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(15 May - 9 June 1995)

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Clin. Vision Sci. Vol. 8, No. 4, pp. 337–344, 1993
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0887-6169/93 $6.00 + 0.00

EMMETROPIZATION AND THE PROGRESSION OF MANIFEST REFRACTION IN CHILDREN FOLLOWED FROM INFANCY TO PUBERTY

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(Received 19 November 1992)

Summary—1. The manifest refractions of 72 children were tracked at regular intervals starting soon after birth and continuing for 9–16 y. Near-retinoscopy, a non-cycloplegic refraction technique, was used for children aged 0–3 y, and non-cycloplegic distance retinoscopy after 3 y. Almost 1400 refractions have been obtained from this group.

2. During the first 6 months the mean spherical equivalent of the group is negative by a small amount. By one year of age the children have an average of 0.5 D of hyperopia which they maintain until 8 y. After 11 y the mean spherical equivalent once again becomes negative, largely because some of the children are becoming myopic.

3. The dispersion of refractions is largest shortly after birth and smallest at 6 y, reflecting the process of emmetropization during the preschool years.

4. The spherical equivalent at 1 y is most predictive of later spherical equivalents. Correlations of spherical equivalent at 1 y with other ages range from 0.43 during the period of emmetropization to 0.76 at some later ages.

5. Children with a negative spherical equivalent in infancy in conjunction with either against-the-rule astigmatism or no astigmatism are more likely to be myopic at school age than children with infantile with-the-rule astigmatism.

6. There is an increased incidence of myopia in children with two (compared to zero or one) myopic parents.

Key words—Myopia; emmetropization; astigmatism; longitudinal; visual development.

INTRODUCTION

"A longitudinal study which begins at birth would be of prime importance in leading to the real story on refraction, and one should be undertaken" (Hirsch, 1964). In fact, just such a study was begun serendipitously 16 y ago in the Infant Vision Laboratory at M.I.T. In the course of studying visual development in infants, each new subject was refracted prior to acuity testing to ensure that the acuity norms being developed would include only infants with little or no refractive error. Our unexpected discovery of a much higher incidence of astigmatism in infants compared to adults (Mohindra *et al.*, 1978; see also Howland *et al.*, 1978; Fulton *et al.*, 1980) was the impetus for the longitudinal study of refraction. We wished to discover when the incidence of astigmatism in infants declined to adult levels and whether the early astigmatism produced meridional amblyopia (Gwiazda *et al.*, 1984, 1986).

All of the refractions in the present study were obtained without cycloplegia, a necessity when obtaining multiple sequential refractions from the same children in a non-clinical setting. In this paper we use the term non-cycloplegic or manifest refraction to refer to the refractive state of the eye as measured without drugs. Non-cycloplegic distance retinoscopy was used to refract children older than 3 y. Near-retinoscopy was used to refract children from birth to 3 y of age (Mohindra, 1977).

Refraction of young infants by near-retinoscopy and cycloplegic retinoscopy reveals a wide range of equivalent spheres, but less hyperopia is found using near-retinoscopy (Santonastaso, 1930; Cook and Glasscock, 1951; Goldschmidt, 1969; Mohindra and Held, 1981; Saunders and Westall, 1992). It is probable that near-retinoscopic refractions include an accommodative component. In a recent study using both techniques on the same infants, near-retinoscopic readings were, on average, 0.85 D less hyperopic than cycloplegic readings (Saunders and Westall, 1992). Relative to adults, infant readings were highly variable. Much of this variability could be attributed to poor repeatability using either cycloplegic or non-cycloplegic retinoscopy.

Non-cycloplegic refraction data in the first year of life reveal a shift from myopic readings in the early months to emmetropic readings by 6 months (Mohindra and Held, 1981). Contrary to the received view, this same trend is also evident in cycloplegic refraction data from three recent longitudinal studies. Cycloplegic refractions were found to shift from myopia or emmetropia in the first months to more hyperopic readings by 6 months of age (Abrahamsson and Sjostrand, 1992; Schalij-Delfos *et al.*, 1992; Wood and Hodi, 1992).

