Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. MARTIN S. BANKS AND PHILIP SALAPATEK.

The importance of assessing infant visual function is indicated by recent demonstrations that early visual experience in part determines the eventual state of adult visual function. It is argued that the contrast sensitivity function (CSF) could be a valuable index in the assessment of infant vision because it provides information concerning several aspects of vision. CSF's were measured in 1-, 2-, and 3-month-old infants. The 'cut-off' spatial frequencies, which are estimates of visual acuity, were 2.4 cpd for 1-month-olds, 2.8 cpd for 2-month-olds, and 4.0 cpd for 3-month-olds. Sensitivity to contrast was shown to increase between 1 and 3 months of age. The CSF's measured also provide evidence for the presence of a low-frequency fall-off at 2 and 3 months.

The presence of ocular abnormality (e.g., strabismus, astigmatism, and myopia) during infancy and early childhood has been shown to have potential deleterious effects on visual development. Thus the detection of visual abnormality during infancy has become of greater clinical concern because intervention procedures may be necessary early in life for successful management. The recent increase in infant visual research reflects this concern.

The present report concerns the development of form vision in normal infants. Several measurements of infant visual acuity have appeared in the literature; visual acuity, however, is but one important aspect of form vision. The contrast sensitivity function (CSF), which is determined by measuring an observer's contrast threshold for sinewave gratings of various spatial frequencies, provides information about acuity as well as other properties of form vision including sensitivity to contrast and low-frequency attenuation. Furthermore, since the intensity distribution of any two-dimensional, time-invariant stimulus can be specified in terms of its spatial frequency content, the CSF provides a useful estimate of the form information to which an observer is sensitive.

The usefulness of the CSF to the study of infant form vision has been recognized by two groups of investigators. Atkinson et al. measured the CSF of a 2-month-old infant. Flashing and drifting gratings were used in a fixation-preference paradigm. Banks and Salapatek reported the CSF's of five 2-month-olds. They used stationary gratings in a somewhat similar fixation-preference paradigm. The present report is an extension of the latter study. The CSF's of 1-, 2-, and 3-month-old infants are reported.

**Method.** The subjects were six 1-month-olds (29 to 40 days), 10 2-month-olds (59 to 71 days), and eight 3-month-olds (87 to 101 days). The apparatus and procedure are fully described elsewhere. The stimuli were produced optically and projected onto a large stimulus field. Each test stimulus consisted of a vertical sinewave grating across half the stimulus field and an immediately adjacent, unpatterned stimulus across the other half of the field. The contrast and spatial frequency of the grating half-field could be independently varied. The space-average luminance of the grating half-field and the unpatterned half-field was 55 cd/m². The stimulus field was very large (96 by 40 deg) to maximize the infants' attention to the stimuli and to ensure that at least 7 cycles were presented at all spatial frequencies. The field was reflected by a large mirror so that the infants could view the stimuli while lying in a supine position. The viewing distance was 53 cm. This distance was chosen to minimize the contribution of accommodative error among the younger infants. Two pieces of evidence suggest the appropriateness of this target distance in this regard. First, the acuity of 1- and 2-month-olds is as high at this distance as at any other. Second, dynamic retinoscopy recently performed with a similar sample of infants indicated that 1- and 2-month-olds exhibit similar, small accommodative errors at 50 cm.

Between stimulus presentations a vertical, cross-hatched bar was projected at the midline of the stimulus field. The bar served as a fixation and accommodative stimulus. When an observer...
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Table I. Standard errors

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<tr>
<th></th>
<th>0.15 cy/deg</th>
<th>0.3 cy/deg</th>
<th>0.5 cy/deg</th>
<th>1 cy/deg</th>
<th>2 cy/deg</th>
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<tbody>
<tr>
<td>1 month</td>
<td>0.38</td>
<td>0.22</td>
<td>0.33</td>
<td>0.09</td>
<td>0.11</td>
</tr>
<tr>
<td>2 months</td>
<td>0.37</td>
<td>0.19</td>
<td>0.29</td>
<td>0.19</td>
<td>0.13</td>
</tr>
<tr>
<td>3 months</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
<td>0.18</td>
<td>0.18</td>
</tr>
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judged that the infant was fixating the bar, a 3 sec presentation of the grating and unpatterned half-fields occurred. Gratings of variable spatial frequency and contrast were presented to either the left or right of center. Two observers, who could not see the stimulus field, indicated whether the infants' first eye movement was to the left or right. The experimenter determined the number of hits and misses by comparing the observers' responses to the side on which the grating had been presented. A hit was recorded when both observers indicated that the first eye movement was to the side the grating had been on. A miss was recorded when both indicated the first fixation was to the side the unpatterned field had been on. A descending- and ascending-staircase procedure was employed to approximate each infant's contrast threshold at each spatial frequency. The procedure continued at a given spatial frequency until a contrast associated with a hit rate below 75% and a contrast associated with a hit rate above 75% had been presented. This required a minimum of 40 trials (20 at the contrast above 75% and 20 at the contrast below 75% at each spatial frequency). The final estimate of contrast threshold was obtained by linear interpolation to the contrast associated with a hit rate of exactly 75%. Five spatial frequencies, 0.15, 0.3, 0.5, 1, and 2 cy/deg, were presented to each infant. Thus each infant's CSF is based on a total of 200 to 300 trials.

