.C. = head circumference (cm.), L. = length (cm.). Format of regression equations :
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R S.E.R. v B.W.	0.81	0.15	0.13	1,207	p = 0.066
L S.E.R. v B.W.	0.69	0.48	0.11	1,208	p = 0.091
R S.E.R. v H.C.	0.35	- 9.06	0.16	1,207	p = 0.016 *
L S.E.R. v H.C.	0.33	-8.57	0.15	1,208	p = 0.028 *
R S.E.R. v L.	0.05	0.44	0.05	1,205	p = 0.514
L S.E.R. v L.	0.06	-0.14	0.05	1,206	p = 0.438

Table A5.3 Details of regression line equations and statistics for miscellaneous factors.
M.A. = maternal age (years), Cyc = duration of cycloplegia (mins.).
Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R S.E.R. v M.A.	0.02	2.34	0.04	1,207	p = 0.593
L S.E.R. v M.A.	0.02	2.21	0.04	1,208	p = 0.564
R S.E.R. v Cyc.	0.0003	2.75	0.00	1,199	p = 0.964
L S.E.R. v Cyc.	-0.004	3.09	0.05	1,200	p = 0.480
R CYL. v Cyc.	0.006	1.17	0.13	1,199	p = 0.083
L CYL. v Cyc.	0.007	1.06	0.19	1,200	p = 0.008 *

ii) Newborn subgroups

Table A5.4 Details of regression line equations and statistics for the newborn samples with and without birth complications.
P.N. (l.h.) = post-natal age (log. hours) and H.C. = head circumference (cm.). Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
High trauma (n=62)					
R S.E.R. v P.N.(l.h)	-0.97	6.53	0.27	1,59	p = 0.034 *
L S.E.R. v P.N.(l.h)	-0.77	5.89	0.23	1,60	p = 0.087
R S.E.R. v H.C.	0.09	- 0.31	0.05	1,59	p = 0.695
L S.E.R. v H.C.	0.04	1.73	0.02	1,60	p = 0.871
Low trauma (n=148)					
R S.E.R. v P.N.(l.h)	-0.86	5.72	0.22	1,146	p = 0.007 *
L S.E.R. v P.N.(l.h)	-0.81	5.39	0.20	1,146	p = 0.014 *
R S.E.R. v H.C.	0.48	-13.71	0.21	1,146	p = 0.009 *
L S.E.R. v H.C.	0.47	-13.49	0.20	1,146	p = 0.014 *

Table A5.5 Details of regression line equations and statistics for newborn infants with one minute apgar scores of up to eight and the remaining sample. Abbreviations etc. as in Table A5.4.

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Apgar ≤ 8 (n=113)					
R S.E.R. v P.N.(l.h)	-0.97	6.33	0.28	1,110	p = 0.003 *
L S.E.R. v P.N.(l.h)	-0.70	5.35	0.20	1,111	p = 0.031 *
R S.E.R. v H.C.	0.38	-10.26	0.21	1,110	p = 0.031 *
L S.E.R. v H.C.	0.38	-10.18	0.20	1,111	p = 0.032 *
Apgar > 8 (n=96)					
R S.E.R. v P.N.(l.h)	-0.70	5.19	0.18	1,94	p = 0.072
L S.E.R. v P.N.(l.h)	-0.74	5.19	0.18	1,94	p = 0.094
R S.E.R. v H.C.	0.29	- 7.11	0.12	1,94	p = 0.107
L S.E.R. v H.C.	0.25	- 5.83	0.10	1,94	p = 0.340

Table A5.6 Details of regression line equations and statistics for the newborn samples with and without retinal haemorrhage. Abbreviations etc. as in Table A5.4.

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Retinal haem. (n=60)					
R S.E.R. v P.N.(l.h)	-0.66	5.22	0.16	1,57	p = 0.122
L S.E.R. v P.N.(l.h)	-0.36	4.01	0.09	1,58	p = 0.496
R S.E.R. v H.C.	0.40	-10.96	0.18	1,57	p = 0.121
L S.E.R. v H.C.	0.44	-12.46	0.20	1,58	p = 0.101
Nil retinal haem. (n=149)					
R S.E.R. v P.N.(l.h)	-0.89	5.95	0.25	1,147	p = 0.002 *
L S.E.R. v P.N.(l.h)	-0.84	5.68	0.23	1,147	p = 0.006 *
R S.E.R. v H.C.	0.34	- 8.86	0.17	1,147	p = 0.048 *
L S.E.R. v H.C.	0.30	- 7.62	0.14	1,147	p = 0.073

Table A5.7 Details of regression line equations and statistics for newborn samples with primiparous or multiparous mothers. Abbreviations etc. as in Table A5.4.

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Primipara (n=70)					
R S.E.R. v P.N.(l.h)	-0.60	5.01	0.16	1,68	p = 0.119
L S.E.R. v P.N.(l.h)	-0.25	3.67	0.07	1,68	p = 0.588
R S.E.R. v H.C.	0.54	-15.77	0.27	1,68	p = 0.027 *
L S.E.R. v H.C.	0.51	-14.66	0.25	1,68	p = 0.042 *
Multiparous (n=140)					
R S.E.R. v P.N.(l.h)	-0.97	6.18	0.26	1,137	p = 0.002 *
L S.E.R. v P.N.(l.h)	-0.96	6.02	0.25	1,138	p = 0.003 *
R S.E.R. v H.C.	0.24	- 5.59	0.11	1,137	p = 0.113
L S.E.R. v H.C.	0.24	- 5.50	0.11	1,138	p = 0.114

Table A5.8 Details of regression line equations and statistics for male and female newborn samples.
Abbreviations etc. as in Table A5.4.

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Males (n=105)					
R S.E.R. v P.N.(l.h)	-1.02	6.56	0.30	1,103	p = 0.002 *
L S.E.R. v P.N.(l.h)	-0.92	6.06	0.27	1,103	p = 0.006 *
R S.E.R. v H.C.	0.11	- 0.77	0.05	1,103	p = 0.627
L S.E.R. v H.C.	0.10	- 0.50	0.04	1,103	p = 0.673
Females (n=105)					
R S.E.R. v P.N.(l.h)	-0.52	4.43	0.13	1,102	p = 0.116
L S.E.R. v P.N.(l.h)	-0.37	3.92	0.09	1,103	p = 0.372
R S.E.R. v H.C.	0.52	-15.05	0.24	1,102	p = 0.013 *
L S.E.R. v H.C.	0.55	-16.07	0.25	1,103	p = 0.011 *

Table A5.9 Details of regression line equations and statistics for Asian and Caucasian newborn samples.
Abbreviations etc. as in Table A5.4.

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Asian (n=113)					
R S.E.R. v P.N.(l.h)	-0.51	4.54	0.13	1,110	p = 0.115
L S.E.R. v P.N.(l.h)	-0.45	4.24	0.10	1,111	p = 0.080
R S.E.R. v H.C.	0.36	- 9.84	0.17	1,110	p = 0.091
L S.E.R. v H.C.	0.35	- 9.44	0.16	1,111	p = 0.078
Caucasian (n=61)					
R S.E.R. v P.N.(l.h)	-1.62	8.62	0.45	1,59	p < 0.001 *
L S.E.R. v P.N.(l.h)	-1.60	8.42	0.44	1,59	p < 0.001 *
R S.E.R. v H.C.	0.40	-10.55	0.20	1,59	p = 0.102
L S.E.R. v H.C.	0.38	-10.13	0.19	1,59	p = 0.109

Table A5.10 Details of regression line equations and statistics for infants whose mothers received pethidine during labour and the remaining sample. Abbreviations etc. as in Table A5.4.

Variable (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Pethidine (n=96)					
R S.E.R. v P.N.(l.h)	-0.58	5.12	0.18	1,93	p = 0.091
L S.E.R. v P.N.(l.h)	-0.32	4.14	0.10	1,94	p = 0.338
R S.E.R. v H.C.	0.43	-11.90	0.23	1,93	p = 0.023 *
L S.E.R. v H.C.	0.41	-11.13	0.22	1,94	p = 0.034 *
Non-pethidine (n=114)					
R S.E.R. v P.N.(l.h)	-1.11	6.50	0.27	1,112	p = 0.004 *
L S.E.R. v P.N.(l.h)	-1.13	6.45	0.27	1,112	p = 0.004 *
R S.E.R. v H.C.	0.25	- 5.82	0.11	1,112	p = 0.100
L S.E.R. v H.C.	0.23	- 5.35	0.10	1,112	p = 0.046 *

5B. Neonatal refractive accuracy study - Raw data

Raw refractive data of 35 newborns participating in a refractive accuracy study. Right eye data (and duration of cycloplegia prior to initial retinoscopy) is provided in Table A5.11. Left eye data (and duration of cycloplegia before second retinoscopy) is given in Table A5.12.

Table A5.11 Unprocessed right eye refractive data of 35 newborn infants participating in repeat refraction study (plus cylinder power).

Patient	Duration Cyc. (1) (minutes)	Right Eye First Refraction Sphere	Cyl.	Axis	Second Refraction Sphere	Cyl.	Axis
1	45	4.50	1.50	95	2.00	3.00	90
2	54	3.00	1.00	90	1.50	2.00	90
3	63	-2.00	1.00	130	-2.75	1.50	130
5	84	-1.50	0.75	90	-3.25	0.75	90
7	98	2.50	0.00	-	0.00	2.50	90
8	46	-3.00	1.00	80	-3.00	2.00	85
9	49	-3.00	2.50	90	-3.00	2.50	90
10	86	-0.50	4.50	90	-1.00	5.00	90
11	93	0.00	2.00	80	-1.00	1.75	80
12	60	-1.00	5.00	95	0.00	4.50	95
13	69	5.00	2.00	80	7.00	1.25	90
14	92	2.50	0.00	-	2.00	0.00	-
15	58	-1.75	0.50	90	-2.50	1.50	90
17	68	-2.00	4.50	90	-0.50	1.00	90
18	73	0.00	2.00	90	-0.50	3.00	90
19	83	2.00	1.00	80	1.00	2.00	90
20	91	3.00	1.00	75	3.25	0.75	90
21	98	3.00	0.50	90	3.00	2.00	90
22	47	0.50	0.00	-	1.00	1.00	90
23	48	3.00	2.00	90	4.00	1.00	80
24	66	6.00	0.00	-	5.00	0.75	50
25	55	0.00	2.00	90	0.50	1.50	90
26	69	4.50	1.50	90	4.00	1.50	90
27	77	5.50	1.50	90	5.00	2.50	90
28	84	5.50	0.50	100	6.50	0.75	90
29	99	6.00	0.00	-	3.00	2.00	90
30	89	-0.50	1.00	90	-2.50	1.00	90
31	45	6.00	0.00	-	5.50	0.50	100
32	48	3.50	0.00	-	3.00	1.00	90
33	50	-2.50	2.00	90	-2.50	1.50	90
35	60	0.00	2.00	90	1.00	1.00	90
36	68	3.00	2.00	85	2.00	3.00	70
37	60	2.50	1.50	105	2.50	2.50	100
38	55	2.50	0.50	90	2.50	1.50	90
39	48	2.50	2.50	70	2.50	2.50	70

Table A5.12 Unprocessed left eye refractive data of 35 newborn infants participating in repeat refraction study (plus cylinder power).