The longitudinal manifest refraction data reported in this paper are from children who had their first refraction between birth and 6 months of age and have been refracted at regular intervals for at least 9 y. New members are added to this initial group as parents express an interest in continuing with the project and indicate that they will remain in the Boston area. Some of the older children are becoming myopic. While the numbers are still relatively small and the group rather select in terms of the educational and socio-economic level of the parents, we can begin to examine the relationship between early and later manifest refractions, including the development of school-age myopia. On the basis of early manifest refraction can we identify which infants are at risk for the later development of myopia? If the early near-retinoscopic readings are predictive, this knowledge could lead us to identify at-risk children who might benefit from preventive intervention when ameliorative measures are better understood.

In summary, in this paper we relate infantile refraction, as determined by near-retinoscopy, and parental refractive error to the equivalent sphere of these children when they reach school age. Since the most dramatic refractive change occurring during the school years is the progression of myopia, we have focused primarily on predicting which children will become myopic.

METHOD

Subjects

Seventy-two children had their first refraction by near-retinoscopy before 6 months of age and are currently aged 9–16 y. They have been refracted without cycloplegia at regular intervals since infancy. The number of measurements obtained from a child in the first year of life ranged from 3 to 20 with a mean of 6. In the second year the mean was 3, in the third and fourth years the mean was 2, with one refraction per year after the age of 4.

Infants were recruited by a letter describing the M.I.T. research program in infant vision sent to parents in the Cambridge, Mass. area. Names and addresses were obtained from birth records on file in Cambridge City Hall. Responses to the letters that resulted in at least one visit to the laboratory averaged 15%. Informed consent of the parents was obtained prior to undertaking any measurements. At the conclusion of the first visit, parents were invited to continue participation of their children in the research program. The sample reported here represents 17% of the infant subjects seen in our laboratory from September 1975 to September 1982.

When a significant refractive error was detected, the child was referred to an appropriate eye care professional for further diagnosis and treatment. At present 23 of the 72 children have had spectacle corrections prescribed. The amount of time that the spectacles are worn varies from full time to not at all.

In the first 6 months 31 of the children had spherical equivalents <0, and 20 had spherical equivalents ≥ 0.5 D. The remaining subjects had spherical equivalents between 0 and 0.49 D and were considered emmetropic ($n = 14$), had early anisometropia ($n = 2$), or had astigmatism which could not be classified due to changing axes in the first 6 months ($n = 5$).

Procedure

Refractions from birth to 3 y were obtained by the near-retinoscopy procedure (Mohindra, 1977). After 3 y of age non-cycloplegic distance retinoscopy was used. The refractions were done by experienced retinoscopists without knowledge of any earlier findings from a particular child. Dr Indra Mohindra performed the early retinoscopies, including almost all of those in the first year of life. Dr Mitchell Scheiman performed most of the preschool retinoscopies

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on this group, and for the past 9 y Dr Frank Thorn has been the refractionist.

In the near-retinoscopy procedure, the child fixated the light of the retinoscope in an otherwise dark room. Retinoscopy was performed at a fixed distance of 50 cm without cycloplegia. An adjustment factor of −1.25 D was added to the spherical component at neutrality to obtain the static distance refraction of the eye. This factor was used rather than −2.0 D, which would normally be used to correct for the working distance of 50 cm. A +0.75 D adjustment for tonic accommodation was made to the working distance correction according to the empirical findings of Mohindra (1977). Owens *et al.* (1980) have shown that the light of the retinoscope is not an effective stimulus for accommodation in adults. These subjects do not focus on the retinoscope, but rather relax accommodation to the tonic level.

All refractions were written using the minus cylinder convention. The axis of the cylindrical component was classified as with-the-rule if the minus cylinder axis was at 180 ± 15 deg (horizontal), against-the-rule for minus cylinder at 90 ± 15 deg (vertical), or oblique (all other axes, shown by < 10% of the children).