Results and discussion. The average CSF's for the three groups of infants are shown in Fig. 1. The 1- and 2-month-olds' functions represent the average of individual functions for six 1-month-olds and six 2-month-olds. The 3-month-old function represents the average of eight 3-month-olds. Standard errors of log contrast sensitivity for each of the data points are given in Table I.

As mentioned earlier, the CSF provides a useful estimate of visual acuity. We followed a procedure commonly used in adult CSF studies to estimate acuity from our data. Each of the CSF's shown in Fig. 1 were replotted in log-linear coordinates. We then fitted lines by the method of least squares through the points at 0.5, 1, and 2 cy/deg for each of these functions to determine the spatial frequency associated with a contrast sensitivity of 1. The "cut-off" spatial frequencies determined by these lines were 2.4 cy/deg (S.E. = 0.4) for the 1-month-olds, 2.8 cy/deg (S.E. = 0.4) for the 2-month-olds, and 4.0 cy/deg (S.E. = 0.8) for the 3-month-olds. Statistical tests performed on the "cut-off" frequencies indicated that the 3-month-old values were significantly greater than the
1-month-old values (t = 4.31, p < 0.005, one-tailed). The 3-month-old values were also significantly greater than the 2-month-old values (t = 3.31, p < 0.005, one-tailed). Values for 1- and 2-month-olds did not differ significantly (t = 1.44, p > 0.10). It should be noted that although these "cut-off" values can be regarded as estimates of visual acuity in human infants, it is not yet known how well such estimates can generalize to other situations in which luminance, field size, duration, and other stimulus parameters are different. If one expressed our "cut-off" values in Snellen notation, these would correspond to acuities of 20/250 for 1-month-olds, 20/215 for 2-month-olds, and 20/150 for 3-month-olds, assuming that 20/20 corresponds to a "cut-off" frequency of 30 cy/deg. Such acuity estimates agree favorably with those of recent visually evoked cortical potential studies, even though a high threshold criterion (75% hit rate) was used in the present study. The 75% criterion used in the present study may in a sense be higher than the criterion used in the evoked-potential studies. If a lower criterion had been adopted, the acuity estimates would have been correspondingly higher. At any rate, this and other reports indicate that visual acuity appears to be quite poor early in infancy, yet to increase significantly during the first few months of life. The question arises from these findings: to what extent do simple optical factors rather than neural factors contribute to this acuity growth? The only purely optical factors potentially significant enough to constrain acuity to such low spatial frequencies are lack of clarity of the optic media and accommodative error. No large changes in media clarity are observed in full-term infants during the first months of life. Salapatek et al. and others have shown that young infant acuity does not vary across target distances between 30 and 150 cm; therefore accommodative error also would not appear to contribute significantly to age changes in acuity at target distances near the one used in the present study. Thus it appears that nonoptical factors such as receptor packing density, spatial tuning of retinal ganglion cells, and others may contribute most significantly to the development of acuity. One should not, however, rule out some potential contribution of optical factors.

Sensitivity to contrast is another important aspect of form vision revealed by measurement of the CSF. The ability of the visual system to detect contrast (which is generally defined as an intensity ratio: \( I_{\text{max}} - I_{\text{min}} / I_{\text{max}} + I_{\text{min}} \)) is intimately involved in the perception of visual form, since contrast generally defines forms in the first place. There are few studies in the literature concerning infants' sensitivity to contrast. Recently, however, Peeples and Teller measured the increment threshold of young infants. Two-month-olds were able to detect vertical stripes whose intensity differed by only 10% from the intensity of the background. This suggests a contrast sensitivity (reciprocal of contrast threshold) of about 19. Atkinson et al. also found a peak contrast sensitivity of about 11 in their 2-month-old. The functions in Fig. 1 of the present study indicate an average peak contrast sensitivity of 9 for 1-month-olds, 12.5 for 2-month-olds, and 15 for 3-month-olds. Thus there seems to be an increase in sensitivity to contrast during the first 3 months of life, an increase which must continue well beyond that age range, since peak adult contrast sensitivity with the same stimulus conditions is about 500 (Fig. 2).

A property of the adult visual system revealed by the CSF is low-frequency attenuation; adult...
contrast sensitivity is greater to intermediate spatial frequencies (2 to 10 cy/deg) than to lower spatial frequencies. Several investigators have argued that this low-frequency fall-off in the CSF is the result of lateral-inhibitory processing. The interpretation has recently been questioned, however. The critics of the interpretation have pointed out that stimulus field size is generally fixed and small in CSF studies, so that for low-frequency gratings, only a limited number of grating cycles are presented. Thus the critics have argued that the low-frequency attenuation generally found in CSF studies may be due to the limited number of cycles in low-frequency gratings and therefore that such attenuation is an experimental artifact and not a manifestation of lateral inhibition.

