Astigmatism and acuity in two primate infants

Davida Y. Teller, Jane L. Allen, David M. Regal, and D. Luisa Mayer

The development of grating acuity was followed in two astigmatic primate infants, one a human being and one a pigtail macaque monkey. Both infants showed variations of acuity with grating orientation, predictable from the orientation and type of astigmatism present. Optical correction of the human infant during testing virtually eliminated the variation of acuity with orientation, suggesting that a neurally based meridional amblyopia had not yet been established.

Key words: astigmatism, development, infancy, acuity, deprivation, monkey vision

An astigmatic eye has different optical refractive power for different meridians. For example, Fig. 1, *A*, shows an astigmatic eye with relaxed accommodation viewing an object at infinity. In this example (compound hypermetropic astigmatism), both the vertical and horizontal elements in the image are focused behind the retina, but the horizontal elements are focused farther behind the retina than the vertical elements, making it impossible for these two orientations to be focused simultaneously. Other configurations also occur, including, for example, compound myopic astigmatism, in which both focal planes fall in front of the retina, and mixed astigmatism (Fig. 1, *B*), in which one focal plane falls in front and the other in back of the retina.

In psychophysical measurements, human adult astigmats typically show variations of acuity with grating orientation. Even after optical correction, up to an octave of difference in acuity for lines parallel to the two principal axes can persist in adult astigmats.[1, 2] These persistent variations in acuity can also be demonstrated with targets created directly on the retina by means of interference fringes, confirming that they are of neural rather than optical origin.[2] The variations in acuity which persist after optical correction are called *meridional amblyopia*.

Mitchell et al.[2] showed that the target orientations for maximum and minimum acuity are different for different kinds of astigmats and are predictable on an empirical basis from the positions of the optical focal planes. Thus, for example, compound hypermetropic astigmats typically show greater acuity for the less hypermetropic focal plane (the vertical in Fig. 1, *A*), and mixed astigmats typically show greater acuity for the hypermetropic rather than the myopic focal plane (the vertical in Fig. 1, *B*).

From the Departments of Psychology and Physiology/Biophysics, Child Development and Mental Retardation Center, and Regional Primate Research Center, University of Washington, Seattle.

This research was supported in part by National Science Foundation grants BNS76-01503 and BNS75-01451, and National Institutes of Health grant 1 T32 EY07031-01; and National Institutes of Health grants RR 00166, 5 P01:HD 02274, and NIH-GM-0066 and EY 01208.

Submitted for publication June 26, 1977.

Reprint requests: Dr. Davida Y. Teller, Department of Psychology, NI-25, University of Washington, Seattle, Wash. 98195.

0146-0404/78/0417-0344$00.60/0 © Assoc. for Res. in Vis. and Ophthal., Inc.

Downloaded from iovs.arvojournals.org on 01/21/2022

In causal terms, there are at least two* viable hypotheses to account for meridional variations in acuity. The first possibility is that these variations are programmed genetically, in correlation with optical astigmatism. The second, more popular possibility, is that the astigmatic optical system, in conjunction with a preferential focusing of one focal plane at the expense of the other, causes selective deprivation of high spatial frequencies in the nonfocused orientation and that this selective deprivation during a critical period early in development causes the later acuity deficit.

The selective deprivation hypothesis is attractive, but not fully compelling on logical grounds. Obviously, an astigmat could potentially bring lines at either orientation to focus by means of variations in viewing distance and accommodative state. Adult astigmats are known to accommodate differentially for lines at different orientations at least some of the time.[3] It is reasonable to suspect that young astigmats also do so, and thus that they may expose themselves to well-focused lines at both principal axes at various times. Furthermore, in the normal visual environment, objects occur simultaneously at different distances, and an astigmatic eye which focuses lines of one orientation at one distance on the retina will, at least on some occasions, coincidentally focus lines of the opposite orientation located at a different distance. The selective deprivation in the astigmat is, then, at best partial rather than total, and the selective deprivation argument must be made quantitatively to be fully compelling.

Empirically, the selective deprivation hypothesis is supported by a few clinical cases in which astigmats optically corrected in early childhood fail to show meridional amblyopia[4] and by the fact that kittens reared with artificial astigmatism show predictable neurophysiological deficits.[5, 6] But not all adult astigmats show meridonal amblyopia.[2] Also, there is recent evidence that the degree and axis of astigmatism often shifts with age in individual infant astigmats,[7] suggesting that the orientations of the astigmat's focal planes could have been shifting rather than constant during early infancy, with unclear quantitative consequences for selective deprivation.