RESULTS

The subject who had the most negative near-retinoscopic readings as an infant also has the most myopia as an older child, as shown in Fig. 1. The myopia, however, was not constant during the intervening period. In fact, as can be seen, dramatic changes occurred in this child's manifest refraction between infancy and school age. The spherical equivalent became increasingly less myopic during the toddler years,

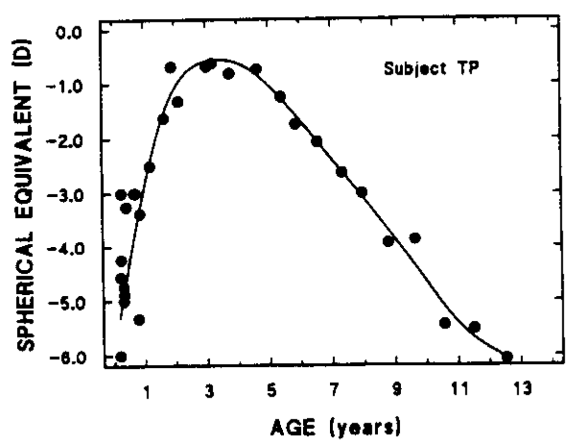

Fig. 1. Longitudinal manifest refractions (spherical equivalent) from one subject from birth to $12\frac{1}{2}$ y.

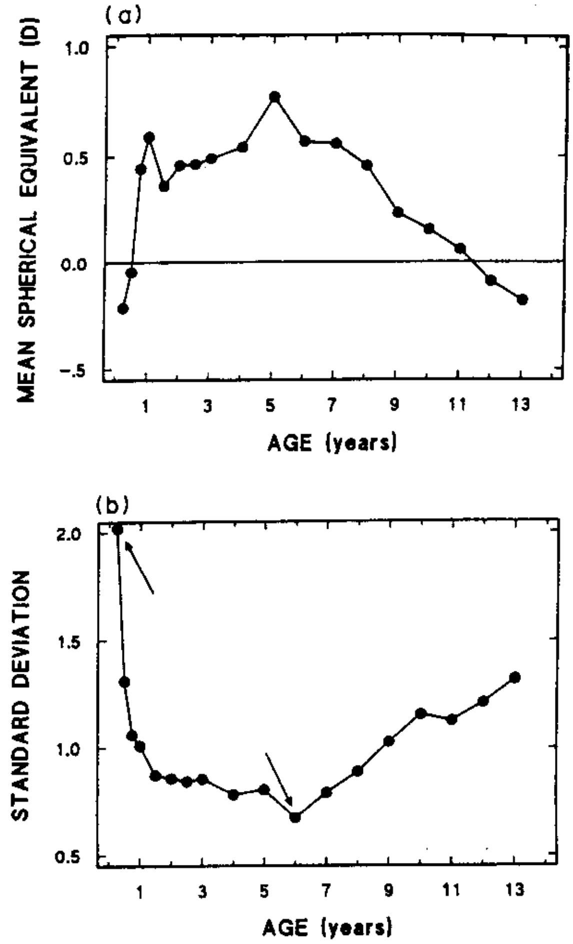

Fig. 2. (a) Longitudinal manifest refractions (mean spherical equivalent) from 72 children from birth to 13 y. (b) Dispersion of manifest refractions in (a), as measured by the standard deviation. Arrows indicate the ages at which the standard deviation is largest (0–3 months) and smallest (6 y).

reflecting the process of emmetropization. In the preschool years the manifest refraction stabilized at a low level of myopia, but after age 5 y it became increasingly myopic again, and by age $12\frac{1}{2}$ y it had returned to the level of early infancy. This child has worn glasses full time since the age of $5\frac{1}{2}$ y.

This individual profile, showing emmetropization in the early years and a return to the infantile refractive state at a later age, is typical of many children in our sample and is reflected in the group data. Figure 2(a) shows longitudinal non-cycloplegic refraction data from all 72 children, comprising almost 1400 individual refractions. In the first 6 months the mean spherical equivalent is negative by a small amount. Most of the negative readings are found in the first 2 months. By 1 y of age the children have an average of 0.5 D of hyperopia which they maintain until 8 y. After that age

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some of the children become myopic, and the mean spherical equivalent of the group becomes more negative. The dispersion of refractive errors, measured by the standard deviation and shown in Fig. 2(b), is largest shortly after birth and smallest at 6 y, reflecting the process of emmetropization during the preschool years.

