The Development of Visual Acuity in Infant Astigments

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Acuity for vertical, horizontal, and oblique gratings was measured in 77 infant astigments using a preferential looking procedure. Measurements were made with the refractive error uncorrected. Most of the infant astigments were slightly to moderately hyperopic with respect to the test distance of 50 cm. Their acuity was not significantly different from that of a group of non-astigmatic infants. Average acuity for vertical and horizontal gratings increased from 6/200 at 1 month of age to 6/24 at 1 yr. Average acuity for oblique gratings increased more slowly, so that by 1 yr of age it was only 6/33. The only infants to show reductions in acuity were those with a strong myopic focus and one infant with a very strong hyperopic focus. When this infant was tested with optical correction, acuity improved to normal levels. This suggests that meridional amblyopia develops sometime after the first year of life or that it is confined to high spatial frequencies. Invest Ophthalmol Vis Sci 26:1717-1723, 1985

In recent years there have been a number of reports on the development of preferential looking (PL) acuity in human infants (reviewed by Dobson and Teller), but only a few have noted whether the infants showed any refractive error, including astigmatism. Given the high percentage of infants who show clinically significant astigmatism, it is almost certain that the studies which make no mention of refractive error included infants with astigmatism. Since PL acuity values obtained from different laboratories show good agreement, including data from non-astigmats exclusively, it would appear that early astigmatism has little effect on acuity. However, both optical considerations and the reduced acuity (meridional amblyopia) shown by some adult astigments would predict otherwise.

With regard to optical considerations, Boltz et al, in testing infants between 3 and 7 months of age, found that 1 to 2 diopters (D) of induced blur with plus spherical lenses produced a significant decrease in acuity for some infants. Powers and Dobson, on the other hand, found that 6 wk old infants were relatively insensitive to optical blur. This suggests that for very young infants the defocus produced by astigmatism should have little effect. Howland found this to be true for 1 month old infants. For older infants, however, he noted that the average amount of astigmatism was large enough so that the minimum defocus was greater than the calculated depth of field. In other words, for all but very young infants, astigmatism should degrade visual acuity.

Astigmatism is a condition in which the refracting power of the eye is not uniform in all meridians. Rays of light from a distant point object are not imaged as a point, but are instead brought to a focus at two separate focal line segments. When both focal lines, in an eye with accommodation relaxed for optical infinity, are behind the retina, the astigmatism is called compound hyperopic, as shown in Figure 1. When one focal line is behind and one on the retina, the astigmatism is simple hyperopic. Gratings viewed in a frontal plane with bars parallel to the orientation of either one or the other of the two principal focal lines can be brought into focus by accommodation, but not simultaneously. Gratings not parallel to the principal focal lines cannot be focused clearly by variation of spherical power.

The focal lines also can fall in front of the retina (compound myopic astigmatism) or one can fall in front of and one on the retina (simple myopic astigmatism). If one focal line is in front of and one behind the retina, the astigmatism is called mixed. When targets are presented at distances less than optical infinity, the plane of focus will be displaced posteriorly with respect to the retina if accommodation remains constant. For example, for a mixed astigmat, with targets presented at a close viewing distance, both focal lines may be hyperopic.

Some adult astigments, even with full optical correction, show optically uncorrectable losses of acuity for gratings oriented along their habitually blurred meridia, a condition called meridional amblyopia. Mitchell et al showed that the orientations of best and worst acuity are predictable on the basis of the positions of the optical focal lines. Hyperopic astigments usually
TYPES OF ASTIGMATISM

- Compound hyperopic
- Simple hyperopic
- Compound myopic
- Simple myopic
- Mixed

Fig. 1. Eye diagrams showing disposition of focal lines for compound hyperopic astigmatism, simple hyperopic astigmatism, compound myopic astigmatism, simple myopic astigmatism, and mixed astigmatism.

show best acuity for the least hyperopic focal line, and mixed astigmats show best acuity for the hyperopic as opposed to the myopic focal line. Myopic astigmats cannot change the clarity of edges of different orientations by changes of accommodation. In their case, edges of the orientation of the focal line that lie closest to the retina will always be seen more clearly.