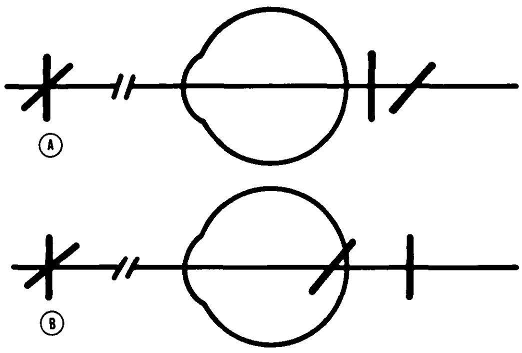

Fig. 1. Examples of focal plane differences in compound hypermetropic (A) and mixed (B) astigmatism. The monkey infant tested in the present study was a compound hypermetrope (approximately +0.75 + 1.50 × 180°). The human infant was a mixed astigmat (approximately −1.0 + 2.5 × 90°).

The presence or absence of variations of acuity with orientation in astigmatic infants may eventually assist us in sorting out causal factors. For example, one may argue that in an uncorrected astigmatic infant, the *absence* of meridional variations of acuity between lines oriented parallel to the two principal axes would be evidence that the infant focuses differentially for targets of the two different orientations, and such data would weigh against the occurrence of selective deprivation in these meridia during the age range tested.

The *presence* of such meridional variations of acuity in astigmatic infants would be sub-

*Many other logical alternatives and combinations are possible; for example, that a neurally-based meridional amblyopia causes or maintains the astigmatic optics; that other environmental factors, as yet unspecified, causes both the astigmatism and the meridional amblyopia; that meridional amblyopia is genetic in some astigmats and environmentally caused in others; that the tendency toward astigmatism and the susceptibility to meridional amblyopia occur in correlation in meridional amblyopes, but that selective deprivation of this kind would have no effect on other genotypes; and so on.

Downloaded from iovs.arvojournals.org on 01/21/2022

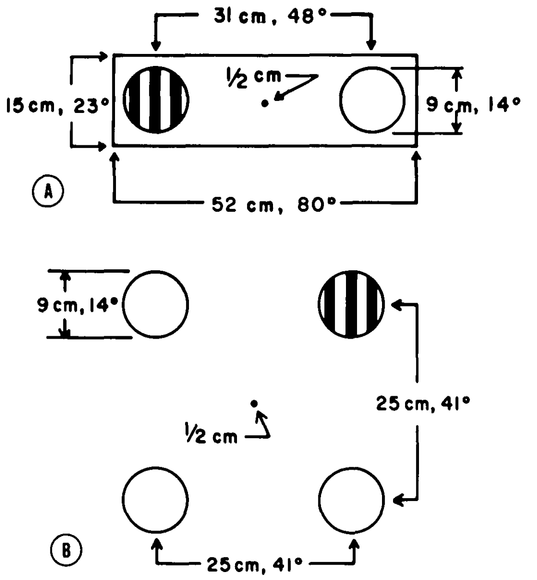

Fig. 2. Stimulus displays used for testing the two infant astigmats via FPL techniques. **A**, Display for two-alternative FPL, used to test the monkey infant. **B**, Display for four-alternative FPL, used to test the human infant. For FPL testing, the infant is held facing the stimulus display and tends to stare in the direction of the striped target. A human observer, blind with respect to stimulus location, is stationed behind the centrally located peephole. By looking at the infant's eye and head movements, the observer must judge the location of the stimulus on each of a series of trials. Targets of various stripe widths are used. Above-chance performance on the part of the observer for a particular target implies that the infant can resolve that target. The technique is described more fully elsewhere.[11, 12] For both infants, the observation distance was 36 ± 3 cm, and the luminance was 0.7 log ft. lambert (1.2 log cd/m^2).

ject to two interpretations: optical and neural. The optical intrepretation—that gratings in one orientation are simply better focused than gratings in the other—would suggest that the infant does *not* focus differentially for targets at different orientations, even when presented with only a single grating at a time[3] and would tend to increase the plausibility of the argument that selective deprivation occurs during the age range tested. The neural interpretation—that the lesser acuity at the poorer orientation is caused by deficits already present at the neural level rather than just by optical factors—would tend to favor a genetic hypothesis or suggest a critical period earlier than the age range tested.

Elimination of meridional variations in acuity by optical correction of the infant during testing would greatly weaken the neural interpretation and strengthen the optical one and would, to this extent, increase the plausibility of the selective deprivation hypothesis. In any case, elimination of the effect by optical correction would show that neurally based meridional amblyopia emerges later than the age range tested, whether for maturational or environmental reasons.