Patient	Duration Cyc. (2) (minutes)	Left Eye First Refraction Sphere	Cyl.	Axis	Second Refraction Sphere	Cyl.	Axis
1	120	4.00	1.50	85	1.50	2.00	85
2	149	3.00	1.00	90	3.00	1.00	90
3	158	-2.25	2.00	35	-3.00	2.00	40
5	167	-1.25	0.75	90	-2.50	0.50	90
7	168	3.00	0.50	90	3.00	2.00	90
8	133	-2.00	1.00	90	-3.00	2.50	90
9	137	-3.00	3.00	90	-3.00	3.00	90
10	158	2.50	3.00	80	2.00	3.00	90
11	164	-1.25	2.25	105	-1.00	2.00	90
12	142	2.00	2.00	80	-0.50	5.50	85
13	147	6.00	1.00	90	6.00	1.00	90
14	160	1.50	0.75	75	1.25	0.75	80
15	116	-1.75	0.50	90	-2.75	1.75	90
17	120	-1.50	3.50	90	0.00	1.75	90
18	128	2.50	2.00	90	2.00	3.00	90
19	135	2.00	1.00	90	3.50	1.00	85
20	144	2.00	2.00	90	1.00	3.00	90
21	156	2.50	1.00	90	2.00	2.00	75
22	147	0.50	0.00	-	0.00	0.50	90
23	146	2.00	2.00	90	3.00	2.00	90
24	151	5.50	1.00	90	4.00	0.50	90
25	170	0.00	3.00	90	-0.50	2.50	90
26	152	5.00	0.50	90	3.50	1.00	80
27	162	5.00	1.50	90	4.00	1.50	80
28	176	5.50	0.50	90	6.50	1.00	90
29	179	3.00	2.00	90	3.00	2.00	90
30	184	-1.00	1.00	90	-1.75	0.00	-
31	90	6.50	0.00	-	5.50	0.00	-
32	90	3.50	0.00	-	2.50	1.00	90
33	85	-3.00	3.00	100	-3.00	3.50	100
35	130	1.00	2.00	90	1.50	1.50	90
36	136	3.00	1.50	90	3.00	2.00	90
37	127	2.50	0.50	90	4.00	0.50	90
38	118	2.50	1.00	100	2.50	1.50	85
39	110	3.00	1.75	90	2.50	2.00	95

5C. Objective v. subjective refraction study

The sample comprised thirty three consecutive patients attending an Optometric practice for eye examination. Ages ranged from five to sixty five years (mean 31.2; S.E. 3.2 years). Patients' corrected acuities varied between 6/5 and 6/9 Snellen in each eye. Examinations (listed in chronological order) pertinent to the determination of distant refractive error were as follows:

a) Streak retinoscopy - using a 67 cm. working distance, with a fogging lens placed before the non-examined eye and the subject instructed to view the green background target of a distant duochrome test.
b) Distance subjective refraction - using cross-cylinder and Humphriss binocular balancing techniques and determination of binocular addition on completion of monocular refractions.
c) Determination of the most positive ophthalmoscopic lens with which the disc margin appeared in best focus - patient instructed to view the green target of the duochrome test.
d) Determination of the most positive ophthalmoscopic lens with which the macula appeared in best focus.

A Keeler Specialist Ophthalmoscope graduated in one dioptre steps and a Keeler Streak retinoscope (and series of trial case lenses allowing 0.25 dioptre steps) were used in carrying out these tests. It is possible that retinoscopy findings could have influenced the subjective results due to the order of testing. Ideally subjective refractions should have been performed without reference to the retinoscopy results or testing altered to an ABBA ordering. Unfortunately this was impractical due to the clinical testing environment and the need to complete tests without inconvenience to the patients. Since the results of the study are for comparison with neonatal data and not to be taken too critically this disadvantage can be overlooked.

i) Regression analyses and coefficients

Raw data for the right eye can be derived from scatterplots (Figures A5.1 to A5.4). Table A5.13 summarises the correlations obtained between objective and subjective refractive findings. Correlations were highly significant for all comparisons ($p < 0.001$).

Retinoscopy Correlations coefficients between retinoscopic and subjective S.E.R. data were very high ($r = 0.99$ for each eye). Slightly more scatter was evident in the cylindrical power data which is reflected in lower correlation coefficients ($r = 0.92$ and 0.91 for the right and left eyes respectively). The function slopes were close to unity and intercepts approached zero.

Ophthalmoscopy (disc and macula) Similar results were found for both methods. Poorer correlations ($r \approx 0.87$) were found than for the retinoscopy data. Function slopes were less close to unity (particularly for the macula data) and intercepts were closer to -1 dioptre than to zero, indicating a tendency to over-minus prescriptions.

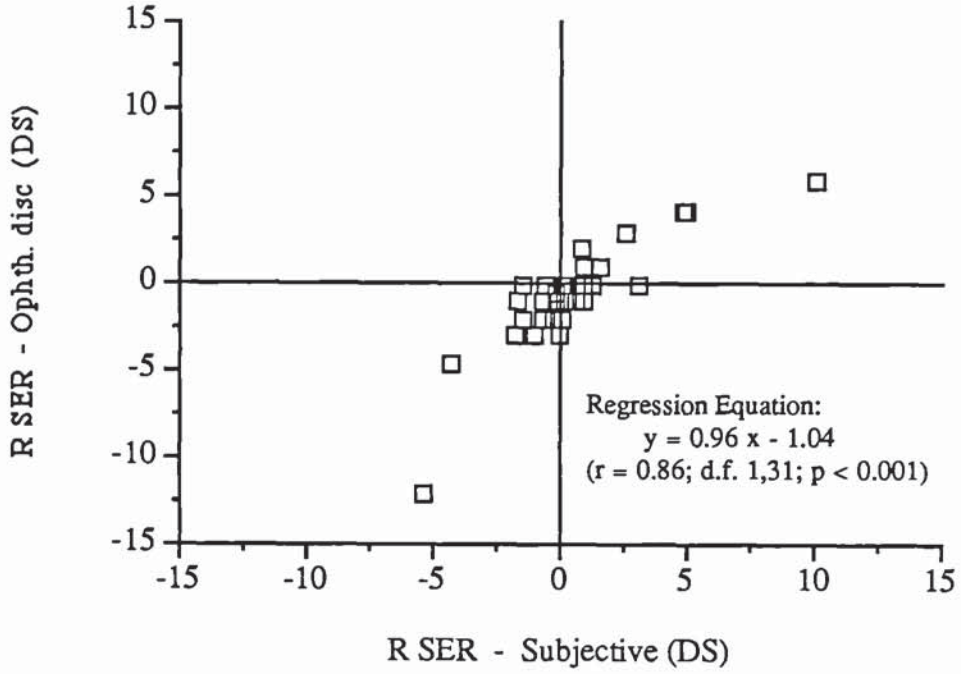


Figure A5.1 Scatterplot of spherical equivalent refraction based on focussing on optic disc during ophthalmoscopy versus subjective findings. The data is for the right eye.

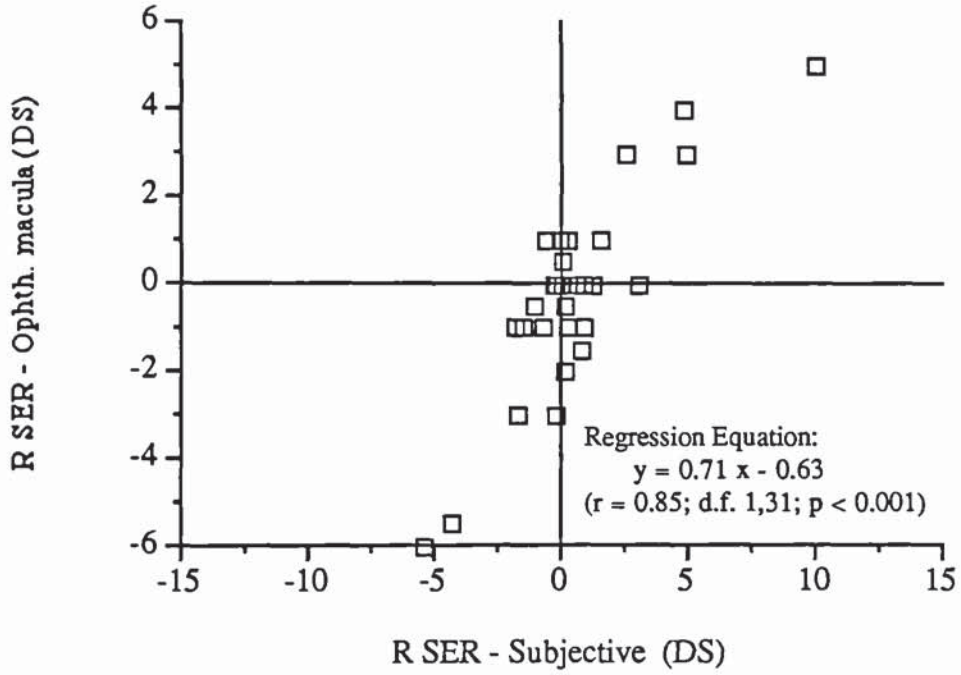


Figure A5.2 Scatterplot of spherical equivalent refraction based on focussing on macular region during ophthalmoscopy versus subjective findings. The data is for the right eye.