It has been proposed that the early abnormal visual experience of astigmas in the form of habitual blur leads to the development of meridional amblyopia. While this proposal is appealing, many factors combine to make it difficult to specify the early visual experience of astigmats. For example, studies of refraction in infants have shown that the amount and axis of astigmatism often change in the first years of life. In particular, the number of infants who retain large amounts of astigmatism past the first year is small. This fact is important since Mitchell et al showed that the severity of the meridional amblyopia is proportional to the amount of astigmatism. In addition, the axis of astigmatism often shifts in individual children, usually from minus cylinder axis 90° in the first year to minus cylinder axis 180° by 5 yr. Also, since changes in accommodation and viewing distance can alter the relative clarity with which edges of different orientations are seen, it may be difficult in some cases to predict what will be the most deprived and the least deprived meridians.

Nevertheless, it is important to track the development of acuity in infant astigmats in order to study the effect of optical blur on acuity and to determine if there are any meridional variations in acuity analogous to the oblique effect shown by non-astigmats. Only a few studies have measured acuity or orientation preference specifically in infant astigmats. Teller and colleagues found variations in grating acuity with stimulus orientation in one human infant with significant astigmatism. Atkinson and French measured refractions using photorefraction and orientation preference using preferential looking with paired gratings as stimuli. The test distance was held constant at 75 cm. They found that infants preferred to look at gratings parallel to the non-myopic focus, a finding consistent with results from our laboratory.

In the present study we measured the acuity for different orientations of a large group of infants (N = 77) who had significant amounts of astigmatism (≥1.0 D). Refractions were obtained by the near-retinoscopy procedure performed in the dark at a distance of 50 cm. PL acuity measurements were also made in a dark room at 50 cm and are reported with respect to that distance following the practice of Atkinson and French. All but seven of the infants were hyperopic at the 50-cm test distance. The spherical component of the 50-cm refraction exhibited enough plus power so that these infants were hyperopic over a wide range of viewing distances. The remaining seven infants, classified as simple myopic astigmats as defined above, had one myopic and one hyperopic focus at the test distance of 50 cm. Their data are analyzed separately.

Materials and Methods

Subjects

Seventy-seven infants ranging in age from 2 to 55 wk were tested. Informed consent of the parents was obtained prior to undertaking the study. Each infant was refracted periodically by near-retinoscopy, and only those showing 1.0 or more diopters (D) of astigmatism within 2 wk of the testing session were included. Most were refracted and tested on the same day. Data
from infants showing anisometropia (defined as a difference between the two eyes of 1.0 D or more in the spherical and/or cylindrical component of refraction), tropia, or ocular disease were not included.

Sixty percent of the infants had against-the-rule astigmatism (minus cylinder axis 90° ± 15°), and 40% had with-the-rule (minus cylinder axis 180° ± 15°). None had oblique astigmatism. The high incidence of against-the-rule astigmatism is typical of infants.2-4

An adjustment factor of −1.25 D was added to the spherical component of the near refraction at neutrality to obtain the static distance refraction of the eye.19 This was used to calculate the mean spherical equivalent, which equals one-half of the cylindrical component plus the spherical component of the distance refraction. For all but the seven myopic astigmats, the mean spherical equivalent ranged from +0.5 D to +4.75 D, with a mean of +1.0 D. The cylindrical component of refraction ranged from 1.0 to 3.75 D with a mean of 2.0 D. For the seven myopic astigmats, the mean spherical equivalent ranged from −1.25 D to −2.75 D, with a mean of −2.0 D. The cylindrical component of refraction ranged from 2.25 D to 5.0 D, with a mean of 3.5 D.

Infants were recruited through letters sent to parents whose names were obtained from central files of birth certificates in Cambridge, MA, or from Lamaze pre-delivery class records in the Cambridge area. Responses to the letters which resulted in participation in the study averaged 10%.

Post-term ages are reported here. For example, an infant born after 38 instead of the full 40 weeks' gestation and tested at ten weeks after birth was considered to be eight weeks old in this experiment. Ninety percent of the infants were born within plus or minus 2 wk of their due date. Six percent were born from 2 to 4 wk before their due date, and 4 percent were born from 2 to 4 wk after the due date.

Stimuli

Slides were made by photographing Ronchi rulings to produce black and white grating patterns. The square wave gratings were of 12 spatial frequencies, 0.38, 0.75, 1.5, 2.25, 3.0, 4.5, 6.0, 9.0, 12.0, 18.0, 24.0, and 36.0 c/deg and 3 orientations, vertical (90°), horizontal (180°), and right oblique (45°). The contrast of the gratings when projected ranged from 90% to 95%. The grating slides were paired with homogeneous gray slides of equal space-averaged luminance (34 cd/m2).