Thus, although interpretations are complicated and open to argument, it is of some interest to study the development of visual acuity in naturally occurring astigmatic infants when they are available. A major project of this kind is in progress in another laboratory.[7-9] The present paper documents behavioral testing of two serendipitously discovered astigmatic primate infants, one a human being and the other a pigtail macaque monkey.

Methods

An infant pigtail macaque *(Macaca nemestrina)*, F2, was a subject in the normative study of acuity development in infant monkeys described elsewhere.[10] For purely exploratory purposes, the infant was tested weekly for acuity for horizontal as well as vertical square-wave gratings.* The forced-choice preferential looking (FPL) technique[11, 12] was used (Fig. 2), with a total of at least 50 trials per plotted point. Testing took approximately 10 hr/week for the 11 weeks of the experiment, for a total of about 110 hr of testing.

Repeated retinoscopic refractions were also carried out under a combination of 1.0% cyclopentolate and 10% phenylephrine, instilled twice at 10 min intervals, in connection with the normative

*In addition, performance for four orientations (vertical, horizontal, and left and right diagonals) was tested with a single stripe width (4 min of arc) with 50 observations per orientation during week 7. The percents correct were V, 85%; H, 72%; RD, 74%; LD, 80%. Thus acuity for diagonals fell between acuity for verticals and horizontals in this data set.

Downloaded from iovs.arvojournals.org on 01/21/2022

study. The correlation between the retinoscopic and behavioral results came to our attention during final data analysis.

The human infant astigmat, Sarah, was discovered when her parents responded to routine recruitment and reported frequent severe astigmatism in the mother's family. Sarah was refracted under a combination of 0.5% cyclopentolate and 2.5% phenylephrine instilled three times at 5 min intervals. She was refracted at 3¼ months, before behavioral testing was begun, and again at 8½ months, at the end of testing. A four-alternative version of the FPL technique was used (Fig. 2). The number of trials per plotted point was at least 64, except for a single point (N = 8 at 4 months, 20 min of arc).

At 4 and again at 5 months of age, Sarah's acuity for vertical and horizontal gratings was tested without optical correction. At 6 months of age Sarah's refractive error was corrected by fitting her with corrective lenses (−0.5 + 2.5 × 90°) held by standard frames (American Optical Co., cat. no. 34-18, size 5½), both of which she accepted readily. The spectacles were worn only during experimental sessions. Acuity for vertical and horizontal gratings was retested in the presence of the optical correction. Each of the three data sets represents approximately 10 hr of testing within a 2-week period, for a total of about 30 hr of testing.

For F2, the means of best-fitting cumulative normal ogives (i.e. 75% correct) for the data of Fig. 3 are plotted as acuity values[10] in Fig. 4. Acuity values (62% correct) for Sarah may be estimated by eye from the data of Fig. 3. Vertical bars in Fig. 3 represent ±1 standard error (S.E. = $\sqrt{PQ/N}$).

Results

Retinoscopy. The results of repeated retinoscopic examination of the monkey infant, F2, are shown in Table I. The two earliest sets of readings indicate a spherical correction of about +3.0 and uncertain readings of astigmatism. The last three sets consistently indicate a spherical correction of about +0.75 plus about 1.50 D of astigmatism at 180°. F2 is thus a compound hypermetropic astigmat and provides the example given in Fig. 1 *A*. As discussed above, she should show best acuity for the less hypermetropic focus,[2] that is, for vertical gratings.

Retinoscopic refractions of the human infant, Sarah, at 3¼ and 8½ months were −0.50 + 2.5 × 90° and −1.0 + 2.5 × 90°, respectively, in both eyes. Sarah is thus a mixed astigmat and provides the example shown in Fig. 1 *B*. She should show best acuity for the hypermetropic focus,[2] that is, for vertical gratings.

Table I. Retinoscopic refractions of F2 at various ages, taken under cycloplegia

Age (days)	*Refraction*	
	O.D.	*O.S.*
34	+2.0 + 1.25 × 180°	+3.0
41	+4.0 (too wiggly)	+4.0 (too wiggly)
97*	+0.75 + 2.0 × 180°	+0.75 + 1.5 × 180°
181	+1.0 + 1.5 × 170°	+1.5 + 1.0 × 175°
185*	+0.5 + 1.0 × 180°	+0.75 + 1.75 × 175°

*Readings taken under general anesthetic (ketamine, 65 mg/kg).

Acuity. All three pairs of psychometric functions generated by Sarah and a sample of the functions generated by F2 are shown in Fig. 3. In each case, the abscissa shows the width of individual stripes in the acuity grating.* The ordinate shows the percent of correct judgments on the part of the observer. Conversions to spatial frequency and to Snellen acuity are shown at the bottom of the figure. Acuity values (75% correct) obtained from weekly testing of F2 are shown in Fig. 4.