The distribution of spherical equivalents at these two ages is shown in Fig. 3. For the neonatal group the distribution is broad, ranging from −4.5 to +4.5 D. Only 22% of infants are emmetropic when refracted with near-retinoscopy. This broad distribution is similar to the cycloplegic refraction data of Cook and Glasscock (1951), but their distribution is shifted toward hyperopia, with a mean of 2.07 D. By 6 y of age the distribution of spherical equivalents in the present study has tightened considerably, and 80% of the children are emmetropic.

Figure 4 shows longitudinal manifest refraction data from the 31 children with spherical equivalents <0 D during their first 6 months and from the 20 children with spherical equivalents ⩾ +0.5 D during their first 6 months. The means of both groups tend to converge on a small amount of hyperopia after 2 y of age, reflecting the process of emmetropization. However, the mean spherical equivalent of the early negative group is significantly less than the mean spherical equivalent of the positive group at all ages (*t*-tests, $P < 0.05$). After 8 y, the infantile manifest refractions recur in some children. The mean spherical equivalent of the group which showed early negative readings is once again negative, and 42% of those children are presently myopic. Only 10% of the children with positive spherical equivalents in infancy are presently myopic.

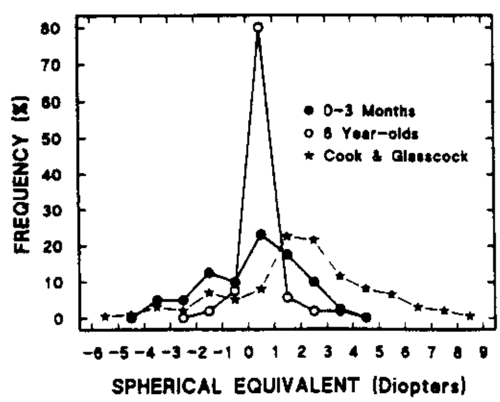

Fig. 3. Distribution of spherical equivalents at 0–3 months (●) and 6 y (○). Newborn spherical equivalents (☆) from Cook and Glasscock (1951), obtained using cycloplegic retinoscopy, are included for comparison.

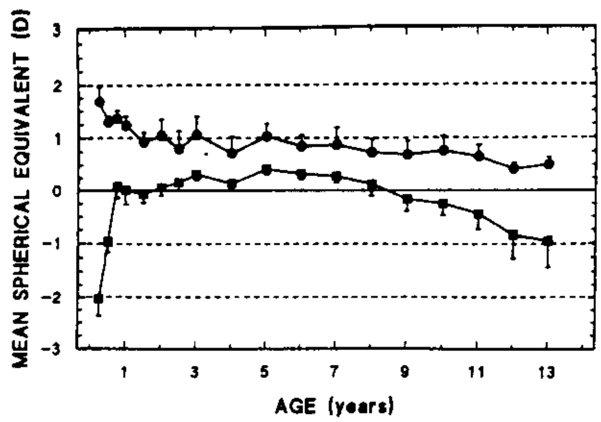

Fig. 4. Longitudinal manifest refractions (mean spherical equivalent) from 31 children with negative spherical equivalents in the first 6 months (■) and from 20 children with spherical equivalents ⩾ +0.5 D in the first 6 months (●).

More than half of the children in the longitudinal group had significant astigmatism (⩾ 1.0 D) as infants, as shown in Fig. 5. During the preschool years, the large cylinder errors of infancy were reduced and the proportion of astigmatic children declined, stabilizing at a low level after 4 y of age.