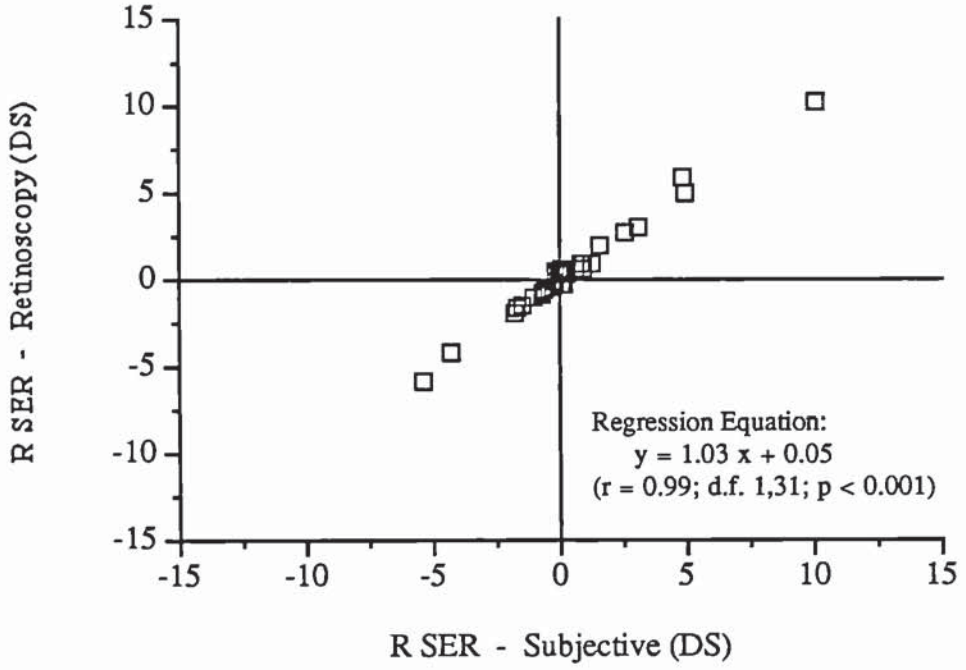


Figure A5.3 Scatterplot of spherical equivalent refraction found by retinoscopy versus subjective findings. The data is for the right eye.

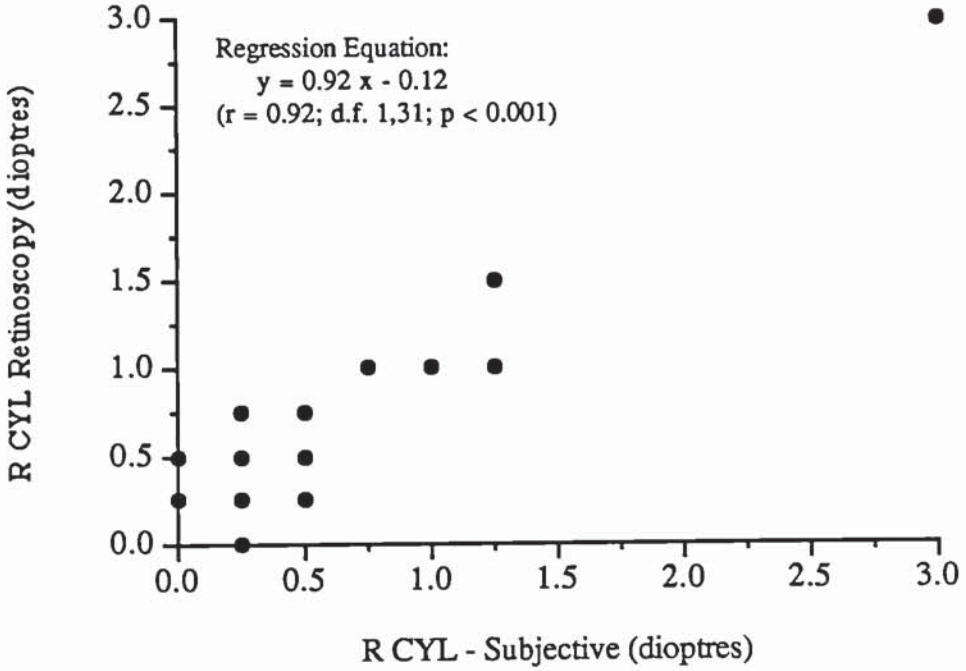


Figure A5.4 Scatterplot of cylindrical refractive power found by retinoscopy versus subjective findings. The data is for the right eye.

Table A5.13 Details of regression line equations and statistics for the objective v. subjective refraction study.
R. = retinoscopy, O.D. = ophthalmoscopy (disc), O.M. = ophthalmoscopy (macula). Format of regression equations:
$y = (m\ x + c)$ where y = objective refraction and x = subjective refraction.

Variable	Regression Coefficents			Statistics	
	m	c	r	d.f.	significance
R S.E.R. (R.)	1.03	0.05	0.99	1,31	$p < 0.001$
(O.D.)	0.96	-1.04	0.86	1,31	$p < 0.001$
(O.M.)	0.71	-0.63	0.85	1,31	$p < 0.001$
L S.E.R. (R.)	1.02	-0.03	0.99	1,31	$p < 0.001$
(O.D.)	0.91	-0.87	0.89	1,31	$p < 0.001$
(O.M.)	0.82	-0.86	0.87	1,31	$p < 0.001$
R. CYL. (R.)	0.92	0.12	0.92	1,31	$p < 0.001$
L. CYL. (R.)	1.00	0.05	0.91	1,31	$p < 0.001$

ii) Systematic differences between refractions

Group averaged data for the various objective and subjective refractions are given in Table A5.14. Similar trends were noted for each eye and the standard deviation of results were comparable for all methods. Retinoscopy showed at tendency to reveal more positive S.E.R. values and higher cylinder powers than subjective tests. Both ophthalmoscopic methods revealed more myopic refractive data. Statistical tests (paired t - tests) were performed to check whether any of the differences between objective and subjective refractive errors were significant. The results of this analysis is given in Table 5.15. Considering retinoscopy, only the changes observed in the right eye cylindrical power findings reached statistical significance. All ophthalmoscopic data was significantly different from subjective data.

Table A5.14 Summary of averaged power findings on objective and subjective refraction for 33 patients.
R. = retinoscopy, O.D. = ophthalmoscopy (disc), O.M. = ophthalmoscopy (macula), S. = subjective refraction.

Variable	Refractive Power (Dioptres)				
	Mean	S.D.	S.E.	Minimum	Maximum
R. S.E.R. (R.)	0.55	2.77	0.48	- 5.75	10.25
R. S.E.R.(O.D.)	-0.58	2.99	0.52	- 12.00	6.00
R. S.E.R.(O.M.)	-0.29	2.24	0.39	- 6.00	5.00
R. S.E.R. (S.)	0.48	2.67	0.46	- 5.38	10.12
L. S.E.R. (R.)	0.41	2.66	0.46	- 5.75	9.50
L. S.E.R.(O.D.)	-0.48	2.66	0.46	- 8.00	6.00
L. S.E.R.(O.M.)	-0.52	2.44	0.42	- 8.00	6.00
L. S.E.R. (S.)	0.42	2.59	0.45	- 5.25	9.50
R. CYL. (R.)	0.51	0.56	0.10	0.00	3.00
R. CYL. (S.)	0.42	0.56	0.10	0.00	3.00
L. CYL. (R.)	0.55	0.46	0.08	0.00	2.00
L. CYL. (S.)	0.50	0.41	0.07	0.00	1.75

Table A5.15 Statistical significances for objective v. subjective refraction study. Paired t - tests. Abbreviations as in Table A5.14.

Variable	Comparison between objective & subjective refractions		
	t - stat	d.f.	sig
R. S.E.R. (R.)	1.23	32	not sig.(0.23)
(O.D.)	- 3.94	32	$p < 0.001$
(O.M.)	- 3.15	32	$p < 0.001$
L. S.E.R. (R.)	- 0.31	32	not sig.(0.76)
(O.D.)	- 4.25	32	$p < 0.001$
(O.M.)	- 4.26	32	$p < 0.001$
R. CYL. (R.)	2.15	32	$p = 0.04$
L. CYL. (R.)	1.36	32	$p = 0.18$

iii) Accuracy of isolated measurements

Differences between objective and subjective refractive power findings were computed for each subject (by subtracting the subjective refraction from the objective and then converting all negative values to their positive equivalent). Table A5.16 summarises group findings and gives some impression of the degree of accuracy that might be expected using each method.

Retinoscopy An accuracy of around ± 0.2 dioptres in determination of S.E.R. and of around ± 0.15 dioptres in estimation of cylinder power was observed. Comparison of the largest differences found (around 1.1 dioptres for S.E.R. and 0.5 dioptres for the cylinder) at first suggests poorer results for determination of spherical power. Removal of one patient (a young high hypermetrope who did not habitually wear a prescription and would not accept full plus correction) from the data leaves maximum discrepancies between retinoscopy and subjective of 0.62 dioptres for S.E.R. and 0.50 dioptres for cylinders but does not alter maximum values on other tests.

Ophthalmoscopy (disc and macula) An accuracy of around ± 1.2 dioptres in determination of S.E.R. was observed using both methods. Comparison of the largest differences found suggests some support for slightly greater accuracy in determination of the left eye power. This could have been related to the examiners eye dominance.

Table A5.16 Summary of differences between objective and subjective refractive power findings of 33 subjects. Abbreviations as in Table A5.14.

Variable	Difference in Obj. & Subj. Ref. Power (Dioptres)				
	Mean	S.D.	S.E.	Minimum	Maximum
R. S.E.R. (R.)	0.19	0.24	0.04	0.00	1.12
(O.D.)	1.30	1.34	0.23	0.00	6.62
(O.M.)	1.19	1.07	0.19	0.12	5.12
L. S.E.R. (R.)	0.22	0.17	0.03	0.00	0.50
(O.D.)	1.14	1.01	0.18	0.12	3.75
(O.M.)	1.20	1.02	0.18	0.12	3.50
R. CYL. (R.)	0.17	0.16	0.03	0.00	0.50
L. CYL. (R.)	0.12	0.15	0.03	0.00	0.50

Appendix 6

6A. Acuity v. refraction statistics

i) Full newborn sample

Table A6.1 Details of regression line equations and statistics for neonatal binocular vertical grating acuity (M.A.R., mins. of arc) versus refraction data.
Format of regression equations :-
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables	Regression Coefficents			Statistics	
(1) v. (2)	m	c	r	d.f.	significance
B(V) v. R. S.E.R.	0.93	59.6	0.07	1,107	p = 0.496
B(V) v. L. S.E.R.	0.61	60.7	0.05	1,107	p = 0.627
B(V) v. R. defocus	0.93	57.3	0.07	1,107	p = 0.496
B(V) v. L. defocus	0.61	59.2	0.05	1,107	p = 0.627
B(V) v. Aniso.	9.72	55.8	0.17	1,107	p = 0.088
B(V) v. R. Cyl.	-0.53	63.2	0.02	1,107	p = 0.840
B(V) v. L. Cyl.	0.42	61.6	0.02	1,107	p = 0.874