The stimulus field in the present experiment was very large so that a sufficient number of cycles could be presented at all spatial frequencies. Thus any observed low-frequency fall-off is unlikely to have been caused by a restriction on the number of cycles presented at lower frequencies.

The functions shown in Fig. 1 indicate the presence of the low-frequency fall-off in 2- and 3-month-olds but not in 1-month-olds. Individual data reveal that only two of the six 1-month-olds had CSF’s exhibiting a low-frequency fall-off. On the other hand, all six of the 2-month-olds’ and seven of the eight 3-month-olds’ functions exhibited a fall-off. To verify this finding, an additional four 2-month-olds were tested on the three lowest spatial frequencies. They too all exhibited a low-frequency fall-off. To perform statistical tests on the low-frequency portion of the CSF’s, lines were fit (using a least-squares criterion) through each subject’s data at the lower two or three spatial frequencies. The slopes of these lines were then calculated. The slopes for the 2-month-olds were significantly greater than zero (p < 0.01, one-tailed) as were the slopes for the 3-month-olds (p < 0.05, one-tailed). The 1-month-olds’ slopes were not significantly greater than zero (p > 0.20, one-tailed). Thus our data suggest that the low-frequency fall-off is generally present in 2- and 3-month-olds but generally not present in 1-month-olds. It is possible, however, that a low-frequency fall-off would be observed in 1-month-olds were lower frequency gratings employed. To the extent that the low-frequency fall-off of the CSF is related to the functional state of lateral-inhibitory processing, our data suggest that the strength and/or spatial tuning of lateral-inhibitory processing increases during the first months of life.

Comparison of Figs. 1 and 2 reveals that infants’ acuity, sensitivity to contrast, and low-frequency attenuation become more adultlike across the first 3 months of life. This implies that the development of these basic properties of form vision proceeds relatively rapidly during early infancy. Studies of infants with ocular pathology (gross refractive error, lenticular opacity, etc.) should reveal the extent to which such development is experientially dependent. Comparison of Figs. 1 and 2 also shows that acuity and sensitivity to contrast must continue to develop beyond early infancy, since by 3 months of age the acuity and sensitivity values attained are still well below those of an emmetropic adult.

Key words: infant vision, visual acuity, contrast sensitivity, lateral inhibition, development of vision, fixation preference

REFERENCES


Albino-beige mice were produced in order to combine two experimentally useful characteristics, albinism and lysosomal dysfunction, in the same animal. The retinal pigment epithelium of albino-beige mice formed giant granules. Additional, incompletely processed lysosomal dysfunction, in the same animal. The retinal pigment epithelium, resulting in intracellular granules. Exposure of albino-beige mice to white light of 150 foot-candles for 3 to 10 hr induced marked phagocytosis of rod outer segment fragments by the retinal pigment epithelium. This new albino mouse should be useful for studying the possible roles of the retinal pigment epithelium and in the maintenance of photoreceptor cells and in their recovery from light damage and other insults.

Beige mice exhibit anomalous lysosomes and delayed breakdown of phagocytized materials, thus providing an opportunity for studying a retinal pigment epithelium which may show altered processing of ingested rod outer segment membranes. Since the light exposures of the pigment epithelium needed to control phagocytosis experimentally are more reproducible in albino than in pigmented animals, an attempt was made to produce mice which were albino yet had the inheritable lysosomal disorder which has been well characterized in beige mice and Chediak-Higashi patients. The development of a new animal model—the albino-beige mouse—should allow more definitive studies on the effects of light on the phagocytosis and processing of rod outer segment disks by the retinal pigment epithelium.

Materials and methods. All mice used were homozygous nonagouti (a/a) and were congenic descendants of albino (c²/c²) and/or beige (t²/t²) mice of the C57BL/6J strain obtained from Jackson Laboratory, Bar Harbor, Maine. They were raised from birth on standard laboratory diet and unlimited water under 12 hr cyclic illumination of less than 4 foot-candles at temperatures of 21° to 27°C. The genetic crosses are described in the next section (Results).

Experimental animals were exposed for the times indicated to 150 foot-candles of white light supplied by three 12-inch Circline fluorescent bulbs (cool white) that were dimmed by a voltage control and shielded by a light diffuser around a 9-inch wire cage. Fans maintained the cage temperatures at 25° to 27°C. Control mice were exposed to 4 foot-candles at the same temperatures.

The mice were sacrificed between 8:00 and 10:00 A.M. by intraperitoneal injections of sodium pentobarbital (0.2 ml). Retinas were fixed and incubated histochemically as described previously, using only regions within 1.0 mm of the optic disc.

Results

Origin of the albino-beige mouse. Albino-beige mice were produced by a dihybrid cross from congenic parental strains. First, C57BL/6J-c²/c² and C57BL/6J-t²/t² were crossed. The F₁ generation, C57BL/6J-c²/t² +/+ bg²/bg², was black, since normal dominant genes were present at the albino (c) and beige (bg) loci.

The gene for pigment formation was contributed by the beige mouse, which can synthesize melanin normally but is grayish rather than black because the pigment is packaged in larger than normal granules.

The gene for standard pigment granule size was contributed by the albino mouse, which is unable to synthesize pigment but has normal-size premelanosome granules.