The two refractive groupings of Fig. 4 were further subdivided by axis of infantile astigmatism: against-the-rule, with-the-rule, or no astigmatism. Figure 6(a) shows that, on average, the children with positive spherical equivalents in the first 6 months in conjunction with against-the rule astigmatism are more hyperopic throughout childhood than those with early with-the-rule astigmatism or no astigmatism. The arrows in Fig. 6(b) indicate that children who had negative spherical equivalents in the first 6 months in conjunction with against-the-rule astigmatism become myopic at an earlier age than children with no astigmatism. Mean ages of myopia onset for the two groups,

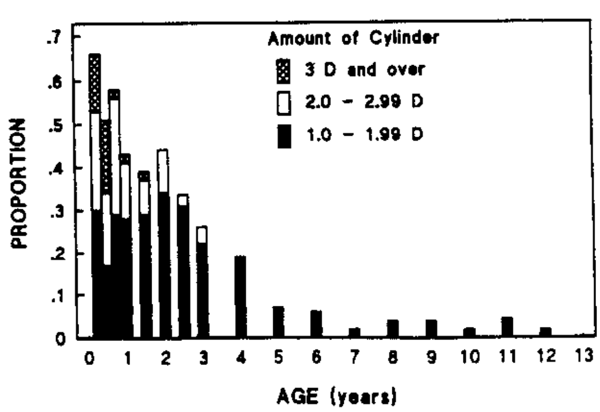

Fig. 5. Proportion of children in the longitudinal group with significant astigmatism.

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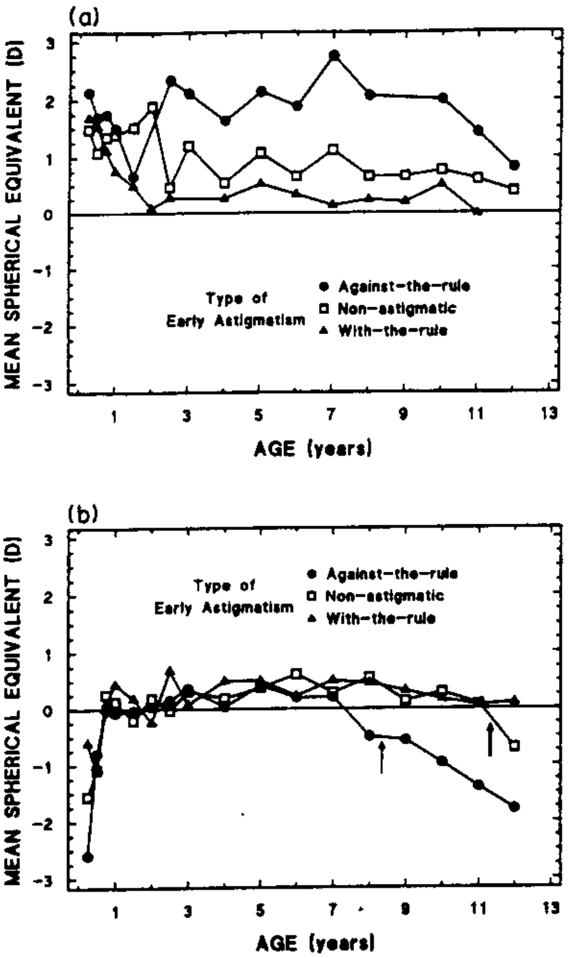

Fig. 6. (a) Longitudinal manifest refractions (mean spherical equivalent) from children with positive spherical eqivalents (≥0.5 D) in the first 6 months broken down by infantile axis of astigmatism. (b) Longitudinal manifest refractions (mean spherical equivalent) from children with negative spherical equivalents in the first 6 months broken down by infantile axis of astigmatism. Arrows refer to the mean age of onset of myopia for children who had either against-the-rule astigmatism or no astigmatism in infancy.

8.3 vs 11.6 y, are significantly different ($t = 3.29$, $P < 0.005$). Children who had infantile with-the-rule astigmatism remain emmetropic in childhood, whether their early spherical equivalent was plus or minus.