Table A6.2 Details of regression line equations and statistics for neonatal mean binocular acuity (M.A.R., mins. of arc) versus refraction data.
Format of regression equations :-
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables	Regression Coefficents			Statistics	
(1) v (2)	m	c	r	d.f.	significance
Mean Binoc v. R. S.E.R.	1.03	58.9	0.08	1,110	p = 0.427
Mean Binoc v. L. S.E.R.	0.69	60.0	0.05	1,110	p = 0.566
Mean Binoc v. R. defocus	1.03	56.3	0.08	1,110	p = 0.427
Mean Binoc v. L. defocus	0.69	58.3	0.05	1,110	p = 0.566
Mean Binoc v. Aniso.	11.06	54.5	0.20	1,110	p = 0.036 *
Mean Binoc v. R. Cyl.	0.11	61.7	0.00	1,110	p = 0.976
Mean Binoc v. L. Cyl.	1.16	59.8	0.04	1,110	p = 0.641

ii) Follow-up samples

Table A6.3 Details of regression line equations and statistics for "three" month monocular acuity (M.A.R., mins. of arc) versus refraction data.
Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R.(V) v. R. S.E.R.	3.46	20.9	0.30	1,11	p = 0.165
L.(V) v. L. S.E.R.	3.58	21.7	0.39	1,13	p = 0.132
R.(V) v. R. defocus	3.46	12.2	0.30	1,11	p = 0.166
L.(V) v. L. defocus	3.58	12.7	0.39	1,13	p = 0.132
R.(V) v. R. Max. Am.	3.09	20.0	0.27	1,11	p = 0.376
L.(V) v. L. Max. Am.	3.05	21.2	0.34	1,13	p = 0.162
R.(V) v. R. Min. Am.	3.45	23.0	0.31	1,11	p = 0.176
L.(V) v. L. Min. Am.	3.57	23.7	0.40	1,13	p = 0.121
Mean R. v. R. S.E.R.	3.43	21.0	0.30	1,12	p = 0.172
Mean L. v. L. S.E.R.	3.04	22.8	0.33	1,13	p = 0.166
Mean R. v. R. defocus	3.43	12.4	0.30	1,12	p = 0.172
Mean L. v. L. defocus	3.05	15.2	0.33	1,13	p = 0.166
Mean R. v. R. Max. Am.	2.87	20.9	0.27	1,12	p = 0.358
Mean L. v. L. Max. Am.	2.53	22.5	0.29	1,13	p = 0.165
Mean R. v. R. Min. Am.	3.65	22.5	0.32	1,12	p = 0.177
Mean L. v. L. Min. Am.	3.10	24.4	0.35	1,13	p = 0.156
Best R. v. R. S.E.R.	3.82	15.8	0.32	1,12	p = 0.177
Best L. v. L. S.E.R.	2.00	21.6	0.26	1,13	p = 0.344
Best R. v. R. defocus	3.82	6.2	0.30	1,12	p = 0.177
Best L. v. L. defocus	2.01	16.5	0.26	1,13	p = 0.343
Best R. v. R. Max. Am.	3.21	15.6	0.28	1,12	p = 0.156
Best L. v. L. Max. Am.	1.50	21.9	0.20	1,13	p = 0.465
Best R. v. R. Min. Am.	4.05	17.5	0.34	1,12	p = 0.173
Best L. v. L. Min. Am.	2.21	22.3	0.30	1,13	p = 0.171

Table A6.4 Details of regression line equations and statistics for "six" month monocular acuity (M.A.R., mins. of arc) versus refraction data.
Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R.(V) v. R. S.E.R.	- 1.21	18.8	0.12	1,20	p = 0.609
L.(V) v. L. S.E.R.	- 6.12	26.5	0.36	1,22	p = 0.080
R.(V) v. R. defocus	- 1.22	21.9	0.12	1,20	p = 0.606
L.(V) v. L. defocus	- 6.14	41.9	0.36	1,22	p = 0.079
R.(V) v. R. Max. Am.	- 1.38	23.7	0.14	1,20	p = 0.539
L.(V) v. L. Max. Am.	- 4.49	28.4	0.29	1,22	p = 0.131
R.(V) v. R. Min. Am.	- 0.77	17.7	0.08	1,20	p = 0.726
L.(V) v. L. Min. Am.	- 5.61	21.2	0.35	1,22	p = 0.080
Mean R. v. R. S.E.R.	- 0.55	18.7	0.06	1,20	p = 0.785
Mean L. v. L. S.E.R.	- 4.61	23.6	0.40	1,22	p = 0.057
Mean R. v. R. defocus	- 0.56	20.1	0.06	1,20	p = 0.785
Mean L. v. L. defocus	- 4.63	35.2	0.40	1,22	p = 0.056
Mean R. v. R. Max. Am.	- 1.14	20.4	0.13	1,20	p = 0.555
Mean L. v. L. Max. Am.	- 2.95	31.5	0.28	1,22	p = 0.135
Mean R. v. R. Min. Am.	0.13	18.2	0.02	1,20	p = 0.974
Mean L. v. L. Min. Am.	- 4.68	19.7	0.44	1,22	p = 0.032 *
Best R. v. R. S.E.R.	0.12	14.3	0.02	1,20	p = 0.934
Best L. v. L. S.E.R.	- 3.88	19.0	0.55	1,22	p = 0.006 *
Best R. v. R. defocus	0.13	14.0	0.02	1,20	p = 0.933
Best L. v. L. defocus	- 3.88	28.8	0.55	1,22	p = 0.006 *
Best R. v. R. Max. Am.	- 0.60	15.6	0.09	1,20	p = 0.675
Best L. v. L. Max. Am.	- 3.23	21.0	0.51	1,22	p = 0.011 *
Best R. v. R. Min. Am.	0.78	14.3	0.13	1,20	p = 0.574
Best L. v. L. Min. Am.	- 3.15	15.6	0.48	1,22	p = 0.017 *

Table A6.5 Details of regression line equations and statistics for twelve month monocular acuity (M.A.R., mins. of arc) versus refraction data.
Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
R.(V) v. R. S.E.R.	- 0.85	13.6	0.27	1,4	p = 0.600
L.(V) v. L. S.E.R.	2.41	12.9	0.60	1,7	p = 0.086
R.(V) v. R. defocus	- 0.55	15.7	0.27	1,4	p = 0.600
L.(V) v. L. defocus	2.40	6.9	0.60	1,7	p = 0.087
R.(V) v. R. Max. Am.	- 0.82	13.9	0.32	1,4	p = 0.535
L.(V) v. L. Max. Am.	1.86	12.6	0.54	1,7	p = 0.127
R.(V) v. R. Min. Am.	- 0.61	12.9	0.18	1,4	p = 0.740
L.(V) v. L. Min. Am.	3.14	13.7	0.66	1,7	p = 0.052 *
Mean R. v. R. S.E.R.	- 0.04	13.2	0.01	1,4	p = 0.980
Mean L. v. L. S.E.R.	1.70	13.8	0.59	1,7	p = 0.093
Mean R. v. R. defocus	- 0.04	13.3	0.01	1,4	p = 0.981
Mean L. v. L. defocus	1.70	9.5	0.59	1,7	p = 0.093
Mean R. v. R. Max. Am.	- 0.25	13.6	0.11	1,4	p = 0.842
Mean L. v. L. Max. Am.	1.24	13.6	0.50	1,7	p = 0.155
Mean R. v. R. Min. Am.	0.38	12.9	0.12	1,4	p = 0.826
Mean L. v. L. Min. Am.	2.35	14.2	0.69	1,7	p = 0.039 *
Best R. v. R. S.E.R.	- 0.85	13.6	0.27	1,4	p = 0.600
Best L. v. L. S.E.R.	1.48	11.7	0.60	1,7	p = 0.085
Best R. v. R. defocus	- 0.85	15.7	0.27	1,4	p = 0.600
Best L. v. L. defocus	1.48	8.0	0.60	1,7	p = 0.085
Best R. v. R. Max. Am.	- 0.82	13.9	0.32	1,4	p = 0.535
Best L. v. L. Max. Am.	1.17	11.4	0.55	1,7	p = 0.116
Best R. v. R. Min. Am.	- 0.61	12.9	0.18	1,4	p = 0.740
Best L. v. L. Min. Am.	1.88	12.2	0.65	1,7	p = 0.059

Table A6.6 Details of regression line equations and statistics for follow-up samples binocular acuity (M.A.R., mins. of arc) versus anisometropia data.
Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Sample & Variables Acuity v. Anisometropia	Regression Coefficents m	c	r	Statistics d.f.	significance
"Three" Month :					
Binoc. (V)	- 9.71	22.1	0.16	1,15	p = 0.552
Mean Binoc.	- 7.25	19.4	0.21	1,15	p = 0.428
Best Binoc.	- 3.46	15.0	0.15	1,15	p = 0.555
"Six" Month :					
Binoc. (V)	2.00	11.3	0.05	1,13	p = 0.863
Mean Binoc.	1.93	11.7	0.05	1,13	p = 0.847
Best Binoc.	- 1.10	11.1	0.03	1,13	p = 0.904
Twelve Month :					
Binoc. (V)	- 14.8	17.7	0.31	1,6	p = 0.461
Mean Binoc.	- 14.8	19.6	0.26	1,10	p = 0.408
Best Binoc.	- 13.5	19.0	0.24	1,10	p = 0.450

Table A6.7 Details of regression line equations and statistics for follow-up samples monocular acuity (M.A.R., mins. of arc) versus astigmatic refraction data. Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Sample & Variables	Regression Coefficents			Statistics	
Acuity v Cyl. power	m	c	r	d.f.	significance
"Three" Month :					
R.(V) v. R. Cyl.	- 2.49	34.1	0.10	1,11	p = 0.743
L.(V) v. L. Cyl.	- 1.84	32.0	0.11	1,13	p = 0.690
Mean R. v. R. Cyl.	- 2.02	32.8	0.09	1,12	p = 0.772
Mean L. v. L. Cyl.	- 1.97	32.0	0.12	1,13	p = 0.664
Best R. v. R. Cyl.	- 2.08	28.7	0.08	1,12	p = 0.776
Best L. v. L. Cyl.	- 2.44	28.9	0.18	1,13	p = 0.519
"Six" Month :					
R.(V) v. R. Cyl.	- 1.17	19.6	0.08	1,20	p = 0.718
L.(V) v. L. Cyl.	1.24	17.4	0.07	1,22	p = 0.757
Mean R. v. R. Cyl.	- 2.63	22.8	0.21	1,20	p = 0.340
Mean L. v. L. Cyl.	2.19	14.6	0.17	1,22	p = 0.414
Best R. v. R. Cyl.	- 2.96	19.6	0.32	1,20	p = 0.118
Best L. v. L. Cyl.	- 0.34	15.2	0.04	1,22	p = 0.838
Twelve Month :					
R.(V) v. R. Cyl.	- 1.32	13.9	0.32	1,4	p = 0.540
L.(V) v. L. Cyl.	1.43	13.9	0.15	1,7	p = 0.692
Mean R. v. R. Cyl.	- 1.22	14.4	0.31	1,4	p = 0.547
Mean L. v. L. Cyl.	0.00	15.3	0.00	1,7	p = 1.000
Best R. v. R. Cyl.	- 1.32	13.9	0.32	1,4	p = 0.540
Best L. v. L. Cyl.	1.27	11.9	0.22	1,7	p = 0.563