Two factors can be noted from the data of Figs. 3 and 4. First, both infants show meridional variations in acuity under some circumstances. For F2, during the first 5 weeks no strong differences of acuity with orientation are apparent. During and after week 6, acuity for vertical gratings consistently exceeds acuity for horizontal gratings by an average of about ¾ octave for this animal. The human astigmat also shows better acuity for vertical than for horizontal gratings by about 1 octave, when tested during months 4 and 5 with uncorrected optics. Both of these differ-

*The chart at the bottom of Fig. 3 allows interconversion of units among stripe width, spatial frequency, and Snellen acuity (adopting the convention that resolution of 1 min/stripe is equivalent to 20/20 Snellen). An *octave* is a halving or doubling of stripe width or frequency, or a halving or doubling of the denominator in Snellen notation, as shown.

Downloaded from iovs.arvojournals.org on 01/21/2022

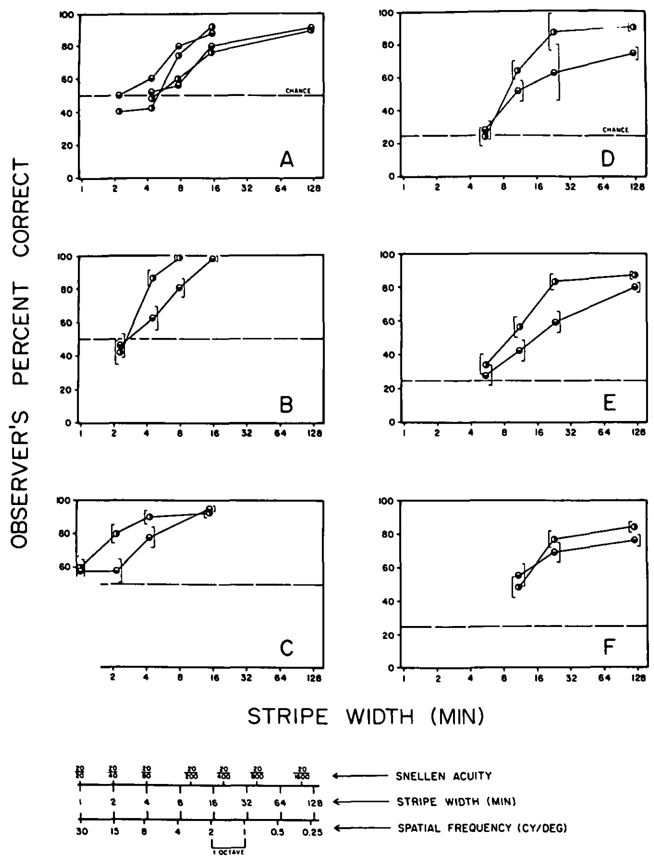

Fig. 3. Psychometric functions generated with vertical (◑) and horizontal (⊖) gratings by the two infant astigmats under various conditions. In each case, the abscissa shows the widths of individual stripes in the acuity grating. The ordinate shows the observer's percent correct in judging the position of the grating. Vertical bars show ±1 standard error. Conversions to spatial frequency and Snellen acuity are shown at the bottom of the figure. **A** to **C**, Results of F2. **A**, Weeks 1 (right) and 3 (left); **B**, week 7; **C**, week 10. **D** to **F**, Results of Sarah. **D** and **E**, Without optical correction at 4 and 5 months, respectively. **F**, With optical correction at 6 months. Acuity for vertical gratings exceeds acuity for horizontal gratings in **B**, **C**, **D**, and **E**. Optical correction of the human infant (**F**) tends to eliminate the difference in acuity with orientation.

ences are in the direction predicted by Mitchell et al.[2]

Second, for the human infant, meridional variations in acuity were virtually absent in the 6-month data set (Fig. 3, *F*), for which the infant wore her optical correction. The effect of optical correction (confounded with age) was to close the gap between the psychometric functions taken with vertical and horizontal targets (Fig. 3, *F*), largely due to an improvement in performance for the horizontal targets.