Figure 7 shows that correlations (Pearson r) between spherical equivalents at 3 months, the age group which includes newborn data and has the greatest dispersion, and all subsequent ages range from a high of 0.62 at the neighboring age of 6 months to lows of 0.42 from 2 to 4 y. Correlations hover around 0.5 after age 5 y. Correlations of spherical equivalents at 1 y with neighboring ages are also high, as expected, but are also quite high after age 5 y ($r = 0.65$ and above). Lower values are found during the

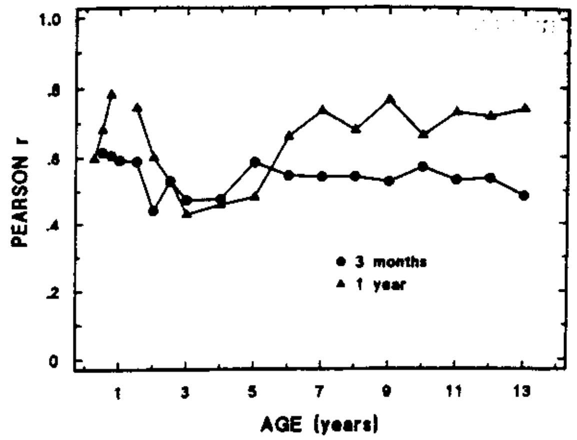

Fig. 7. Correlations between spherical equivalents at 3 months and all later ages (●) and at 1 y and all other ages (▲). The r valves for 3 months with 3 months and 1 y with 1 y have been omitted.

preschool years when most children are emmetropic. In our sample the spherical equivalent at 1 y is most predictive of later spherical equivalents. Predicting from later to earlier spherical equivalents is also possible because of high correlations. For example, correlations between spherical equivalents at 9 y and those at all earlier ages range from 0.42 to 0.92, all significant at $P < 0.005$.

The parents of children in our longitudinal group tend to be myopic. 65% of the mothers and 62% of the fathers are myopic, much higher than the incidence of 25% reported for adults in the United States. The mean spherical equivalent of the mothers is −1.34 D (range −6.25 to +2.50 D), and the mean spherical equivalent of the fathers is −2.16 D (range −18.50 to +1.75 D). Figure 8 shows that when both parents of children in the longitudinal group are myopic, 42% of the children are myopic. When only one parent

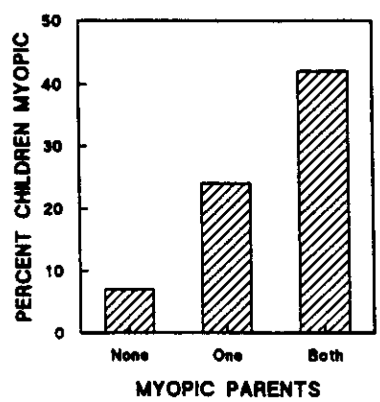

Fig. 8. Percent of myopic children with none, one, or two myopic parents.

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is myopic, the incidence of myopia in the children drops to 22.5%, and with neither parent myopic, the incidence is further reduced to 8%.

DISCUSSION

"It is impossible without a longitudinal study to state whether the very early changes are in any way related to those occurring later. For example, it is not known whether the infant who had 6 D of myopia and who became hyperopic or emmetropic during the preschool years is the same individual who at puberty again becomes myopic" (Hirsch and Weymouth, 1991). By coincidence this hypothetical individual of Hirsch and Weymouth is a real subject in our longitudinal study of manifest refraction (Fig. 1). For this subject we can state that the early myopia determined by near-retinoscopy, which is reduced almost to emmetropia during the preschool years, does indeed return. By puberty this child has reacquired the same degree of myopia shown in infancy. The final level of myopia is unknown at this point, but we hope to refract this child at least until the myopia stabilizes.

Refraction of young infants by near-retinoscopy reveals a wide range of equivalent spheres, as does cycloplegic refraction, but there is less hyperopia with near-retinoscopy, most likely resulting from accommodation. The increase in mean spherical equivalent from −1.48 D soon after birth to Plano by 3–4 months may reflect improved accommodative control over this period. The shape of the distribution of neonatal spherical equivalents in the present study agrees quite well with the neonatal cycloplegic refractions of Cook and Glasscock, as shown in Fig. 3, but our distribution is shifted toward more negative values. A recent study using both cycloplegic retinoscopy and near-retinoscopy on the same infants found more hyperopia with cycloplegia, but concluded that some of the difference between the techniques can be attributed to variability within both techniques (Saunders and Westall, 1992).