6B. Acuity v. other factors statistics

i) Full newborn sample

Table A6.8 Details of regression line equations and statistics for neonatal acuity versus various factors.
P.N. (h) = post-natal age (hours), P.N. (l.h) = post-natal age (log. hours), B.W. = Birth weight (kg.), H.C. = Head circumference (cm.) and Mat. Age = Maternal age (yrs). Format of regression equations:
y = (m x + c) where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	d.f.	Statistics significance
B(V) v. P.C.A.(wks)	- 4.6	245.2	0.16	1,122	p = 0.084
Mean Binoc v. P.C.A.(wks)	- 3.1	184.3	0.11	1,125	p = 0.115
B(V) v. P.N. (h)	- 0.2	72.0	0.16	1,122	p = 0.081
Mean Binoc v. P.N. (h)	- 0.2	71.3	0.16	1,125	p = 0.078
B(V) v. P.N. (l.h)	- 10.2	97.9	0.23	1,122	p = 0.010 *
Mean Binoc v. P.N. (l.h)	- 9.6	95.5	0.22	1,125	p = 0.011 *
B(V) v. Labour (hrs)	1.9	57.4	0.20	1,45	p = 0.121
Mean Binoc v. Labour (hrs)	1.6	56.7	0.18	1,47	p = 0.126
B(V) v. B.W. (kg.)	- 3.8	75.2	0.04	1,122	p = 0.634
Mean Binoc v. B.W. (kg.)	- 1.0	59.4	0.01	1,125	p = 0.897
B(V) v. H.C. (cm.)	- 3.3	174.5	0.10	1,122	p = 0.102
Mean Binoc v. H.C. (cm.)	- 1.6	118.0	0.06	1,125	p = 0.537
B(V) v. Length (cm.)	- 0.1	69.2	0.01	1,122	p = 0.918
Mean Binoc v. Length (cm.)	- 0.2	50.5	0.02	1,125	p = 0.835
B(V) v. Mat. Age (yrs)	- 0.7	80.1	0.11	1,122	p = 0.106
Mean Binoc v. Mat. Age (yrs)	- 0.6	78.6	0.10	1,125	p = 0.103

ii) Newborn subgroups:

Table A6.9 Details of binocular acuity versus post-natal age regression line equations and statistics for the newborn samples with and without birth complications.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations:
y = (m x + c) where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
High trauma (n=35)					
B(V). v P.N.(l.h)	-16.16	117.3	0.31	1,33	p = 0.076
Mean Binoc v P.N.(l.h)	-17.73	122.4	0.34	1,33	p = 0.050 *
Low trauma (n=92)					
B(V). v P.N.(l.h)	-7.90	91.2	0.19	1,87	p = 0.087
Mean Binoc v P.N.(l.h)	-6.60	86.4	0.17	1,90	p = 0.089

Table A6.10 Details of binocular acuity versus post-natal age regression line equations and statistics for newborn infants with one minute Apgar scores of up to eight and the remaining sample.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Apgar ≤ 8 (n=64)					
B(V). v P.N.(l.h)	-15.48	120.6	0.32	1,59	p = 0.012 *
Mean Binoc v P.N.(l.h)	-17.04	125.4	0.35	1,62	p = 0.005 *
Apgar > 8 (n=62)					
B(V). v P.N.(l.h)	-4.94	76.0	0.13	1,60	p = 0.326
Mean Binoc v P.N.(l.h)	-2.11	65.6	0.06	1,60	p = 0.644

Table A6.11 Details of binocular acuity versus post-natal age regression line equations and statistics for the newborn samples with and without retinal haemorrhage.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Retinal haem (n=32)					
B(V). v P.N.(l.h)	-21.83	132.1	0.48	1,28	p = 0.007 *
Mean Binoc v P.N.(l.h)	-21.32	130.5	0.47	1,30	p = 0.006 *
Nil retinal haem (n=80)					
B(V). v P.N.(l.h)	-9.18	95.3	0.21	1,77	p = 0.069
Mean Binoc v P.N.(l.h)	-7.78	89.7	0.19	1,78	p = 0.081

Table A6.12 Details of binocular acuity versus post-natal age regression line equations and statistics for the newborn samples with primiparous or multiparous mothers.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations:
$y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Primiparous (n=33)					
B(V). v P.N.(l.h)	-18.79	131.1	0.48	1,31	p = 0.004 *
Mean Binoc v P.N.(l.h)	-15.86	118.6	0.46	1,31	p = 0.007 *
Multiparous (n=94)					
B(V). v P.N.(l.h)	-6.97	86.2	0.15	1,89	p = 0.109
Mean Binoc v P.N.(l.h)	-7.17	87.11	0.16	1,92	p = 0.100

Table A6.13 Details of binocular acuity versus post-natal age regression line equations and statistics for infants whose mothers received pethidine during labour and the remaining sample.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations: $y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Pethidine (n=57)					
B(V). v P.N.(l.h)	-19.25	134.5	0.38	1,52	p = 0.004 *
Mean Binoc v P.N.(l.h)	-17.57	127.5	0.36	1,55	p = 0.006 *
Non pethidine (n=70)					
B(V). v P.N.(l.h)	-2.80	69.1	0.07	1,68	p = 0.541
Mean Binoc v P.N.(l.h)	-2.94	69.5	0.08	1,68	p = 0.505

Table A6.14 Details of binocular acuity versus post-natal age regression line equations and statistics for the male and female newborn samples.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations: $y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Males (n=62)					
B(V). v P.N.(l.h)	-11.35	98.6	0.31	1,60	p = 0.015 *
Mean Binoc v P.N.(l.h)	-10.48	96.2	0.29	1,60	p = 0.023 *
Females (n=65)					
B(V). v P.N.(l.h)	-8.83	96.5	0.15	1,60	p = 0.119
Mean Binoc v P.N.(l.h)	-8.49	94.0	0.16	1,63	p = 0.121

Table A6.15 Details of binocular acuity versus post-natal age regression line equations and statistics for Asian and Caucasian newborn samples.
P.N. (l.h.) = post-natal age (log. hrs). Format of regression equations: $y = (m x + c)$ where y = variable 1 and x = variable 2

Variables (1) v (2)	Regression Coefficents m	c	r	Statistics d.f.	significance
Asian (n=63)					
B(V). v P.N.(l.h)	-7.16	88.3	0.14	1,60	p = 0.097
Mean Binoc v P.N.(l.h)	-4.64	78.3	0.10	1,61	p = 0.454
Caucasian (n=45)					
B(V). v P.N.(l.h)	-6.99	79.8	0.20	1,41	p = 0.127
Mean Binoc v P.N.(l.h)	-7.20	81.9	0.21	1,43	p = 0.119

iii) Follow-up samples

Table A6.16 Details of mean monocular acuity (M.A.R., mins. of arc) according to order of testing for various follow-up age groups. Paired samples.

Staircase Number (A) v. (B)	n	Acuity on Staircase "A" Mean	S.E.	Acuity on Staircase "B" Mean	S.E.
3 Month:					
1 v. 2	8	32.6	7.5	30.3	8.2
1 v. 3	5	38.0	11.1	37.0	14.2
1 v. 4	3	30.3	10.3	17.2	1.6
2 v. 3	8	29.0	8.2	32.9	8.5
2 v. 4	4	32.4	15.9	17.6	0.9
3 v. 4	4	24.1	4.6	17.6	0.9
4 Month:					
1 v. 2	14	19.2	1.8	24.0	3.1
1 v. 3	8	21.3	2.5	26.4	4.3
1 v. 4	3	21.8	6.0	17.5	4.9
2 v. 3	11	22.4	2.7	27.9	3.5
2 v. 4	3	23.3	11.2	17.5	4.9
3 v. 4	6	20.6	3.4	15.9	2.5
5 Month:					
1 v. 2	7	13.4	2.6	11.9	1.7
1 v. 3	4	10.6	1.6	13.3	1.7
1 v. 4	2	10.5	3.5	12.0	1.4
2 v. 3	4	8.8	0.6	13.3	1.7
2 v. 4	2	8.0	0.0	12.0	1.4
3 v. 4	2	11.3	0.4	12.0	1.4
6 Month:					
1 v. 2	14	17.2	2.5	21.3	4.8
1 v. 3	10	18.4	3.4	15.3	2.6
1 v. 4	7	20.2	4.6	15.2	2.4
2 v. 3	10	19.4	5.8	15.3	2.6
2 v. 4	7	21.1	8.1	15.2	2.4
3 v. 4	8	13.6	1.7	14.4	2.2
7 Month:					
1 v. 2	13	18.2	3.8	15.0	1.6
1 v. 3	10	19.0	4.8	23.7	9.1
1 v. 4	8	20.4	6.0	15.2	2.9
2 v. 3	10	14.6	1.8	23.7	9.1
2 v. 4	8	13.9	1.6	15.2	2.9
3 v. 4	8	23.4	11.6	15.2	2.9
12 Month:					
1 v. 2	7	11.6	1.5	15.6	2.2
1 v. 3	4	9.3	1.4	17.0	5.7
1 v. 4	4	9.3	1.4	13.0	2.2
2 v. 3	4	13.5	2.3	17.0	5.7
2 v. 4	4	13.5	2.3	13.0	2.2
3 v. 4	4	17.0	5.7	13.0	2.2

Appendix 7

Details of scientific poster presented at the Third International Symposium of the Northern Eye Institute, U.M.I.S.T., Manchester. (August 9 - 13 th):

ASSESSMENT OF GRATING ACUITY IN INFANTS AND YOUNG CHILDREN : CLINICAL EXPERIENCE WITH PREFERENTIAL LOOKING TESTS

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INTRODUCTION

Early preferential looking methods for assessment of infant visual acuity relied upon formal psychophysical procedures which were lengthy and really only applicable to laboratory studies. Recent interest has been directed to the development of more clinically appropriate methods. Two such techniques have been evaluated in the present study. Both maintain a forced-choice testing protocol, are administered by a single examiner and rely on gratings arranged in $\sqrt{2}$ (i.e. 0.5 octave) steps of spatial frequency. In the first method presentation of acuity gratings (vertical or horizontal) was achieved using a specially constructed optical projection system. Tests were conducted in a darkened room. The second method consisted of the use of a commercially available acuity card test for which good room lighting is required. Each card comprises a photographically reproduced rectangular (vertically orientated) square-wave grating embedded in a surround of equivalent mean luminance.