Discussion

Our primate infants, F2 and Sarah, generated data of some relevance to the selective deprivation hypothesis. Variations in acuity with orientation were found in these infants, in the directions consistent with the rules derived for adult astigmats.[2] Furthermore, after optical correction the human infant demonstrated no variation of acuity with orientation in the single data set available. Thus one may speculate that the observed variations in acuity were optically rather than

Downloaded from iovs.arvojournals.org on 01/21/2022

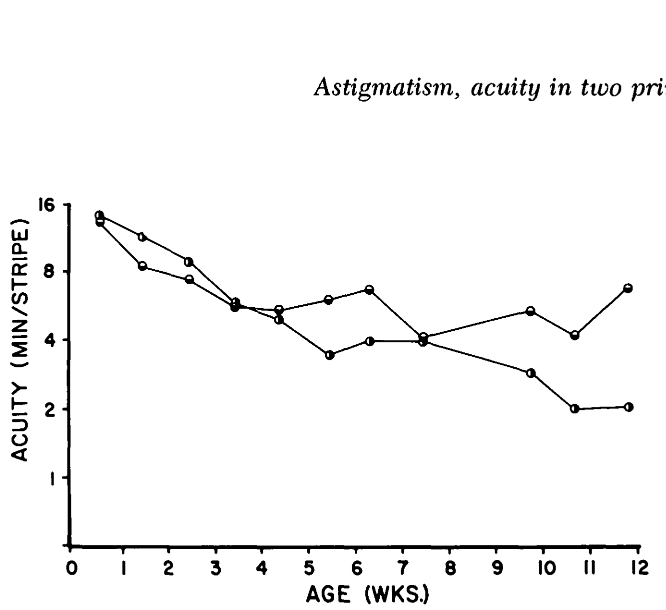

Fig. 4. Acuity values (75% correct) for the macaque infant, F2, plotted as a function of postnatal age. For weeks 6 to 12, acuity for vertical gratings was consistently finer than acuity for horizontal gratings, as predicted from the type and axis of astigmatism.

neurally caused and that without optical correction the infants failed to accommodate differentially for the two target orientations.

As argued in the introduction, these data tend to increase the plausibility of selective deprivation as a possible cause of meridional amblyopia in astigmats. However, the final sorting out of genetic and experiential causes of meridional amblyopia in astigmats will obviously require more extensive and systematic study than is provided by the present paper.

We thank E. McLean for refractions of F2, Robert Kalina for refractions of Sarah, and Tim McAnally of American Optical Company for donation and fitting of Sarah's corrective lenses. We also thank Donald Mitchell, Ralph Freeman, Richard Held, and Indra Mohindra for valuable discussions, Tom Videen for assistance in running the infant monkey tests, Stephen Teller for assistance in proofreading, and Marjorie Zachow for secretarial assistance.

REFERENCES

1. Freeman, R. D., Mitchell, D. E., and Millodot, M.: A neural effect of partial visual deprivation in humans, Science **175**:1384, 1972.
2. Mitchell, D. E., Freeman, R. D., Millodot, M., and Haegerstrom, G.: Meridional amblyopia: evidence for modification of the human visual system by early visual experience, Vision Res. **13**:535, 1973.
3. Freeman, R. D.: Asymmetries in human accommodation and visual experience, Vision Res. **15**:483, 1975.
4. Mitchell, D. E.: The influence of early visual experience on visual perception. *In* Harris, C. S., editor: Visual Coding and Adaptability, New York, 1977, John Wiley & Sons, Inc.
5. Freeman, R. D., and Pettigrew, J. D.: Alteration of visual cortex from environmental asymmetries, Nature **246**:359, 1973.
6. Cynader, M., and Mitchell, D. E.: Effect of monocular image blur on the development of kitten visual cortex, Nature (in press).
7. Gwiazda, J., Brill, S., and Held, R.: Meridional acuity in infant astigmats, paper presented at ARVO Meeting, Sarasota, Fla., 1976, and personal communication.
8. Held, R., Mohindra, I., Gwiazda, J., and Brill, S.: Visual acuity of astigmatic infants and its meridional variation, paper presented at ARVO Meeting, Sarasota, Fla., 1977, and personal communication.
9. Held, R.: Early deprivation and meridional variation in visual acuity. *In* Dowling, J., Held, R., and Poppel, E., editors: Perceptual and Neuronal Aspects of the Visual System, NRP Bulletin, Boston, Neurosciences Research Program, 1977.
10. Teller, D. Y., Regal, D. M., Videen, T. O., and Pulos, E.: Development of visual acuity in infant monkeys *(Macaca nemestrina)* during the early postnatal weeks, Vision Res. (in press, 1978).
11. Teller, D. Y., Morse, R., Borton, R., and Regal, D.: Visual acuity for vertical and diagonal gratings in human infants, Vision Res. **14**:1433, 1974.
12. Regal, D. M., Boothe, R., Teller, D. Y., and Sackett, G. P.: Visual acuity and visual responsiveness in dark-reared monkeys *(Macaca nemestrina)*, Vision Res. **16**:523, 1976.

Downloaded from iovs.arvojournals.org on 01/21/2022