Apparatus and Procedure

The apparatus has been described in detail in a previous paper.5 Briefly, it consisted of a wooden partition containing two circular translucent screens, one to the right and one to the left of a red fixation light. Each screen subtended 11° of visual angle with inner edges separated by 25°. Two Kodak Carousel projectors (auto-focus 850H Kodak, Rochester, NY), each equipped with a Kodak zoom lens (Ektanar-C), were used for projection of the stimuli onto the screens. A Kodak Wratten 1.0 neutral density filter covered each lens, and the projector lamps (ENH 250 watt 120 volt) were run on the low setting. A circuit was constructed so that by using two remote control buttons, both projectors could be advanced or reversed simultaneously.

The methods used were two variants of the two-alternative forced choice preferential looking procedure: the method of constant stimuli5 and a fast method.6-20-25 For both methods, the infant looked at the projected stimuli, grating on one screen, gray field on the other, and the observer decided which side, left or right, the infant preferred. Acuity measures obtained by the two methods show good agreement.20

The infant sat on the parent's lap in a dark room with head and eyes positioned 50 cm from the stimuli. Before each trial, the red fixation light was flashed to insure that the infant was looking straight ahead. When the infant's gaze was directed at the fixation light, the stimuli (grating on one screen, gray field on the other) were presented. During each trial the observer looked at the infant's head and eye movements through a peephole directly beneath the fixation light and made a forced choice judgment as to which side the infant preferentially fixated. The observer made a judgment based on one or more cues given by the infant, such as first fixation, duration of fixation, and facial expression. Corneal reflections of the gratings were too small to be resolved by the observer. The observer wore goggles with one eye occluded to insure that the location of the gratings was unknown. The length of a trial was variable, averaging 5–10 sec, depending on the length of time required by the observer to make a judgment. As soon as a judgment was made, the trial stimuli were removed and slides containing brightly colored circles were presented while the observation was recorded.

Forty-seven of the infants were tested using the method of constant stimuli. In each session only one orientation was tested. The slide pairs (grating and gray) were arranged in 2 Carousel trays in a pseudo-random order so that 5 spatial frequencies (from 0.75 to 12.0 c/deg in octave steps) could be tested 4 times each in 20 trials. This set was then cycled through either 3 times to constitute 60 trials or 2 times for 40 trials. A minimum of 2 cycles was necessary for inclusion in the results. An equal number of trials of each spatial frequency occurred on the left and the right screens. To mitigate against an infant's gaze becoming fixed on one screen, no more than three gratings in a row occurred on the same side.
Raw scores of the infant's looking behavior at each spatial frequency were converted into a percentage preference for the grating. An infant's acuity threshold was defined as the highest spatial frequency, of the 5 tested, at which the infant's preference for gratings over the homogeneous field was not less than 75%.

Thirty of the infants were tested with a fast version of the preferential looking procedure. Three slide pairs per spatial frequency were arranged in the trays in order of increasing spatial frequency, starting with 0.38 c/deg and ending with 36.0 c/deg. For each infant tested, the starting spatial frequency was taken to be one octave below the age norm spatial frequency. For example, the acuity norm for a 6-month-old infant is 6.0 c/deg; the session, therefore, would begin with the first slide pair at 3.0 c/deg.

The movement of the slide trays depended on the observer's judgment. When the observer was correct, i.e., judged that the infant preferred to look at the side on which the grating appeared, the slide trays advanced. When the observer was incorrect, the slide trays reversed. Obviously, as long as the observer was correct, the gratings increased in spatial frequency. The sessions continued until a spatial frequency was reached where the hypothesis that the infant preferred the gratings on at least 70% of the trials could be rejected at $P < 0.05$.

The next lower spatial frequency was then taken as the infant's acuity threshold. The mean number of trials per session was 23.

### Data Analysis

The acuity data from the method of constant stimuli and the fast method were treated in the same manner, since they showed good agreement in both the present and a previous study. The data from the 70 infants who were hyperopic with respect to the 50-cm test distance were divided into three groups depending on the infant's refraction and the orientation tested: (1) anterior—an infant was tested with main axis gratings (either vertical or horizontal) which were parallel to the orientation of the anterior focal line. For example, vertical acuity data from an infant with compound hyperopic astigmatism as shown in Figure 1, would be included in the anterior group; (2) posterior—an infant was tested with main axis gratings which were parallel to the orientation of the posterior focal line; (3) oblique—an infant was tested with oblique gratings ($45^\circ$).