AIMS

1. Collection of normative acuity data for comparison with published normative data and with data of clinical patients examined using the same procedures.
2. Evaluation of test success rates for various age categories.
3. Collection of interocular acuity difference data from normals to evaluate the diagnostic sensitivity of the methods.

RESULTS

1. NORMATIVE DATA

OPTICAL PROJECTION SYSTEM

Initially 174 healthy infants (free from ocular abnormality) were examined whilst in a hospital maternity ward during the first week of life. Subsequent examinations (a maximum of five per infant) were conducted in departmental clinics at Aston University in some cases for up to one year. The results produced were similar to published normative data using the acuity card procedure and slightly lower than, but comparable with, acuity data derived using extended preferential looking methods (Figure 1).

TELLER ACUITY CARD SYSTEM

A sample of 63 normal children (3 to 52 months; 68% ≤ 3 years), examined either at a health centre, nursery or in departmental clinics produced acuity results comparable with normative data published for the test. Figure 4 illustrates monocular acuity data collected from these children and from 9 children having clinical histories of monocular deprivation. The latter formed part of an additional sample of 49 children (80% ≤ 3 years) having various ocular or neurological abnormalities that were examined (on up to seven occasions) whilst attending an ophthalmic clinic at Birmingham Children's Hospital.

2. TEST SUCCESS RATES

OPTICAL PROJECTION SYSTEM

Normals (Newborn to 12 months)

Up to six distinct acuity determinations were attempted per visit. Of the 321 test sessions, 92% resulted in at least one acuity estimate. The success rate of the test varied with age (87% of newborns and 98% of older infants were testable). Figures 2A &2B summarise the success rates amongst infants of between one month and one year. Testing of infants below three months was the most difficult (particularly monocularly). Infants of around six to seven months were most easily tested. Testing was typically completed within 20 minutes.

TELLER ACUITY CARD SYSTEM

Normals (3 to 52 months)

Up to three distinct acuity determinations (right eye, left eye and binocular) were attempted. At least one acuity estimate was obtained from each child and in most cases all three measurements were completed within 10 minutes. Figure 5 summarises the success rates for five age categories. Apart from a slight dip during the latter half of the first year, "testability" steadily improved with age reaching a maximum during the third year.

Clinical sample (1 week to 8 years; 80% ≤ 3 years; n = 49)

At least one estimate of acuity was obtained in 96% of sessions, which were typically completed in 15 minutes.

3. INTEROCULAR ACUITY DIFFERENCES

OPTICAL PROJECTION SYSTEM

Figure 3 summarises interocular acuity differences found in normal infants during the first year. Acuity differences of up to two octaves were found but most values did not exceed one octave. There was a trend for acuity differences to decline with age which just reached statistical significance.

TELLER ACUITY CARD SYSTEM

Figure 6 summarises interocular acuity difference findings amongst normal children (3 to 52 months) and clinical patients having histories of monocular deprivation. Acuity differences of up to 1.5 octaves were found in about one third of normals but each of five re-examined children showed equal monocular acuities on retesting. In clinical patients, acuity differences were more frequently encountered and tended to be of at least one octave.

CONCLUSION

These findings demonstrate that suitably adapted preferential looking methods can provide rapid and valid estimates of visual acuity in infants and young children. The tests appear sufficiently robust to be appropriate for routine clinical use although it is important that the examiner be aware that the likely sensitivity of individual measurements is of the order of ± 1 octave so repeated testing may be required on occasions.

Figures 1 to 3 show normative data obtained with the optical projection system.

Figures 4 to 6 show acuity card findings.

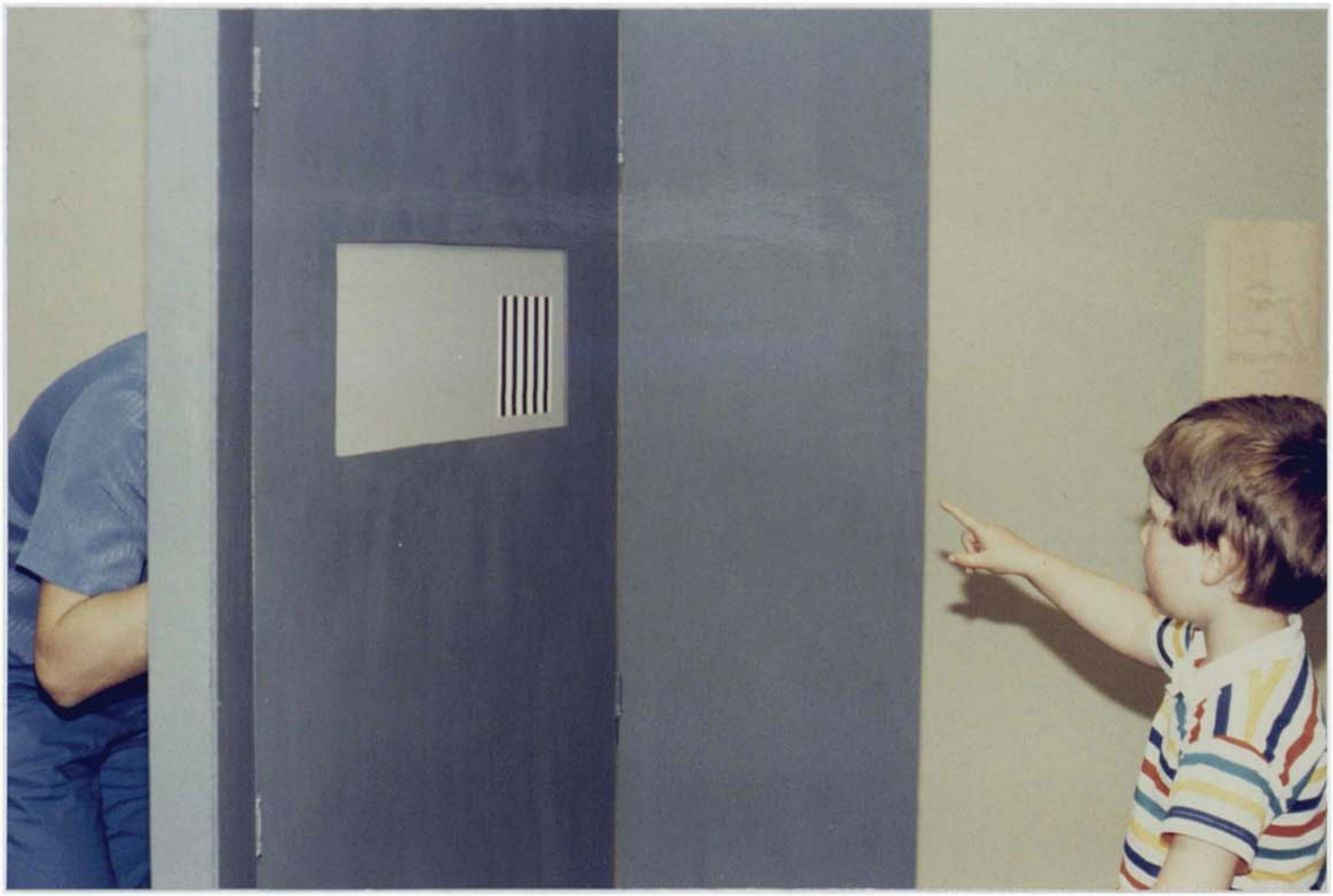

Plate 7.1

Three year old participating in Teller acuity card test.

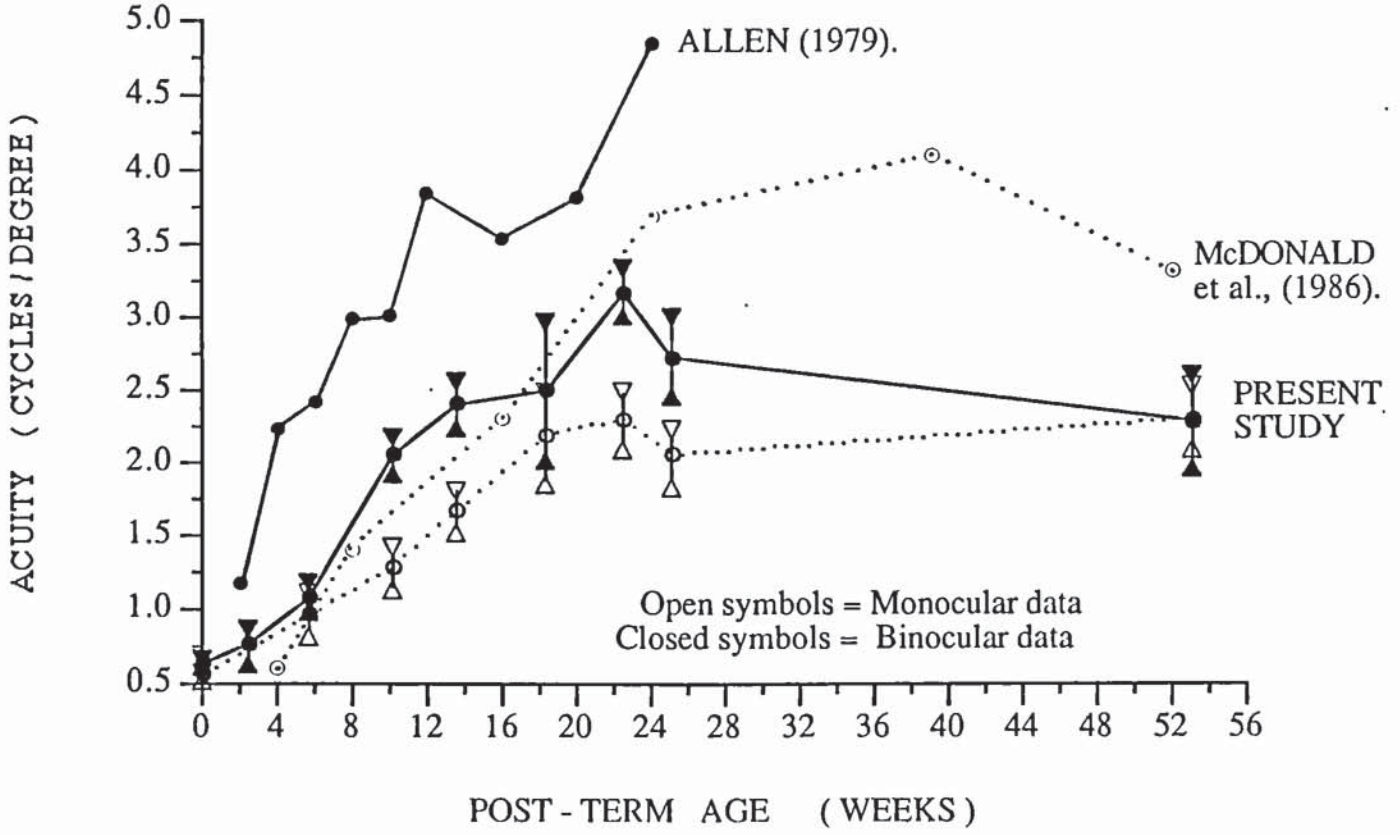

Figure 1. Comparison between group averaged normative data obtained in this study and in previous studies using laboratory FPL (Allen, 1979) and Teller acuity card (McDonald et al., 1986) methods.