Our longitudinal data reinforce cross-sectional data from this laboratory which indicate that an emmetropization process occurs during the first 4–5 y (Mohindra and Held, 1981). During this period the manifest refractions of most children tend to converge on a slight degree of hyperopia. Our data demonstrate this fact longitudinally [Fig. 2(a)] and agree with cycloplegic longitudinal refraction data from birth to 1 y which show a trend to increasing hyperopia during this time (Abrahamsson and Sjostrand, 1992; Schalij-Delfos et al., 1992; Wood and Hodi, 1992). Our data further show in Fig. 4 that the children who had negative spherical equivalents as infants on average never reach the same level of hyperopia as those who had positive spherical equivalents.

Although the mechanism of emmetropization is unclear, there are some suggestive leads. To some degree the overall uniform growth of the eye reduces ametropia (Wallman and Adams, 1987). Infants who suffer a lack of visual feedback owing to pattern deprivation tend to develop axial myopia, which suggests an altered process of emmetropization (Rabin et al., 1981). In addition, cylindrical errors emmetropize, as shown in Fig. 5. Most of the infantile astigmatism, which is corneal (Howland and Sayles, 1985), is greatly reduced or eliminated by 5 y of age, similar to the time period for the overall emmetropization process. We are presently examining the cylinder amounts and axes in the older children in our longitudinal group to see if, like the spherical error, the astigmatism of infancy returns after a period of emmetropization.

Our data confirm the well-known finding that after a period of emmetropization some school age children start to develop myopia (reviewed by Curtin, 1985). Fulton et al. (1982) have suggested that uncorrected astigmatism early in life might influence the progression of myopia. Against-the-rule astigmatism occurring in children starting school is predictive of later development of myopia (Hirsch, 1964) and faster progression of existing myopia, (Grosvenor et al., 1987). The news from the present study is that the children who develop school-age myopia can be predicted from their infantile manifest refraction. These children in infancy had negative spherical equivalents as determined by near-retinoscopy, often in conjunction with either against-the-rule astigmatism or no astigmatism. Moreover, those with against-the-rule cylinder develop myopia significantly earlier than the non-astigmats. So far those children in our group with early negative spherical equivalents in conjunction with with-the-rule astigmatism have remained emmetropic. It remains to be seen whether they will develop myopia at a still

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later age. A related finding, reported by Atkinson and Braddick (1988), is that hyperopia accompanied by astigmatism, especially with-the-rule, is more likely to persist from 6 to 30 months of age.

Refractions in older children can be predicted from their earliest manifest refraction, although the refraction at 1 y is a better predictor than that at 3 months, as shown in Fig. 7. The high correlations throughout childhood demonstrate that individuals tend to remain at their initial positions in the distribution of manifest refractions, even though its dispersion reduces during the preschool years. During this period there is a slight drop in the r values. After a period of emmetropization, the distribution of spherical equivalents increases in dispersion, but the correlations remain high. A longitudinal study of focusing and refraction using photorefraction, another non-cycloplegic technique, confirms the results of the present study, namely, that early focusing behavior predicts later refractive state, despite the intervening years of emmetropization (Howland *et al.*, 1993). It appears probable that a longitudinal study of cycloplegic refraction would have similar results.

Our results, showing an increased incidence of myopia in children with two (compared to zero or one) myopic parents, agree with those from earlier studies (Paul, 1938; as reported in Curtin, 1985). This familial incidence suggests a genetic component in the etiology of myopia.

In conclusion, our data demonstrate that within limits myopia can be predicted from consideration of early refractions determined by near-retinoscopy, including both sphere and cylinder, and the parents' refractive error. Recent work from our laboratory indicates that insufficient accommodative response to blur is found in newly myopic children and may be predictive of future myopia development and progression (Gwiazda *et al.*, 1993). If we can identify children at risk for myopia based on the above-mentioned factors, then as ameliorative measures become better understood they can be applied selectively to those children.

Acknowledgements—The authors wish to thank Dr Indra Mohindra and Dr Mitchell Scheiman for their technical assistance. We thank the children in the longitudinal group and their parents for their dedication to the project over many years. This research was supported by NIH Grants EY01191 and EY02621.

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