These data were further divided into 5 10-wk age groups from 1 to 50 wk. For each condition (anterior, posterior, and oblique), no infant was tested more than once within a given age group. Thirty-three of the infants were tested within more than one of the age groups. An attempt was made to test each infant on all three grating orientations within 10 wk in order that the measures fell within a single age group. This was not possible for all infants, however, due to the loss of astigmatism of some infants and/or scheduling conflicts.

For each age group within each condition tested, a tally was made of the number of infants whose PL acuity threshold fell at each spatial frequency. The median threshold spatial frequency and the variability, as measured by the semi-interquartile range, were determined for each age group within each condition.

The data from the seven myopic astigmats, all 21-30 wk of age, were analyzed separately. Medians and semi-interquartile ranges for the anterior, posterior, and oblique conditions were calculated as above.

### Results

Median acuity values for infant astigmats, hyperopic at 50 cm, are plotted as a function of mean age in Figure 2. Six to ten infants are represented by each point on the graph. Variability, as measured by the semi-interquartile range, at each age on the graph is small. Acuity for gratings parallel to the orientation of both the anterior and posterior focal lines (main axis gratings) increases from 6/200 at 5 wk of age to 6/24 at about 1 yr of age. Acuity for oblique gratings is lower than that for main axis gratings throughout the first year. It increases from 6/330 at 5 wk of age to 6/33 at 1 yr.

Results of a Fisher exact probability test performed on each pair of anterior-posterior points for the five age groups revealed that the median acuity for gratings parallel to the orientation of the anterior focal line was not significantly different from that for gratings parallel to the orientation of the posterior focal line for any pair of points ($P > 0.05$ for each pair of points).

The data for the anterior and posterior conditions shown in Figure 2 were combined, and a median threshold spatial frequency for the combined conditions (main axis gratings) was determined for each age group. A Fisher exact probability test was then performed to determine if there was a significant difference between the median acuity for main axis versus oblique gratings for each age group. Results showed that the median for main axis gratings was significantly higher than that for oblique gratings for the 31-40 week age group ($P < 0.025$) and the 41-50 wk age group ($P < 0.025$).

Figure 3 compares median acuity values for astigmats and non-astigmats tested with both main axis (Fig. 3a) and oblique gratings (Fig. 3b). The data for the astigmats are taken from Figure 2. For comparison, acuity data from non-astigmats are shown in the same figure. The differences in acuity between astigmats and
non-astigmats are not statistically significant ($P > 0.05$, Fisher exact probability test).

For the seven myopic astigmats, aged 21–30 wk, acuity for gratings parallel to the orientation of the anterior focal line (which was still myopic at 50 cm) was an octave lower than that for gratings parallel to the orientation of the posterior focal line, which was hyperopic at 50 cm (3.0 c/deg versus 6.0 c/deg). This difference is significant by a Fisher exact probability test ($P < 0.05$). By comparison, median acuity values for the 21–30 wk old astigmats shown in Figure 2 were 5.5 c/deg and 5.3 c/deg for the anterior and posterior conditions, respectively. Acuity for gratings parallel to the orientation of the anterior focal line was almost an octave lower in the myopic astigmats compared to the 21–30 wk old infant astigmats shown in Figure 2 (3.0 versus 5.5 c/deg). This difference is significant ($P < 0.025$, Fisher exact probability test). There were no significant differences between the two groups in their acuity for gratings parallel to the orientation of the posterior focal line and their acuity for oblique gratings ($P > 0.05$, Fisher exact probability test).

For all infants who were tested on both main axes within a 2-wk period, a correlation was calculated between the amount of astigmatism and the ratio of the acuities for vertical and horizontal. The numerator of the ratio was the acuity for the orientation which should have been seen least clearly, according to the rules specified above. The denominator was the acuity for the orientation which should have been seen most clearly. This correlation was not significant ($r = -0.16$).