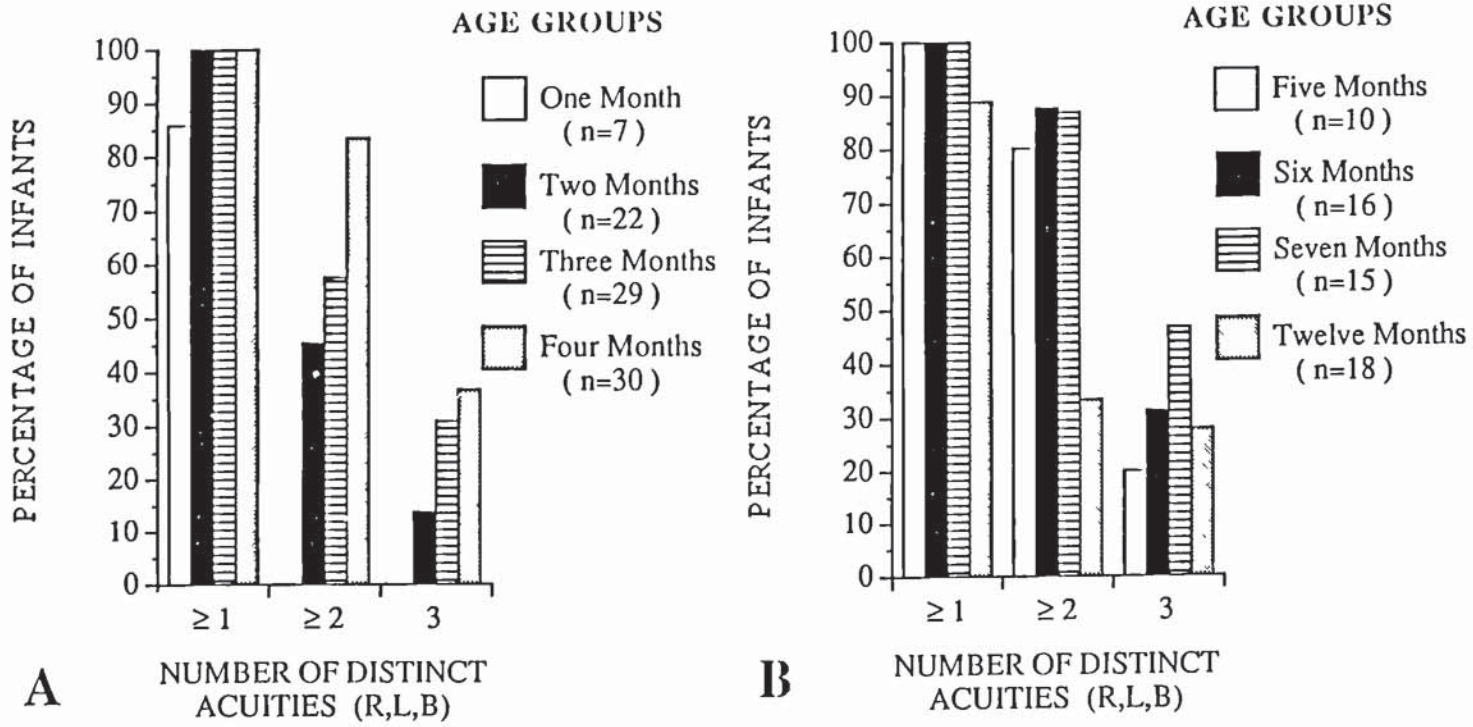

Figure 2 (A & B). Test success rates in normal infants using the optical projection system. The histograms illustrate the percentages of infants within 8 age groups completing specific monocular (R.E. and/or L.E.) and/or binocular tests. Infants completing tests using both horizontal and vertical grating orientations for a particular condition have only been credited with one test. At least one acuity estimate was obtained from all infants apart from one 1 month-old and two 12 month-olds. Performance improved steadily reaching a maximum at seven months when almost 50% completed all three tests. One year olds were easily distracted and generally difficult to test.

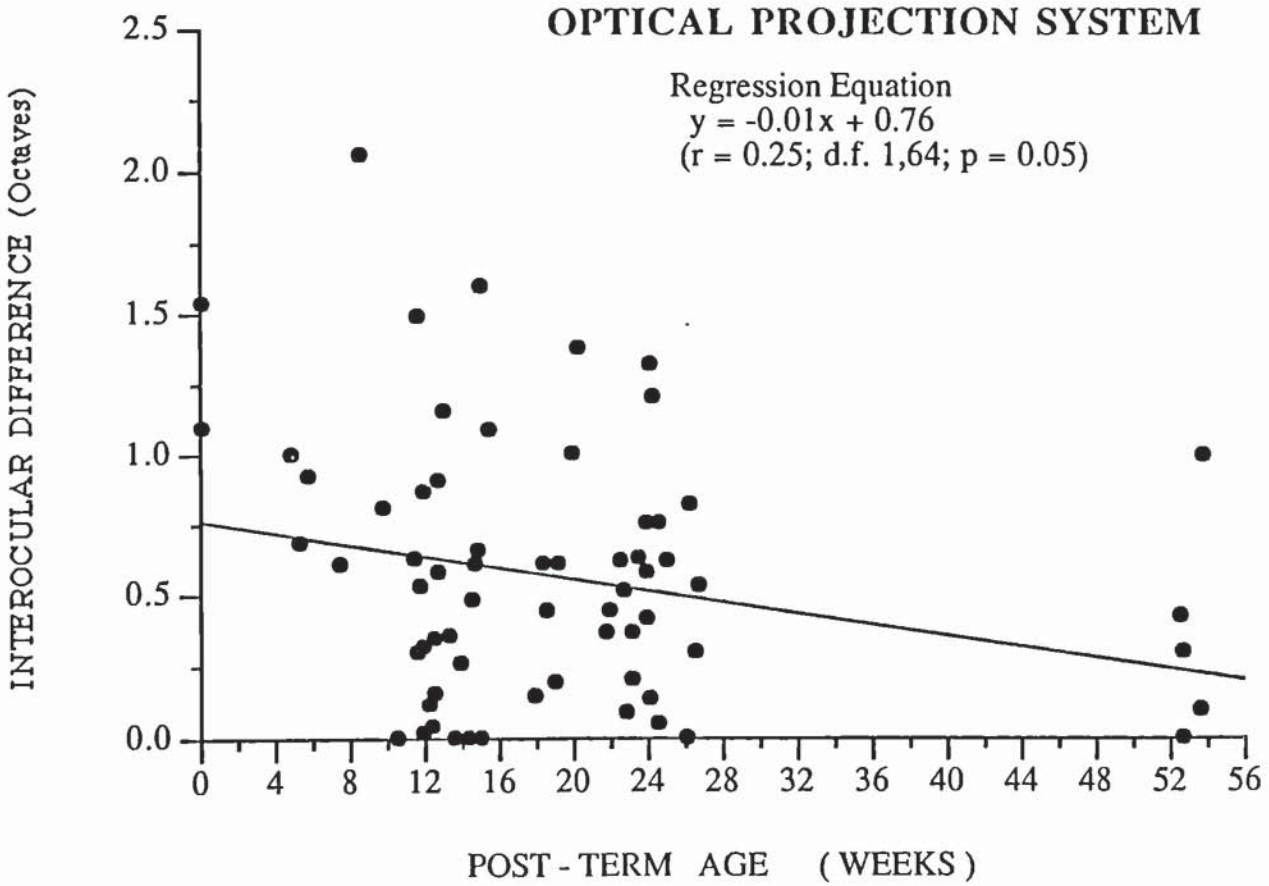

Figure 3. Scatterplot showing interocular acuity differences found in normal infants during their first year. (Group averaged findings declined from 1.3 octaves at birth to around 0.5 octaves during months 4 to 7 and reached about 0.4 octaves by one year).

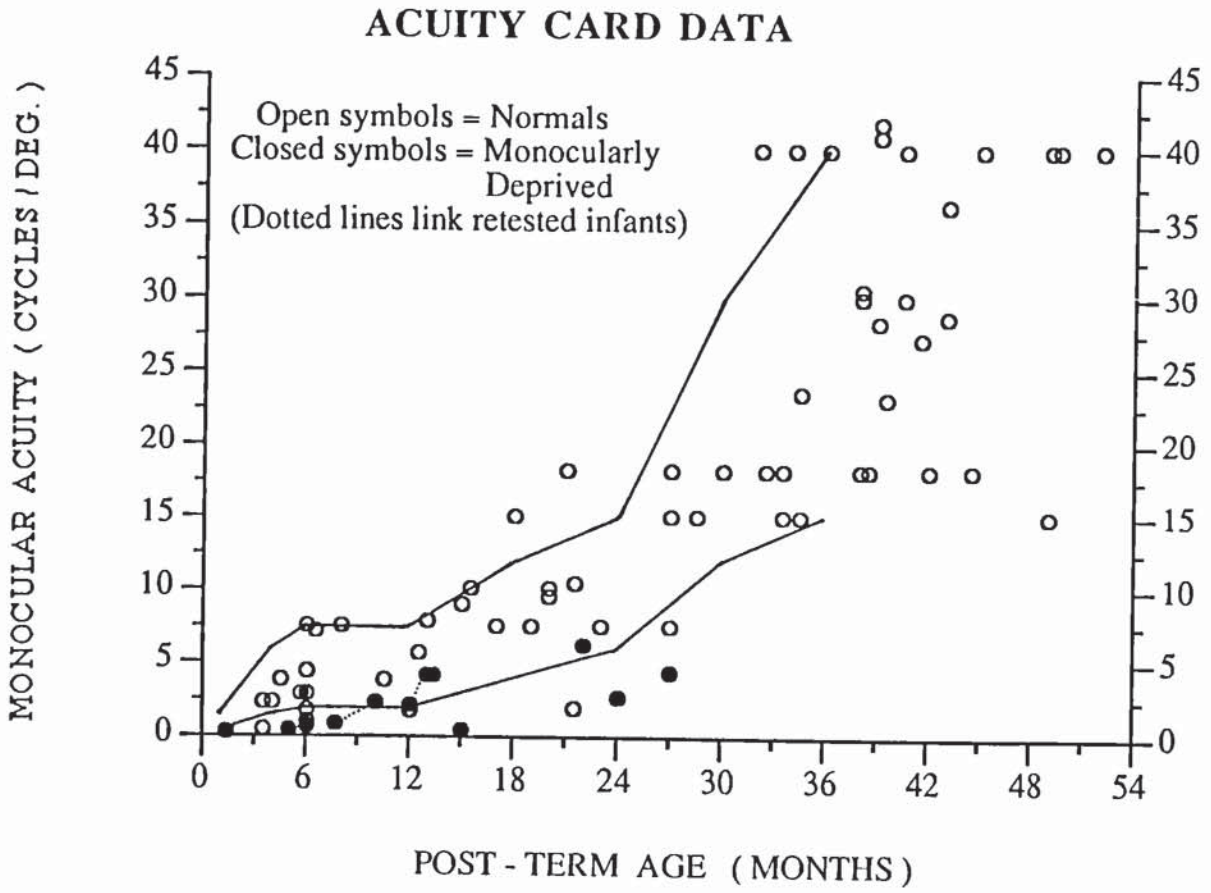

Figure 4. Monocular acuities of 61 normal infants (either right or left eye) and 9 monocularly deprived infants (deprived eye). The solid lines denote the range of acuity values expected in normals (derived from preliminary norms in March 1986 Handbook).