Figure 4 (a, b, c) shows acuity data from three individual infants tested repeatedly over the first year of life. Data from two of them, an infant with a small amount of hyperopic astigmatism (Fig. 4a), and a myopic astigmat (Fig. 4b), are representative of the group data presented above. The third infant, whose data are shown in Fig. 4c, had the largest amount of hyperopia in combination with astigmatism in our sample. All three infants had many acuity measurements for different orientations in the first year. They were refracted 15, 16 and 21 times in the first year, and their refractions remained relatively stable over that period.

Figure 4a shows data from an infant with a small amount of hyperopic astigmatism, a refraction typical of the majority of infants in the study. Acuity for all three orientations, vertical, horizontal, and oblique, is nearly equal in the first 20 wk. Horizontal and vertical are both equal to each other and the age norm (9.0 c/deg) at 40 wk.

Acuity data from an infant with myopic astigmatism are shown in Figure 4b. Acuity for vertical gratings, which for all viewing distances was hyperopic, was greater than that for horizontal and oblique at all ages and showed a normal developmental trend with age.

Acuity for horizontal, the myopic focus, was reduced significantly compared to vertical at 20 wk of age and still reduced, though to a lesser extent, at 30–40 wk of age.
Figure 4c shows acuity data from an infant who had the largest amount of hyperopia in combination with astigmatism in our sample. Compared to acuity norms and to his measured acuity for horizontal at 30 wk, this infant shows reduced acuity for gratings parallel to the orientation of the more hyperopic focal line, which in this case is vertical. When tested with optical correction at three different ages, acuity for vertical improves to normal levels (9.0–12.0 c/deg for a 9 to 12 month old infant).

Discussion

The only infant astigmats to show reduced acuity were those with a strong myopic focus and one infant with a very strong hyperopic focus. Their data reveal the consequences of the blurring effects of astigmatism when they cannot be compensated for by accommodation. The infant astigmats who were slightly to moderately hyperopic with respect to the 50-cm test distance show equal acuity for gratings parallel to the orientations of the anterior and posterior focal lines. In these cases, accommodation must be operating to compensate for the optical power differences between the two principal axes. Another possibility, especially for the younger infants, is that the blur produced may not have exceeded the infant's depth of focus.

Adults with large amounts of astigmatism have more severe deficits in acuity than those with smaller amounts. It is interesting to note that in the present study the myopic astigmats had the largest amounts of astigmatism, with a mean cylindrical error equal to almost twice that of the other infants. The large amount of astigmatism in combination with a myopic focus for all but the closest viewing distances resulted in deficits in acuity when these infants were tested without optical correction. When the data of the other infant astigmats, hyperopic for a wide range of viewing distances, were analyzed by amount, they failed to reveal a significant correlation between amount of astigmatism and acuity deficit.

One infant (Fig. 4c) had an unusually high amount of hyperopia in combination with astigmatism. His
data reveal a difference in acuity between vertical and horizontal when tested without optical correction. When tested with correction, however, the acuity of this astigmat was normal for his age, indicating an absence of meridional amblyopia. Data from one 6-month-old infant tested by Teller et al\textsuperscript{14} are in agreement. In addition, an extensive study in our laboratory of the orientation preference of infant astigmats also revealed no evidence for meridional amblyopia in the first year of life.\textsuperscript{16-18} Based on all these data, we conclude that meridional amblyopia must develop some time after the first year. Another possible interpretation is that meridional amblyopia is confined to high spatial frequencies. Infant acuity measured by preferential looking only reaches 12.0 c/deg by the end of the first year. The amblyopia may not manifest itself in that frequency range.

The acuity of most infant astigmats, excluding the myopes and the one strong hyperope, is not significantly different from the acuity of a group of otherwise comparable non-astigmats. Especially for oblique gratings, we had expected that the astigmats would show reduced acuity compared to the non-astigmats. However, depth of focus calculations from Green et al\textsuperscript{10} suggest that optical blur produced by oblique gratings would be less than the depth of focus, especially for the younger infants. This may partially account for these results.

The results reported here help to explain why the acuity values obtained from different laboratories show good agreement, even though few studies noted whether the infants tested had any refractive error. Approximately 50% of infants under 1 yr of age show astigmatism, but most are hyperopic for gratings presented at a close distance, and most show against-the-rule astigmatism.\textsuperscript{2-4} Since most researchers use vertical gratings presented at viewing distances of 30–50 cm, it is not surprising to find acuity within the normal range in infants with unknown refractions.

**Key words:** astigmatism, visual acuity, human infants, preferential looking, infant vision

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**References**