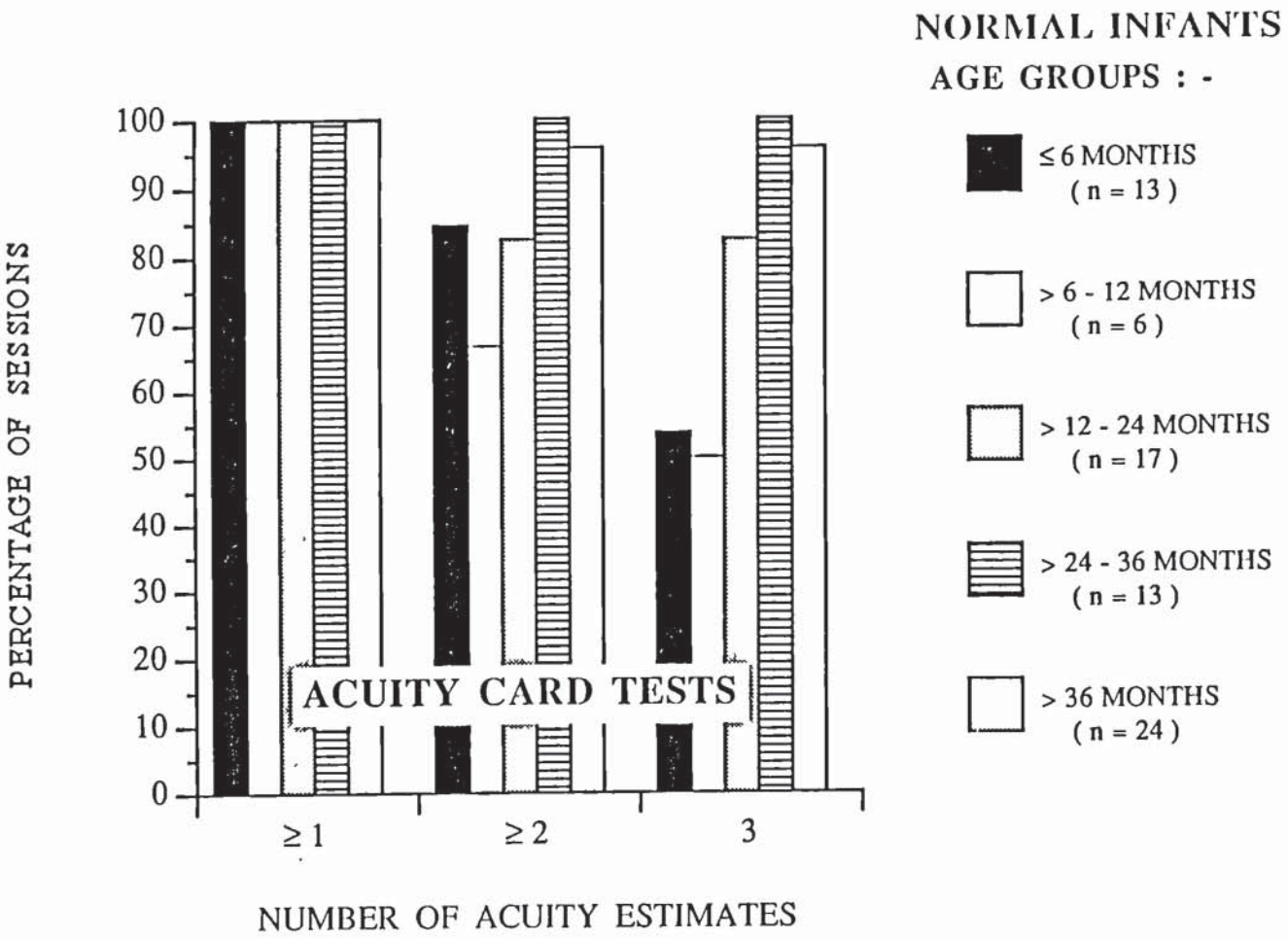

Figure 5. Success of acuity card testing of 63 normal pre-school children in 5 age ranges; in all cases at least one acuity estimate was obtained.Testability improved with age (except from 6 to 12 months), reaching 100% at 3 years. One older child refused to be patched.

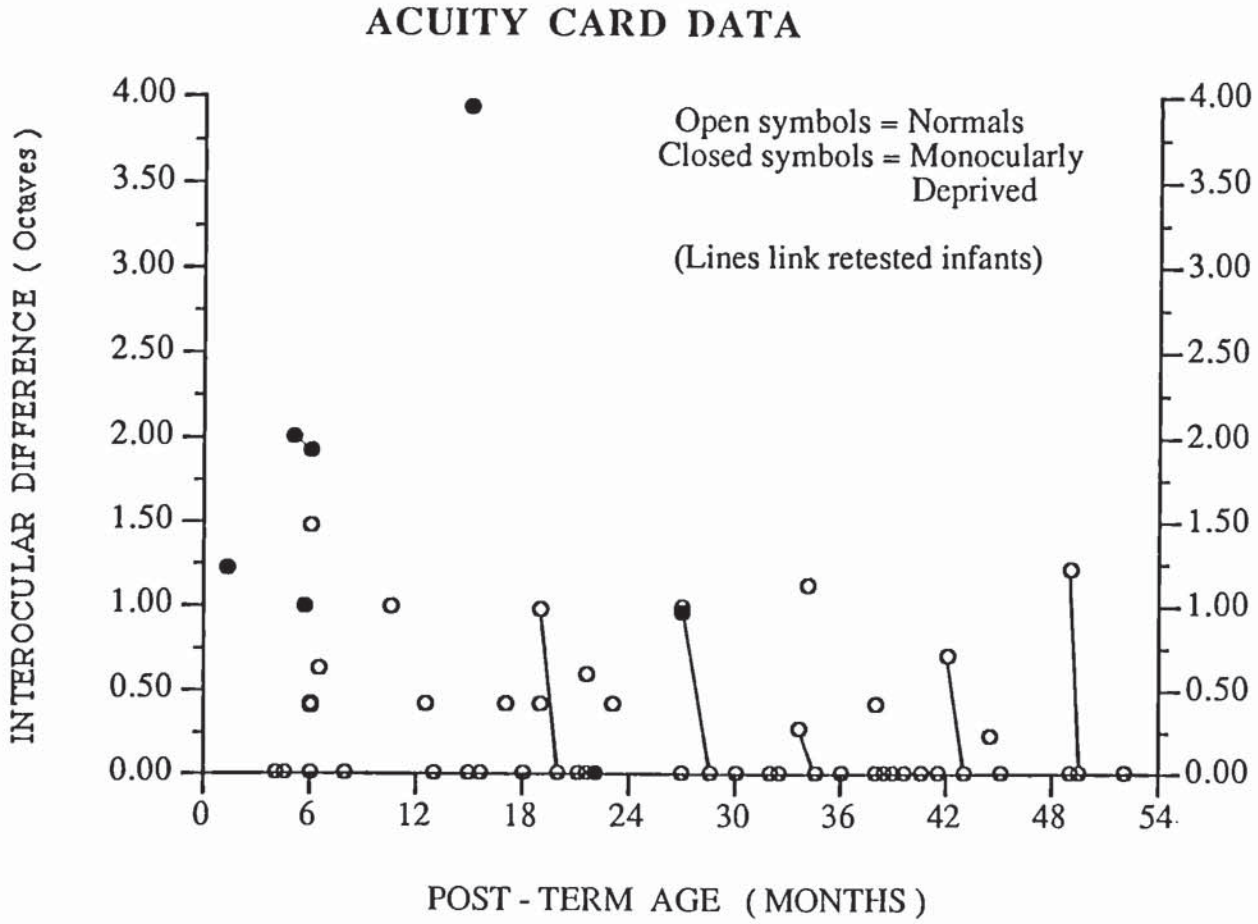

Figure 6. Interocular acuity differences in 54 normal and 6 monocularly deprived infants; 35.2% of normals and 85.7% of deprived infants had unequal monocular acuities. In normals acuity differences never exceeded 1.5 octaves and were not found on retesting.

Appendix 8

Publications:

1 **Thompson, C M** and Drasdo, N. (1984)
The VEP and complementary techniques in paediatric visual assessment.
In W N Charman (Ed) "The Frontiers of Optometry"
Transactions of the First International Congress.
The British College of Ophthalmic Opticians (Optometrists) Vol. 2, London 63 - 78

2 **Thompson, C.** (1985)
Infant visual assessment : Electrophysiological techniques.
Association of Paediatric Chartered Physiotherapists Newsletter No 35 (May), 3 - 10

3 Drasdo, N, Thompson, D, **Thompson, C M**, and Edwards, L. (1987)
Complementary components and local variations of the pattern electroretinogram.
Invest. Ophthalmol. Vis. Sci. 28 : 158 - 162

Abstracts:

4 **Thompson, C M** and Drasdo, N. (1986)
Infant visual assessment : Evaluation of a clinically viable method.
Ophthal. Physiol. Opt. 6 (2), 245

5 **Thompson, C M** and Drasdo, N. (1987)
Infant refractive errors - a longitudinal study from birth to one year.
Ophthal. Physiol. Opt. 7 (1) 93

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